

Edited by
ANGELA L. COE



GEOLOGICAL FIELD TECHNIQUES

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GEOLOGICAL FIELD TECHNIQUES

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Front cover image: Carboniferous age (Namurian) rocks exposed at Sugar Sands Bay, near Alnwick, Northumberland, UK. These are part of a succession of rocks interpreted as infill of an interdistributary bay or lagoon along the shore of a delta. Superimposed on the photograph is part of a graphic log of the succession summarizing the thickness of the units, lithology, sedimentary structures and cycles. (Angela L. Coe, The Open University, UK.)

Back cover images (in descending order):

1. Walcott Quarry, Canadian Rockies during 1998 showing the exposure of the Burgess Shale (Cambrian) that is famous for the exceptional soft body preservation of some of the oldest fossils on Earth. (Angela L. Coe, The Open University, UK.)
2. Geologists working on the organic-rich mudrocks of the Monterey Formation (Miocene), Naples Beach, California, USA. (Anthony S. Cohen, The Open University, UK.)
3. Asymmetric folds in Proterozoic strata, Harvey's Return, Kangaroo Island, Australia. Lens cap is 5.5 cm across. (Tom W. Argles, The Open University, UK.)
4. A Silva compass-clinometer being used to measure the dip of a fault plane, Whitesands Bay, St David's, Wales, UK. (Tom W. Argles, The Open University, UK.)
5. The ammonite *Psiloceras planorbis* (J. de C. Sowerby) from the Lias Group, UK. This species defines the lowermost ammonite zone of the Jurassic. Ammonite is *c.* 4 cm across. (Peter R. Sheldon, The Open University, UK.)

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- All figures and tables from the book
- Additional exercises and answers
- Useful websites, selected by the authors

GEOLOGICAL FIELD TECHNIQUES

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Preface

Working in the field contributes a crucial element to our knowledge and understanding of Earth processes, whether it is the prediction of volcanic eruptions, understanding periods of past climate change recorded in sedimentary deposits, deciphering an episode of mountain building, or working out where to find mineral resources. Without primary field data and geological samples of the highest quality, further scientific study such as sophisticated isotope measurements or the reconstruction of past life assemblages and habitats is at best without context, and at worst, completely meaningless.

Geological fieldwork can be both fun and challenging. It provides the chance to work outdoors under a range of conditions and to explore our natural world. It also provides an often unparalleled opportunity to travel and visit localities as more than a tourist. Indeed it often takes you to unspoilt parts of the world that tourists rarely penetrate. Almost all fieldwork enables us to work as part of a team, often with international partners, and this can be one of the most rewarding experiences of being a geologist because we can learn from each other. Many long-term friendships have been forged through geological fieldwork.

This book is aimed primarily at undergraduates studying geology and Earth sciences. It will also potentially be of use to engineers, archaeologists and environmental scientists who need to collect information on the bedrock. The increasingly multidisciplinary nature of science will make the text useful to masters, doctoral and professional scientists who do not have a background in practical geology or Earth science. The book is non-site specific and includes examples from around the world. There are chapters covering data collection from igneous, metamorphic and sedimentary rocks as well as specific chapters on palaeontological and structural data collection. It also deals with the basics of geological mapping.

The book assumes a basic understanding of the main concepts and theory in geology. It assumes that the reader is familiar with: the major rock-forming minerals, how to identify minerals in hand specimen, rock classification, geological processes and common geological terms. The further reading lists at the ends of the chapters provide a selection of introductory geological texts as well as more specialist ones. In addition there are appendices summarizing key geological features and classification schemes. There is also an accompanying website (www.wiley.com/go/coe/geology) with all of the figures, tables, links to other websites and other material. Reviews of the original book proposal suggested expansion of certain chapters and even the deletion of others, however, none of the reviewers agreed on which chapters these should be so clearly it is a matter of personal preference. We have therefore kept to the broad overview, and refer the reader to more specialist fieldwork texts that are available, and hope that this book inspires others to write textbooks on more specific fieldwork topics that are not available.

Writing a book on field techniques has long been an ambition of mine; the style and organization has had a lengthy gestation period during many months of fieldwork, both as a researcher and a university lecturer. I am delighted that when I was eventually able to spend some time completing this task I was joined by a number of colleagues who had expertise that complemented my own; it has been a pleasure to work with them. I would like to thank all the colleagues, PhD students and undergraduate students that I have worked with. My experience of being with them in the field has helped me to shape this book.

Wishing you both enjoyable and highly productive fieldwork.

Angela L. Coe
The Open University, November 2009

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We are very grateful to Tiffany Barry, Kate Bradshaw, Richard Brown, Brian McDonald, Susan Ramsay, Janet Sumner, Paul Temple and Clare Warren, all of whom were brave enough to lend us their field notebooks for reproduction in this book. We are also grateful to Kate Andrew and Susie Clarke who kindly allowed us to copy part of their geological field and fair copy maps. The unpublished field notes of these individuals are accredited in the figure captions.

Many thanks go to Ian Wightman whose inspiring and amusing cartoons have livened up this book. Andrew Tindle (The Open University) is thanked for his excellent photography of most of the hand specimens (particularly Chapters 8 and 9) and for providing a set-up for photographing specimens and field notebooks. Various colleagues have allowed us to reproduce their photographs in this book, for which we are grateful. These individuals are acknowledged in the figure captions. Andrew Whitehead and David DuPlessis with the help of Chris Hough and Jon Owen (The Open University) prepared the final version of the figures. Richard Howes is thanked for general assistance with the electronic files. We are grateful to Andrew Lloyd for help with scanning, image processing and also for contributing to the design and preparation of the cover image for this book.

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Last, but not least, we would like to thank our field colleagues, and students, for interesting and stimulating discussion in the field.

Figure acknowledgements

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1 Introduction

Angela L. Coe

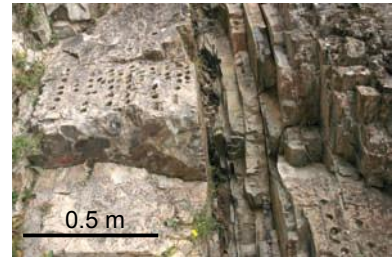
The main aim of field geology is to observe and collect data from rocks and/or unconsolidated deposits, which will further our understanding of the physical, chemical and biological processes that have occurred over geological time. Many of the basic observational principles used in field geology have not changed for hundreds of years, although the interpretation of the data, the scale of resolution and some of the equipment has advanced greatly. Fieldwork involves making careful observations and measurements in the field (Figure 1.1a) and the collection and precise recording of the position of samples for laboratory analysis (Figure 1.1b). The very act of collecting field data often raises questions about processes on Earth, which had perhaps not previously been envisaged. Furthermore, during fieldwork it is usual to initiate, or to build on, constructing and testing different hypotheses and interpretations based on the observations; this iterative process will help to determine the essential data and samples to collect.

This book is divided into 14 chapters. Chapter 2 covers the most commonly used field equipment and outlines field safety procedures. Chapter 3 explores the general objectives of fieldwork and how to make a start. Chapter 4 is devoted to the production of a field notebook (hard copy or electronic), as this is the key record of geological field data. The bulk of the book comprises five chapters covering the necessary skills for the collection of palaeontological (Chapter 5), sedimentological (Chapter 6), igneous (Chapter 7), structural (Chapter 8) and metamorphic data (Chapter 9). Chapter 10 uses the field techniques covered in the previous five chapters to introduce geological mapping, where it is usually necessary to deal with a range of rock types and different kinds of exposure*. The book concludes with short chapters on recording numerical and geophysical data (Chapter 11), photography (Chapter 12) and sampling (Chapter 13).

*The term exposure is used to indicate areas where rocks are visible at the Earth's surface. This is in contrast to the term outcrop which also encompasses those areas where the rock is at the Earth's surface but is covered by superficial deposits and soil.



(a)



(b)

Figure 1.1 (a) Geologists collecting data for a graphic log (Section 6.3) to record how a sedimentary succession has changed through time and to decipher the overall depositional environment. By working together they can share tasks and discuss their observations. (b) The recessed bed marks the Cretaceous–Paleogene boundary at Woodside Creek, near Kekerengu, New Zealand. Note the holes where samples have been extracted for palaeomagnetism studies. In this case the number of holes is rather excessive and breaks the code of good practice (Section 2.12 and Chapter 13). (a and b: Angela L. Coe, The Open University, UK.)

Field geology presents four main intellectual challenges. These are:

1. Deciding what data to collect in order to address the scientific question(s).
2. Finding the most suitable exposures from which to collect the data.
3. Making a good record of the data collected; preferably a record that can be understood by others and can be used years after the data were collected.
4. Understanding and interpreting the basic observations that you make.

This book deals with challenges 1, 2 and 3. Challenge 4, interpreting the observations, is to a large extent a matter of experience and having a good theoretical understanding of geology and geological processes. There are many general geological and Earth science textbooks on the market, a selection of which are included in the further reading lists at the end of each chapter. Deciding what data to collect relates directly to the objective of the fieldwork (Chapter 3). Some typical overall objectives are: constructing the geological history of a region (Chapter 10), collecting data on a period of climate change (Chapter 6), gathering evidence for a mass extinction event (Chapter 5), understanding a phase of igneous activity (Chapter 7) or mountain building (Chapters 8 and 9), together with finding and evaluating mineral or water resources and understanding natural hazards (e.g. landslides, earthquakes and floods; Chapters 6 and 8). Within each of these major objectives the fieldwork should be broken down into achievable daily tasks. Locating the most suitable exposures is crucial if the objective of the fieldwork is anything other than detailed mapping where ideally all exposures need to be examined. The different types of exposure are dealt with in Chapters 3 and 10, and more specific examples are given in Chapters 5–9. Throughout the book, but particularly in Chapter 4, we have provided ideas and examples for constructing effective field notebooks. We have also added practical tips in the margin, and flowcharts for deductive thinking processes and tasks. In Chapters 5–10 we have used worked examples to demonstrate both the method of reasoning and the way in which particular problems have been tackled.

1.1 A selection of general books and reference material on geology

Allerby, M. 2008. *A Dictionary of Earth Sciences*, Oxford University Press, 672 pp.

- Bishop, A., Woolley, A. and Hamilton, W. 1999. *Minerals, Rocks and Fossils*, Cambridge University Press, 336 pp. [Small book with colour photos and brief, reliable descriptions of minerals, rocks and fossils.]
- Cockell, C., Corfield, R., Edwards, N. E. and Harris, N. B. W. 2008. *An Introduction to the Earth-Life System*, Cambridge University Press and The Open University, 328 pp. [Full colour book covering Earth system science at the Earth's surface with particular reference to life systems.]
- Grotzinger, J., Jordan, T. H., Press, F. and Siever, R. 2006. *Understanding Earth* (5th edition) W. H. Freeman & Co., 670 pp. [An outstanding, clearly written, widely used introduction to Earth sciences with many colour illustrations providing a global perspective.]
- Keary, P. 2005. *Penguin Dictionary of Geology*, Penguin, 336 pp.
- Murck, B. W. 2001. *Geology: A Self-teaching Guide*, John Wiley & Sons, 336 pp.
- Rogers, N. W., Blake, S., Burton, K., Widdowson, M., Parkinson, I. and Harris N. B. W. 2008. *An Introduction to Our Dynamic Planet*, Cambridge University Press and The Open University, 398 pp. [Full colour book covering the solid Earth aspects of Earth system science, including planetary formation, the Earth's structure, plate tectonics and volcanology.]
- Rothery, D. A. 2010. *Teach Yourself Geology* (4th edition), Hodder and Stoughton, 288 pp. [Covers all of the basics and is useful as either a primer or a refresher.]
- Stanley, S. 2005. *Earth System History*, W. H. Freeman & Co., 567 pp. [Accessible look at the Earth as a system. Extensively illustrated in full colour.]

1.2 Books on geological field techniques

- Compton, R. A. 1985. *Geology in the Field*, John Wiley & Sons, 398 pp. [Comprehensive but dense black and white book on basic geology and field techniques. Replacement of Compton's *Manual of Field Geology* (1962).]
- Freeman, T. 1999. *Procedures in Field Geology*, Blackwell Science, 93 pp. [Pocket sized, black and white book covering mainly mapping techniques, with particular emphasis on compass-clinometer and trigonometric solutions for recording the geometry of geological features.]
- Maley, T. S. 2005. *Field Geology Illustrated*, Mineral Land Publications, 704 pp. [Book illustrating geological features and terms through hundreds of clear black and white photographs and line drawings.]

See also: Barnes and Lisle 2003 (Section 10.7); Fry 1991 (Section 9.5); McClay 1991 (Section 8.4); Stow 2005, Tucker 2003 (Section 6.6); and Thorpe and Brown 1991 (Section 7.5).

2 Field equipment and safety

Angela L. Coe

Table 2.1 Equipment required for most geological fieldwork. Clothing and safety equipment is discussed in Section 2.11.

Essential field equipment

Field notebook

Pencils, eraser, pencil sharpener

A few coloured pencils

Tape measure, surveyor's tape or folding ruler

Hand lens

Compass-clinometer

Comparison and identification charts appropriate to the task

Relevant topographical maps

First aid kit and any personal medical supplies that might be required

Backpack/rucksack

Food and water sufficient for the fieldwork period

Emergency food supplies

Suitable clothing and footwear

Spare clothing and/or sunblock as appropriate

Mobile phone, radio or satellite phone

Safety equipment as appropriate

This chapter covers general geological field equipment and its use. It also provides an overview of the health and safety requirements in the field. More specialist field equipment and safety considerations are covered within Chapters 5–10 where appropriate. Sampling is covered as a separate topic in Chapter 13 and photographic equipment is briefly reviewed in Chapter 12. All the health and safety notes provided in this book are generic. Other sources and regulations will need to be consulted and followed depending on the field area, the country, the nature of the fieldwork and the regulations of your employer or educational institution.

2.1 Introduction

Before going out into the field it is necessary to: (1) assemble all of the field equipment that you might need; (2) assess any safety issues; and (3) if necessary obtain permission to visit the area. Both the safety and permission aspects may require documentation to be completed. Exactly what equipment you will need depends on the type of fieldwork you will be undertaking. The items required for most fieldwork tasks are listed in Table 2.1, and the equipment usually needed for sampling in Table 2.2 on p. 6. Optional equipment and that needed for more specialist tasks is listed in Table 2.3 on p. 6.

Quantification of geological observations

In almost all cases geological observations should be quantified because of the need to construct accurate and precise records. This is achieved through the use of measuring tapes, a compass-clinometer, rock comparison charts and more sophisticated geophysical equipment. This chapter provides information on how to master the basic geological measurements. More advanced techniques and those applicable to particular rock types are covered in the later chapters and more specialist books.

How accurate the measurement needs to be, or whether an estimate is sufficient, depends on the objective of the exercise and the quality of the exposure. For example, if all you need is a general description of a sandstone body it may be sufficient to describe it as a sandstone with beds of variable thickness between about 10 cm and 2 m. However, if you need to sample the sandstone or determine how the thickness of the individual units varies laterally then it will be necessary to measure the thickness of each of the units. Equally in most cases there is a need to record the azimuth (direction relative to north) and the magnitude of the vertical angle or dip to the nearest couple of degrees rather than just the general direction. This is because of the need to convey important information on the direction of different processes (e.g. folding or palaeocurrents) and, importantly, enable an accurate record of the geometry of rock units to be calculated and recorded.

2.2 The hand lens and binoculars

The hand lens is an essential piece of equipment for the detailed observation of all rock types and fossil material. Most have a lens with 10× magnification and some contain both a 10× and a 15× or 20× lens (Figure 2.1). If your eyesight is poor, a better quality lens will often help, especially a larger lens. It is also possible to obtain lenses with built-in lights, which can enhance the image considerably, e.g. Figure 2.1; lenses 2 and 3.

To use the hand lens, ensure that you are standing firmly or sitting down. Examine the specimen carefully first with the naked eye to find an area where it is fresh rather than weathered or covered in moss or lichens or algae, and also so that you can see where there are areas of interest such as well defined grains or crystals. If necessary, to ensure that when you look through the lens you have the correct area, place your finger tip or thumb tip as a marker adjacent to the area of interest identified with your naked eye. Place the lens about 0.5 cm away from your eye. Then, gradually move either the rock if it is a hand specimen, or yourself and the lens if it is an exposure, until the majority of the field of view comes into focus (usually about 1–4 cm away; Figure 2.2). Not all of the rock's surface will be in focus at the same time because of its unevenness. You will need to rotate the hand specimen or move your position to look at different areas. In the case of some metamorphic rocks and carbonate sedimentary deposits it is also useful to examine a weathered surface because the minerals or grains sometimes weather out and are often easier to see.

Binoculars can be very useful during fieldwork. They can be used to assess access, for instance in mountain regions.

However, their most common use is to obtain a better view of



Figure 2.1 A variety of different hand lenses. (1) Standard 10× single lens; (2) 10× lens with built-in light – the lens casing matches the focal length; (3) 8× lens with built-in light; (4) 10× and 15× dual lens.



Figure 2.2 Photograph to show correct use of the hand lens. Note that the person is holding the lens close to his eye. The lens is fastened on a lanyard around his neck for ease of access and use.

Table 2.2 Typical sampling equipment. See also Chapter 13.

Sampling equipment

Geological hammer

Sample bags

Paper, cling film or bubble wrap to wrap delicate samples

Marker pens/tile scribe/correction fluid for labelling

Chisels and other hammers

Trowel and/or spade for soft sediments and pyroclastic deposits

Table 2.3 Optional and specialist field equipment.

Optional and specialist equipment

Mapping pens/fine tipped pens

Relevant literature

Handheld GPS

Camera (Chapter 12)

Geophysical tools (Chapter 11)

Penknife

Weak hydrochloric acid (c. 10%)

Clipboard or mapping case

Rule and protractor

Mapping pens, coloured pencils

Binoculars

Scratch/streak plate

Pocket stereoscope

Geological Munsell colour chart

Jacob staff

Hand brush to clean exposure

Hoe pick for cleaning sections

the details within parts of an exposure that are impossible to reach safely, or are simply better viewed from a distance (e.g. geometry of features such as faults and river channel infills). They are particularly useful for examining the detail of contacts between different units in vertical sea cliffs and quarry faces. A wide range of good quality lightweight binoculars is available on the market.

2.3 The compass-clinometer

The compass-clinometer is used to measure: (1) the orientation of geological planes and lineations with respect to north; and (2) the angle of dip of geological features with respect to the horizontal. This allows an accurate record of the geometry of the features to be constructed. The compass-clinometer can also be used in conjunction with a topographic map to accurately determine location.

There are two main types of compass-clinometer design on the market (Figure 2.3, pp.8–9): the first type is made by Brunton, USA, Freiburger, Germany and Breithaupt, Germany; the second type is made by Silva and Suunto, both based in Sweden. The Brunton-type compass-clinometer is a more sensitive device because of the in-built spirit levels and the graduation of the scales in 1° rather than 2° increments. The Brunton-type can also be used for more tasks (see below); however, it is bulkier, more expensive and for some functions more difficult to use. The accuracy of the Silva-type compass-clinometer is sufficient for most purposes and is much better designed for directly transferring compass directions to a map (Section 2.3.3). Because the design of the two compass-clinometers is different, their operation for some measurements is also different. Instructions for both types of compass-clinometer are provided in this section*.

The compass-clinometer is both a magnetic compass and a device to measure the magnitude of the angle of dip of a surface from the horizontal. In order to do this it has two needles and two quite different scales (Figure 2.3b and d). When the compass-clinometer is orientated with the compass window horizontal the magnetic needle will always point towards magnetic north – unless, that is, there is another magnetic body that is affecting it such as your hammer, a metal pen or a large magnetic body of rock. In addition if you are at very high latitudes compasses do not work well. Associated with the magnetic needle is a circular dial on the outside of the compass

*Apple have incorporated both a digital tilt meter (clinometer) and a compass in their iPhone making it possible to measure dips and strikes of planes and lineations. However, there is no sighting apparatus so it is not possible to do everything you can with a compass-clinometer.

window that provides a measure of the azimuth in degrees away from north. The azimuth method for determining direction uses a circle with the value increasing clockwise from north at 0° (= 360°). On the Silva-type the dial can be rotated to place the needle at 0° . The azimuth reading for the direction in which the sight at the end of the mirror is pointing can be read off using the 'marker for azimuth reading (1)' (Figure 2.3d). Note that because the azimuth scale is fixed in the Brunton-type and the needle moves relative to this the compass is numbered and labelled anticlockwise. The azimuth for the direction in which the long sight on the Brunton-type is pointing (Figure 2.3b) is the reading at the north end of the compass needle. Compass directions from north can either be reported approximately, e.g. northwest, east, etc., or to the nearest degree. The Brunton-type compass also has a built-in locking pin for the magnetic needle to temporarily hold the needle in place when a reading is taken (Figure 2.3c).

The design and working mechanism of the clinometer part of compass-clinometers varies between the different makes and models. However, the principle of the clinometer is exactly the same. On both types of compass there is a scale on the inner part of the compass window to measure the magnitude of the angle between the needle and the horizontal (clinometer scale; Figure 2.3b, d and e). To use the clinometer part, the instrument needs to be held with the compass window vertical and the long edge at the same angle as the dipping surface. In the case of the Brunton-type the long edge adjacent to the east on the azimuth scale needs to be at the base because of the way the clinometer scale is orientated. The Brunton-type compass has a clinometer arm, the position of which can be adjusted using the lever on the back of the device (Figure 2.3c). When it is correctly adjusted for a particular dip angle the bubble in the long level should be in the centre. In contrast, the Silva-type has a clinometer needle that floats free and vertically downwards when the device is held on its edge vertically. The clinometer needle will hold its position if the instrument is carefully tilted about 20° from the vertical to the horizontal. In order to measure the dip on the Silva-type the compass dial needs to be set so that (i) the 'marker for azimuth reading (1)' (Figure 2.3d) is at 90° or 270° and (ii) the long edge of the compass-clinometer is orientated so that the clinometer scale is at the bottom where the clinometer needle is located. It may help to think of the clinometer as a protractor within the compass housing with a plumb line (the needle) indicating the magnitude of the angle relative to the horizontal. To test how your model works try holding the compass-clinometer as if it was on a horizontal plane and then increasing the angle to 45° and then to 90° . The operation of both types of compass-clinometer for specific applications is explained and illustrated later in this section.



BEWARE! Compasses can be affected by rocks containing magnetic minerals (e.g. serpentinite, gabbro), iron objects (gates, hammers, cars), and wires with electric currents passing along them (e.g. power lines). Always check odd readings!

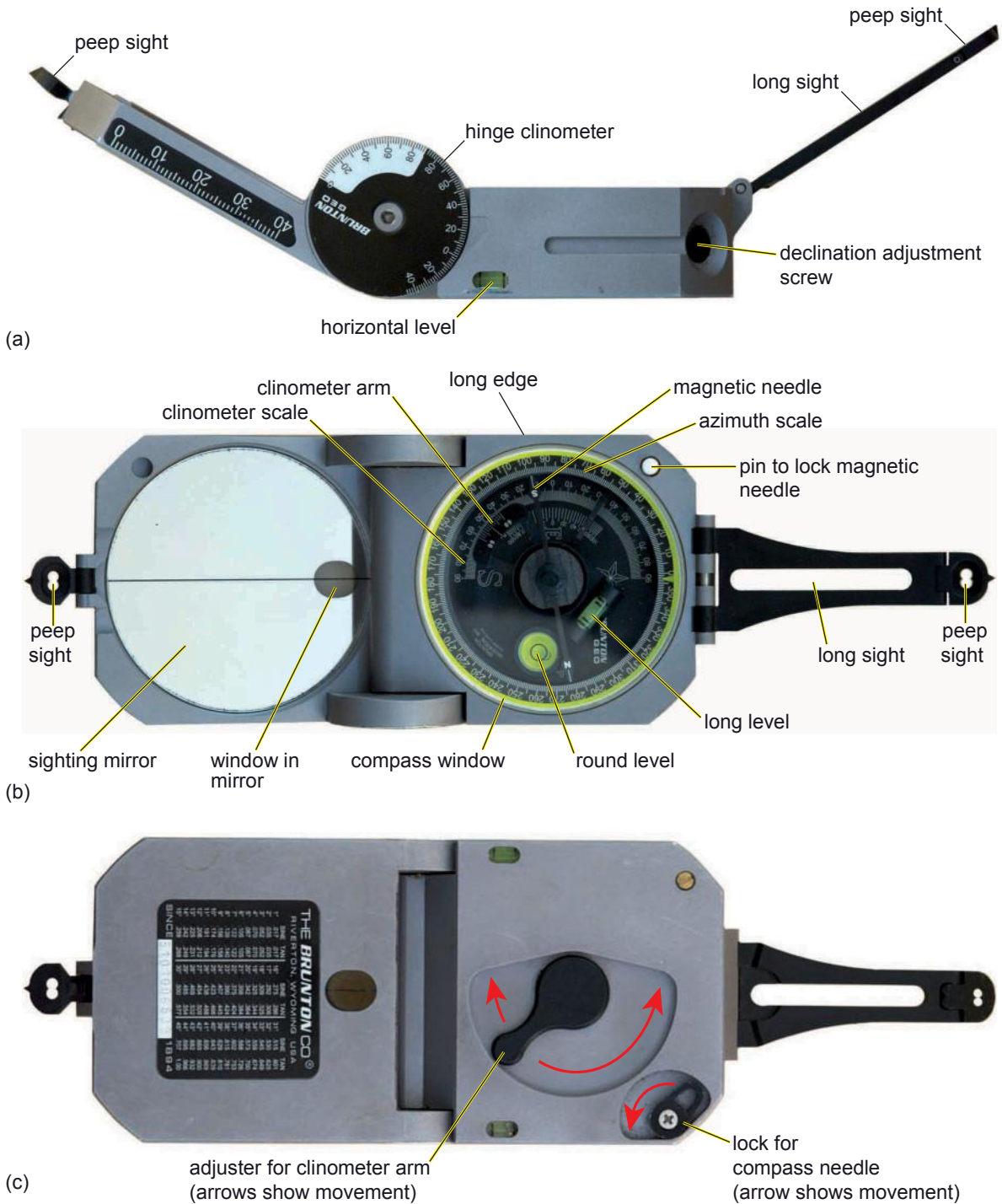


Figure 2.3 Labeled photographs of the parts of two of the most commonly used types of compass-clinometer. These terms are referred to in the text and in other figures. (a)–(c) The Brunton-type compass-clinometer: in this case the Brunton Geo. Views: (a) side; (b) top; (c) bottom.

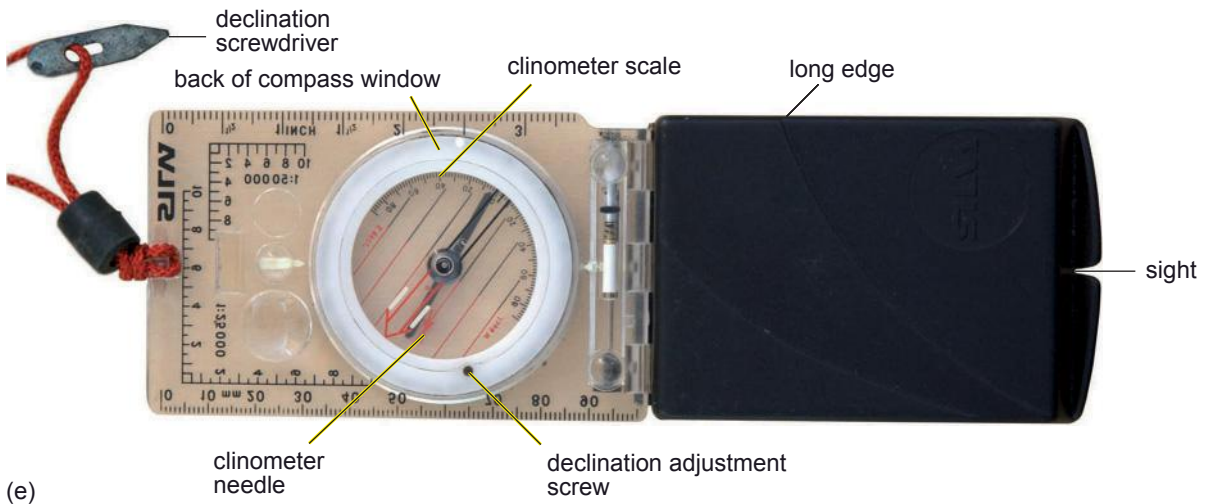
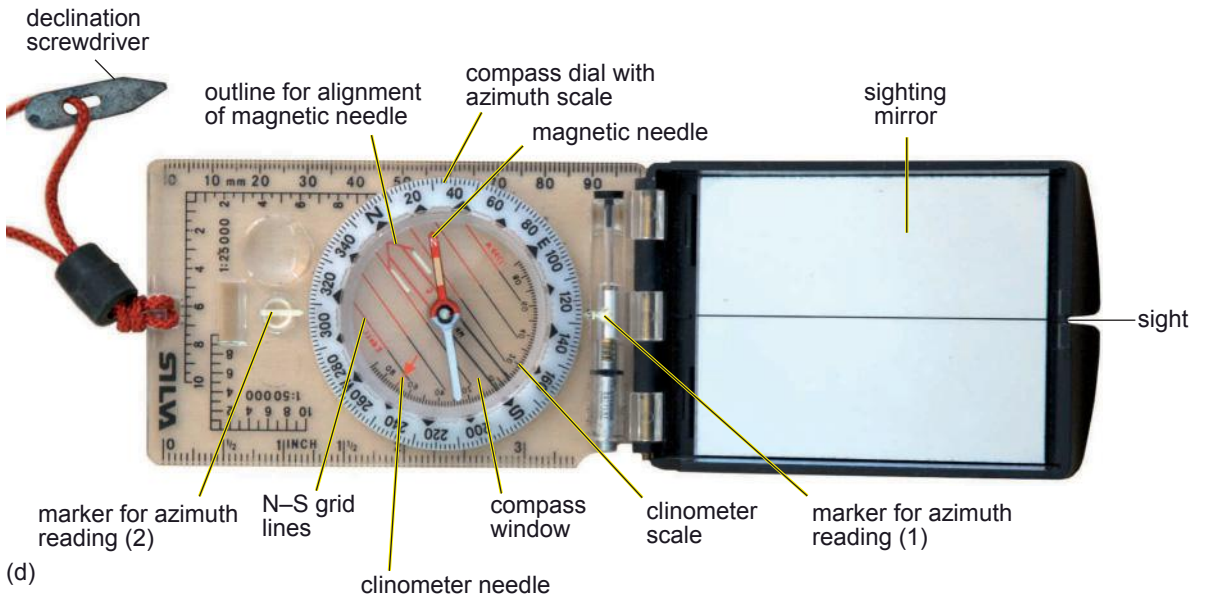
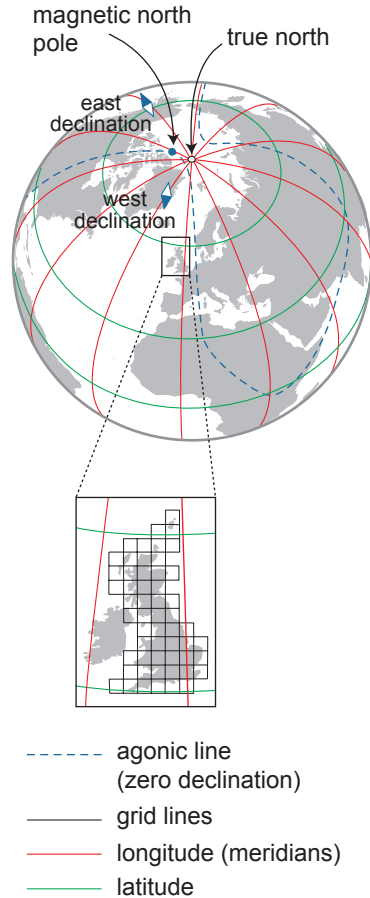
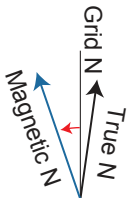


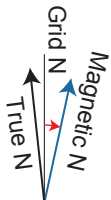
Figure 2.3 *Continued* (d)–(e) Silva-type compass-clinometer: in this case the Silva Expedition 15TDCL. Views: (d) top; (e) bottom. There are small variations from model to model, with more features on some models. Compass-clinometers from other manufacturers have similar features.



(a)



(b)



(c)

Magnetic declination

The Earth's rotational pole (true north) is not coincident with magnetic north and varies by as much as 30° either side of true north and even greater closer to the poles. Not only that, this declination varies with geographical location *and* over time. On maps the N–S grid lines are orientated as close as possible to true north but again this varies by a very small amount depending on your location. This is because grid systems are rectangular but meridians (lines of longitude) converge towards the Earth's pole (Figure 2.4).

Before taking any azimuth readings it is strongly advised that you adjust your compass for magnetic declination for the area you are visiting and the year so that there are no resulting errors in the azimuth measurement. It is a good idea to also make a note of what you have done in your field notebook so that there is no ambiguity later. The less favoured alternative is to make a note at the start of your field notes for that locality that the readings need adjusting for magnetic declination and then to correct them after you return from the field, *except*, that is, if you are using your compass for triangulation to plot your position (Section 2.3.3) or if you are plotting measurements directly on the base map – i.e. the topographical map onto which geological data will be added (Chapter 10). In this case it must be adjusted at the time of the measurement if your readings are to be accurate.

Adjusting your compass to take the magnetic north variation into account is easy. On the compass dial or side of the compass there is a screw, the declination adjustment screw (Figure 2.3a and e, pp.8–9); turn this screw by the amount of declination relative to grid north for the area and year using either a screwdriver or, for the Silva-type, the tool provided. To find out how much the magnetic declination is for the area there are three possibilities: (a) consult the legend of the topographical map of the area, taking note of changes since the publication date; or (b) use one of the many web pages now available that will calculate the declination for the area where you are completing fieldwork; or (c) determine the declination yourself in the field as follows.

1. Ensure that the magnetic declination on the compass-clinometer is set to 0° .



Figure 2.4 (a) Simplified sketch of the Earth to show the relationship between magnetic declination, magnetic north, true north and, via the inset, the longitude, latitude and a grid system (in this case the UK grid squares). (b and c) Typical map information showing magnetic north, true north and grid north. The adjustment of the magnetic declination is shown by the red arrows; (b) is for a westerly declination of magnetic north from true north and (c) is for an easterly declination.

- Stand at a known location and take a bearing on a feature identified on a map of the area (Section 2.3.3 explains how to do this).
- Compare the compass reading with the azimuth between your location and the feature provided by the map; the difference is magnetic declination.
- Alternatively use a straight feature on the map such as a wall or forest boundary and compare the reading from sighting along the linear feature with that given on the map.

Once you have determined the declination ensure that you adjust the declination in the correct direction. On the Silva-type compass the numbers increase in a clockwise direction whereas they increase in an anticlockwise direction on the Brunton-type. This is because of the different way in which the dial works; when used correctly they will give exactly the same azimuth reading.

2.3.1 Orientation of a dipping plane

The most common type of measurement in geology is the orientation of a dipping plane: for instance a bedding plane, a cleavage plane or a fault plane. The following three parameters need to be measured and recorded: (1) maximum angle at which the plane dips (dip magnitude) in degrees relative to the horizontal; (2) the orientation of the plane relative to north (strike, i.e. orientation of the *horizontal* line defined by the plane) in degrees; and (3) the general dip direction (Figure 2.5) because from the strike alone the plane could be dipping in one of two directions at 180° to each other. To prevent confusion, strike is always recorded as a three-digit number and dip as a two-digit number. Apart from this convention on the number of digits, there are several equally valid and commonly used notations to combine the dip and strike; these are summarized later in Table 8.1. For clarity, a consistent style of notation should be chosen.

Determination of the orientation of a dipping plane by the contact method

The orientation of a dipping plane is most commonly measured using the contact method. This is illustrated for the Silva-type compass-clinometer in Figure 2.6 (pp. 12–13) and the Brunton-type compass-clinometer in Figure 2.7 (pp. 14–15). The exact order that you complete the steps and obtain the strike and dip of the plane is not crucial; this will depend on the instrument used, field conditions and personal preference. What is important is ensuring that you record the three pieces of information (strike, dip magnitude and dip direction). Note that the order of the steps in Figures 2.6 and 2.7 is different to take account of the

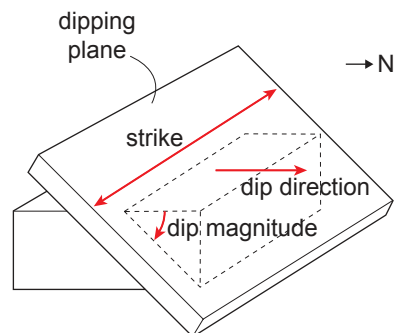


Figure 2.5 Sketch to show strike, dip magnitude and dip direction of a plane. See also Figures 2.6 and 2.7. Using the north arrow shown this imaginary plane is striking east–west (270° or 090°) and dipping to the north. Any direction down the dipping plane that is not at right angles to the strike will be an apparent dip direction and will have a smaller dip magnitude than the true dip magnitude.



E

1. General orientation

Find a good surface that is representative of the overall dip of the plane to measure. Determine the general direction of dip by looking at the plane or you can pour fluid over the bedding plane to see which way it runs. In some cases it may be necessary to smooth out the variations on the surface by placing a notebook or clipboard on the bedding plane, but take care to ensure that this is not biased by a small irregularity. Hammer near left hand side shows the plane chosen in this case.



2. Set the clinometer mode

Prepare the compass-clinometer for the clinometer mode by setting the top of the clinometer part so that it is parallel to the long edge of the compass-clinometer (i.e. put the compass dial at 90–270°).



3. Dip magnitude

Place the long edge that is at the base of the clinometer scale on the bedding plane, with the long edge of the compass-clinometer parallel to where you estimate the maximum dip direction lies (i.e. pointing down the slope). While looking at the clinometer reading, carefully rotate the compass-clinometer device slightly (as shown by the arrows) to find the line of maximum dip.



Read off the maximum dip. In this case it is 12°. Note that the dip can be read from either side of the Silva-type compass-clinometer.

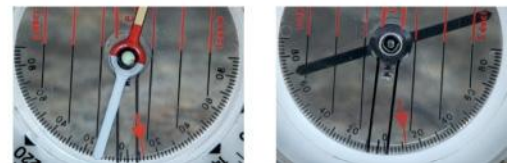


Figure 2.6 How to use the Silva-type compass-clinometer to measure the orientation and dip of a plane using the contact method. The parts of the compass-clinometer are shown in Figure 2.3d and e.



4. Strike direction

The strike direction is exactly perpendicular to the dip direction, so remembering where the maximum dip lies, lift the compass-clinometer and place the long edge of the compass-clinometer along the line of strike. Pivot the compass-clinometer window (as shown by the red arrow) until it is horizontal.



Rotate the compass dial so that the compass needle lines up with the red outline for the north direction, checking that the compass-clinometer is still horizontal. Take the reading of the strike from the dial. In this case it is 008° or the other end of the line, 188°.



You can double check that the strike direction is correct by placing the compass on its long edge along the strike line and checking that the dip is 0° (don't forget to adjust the compass to the clinometer mode (step 2)).

5. Dip direction

The last measurement is the direction of dip to the nearest cardinal point (e.g. NW or SE, E or W). In this case it is E.

6. Record

Record the orientation of the plane in your notebook; in this case 008/12E. Note that the strike is always recorded as a 3-digit number to avoid any confusion and that the degree symbols are not normally shown to prevent any confusion with zeros.

Figure 2.6 *Continued*



E

1. General orientation

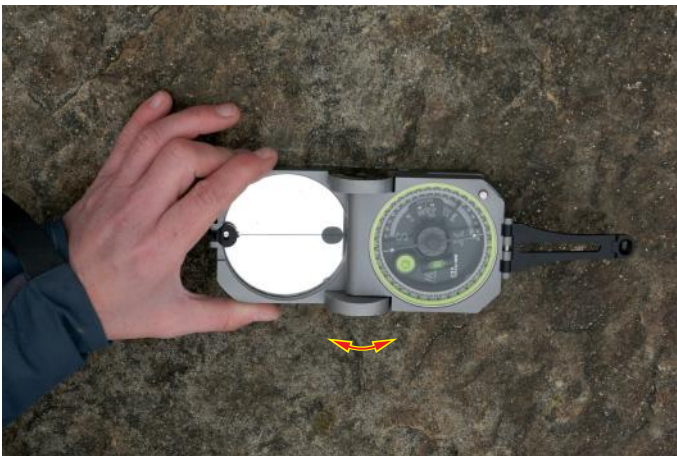
Determine the general direction of strike to within $c. 20^\circ$ by noting where the maximum dip lies; the strike is at 90° to this. In some cases it may be necessary to smooth out the variations on the surface by placing a notebook or clipboard on the bedding plane but take care to ensure that this is not biased by a small irregularity. Hammer shows the plane chosen in this case.



2. Strike direction

Place the long edge of the compass-clinometer down where you roughly estimate the line of strike is. Using the round spirit level, position the compass exactly horizontal by both:

(i) Tilting the compass about its short axis so it is horizontal (as shown by the red arrow);



(ii) Slightly pivoting the long edge of the compass in contact with the bedding plane about its central point (as shown by the red arrow) to obtain the exact line of strike within your 20° window.

Figure 2.7 How to use the Brunton-type compass-clinometer to measure the orientation and dip of a plane using the contact method. The parts of the compass-clinometer are shown in Figure 2.3 a–c.



Take the reading of the strike from the dial. In this case it is 008° or the other end of the line, 188°.



3. Dip magnitude

Remembering exactly where the line of strike is, place the long edge of the compass-clinometer at 90° to this on the bedding plane. Ensure that the clinometer scale is on the side in contact with the rock. Move the clinometer arm until the bubble in the long spirit level indicates that it is level.



Read off the maximum dip. In this case it is 12°.

4. Dip direction

The last measurement is the direction of dip to the nearest cardinal point (e.g. NW or SE, E or W). In this case it is east.

5. Record

Record the orientation of the plane in your notebook; in this case 008/12E. Note that the strike is always recorded as a 3-digit number to avoid any confusion and that the degree symbols are not normally shown to prevent any confusion with zeros.

Figure 2.7 *Continued*

easiest way to measure a dipping plane with the different instruments. If this technique is new to you, or the reading seems unreasonable, or the bedding surface is not ideal, take a second or even third reading and use the average or the best one.

Determination of the orientation of a dipping plane using the clinometer hinge of the Brunton-type compass-clinometer

You can also use the graduated hinge ('hinge clinometer'; Figure 2.3a) of the Brunton Geo or the Freiburger Stratum compass-clinometer to measure the dip magnitude. This feature is cleverly designed so that you can measure both the azimuth of the dip direction (at 90° to the strike) and the dip magnitude in one go without needing to move the compass-clinometer to obtain the two readings (Figure 2.8a). To measure the orientation of a plane using the hinge clinometer:

1. Place the compass-clinometer on the dipping plane with the back of the mirror part flat on the plane (Figure 2.8).
2. Keeping the back of the mirror flat on the plane, rotate the compass window to the horizontal using the round spirit level (Figure 2.8a).
3. Note the two readings; the hinge clinometer shows the magnitude of the dip (Figure 2.8b) and the compass needle shows the dip azimuth (Figure 2.8c).

The strike can be obtained by subtracting or adding 90° to the dip azimuth. If you record the strike you will also need the general dip direction (e.g. east). Note that if you are quoting dip azimuth rather than the strike it is important to check that you are not 180° out and to make it clear that this is what you are recording (see Section 8.1.1 and Table 8.1 for further discussion).

2.3.2 Orientation of a linear feature

The need to measure the orientation of linear features is common in sedimentary rocks (Chapter 6) and rocks that are deformed (Chapter 8). The steps are similar to measuring a plane except that in this case the orientation of the feature with respect to north (the azimuth) is recorded by orientating the long edge of the compass-clinometer parallel to the linear feature (Figures 2.9 and 2.10, pp.18–19 and 21). As for a dipping plane the azimuth should be recorded as a three-digit number and the plunge as a two-digit number. Alternative notations for the notebook to that shown in Figures 2.9 and 2.10 are shown later in Table 8.1.



(a)



(b)



(c)

Figure 2.8 Measurement of the dip direction and dip magnitude of a plane with the Brunton Geo compass-clinometer in one position. (a) Side view of the compass-clinometer in position for measuring both the dip magnitude and dip azimuth. (b) Close up view of the hinge area. The dip magnitude is read off where the top of cut-out intersects with the scale; in this case it is 12° . Note also the extra spirit level on the side indicating that the compass window is horizontal. (c) View of the compass window showing that the compass window is level (round spirit level) and that the dip azimuth is 098° . This bedding plane is thus orientated at $008/12E$.



1. General orientation

Assess the linear feature and select a clear part to measure. In this case the feature is current lamination on a sedimentary bedding surface (parallel to the penknife). This feature can be used to obtain a palaeocurrent flow direction.

2. Azimuth

Place the edge of your notebook or clipboard on the linear feature, holding the book/clipboard vertical and parallel to the feature so as to create a vertical plane above it. Hold the long side of the compass-clinometer against the vertical side of the book and measure the azimuth of the lower end of the linear feature relative to north (i.e. the direction of plunge). For the Silva-type compass-clinometer you will need to rotate the dial until the magnetic needle is aligned with the north arrow of the compass. Ensure the compass window is horizontal before recording this measurement (for the Brunton-type compass you can do this by checking the round spirit level). In this case the azimuth is 148° .

Azimuth: Silva-type



Azimuth: Brunton-type



Figure 2.9

3. Plunge

Set the compass dial so that the instrument can be used as a clinometer (see Figures 2.6, 2.7). Place the compass-clinometer along the linear feature and read off the plunge angle from the clinometer. In this case the plunge is 15° .

Plunge: Silva-type



Plunge: Brunton-type



4. Record

Record in your notebook the plunge as a 2-digit figure (15°) and the azimuth as a 3-digit figure (148°). For linear features the usual notation is the plunge first, then an arrow indicating 'to' and then the azimuth ($15 \rightarrow 148$).

Figure 2.9 *Continued* Steps in the measurement of the azimuth and plunge of a linear feature (lineament) by the contact method – for both types of compass-clinometer. The parts of the compass-clinometers are shown in Figure 2.3.

Contact method for measuring the orientation of a linear feature

Either a Brunton-type or a Silva-type compass-clinometer can be used for the contact method (Figure 2.9, pp. 18–19). The Brunton-type has the advantage that the azimuth can simply be read off without having to rotate the compass dial while also holding the notebook.

Sighting method for measuring the orientation of a linear feature

A more accurate method of measuring a linear feature, and one that is easier with only two hands, is the sighting method (Figure 2.10). This can be done easily with a Brunton-type compass-clinometer and the azimuth reading can also be done with a Silva-type compass-clinometer although it is not as accurate. The slope of a large surface or hillside can also be measured in the same way as the plunge.

2.3.3 Triangulation: Determining location using a compass

A further important use of the compass is to determine your position by taking a compass direction (bearing) off at least two, and preferably three, features that are marked on the topographical map of the area – a process known as triangulation. The most accurate triangulation will result from using features that are between about 60° and 90° apart, but in some cases this is not possible. The closer the features are to you the more accurately you will be able to find your position. The types of features used are: the corner of a building, corner of a tree plantation, road junction, river confluence, telecommunications mast, the top of a hill or other distinct feature. Ensure that you take the azimuth and draw the line on the map using the edge of the building or particular side of the road (rather than the middle or general direction) because any small variation will result in an inaccurate position. The point at which the two or three lines cross determines your position. If the lines do not cross, one or more of your azimuth readings is poor; recheck your azimuth readings and/or pick another feature to sight off. Alternatively take the midpoint of the triangle (see Worked Example 10.2 and Figure 10.5).

If you know you are somewhere along a linear feature such as a road just one azimuth sighting from a feature at a high angle to the linear feature can be used to produce a single intersection. However, an azimuth reading from a second feature will reduce the possible error. The steps to determine your location on a map for the two different types of compass commonly available are described in Figures 2.11 and 2.12, pp. 22–24. The Silva-type compass has three significant advantages for this type of



1. Place pencil

Put a pencil on the exposure parallel to the lineation and then stand where you can look down the linear feature. Use a piece of tape to hold the pencil in place if necessary.



2. Measure azimuth

Holding the compass window horizontal (use the round level to check this), and with the mirror at about 120° to it, sight through the small peep sight at the end of the long sight through the sighting window at the base of the mirror and down the pencil (see inset). Read off the azimuth. If necessary use the locking pin to hold the magnetic needle in place while you note the azimuth.



3. Measure plunge

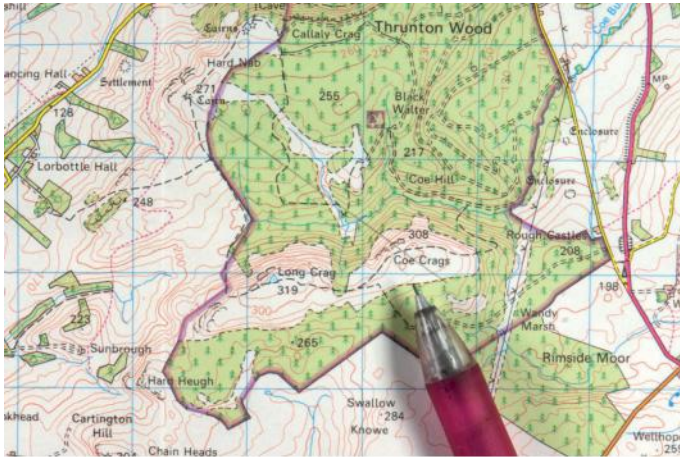
Hold the compass-clinometer on its edge so that the compass window is vertical and the clinometer is at the bottom. Fold the mirror in to the compass window at about 60° . Fold in the peep sight at the end of the long sight.

Sight through the peep sight at the end of the long sight, the window at the base of the mirror and down the pencil (see inset). Carefully adjust the angle of the mirror so that you can also see the long level. Adjust the clinometer so that the bubble in the long spirit level is in the middle. Read off the magnitude of the plunge.

4. Record

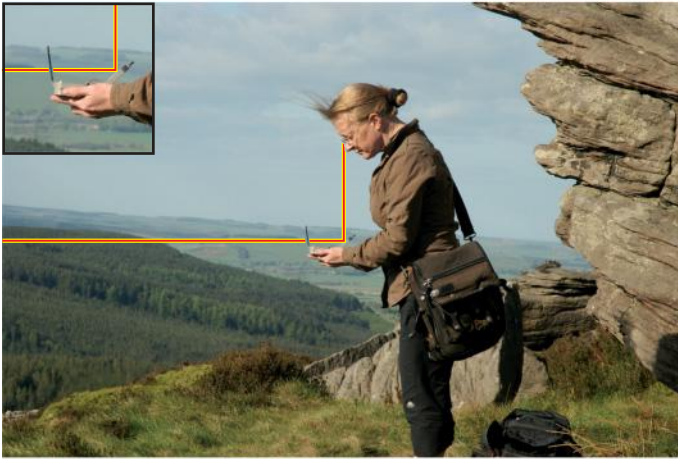
Record in your notebook the plunge as a 2-digit figure and the azimuth as a 3-digit figure.

Figure 2.10 Measurement of the azimuth and plunge of a linear feature (slickenside lineations (Section 8.2.2)) on a fault plane using the sighting method with the Brunton-type compass-clinometer. Insets show detail of line of sight. The parts of the compass-clinometer are shown in Figure 2.3 a–c.



1. Identify features

Identify two features on the map and on the ground on which to take bearings. In this case the purpose was to identify the location along the exposure known as Coe Crag (shown on the map by the end of the pencil). Various landmarks can be picked out on the hills to the north.



2. Measure azimuth

Hold the compass horizontal at waist height with the back of mirror towards you and the mirror at about 120° to the compass window. Line up the feature so that you can see the feature through the long sight in the mirror, ensuring that the compass is level using the round spirit level.

Read off the azimuth.



3. Orientate the map

Put the compass-clinometer on to the map with the long edge of the compass-clinometer parallel to a N–S grid line. Check that you have the compass the correct way round and not 180° out, i.e. that the north needle is pointing roughly north on the map. Rotate the map and compass together until the north needle is at its zero mark.

Figure 2.11 Triangulation using a Brunton-type compass. The terms for the different parts of the compass-clinometer are given in Figure 2.3a–c. (Map: Ordnance Survey, Landranger Series, Sheet 81. Ordnance Survey on behalf of HMSO © Crown Copyright 2010. All rights reserved. Ordnance Survey Licence number 100018362. (extract is from within 10 km grid square NU(46)00.)



The map is now orientated. Note that the long edge of the compass is parallel to the N-S grid line and the compass needle is at its 0° mark. Note also that the compass has been corrected for magnetic declination.



4. Transfer azimuth to the map

Keeping the map orientated in exactly the same way, place the long edge of the compass so that it runs through the feature that you sighted. Rotate just the compass until the compass needle shows the azimuth of the feature that you sighted off.

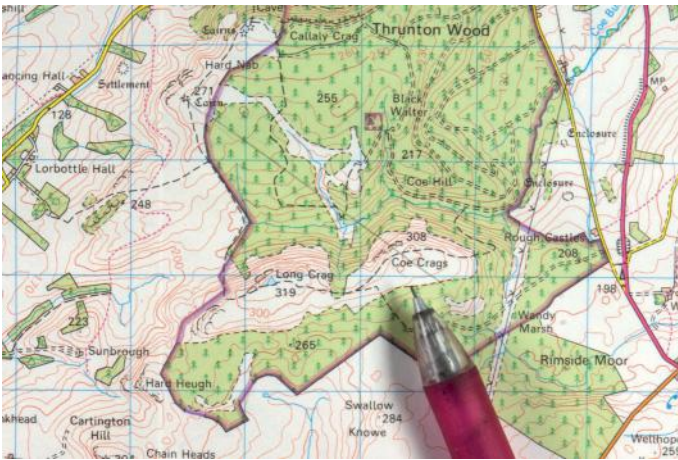


Draw a faint line along the edge of the compass. You are somewhere along this line.

5. Repeat stages 2 to 4

Repeat for at least one more feature. The point at which the lines intersect marks your position. See further notes on checking your position in Sections 2.3.3 and 10.3.

Figure 2.11 *Continued*



1. Identify features

Identify two and preferably three distinct features on the map and on the ground from which to take bearings. In this case the purpose was to identify the location along the exposure known as Coe Crag (shown by the end of the pencil). Various landmarks can be picked out on the hills to the north.



2. Measure azimuth

Hold the compass at arm's length and eye level with the mirror tilted towards you so that you can see the compass window in the mirror and the compass window is horizontal (inset). Using the sight (i.e. small slot in middle of the short edge of the compass), align the feature with the sight. Rotate the compass dial so that the compass needle is aligned with the red outline for the north direction on the dial.



3. Transfer azimuth to the map

Lower the compass and place it on the map with the N–S grid lines on the compass dial (ignore the compass needle) aligned with the N–S grid lines on the map. Retaining this orientation place one edge of the compass adjacent to the feature that you have sighted. Draw a faint line on the map using the edge of the compass that passes through the object that you used for sighting. Your position is somewhere along this line.

4. Repeat stages 2 and 3

Repeat for at least one more feature. The point at which the lines intersect marks your position. See further notes on checking your position in Sections 2.3.3 and 10.3.

Figure 2.12 Triangulation using a Silva-type compass. Inset shows line of sight. The terms for the different parts of the compass-clinometer are given in Figure 2.3d and e. (Map extract as Figure 2.11. © Crown Copyright 2010. All rights reserved. Ordnance Survey Licence number 100018362.)

measurement: (1) the azimuth is retained by the compass when one moves away from the sighting; (2) the map does not have to be orientated to transfer the measurement (step 3, Figure 2.12); (3) the transparent compass-needle housing makes transfer onto the map easier.

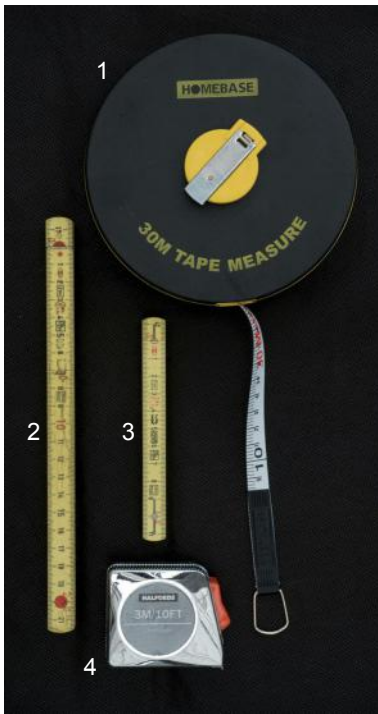
2.4 Global positioning systems and altimeters

Global positioning systems (GPS) use ultra high-frequency radio wave signals from satellites to trigonometrically derive your position to within a few metres laterally. A wide range of GPS systems are available on the market and the reader should refer to specialist reviews and literature for more information. Increasingly, mobile phones contain a GPS unit. Global positioning systems units do not work in deep ravines and on some coastal sections; they are also not particularly accurate for altitude. The GPS can be set up for the particular grid system that you are working with or for a global reference that is based on latitude and longitude. The global reference World Geodetic System 1984 (WGS84) is the most commonly used. Instructions on how to set up your GPS will be in the manufacturer's manual. After setting it up or modifying any settings, for instance when you go to a new country, it is a good idea to test it out at a known location. The unit may take some time to locate the satellites if the GPS has been moved hundreds of kilometres.

If you use a GPS together with hard copy maps as your main location device in the field you should ensure that you also have a ruler with you so that you can accurately plot your position. A GPS should not be a total substitute for basic navigation skills. You should also know how to locate yourself with a map and a compass (Section 2.3.3) so that if the GPS goes wrong, the batteries fail, or you are in an area where the satellites are obstructed, you have an alternative means of location and navigation. Alternatively if you are in an area of the world where the base maps are poor or only available at a small scale, a GPS reading will probably be more precise than compass triangulation and will more easily allow exactly the same locality to be found again.

An altimeter is useful for recording elevation more precisely than a GPS when mapping or working in steep terrain, for instance recording a steep stream section. Altimeters use air pressure to measure elevation and this will vary with the weather. You need to calibrate your altimeter by taking a reading when you are at a known elevation at least once a day and throughout the day if the weather is changing significantly. A Brunton-type compass-clinometer and Jacob staff (Section 2.5.2) can also be used to determine elevation above a known datum.

Ensure that you have set up your GPS or altimeter correctly otherwise you could spend the entire day being somewhere other than where you thought you were!



(a)



(b)

Figure 2.13 (a) A variety of useful tape measures for field use: 1, surveyor's tape; 2, folding rule; 3, 1 m folding rule; 4, retracting metal-tape measure. (b) Home-made wooden pole with decimetre graduations to give a general idea of scale.

2.5 Measuring distance and thickness

Thickness and distance are two of the most basic measurements that need to be made for many geological tasks. For most of them a tape measure or folding ruler (Figure 2.13) will suffice but when working on slopes a Jacob staff and compass-clinometer can be useful (Section 2.5.2).

2.5.1 Standard thickness and distance measurements

A surveyor's 30 m tape is useful for large-scale measurements, for instance during regional mapping (Section 10.2.2; Figure 2.13, item 1). Smaller, shorter and much cheaper, 2 or 5 or 10 m length, retracting metal-tape measures (Figure 2.13, item 4) are, however, perfectly adequate for small-scale work and for graphic logging (Section 6.3). The retracting metal-tape measures also have the advantage that they are stiff and therefore can be used much more easily to obtain an accurate measurement of the thickness of the bed by holding it perpendicular to the bedding. Folding plastic metric rulers that extend to 1 m or 2 m can be obtained in some countries and are very useful as a scale for photographs and for graphic logging (Figure 2.13, items 2 and 3). These stiff rulers can easily be used to measure the thickness of partially submerged beds, for instance in a rock pool on the foreshore, and can be held at the bottom and pointed up cliffs to measure the thickness of otherwise inaccessible beds. They are also much easier to use when measuring on your own because the thickness of beds that are greater than that of your arm span can be measured. A pole of known length or a long steel rule or wooden rule can also be used for this purpose and for general measurements (Figure 2.13b). When measuring the dimension of a geological feature it is important to ensure that you have not overestimated the distance by placing the tape oblique to the bedding plane. For instance, in Figure 1.1a to obtain a true thickness the top of the tape would need to be placed closer to the bed so that it was perpendicular to the bedding plane.

When dipping rocks are exposed on a horizontal surface only (e.g. on a quarry floor, in a stream section or in the foreshore) it is very difficult or impossible to measure directly a true bed thickness. By measuring the horizontal distance perpendicular to strike (d) and the angle of dip of the beds (θ) this can be solved (Figure 2.14). The true thickness is given by the equation:

$$\text{True thickness} = d \times \sin \theta$$

This technique can be used to obtain a very good estimate of the thickness of beds, to estimate the distance over which beds are not exposed (for instance on the foreshore between resistant

beds when the non-resistant bed is covered by beach deposits) or to check the cumulative thickness of a series of dipping beds. If the thickness of a bed is critical to the objective of the fieldwork it is always a good idea, if possible, to measure the thickness in more than one way, for instance by measuring each bed individually and then by measuring the thickness of a group of beds.

2.5.2 Use of the Jacob staff to measure the thickness of inclined strata

It is difficult to measure the thickness of inclined strata exposed on a slope such as a hillside if, as is nearly always the case, the slope of the hill does not cut the strata at 90° (Figure 2.15). A Jacob staff and Brunton-type compass-clinometer can be used to measure such sections quickly and easily. They can also be used together as a very accurate measure of vertical distances.

A Jacob staff can either be purchased or fashioned from a length of wood about $2\text{ cm} \times 5\text{ cm}$ and between about 1.25 m and 2.0 m long (choose a length that is just below your eye level and which is convenient for multiple measurements). Mount the compass-clinometer with its east side (so the clinometer is at the base) in contact with one end of the staff. Ensure that the end of the staff is at exactly 90° to the length of the staff so that the compass-clinometer is perpendicular to the staff. For an exact measure, remove from the base of the staff the distance that is equivalent to the few centimetres between the long edge of the compass-clinometer and the centre of the sights. Fold the peep sight at the end of the long sight in at 90° . Angle the mirror so that you can see the compass window when looking through the peep sight and hole in the mirror. To measure the thickness of the beds complete the following.

1. Measure the strike and dip of the strata you are going to calculate the thickness of (Section 2.3.1) and work out a line of traverse that is perpendicular to the strike.
2. Set the clinometer on the Brunton-type compass-clinometer to the angle of dip of the strata.
3. Starting at the base of the traverse, place the base of the Jacob staff on the point in the stratigraphy you wish to measure from and lean the Jacob staff down until the bubble in the long spirit level is in the middle (i.e. the Jacob staff is perpendicular to the bedding plane).
4. Sight through the peep sight and window in the mirror to a point on the ground ensuring that you keep the long spirit level horizontal. This point on the ground is the length of

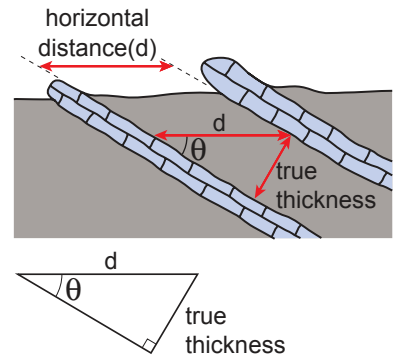


Figure 2.14 Sketch to show the basic trigonometry for obtaining a true thickness by measuring the horizontal distance between dipping beds.

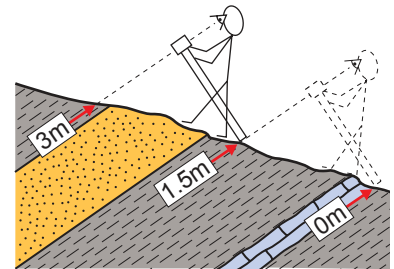


Figure 2.15 Sketch to show how to measure thickness up a slope with a Jacob staff of 1.5 m length and a Brunton-type compass-clinometer.

For particular situations it may be necessary to improvise a scale: e.g. mark a thin, straight piece of wood in black and white stripes (Figure 2.13b) or, for measuring inaccessible cliffs, paint a length of rope and then take photographs while the rope is hanging over the cliff.

your Jacob staff above the point where you started (Figure 2.15).

5. An entire slope can be measured this way by cumulatively moving up the slope to the point where the last measurement was taken. Beds and boundaries between the sighting points will need to be interpolated.

If you have a field partner you can use a pole or folding rule of known length as a crude Jacob staff when measuring up a slope or a large thickness of dipping strata. Hold the pole roughly perpendicular to the strike of the strata to be measured. With your field partner standing about 5 m away, get them to first, by eye, tell you how to alter the angle of the pole so that it is perpendicular to the strike. Then, the person not holding the rule can obtain a good estimate of the stratal thickness that is equivalent to the length of the pole by extending an imaginary line by eye perpendicular from the top of the staff to the strata.

2.6 Classification and colour charts

Various well-established comparison charts can be used to provide a semi-quantitative description of the rock and any changes in it. These include grain-size charts and rock classification diagrams. The figures commonly used are included in the appendices at the end of this book but charts such as those for grain size and texture can also be purchased for use in the field. The grain size chart should be used by placing the edge of the card on top of a clean fresh surface of rock and comparing the grain size on the chart to that of the rock until a match is found for the average grain size and if appropriate the maximum and minimum size (Figure 2.16). If the grain size is small it might also be necessary to use a hand lens on the card and rock. If the rock is poorly consolidated, scatter a few representative grains across the grain-size images to determine the average size.

Weak hydrochloric acid can be used to test for carbonate. A fresh surface of the rock free from any coating minerals and weathered coating must be obtained before dropping acid on the rock. The acid will fizz strongly with fresh calcium carbonate but much less strongly for dolomite (calcium-magnesium carbonate). Freshly powdered dolomite will fizz more readily. Health and safety precautions for the handling of acid should be followed. In sedimentary rocks an easier and less destructive method of determining whether there is carbonate is to test the hardness of the rock. The most common colourless minerals in sedimentary rocks are quartz and calcite (with feldspar less frequently). Quartz will scratch steel

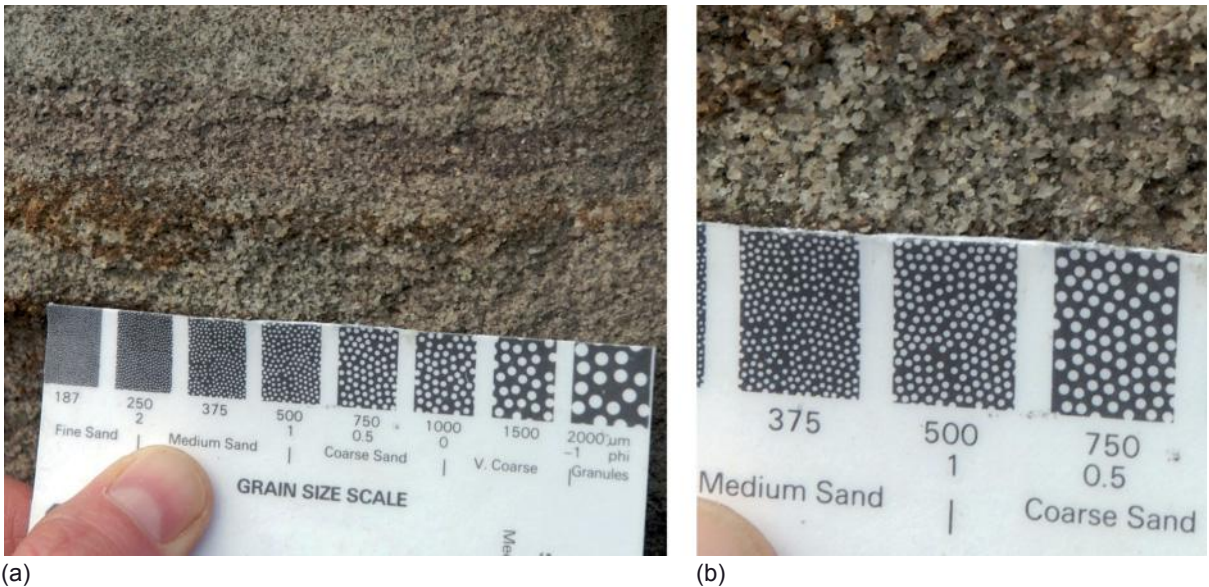


Figure 2.16 Use of a grain-size chart to determine the average grain size. (a) In this case the average grain size is 500 μm . The grain size varies between 375 and 750 μm . (b) Close up view of (a).

whereas calcite will not. Feldspars have distinct cleavage and tend to go white and powdery as they weather.

Colour variation can be ascertained using Munsell colour chips compiled onto charts. This is particularly useful in successions where one of the main variations is colour (for instance in mudstones) and/or colour has been demonstrated to be an important indicator of the composition. A full Munsell colour chart is bulky for field use but short versions with the typical colours of rocks can be obtained from stockists of geological equipment and various Geological Society publishers.

A streak plate (ground glass or ceramic plate across which the rock is scratched) can be useful for getting an even colour from a rock or mineral that is then easier to compare with the colour chart.

The Munsell colour system is based on all variation in colour being definable by a point in a sphere. To define where the colour lies in the sphere there are three aspects to consider.

- *Value (or Lightness)*: This is the paleness or darkness of the colour, i.e. for the colour grey where it lies between black (1) and white (9). Value defines the vertical axis through the sphere (Figure 2.17, p. 30).

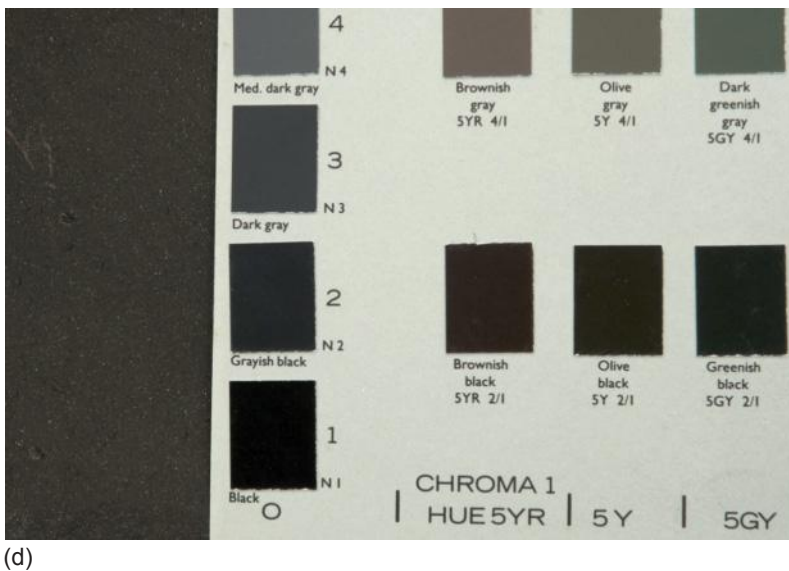
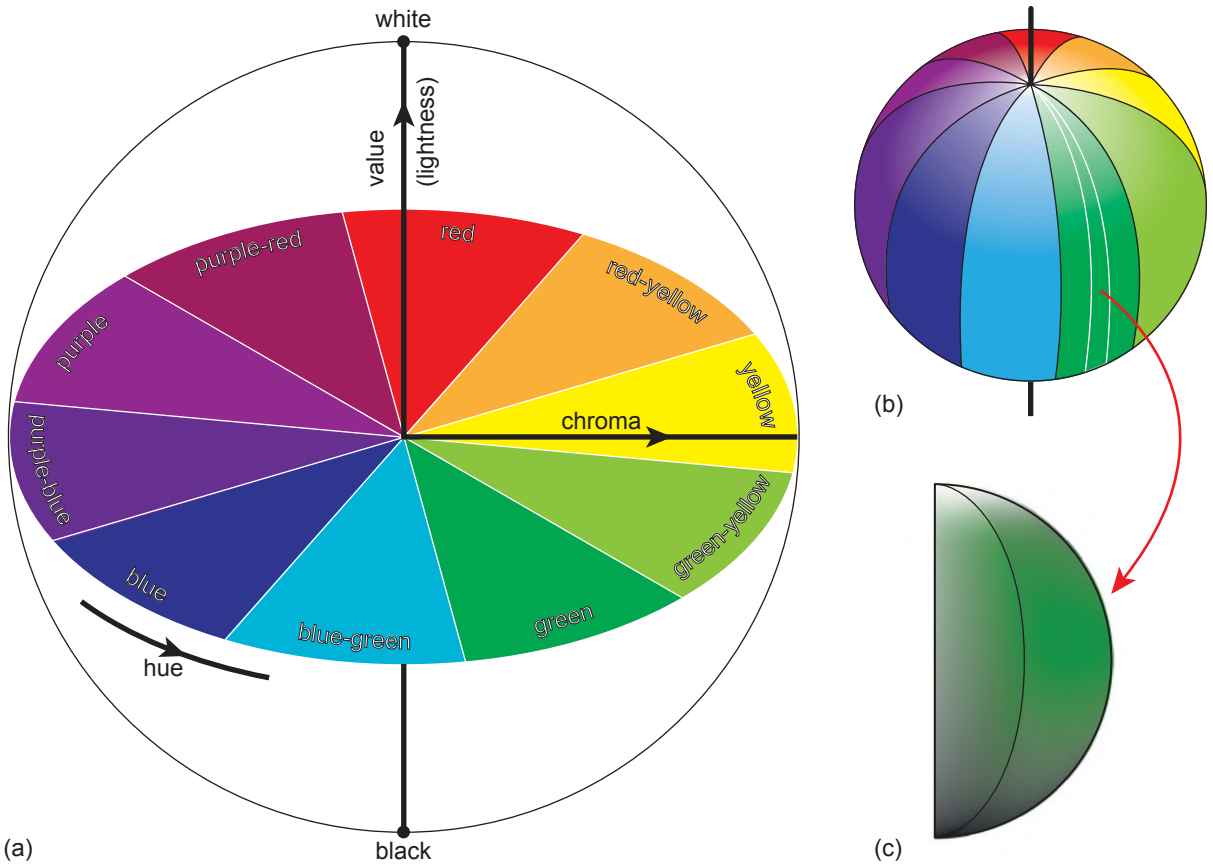


Figure 2.17 Highly simplified three-dimensional representation of Munsell colours. (a) The axes for value, hue and chroma within a sphere. The 10 hues are shown but for simplicity the 10 subdivisions within each hue are not shown and neither is the chroma. (b) Sphere of colour with the colours becoming lighter towards the top (increase in value). (c) Part of one segment showing very generally the increase in value towards the top and the increase in chroma towards the outer edge of the segment. (d) Part of a Munsell colour chart specially designed for rocks. In this case the grey organic-rich mudstone sample on the left has a Munsell colour of 5Y 2/1 (olive black).

- *Hue*: There are 10 major hues defined by the Munsell colour system. These are represented on the sphere by division of the sphere into 10 'slices' or segments (Figure 2.17a). Each slice is further subdivided into 10 numbered slices. The number 5 marks the centre of the hue and 10 the boundary with another hue.
- *Chroma*: This is the degree of saturation of the hue with respect to the equivalent grey. This is defined on the sphere by how far it lies between the centre of the sphere and the circumference (Figure 2.17a and c).

The Munsell colour value is given in numbers as: Hue Value/Chroma. So, for instance, 5R 4/6 refers to a hue of 5R, a value of 4 and a chroma of 6.

2.7 Hammer, chisels and other hardware

A geological hammer is necessary for most geological fieldwork, both for the collection of samples and, where necessary, to create fresh surfaces so that the rock and the minerals within it can be described (Figure 2.18). Having said this it is perfectly possible to do a lot of geological fieldwork without a hammer provided samples are not required. Rocks that are exposed in sea-cliffs and along foreshores, in new trenches or in road cuts often do not need hammering and indeed the slightly weathered or wave washed surface is often as good as, if not better than, a hammered surface. For sedimentary rocks a 1 lb (c. 0.5 kg) hammer is often sufficient. For igneous, metamorphic and hard or well-cemented sedimentary rocks a 2 lb (c. 1 kg) or even a sledge-hammer may be necessary if good quality and/or large samples are required. However, a good chisel or pick hammer can be used to exploit planes of weakness (joints, bedding planes, foliation, vein margins) and extract samples from tougher rock types (Section 13.2.2). Matters of conservation should always be considered (Section 2.12).

For safety reasons it is important to use a geological hammer rather than one designed for other materials such as wood or metal. This is because to hammer rocks you need a head that is robustly mounted on to the hammer shaft, made of a suitable grade of steel that will not splinter and is of an appropriate ergonomic design. Brick and stone hammers can be used if a specific geological hammer is not available. Other features to consider when purchasing a hammer are the type of head that is most suitable for your use and whether it feels comfortable when you use it. All geological hammers have one flat face: the other end is either a chisel or pick (Figure 2.18). The chisel end is useful for splitting rocks apart although it is

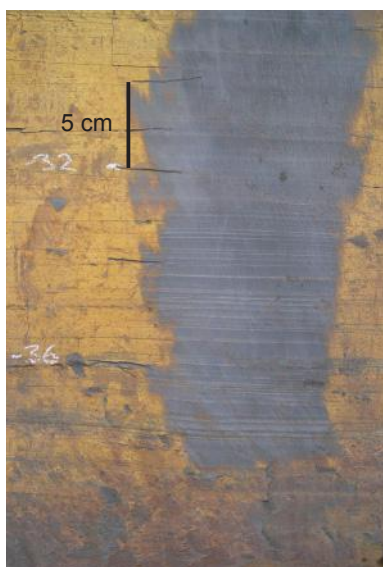


Figure 2.18 Some of the different geological hammers and cold chisels available on the market. (1) Estwing pick end hammer, (2) Estwing chisel end hammer, (3) cold chisel with hand guard, (4 and 5) 2.5 lb and 1 lb geological hammers with fibreglass shafts, (6) pencil chisel, (7) tile scribe and (8) 3 lb lump hammer.

Stainless steel spades and trowels are particularly useful for work in sticky clay as the clay slides off more easily.



(a)



(b)

not as effective or accurate as using a hammer with a separate chisel; the pick is useful for hammering into crevices to lever samples out and for generally weakening a rock surface before extracting a sample. Some geological hammers have the head and shaft all cast from one piece of metal and this makes them exceedingly robust; however, they pass more of the impact from hammering through the shaft and into your hand and arm. The other option is a steel head mounted on a wooden or fibreglass shaft. The shaft on these absorbs most of the impact; however, the head on this type of hammer can work its way off. This is, however, very uncommon with the new fibreglass models. Note that the rust on the hammer or chisel that is an inevitable consequence of use in wet conditions (e.g. Figure 2.18 items 2, 4, and 5) is a potential contaminant for samples being used for geochemical analysis. The hammer can be cleaned with a wire brush and wire wool (e.g. Figure 2.18, item 1).

If the rocks have no good partings or fractures and/or precisely placed samples are required, it is best to use a chisel. Many of the larger cold chisels are now supplied with hand guards (Figure 2.18, item 3). For delicate specimens such as fossils or minerals a small pencil chisel is useful (Figure 2.18, item 6). If you need to do lots of chiselling, a lump or crack hammer may be useful (Figure 2.18, item 8).

For unconsolidated and poorly consolidated sedimentary deposits a spade or hoe pick and/or a masonry trowel is invaluable for removing the weathered or slipped material on the surface and then cleaning the surface so that the sedimentary structures can be seen (Figure 2.19a). If the surface of the rock is hard and coated with a thin layer of lichen, moss or iron minerals and there is not an alternative exposure surface, a hard nylon brush or a wire brush can be used to clean the surface (Figure 2.19b).

Figure 2.19 (a) Poorly consolidated sandstone showing current-formed climbing ripples. This structure has been revealed by carefully scraping the surface of the sandstone with the edge of a trowel. An unprepared surface lies to the right and at the level of the trowel. Shellingford cross-roads quarry, Oxfordshire, UK. (Angela L. Coe, The Open University, UK.) (b) Lower Jurassic mudstones shown with the surface iron coating (yellow) and after a clean surface was obtained through vigorous wire brushing. Note how the scraped surface shows laminations that were not previously apparent. Deep scratch marks are 5 cm apart. Such slight surface abrasions quickly weather and do not pose significant conservation issues. (Anthony S. Cohen, The Open University, UK.)

2.8 The hardcopy field notebook

Except for safety equipment, provisions and suitable clothing (Table 2.1, Sections 2.11.1 and 2.11.3), the hardcopy or electronic field notebook (Section 2.9) is probably the most essential piece of field kit. The types of data to record in a field notebook, whether hard copy or electronic, are covered in Chapter 4. There is a wide range of hardcopy notebooks suitable for fieldwork available on the market and the choice is a matter of identifying something suitable for the particular task that is to be undertaken and personal preference. The advantages and disadvantages of different features are listed below.

- *Hardback or softback:* Given that the notebook will need to be used outdoors hardback notebooks are more robust and are therefore recommended. Some notebooks have a soft inner cover and an outer plastic cover and these are also relatively robust.
- *Size:* The size of the notebook is a matter of personal preference. Points to consider are the normal size of your handwriting, how you will be carrying it, how much sketching you need to do and whether you will be working in awkward places, for instance in a confined space where a small notebook can be easier to hold. Many professional geologists use notebooks that, when closed, are about 15×20 cm, although some prefer a larger size of about 30×20 cm.
- *Sewn, glued or spiral binding:* Sewn and ring bindings are robust in the field. Glued bindings can fall apart unless they are very well secured and are therefore not recommended. Spiral bindings enable the notebook to be bent back on itself, which is useful if the notebook is large; however, in these notebooks it is less easy to use facing pages as is sometimes required. In addition, the pages can accidentally tear out and become lost.
- *Plain, lined or graph paper:* Again this is very much a matter of personal choice. Plain paper allows the most flexibility and is particularly good for sketches, but lines or a grid can help to order the notes, and they are also useful for scale and guidelines in figures and tables.
- *Standard paper, water resistant and fully waterproof paper:* Poor quality paper soon disintegrates under extensive field use or in adverse conditions. It is therefore well worth purchasing a notebook with good quality paper. Some surveyor's notebooks have water-resistant paper that lasts well during extensive field use. Most art sketchbooks have good quality paper. It is also possible to purchase notebooks

A couple of bulldog clips or elastic bands are useful to hold together the notebook pages that you are not writing on especially if it is windy or raining. A large polythene bag in which to house the open notebook and your hand is useful if it is raining heavily.

with totally waterproof paper; these are excellent in areas where the weather is particularly wet or that involve working close to water, for instance on a foreshore or in river sections where the chances of the notebook getting wet are high.

- *Position of the hinge:* Some notebooks hinge along the top edge whereas others hinge along the right-hand edge. This is worth considering in conjunction with whether you are right or left handed.

2.9 The laptop, netbook or PDA as a notebook

Small computer laptops, electronic notebooks and Personal Digital Assistants (PDAs) can be used in the field to record field data. Some companies and government institutions are now using these quite extensively for specific field assignments. A number of factors need to be taken into account when choosing whether or not to use an electronic or hardcopy system and indeed what type of electronic system to use. In order of relative importance these are:

1. Is the system practical and built ruggedly enough to work reliably under the particular field conditions you will be working in? Do you have a backup system in place where you can download data each day? If you do not have this, using an electronic notebook is a high-risk strategy because you may easily lose your valuable data.
2. Is the electronic notebook suited to the type of data you wish to collect and how the data will be used? For instance, if the data need to be shared by many people, or input into a Geographical Information System (GIS) database, an electronic notebook is more efficient and suitable than a hardcopy notebook. If, however, you are completing lots of drawings of cliff faces and features in the rocks (Section 4.3) an electronic notebook is probably not the most efficient or flexible method and a conventional notebook is probably much better.
3. Do you have a ready power supply for recharging the batteries? This could be anything from a household power supply, to vehicle batteries, portable generators and portable solar panels.
4. Can you read the screen easily even in bright sunlight?
5. Do you have appropriate software for the range of data that needs to be collected?
6. Will the equipment work fully under the ambient temperature and humidity of the field area? (Low temperatures and high humidity can be problematic.)

There are significant advantages to using an electronic system: the data set is easily accessible to others; you can incorporate data directly into an existing electronic database; and you can access and overlay your data with those of others.

2.10 Writing equipment, maps and relevant literature

2.10.1 Writing equipment

- *Pencils*: Several pencils for recording notes and sketches are essential. Mechanical pencils (also known as propelling pencils) work well for notes and labels on sketches. Conventional pencils tend to work better for the line work of different thicknesses and shading in sketches (Section 4.3). Leads for either mechanical or conventional pencils of HB to 2H hardness are appropriate for most purposes. Leads of H or greater hardness have the advantage of being fairly permanent and not smudging as the notebook becomes used. Softer leads of B and 2B are useful for writing on damp paper without tearing it, for shading and for very cold conditions. Under hot conditions pencils of 2H or greater will not tend to smudge as much.
- *Pens*: Most geologists never use pens in the field whereas a few prefer them. Pens have the disadvantage that the work cannot be erased and they are not always reliable under outdoor conditions. Care needs to be taken to ensure that the ink is waterproof and also that it does not blot under hot conditions. Ball point pens will not write on damp paper.
- *Pencil sharpener or penknife*: Conventional pencils will need to be sharpened. A good quality sharp pencil can make all the difference between neat and untidy notes. If the pencil is being used for shading it often works better if it is slightly blunt (Section 4.3).
- *Coloured pencils*: A few coloured pencils are useful in the field for recording specific items, e.g. samples. The potential use of coloured pencils is covered further in Chapter 4.
- *Eraser*: Essential for correcting mistakes and/or improving parts of the sketches.

2.10.2 Maps and relevant literature

Geological and topographical maps, field maps*, photographs, published papers, etc., can form an essential part of your field tools. A topographic map for locating your position is fairly essential; aerial photographs are also useful for this. If the area

*Topographical base maps on to which geological information is added in the field are also referred to as field slips.

For robustness under field conditions it can be useful to laminate maps or diagrams such as fossil identification charts or stratigraphic logs that are used regularly.

and exposures are well studied and part of the objective of your fieldwork is to assess and/or correlate your work with published material then you will need to take key publications and/or relevant sections from these into the field. This will enable you to check up on the details of these previous studies and to correlate your new data with those of others. It is much easier and more useful to do this in the field where you can test different possibilities and identify key features that have been described in the literature than it is to try and do it when you return.

2.11 Comfort, field safety and field safety equipment

2.11.1 Clothes, backpack/rucksack and personal provisions

Fieldwork usually involves physical exertion and can involve being outside in extreme weather conditions and/or working in inhospitable or remote areas. For these reasons it is important to select comfortable clothing and to be prepared for a range of conditions. Find out the expected weather conditions in the area at the time you will visit. Most mountain walking and outdoor clothing is suitable. An outer layer with pockets to store field equipment such as pens, pencils and compass-clinometer so that they are readily accessible is useful. Alternatively, a small shoulder or belt-mounted bag is useful for this field equipment together with your notebook. If you are working in an area where you may get wet it is important to wear clothes that dry relatively quickly for comfort and to prevent exposure. If you are working where conditions are hot, loose clothing made from natural fabrics is often the most comfortable and it is advisable to cover most of your exposed skin to protect against sunburn. On most geological fieldwork it is essential to wear a hard hat (Section 2.11.2); head protection (either a sun hat or large piece of material) should also be used when you will be under the sun for prolonged periods. A hat is also important in cold conditions to help prevent heat loss. A backpack/rucksack is usually essential to carry all your field equipment, food, drinking water, first aid and spare clothing. Further advice on clothing and personal field kit can be found in mountain walking guides (Section 2.13).

2.11.2 Field safety

It is essential that you plan for emergencies and for hazards particular to the area that you are visiting. There are, however, three aspects that are important for safety in the field anywhere:

(1) Be prepared

Ensure that you or one of the members of the field group have the correct equipment and that it is all in good working order. This not only includes the specific safety items such as those listed in Section 2.11.3, but also the means to locate yourself and to return via a safe route to civilization (i.e. a map and compass and/or a GPS), enough food and drink for the time you will be spending in the field along with some emergency rations, sufficient clothing for the expected range of weather conditions, a first aid kit and the means of raising the emergency services (i.e. mobile phone, radio or satellite phone; Table 2.1). At least one member of the party should be trained in first aid. If required by your field organizer, university or employer you should complete a risk assessment form (example risk assessments are provided on the website that accompanies this book – www.wiley.com/go/coe/geology). The party members should also decide whether they are physically fit enough to traverse the terrain that they will encounter.

(2) Assess and monitor the potential hazards

If possible, assess the hazards before going into the field area either by talking to someone who has been before or with the use of maps, guidebooks to the area, satellite images (such as Google Earth™), aerial photographs and field photographs. Even if you are able to assess the hazards prior to your visit, or it is a locality you have visited before, it is still necessary to constantly monitor any potential dangers whilst you are in the field. If it is really dangerous and there is a high probability of injury or worse you should be prepared to discontinue fieldwork at this locality. Common hazards and the preventative action that can be taken to avoid them are as follows.

- *Falling rocks:* Avoid areas of recent rock fall and/or areas with large overhangs or unstable faces. Wear a hard hat that meets safety standards at all times. Take care not to dislodge rocks onto other people. Many cliffs and slopes become unstable as the weather conditions change, e.g. after heavy rain or as they dry out and heat up in the sun. If the rocks are often unstable observe under what conditions they are least likely to fall and complete fieldwork at these times if possible.
- *Snow avalanches:* These are only a hazard in high mountain areas where there has been snow fall. They are most common after new snow fall, on convex slopes of 30–45° and as temperature changes. You should ensure you know where avalanches occur, take note of any avalanche warnings, and pick routes that use uneven/wooded slopes or follow a ridge.
- *Mudslides and unconsolidated rocks:* Freshly formed mudslides and other water-saturated sediments are



Maintain an awareness of hazards around you and ensure you warn others if you think that they are in a dangerous position.

dangerous to walk on because of the possibility of getting stuck. Mudslides tend to occur during heavy rainfall and care should be taken to avoid areas where they are active.

- *Rising tides:* If you are working in a tidal coastal area ensure that you know the time and position of high tide, where any potential tidal cut-offs are along your access route, and be aware of any onshore winds or high surf conditions that will drive the tide in more quickly and potentially higher than average.
- *Slippery rocks:* Algae-covered rocks on the foreshore or stream beds can be exceedingly slippery. Avoid these areas wherever possible, for instance by walking above the high water mark on the beach or well below it where the algae has been scoured away by waves. The area will also tend to be less slippery when the algae-coated surfaces are dry.
- *Uneven surfaces and surfaces covered with boulders:* Ensure that you are wearing strong footwear that will protect your ankles, toes and feet, take your time to pick out a good route and ensure that you do not become fatigued and slip.
- *Unpredictable weather:* This can easily result in hypothermia, sunstroke or dehydration. Be prepared for the range of possible weather conditions. In hot conditions ensure you have something to cover your head with, sunglasses, sunblock and plenty of fluids. In winter ensure you wear warm clothing and have good quality waterproofs, which will also protect you from the wind. A warm hat is essential since a significant proportion of the heat that your body generates is lost through your head.
- *Lightning:* If you are caught out in the open in a thunderstorm that is less than about 5 miles away, avoid sheltering under a tree or anything tall where lightning is likely to ground. If there is time, retreat from high ground. Crouch down in an open space touching as little of the ground as possible. If you are in a vehicle you will be fairly safe, but avoid touching any of the metal body of the car. If you are close to water (e.g. a lake or the sea) move away from the water's edge where lightning is likely to strike.
- *Dangerous beasties and plants:* Be aware of any local dangerous or poisonous biota, e.g. bees, wasps, snakes, leeches, scorpions, spiders, bears, poison oak (USA) and ticks, water-borne infections and how to deal with any other hazards that are particular to your field area.
- *Working machinery, toxic substances:* In quarries and mines, working machinery is a major hazard. The position of the driver in large diggers and excavators often means

that they have a considerable blind area so special care must be taken. For hazardous substances follow the specific health and safety guidelines provided.

- *Fatigue*: Tiredness is dangerous because reactions are slowed. It is quite easy on fieldwork to work long hours especially when there are many hours of daylight. Maintain your normal working hours if possible and ensure that you eat and drink at regular intervals. In a party the leader or first aider should look out for any members of the party who show fatigue, headaches or nausea and take appropriate action (e.g. for altitude sickness, immediate descent).

(3) Know what to do in an emergency

Members of the party should know who is trained in first aid. In larger field parties it is also advisable to set up a chain of command in case an incident occurs. Ensure that you know how to contact the emergency services, what the emergency telephone number is for the country that you are visiting, what the local mobile phone signal coverage is and where you have to go to obtain a signal. On many beaches with sea-cliffs and in mountainous areas the coverage is poor or patchy. In some parts of the world it may be necessary to carry a satellite phone or radio.

Working alone

Sometimes, it may be necessary to do fieldwork alone. In this case regular (i.e. daily) contact should be maintained with someone who can organize help in the event that you go missing. In case help does need to be raised, it is also good practice to leave information indicating the route that you will take and where you will be working that day.

2.11.3 Field safety equipment

It is not only necessary and sensible to wear protective clothing when working in hazardous areas, it is also now law in much of the world, along with the completion of some type of risk assessment form. All safety equipment should be checked regularly.

- *Hard hat*: In areas where there are cliffs and therefore risk of rock falls a hard hat is essential. The hard hat will prevent concussion or skull fracture from rocks up to fist-sized; it will not, of course, protect you from much larger pieces of falling rock. The plastic builder-type hard hats with an internal plastic cage that is adjustable for the size of your head and leaves a space between the top of your head and the hat are adequate for most purposes. These are available from most builders merchants/hardware



Figure 2.20 Geological hammer with head showing spalling (head is 12 cm long). Further use is likely to result in small sharp pieces of metal flying loose.

stores. In addition, more specialist hard hats can be used, e.g. rock climbing and caving helmets. The advantage of these is that they have a chin strap, which holds the hat in place; a disadvantage is that they often lack a brim at the front and therefore do not protect your face as well. Sunlight degrades plastics and they eventually become brittle so check that your hard hat has not exceeded its use-by-date. Hard hats with a small rear gutter are also useful in rainy conditions as it prevents the water running down the back of your neck.

- *Reflective clothing:* When working in quarries and at the side of a road it is often necessary and practical to wear specialist fluorescent clothing so that you can easily be seen.
- *Goggles:* When hammering rocks it is good practice to protect your eyes with goggles or wrap-around protective glasses to prevent eye injury from rock splinters. Rock splinter wounds are a reasonably common cause of injury among geologists. Depending on the type of rock being hammered it is also sensible to cover other bare flesh. There have been incidents with rock or hammer splinters from hammering not only entering a person's eyes, but also neck, legs and arms. Different types of rock splinter in different ways. Igneous rocks, particularly peridotites, are very splintery, as are cherts.

All items of field equipment should be checked regularly, for instance whether the head of your geological hammer is secure on its shaft and whether your hammer and chisels show any metal fatigue, spalling and cracks (Figure 2.20). Many cold chisels are now supplied with hand guards (Section 2.7); these are very effective in preventing you from inadvertently hitting your hand with the hammer.

2.12 Conservation, respect and obtaining permission

For all geological sites on private land, or those that involve crossing private land to get to them, a member of the field party should first seek permission for the party to enter the land and if necessary to sample. This can be quite a complex process as it is commonly not obvious who owns the land unless it is something like a working quarry. Geological surveys, other geologists who have visited the area, local councils, national park authorities and people who live in the neighbourhood may all be able to provide information.

With all sites you should respect the land and follow the code for the area. Do not forget that other geologists may wish to

visit the site too. In addition there may be local cultural, religious or national heritage codes of conduct that should be respected. These may in some cases not permit any access to certain sites and certainly not allow the removal of samples without special permission. Codes of conduct vary from country to country and area to area but most of it is common sense. The main points to consider are summarized in Table 2.4.

Many countries have conservation or protected sites of either biological and/or geological interest. These sites are protected from building development but also special rules may apply to sampling *in situ* material and sometimes even to loose material. Conservation is a particular issue for fossiliferous sites (Section 5.1.2).

2.13 Further reading

- Backer, H. D. (ed.). 1997. *Wilderness First Aid: Emergency Care for Remote Locations*, Jones and Bartlett Publishers, 350 pp.
- Bagshaw, C. 2006. *The Ultimate Hillwalking Skills Handbook*, David and Charles. 160 pp. [Guide to hillwalking that covers matters which are directly transferable to geological fieldwork, including fitness, navigation, first aid, clothing, weather, etc.]
- Duff, J. and Gormly, P. 2007. *Pocket First Aid and Wilderness Medicine*, Cicerone Press, 247 pp.
- McNab, C. 2004. *How to Survive Anything, Anywhere: A Handbook of Survival Skills for Every Scenario and the Environment*, McGraw Hill Higher Education, 320 pp.
- Mears, R. 2001. *Outdoor Survival Handbook: A Guide to the Resources and Materials Available in the Wild and How to Use Them for Food, Shelter, Warmth and Navigation*, Ebury Press, 240 pp. [Month by month guide to living in the wild and advice on navigation.]
- Mears, R. 2003. *Essential Bushcraft*, Hodder and Stoughton, 240 pp.
- Pollard, A. J. and Murdoch, D. R. 2003. *The High Altitude Medicine Handbook*, Radcliffe Medical Press, 193 pp. [Invaluable guide to the recognition and treatment of altitude sickness, as well as many other conditions liable to be encountered at altitude or simply when travelling. Contains other useful sections on trekking including legal information.]
- Wiseman, J. 1993. *SAS Survival Guide*, Collins, 384 pp. [Useful sections on clothing, first aid, what to expect in a variety of terrains, and other tips for survival in more remote regions of the world.]

The web addresses of selected geological equipment suppliers are provided on the accompanying website for this book – www.wiley.com/go/coe/geology.

Table 2.4 Summary of the main code of ethics for countryside and wilderness areas.

Countryside/wilderness code of ethics

Take responsibility for your own actions

Leave gates and property as you find them

Respect other people's privacy and/or cultural sensitivities

Do not disturb plants and animals

Leave nothing behind

Do not hammer or sample unless it is necessary

Follow any signs and landowner's instructions

3 Introduction to field observations at different scales

Angela L. Coe

3.1 Introduction: What, where and how?

Going out into the field and examining rocks at an exposure for the first time, or even subsequently, might well reveal features that you cannot recognize, do not understand or cannot explain. Overcoming this challenge is a matter of careful study, persistence and experience. This chapter provides an introduction to some of the key questions for geological fieldwork and a systematic way of overcoming the challenge of collecting data and understanding an exposure. The key questions are:

1. What are the objectives of the fieldwork? (Section 3.1.1)
2. Where is the best place to gather the data? (Section 3.1.2)
3. How do I precisely determine my position? (Section 3.1.3)
4. Faced with a new exposure, where do I start? (Section 3.2)
5. What is the most appropriate way of collecting the data? (Section 3.3, Chapters 5–10)



If you are faced with a lot of good exposure and do not know where to start, break it down into small parts.

Concentrate on a section of one cliff face first. If possible use a face that is either roughly perpendicular or parallel to the strike of the beds.

3.1.1 Defining the fieldwork objectives

Fieldwork is undertaken to address particular scientific problems; these should be clearly defined before going into the field. This is because it is very easy, when out in the field and faced by excellent rock exposures, to become distracted by other interesting features or to spend too long on particular aspects. For instance, if the objective of the fieldwork is to determine the orientation, sense and amount of displacement on a series of faults bounding a sedimentary basin then the *only* critical feature of the sedimentary beds required is a knowledge of the stratigraphy to determine the amount of displacement across the faults. On the other hand if the objective of the fieldwork is to produce a graphic log of the succession then the details of any later structural movement are

not required, except of course to be able to place the beds in stratigraphic order and to compensate for any displacement.

Before you go into the field, decide on the overall objectives of the fieldwork and at frequent intervals during the fieldwork remind yourself of these. On a day-to-day basis in the field, break the work down into achievable tasks; these may need to be reviewed and amended if the weather or time available changes. Another important point to remember is not to overinterpret the rocks based on a single observation. Instead combine as many lines of evidence as possible in order to put together one or more hypotheses. Write down the questions that each hypothesis raises, and think about what other data you need to collect or find in the literature to distinguish between these competing working hypotheses. Almost all of the geological record is incomplete so there are only ever a series of clues about what happened in the past.

The common overall objectives of fieldwork are summarized in Table 3.1 (p.44), which also provides reference to the chapters where there is further information both on the techniques and how to tackle the objectives. Specific day-to-day activities to achieve these overall objectives will be tasks such as: explore a particular region for new exposures; collect data on certain units; map a particular area; collect samples; or check data collected on the previous day.

3.1.2 Deciding where to do the fieldwork

The amount and type of rock exposure varies according to climatic zone – from almost 100% in arid areas to almost nothing in heavily vegetated areas such as the tropics. Provided they are safe and accessible, sea-cliffs, working quarries and new road cuts provide some of the best exposures because of the amount of rock exposed and their unweathered nature. Stream and river sections can also be important. If you are going into a field area for the first time and do not have a specific set of locations to visit based on published information from previous research on the area, spend a few hours or days completing a reconnaissance of the area to find the exposures that are most suitable for the objectives of the fieldwork. Table 3.2 (p.45) provides a list of the types of places to search for suitable exposures. If you are completing detailed mapping then all exposures need to be considered, unless there is 100% exposure in which case traverse or contact mapping are more appropriate (Sections 10.5.1 and 10.5.2 respectively). To address all other fieldwork objectives, the following points are worth considering when choosing the exposures to concentrate on:

- whether or not they are representative;
- stratigraphic completeness;

Table 3.1 Common objectives for completing geological fieldwork and cross references.

Overall objective	Main data to collect	Chapter references
Gain a general insight into the geology of an area	Lithology, structural and age data from selected representative exposures	5–10 inclusive
Construct the geological history of an area	Relative age data and basic geological information on each of the major units in the area and their relationship to each other	5–10 inclusive
Produce a geological map	Lithology and structural information from as many exposures as possible within the time and resources available	10
Determine the sedimentary depositional environment	Graphic logging of both sedimentary and palaeontological features, sketches and facies analysis	5 and 6
Make a record of a period of climate change	Graphic logging with particular emphasis on the collection of data that are indicative of climatic conditions; high-resolution relative dating of the succession and collection of high-resolution samples for proxy analysis (e.g. carbon isotopes)	5 and 6
Determine the sea-level history over a period of geological time	Graphic logging along a proximal to distal transect; application of the principles of sequence stratigraphy	6
Biostratigraphy	Collect zonal significant body fossils systematically through the stratigraphy or samples for microfossil analysis	5
Determine the level of an extinction event	Record the finds and hence stratigraphic ranges of the fossils	5
Determine the nature and order of a series of igneous events	Determine the overall mineralogy and rock fabric including the presence/absence and composition of phenocrysts, and size, shape and fabric of any vesicles; examine the cross-cutting and chilling relationships	7
Monitor the activity of an active volcano	Seismic, gas emission, gravity, thermal and observational data	7
Collect samples for geochemical analysis in order to understand Earth processes	Position of the exposures where samples were collected from and features of the rock body	6–9, 13
Locate mineral resources	Mapping and collection of samples for analysis	10, 13
Record the deformation history of an area	Mapping, structural measurements, cross-sections and stereonet	8, 10
Prediction and monitoring of earthquakes	Mapping and geophysical measurements	10, 11

- how weathered the rocks are;
- whether they are suitable for sampling without the need to clean the exposures;
- accessibility;
- safety.

3.1.3 Locating your position

Geological data are spatial therefore it is very important to be able to record the position of geological features accurately. The first part of this is locating the position of the exposure. If you are using a GPS check that it is correctly adjusted for the country that you are visiting or an appropriate grid system (Section 2.4). Your position might also be immediately obvious from a topographical map. There are instances, however, when it is not possible to use either of these methods or when a more accurate position is required. In this case use your compass for triangulation (Section 2.3.3, Figures 2.11 and 2.12, pp.22–24).

Other methods of determining your position

In wooded areas, remote featureless regions and in some river valleys it may not be possible to work out your position using compass readings. Near to the Earth's poles compasses are unreliable and you need to use a GPS or one of the shadow stick methods (see Wiseman 1993). If you are in an area of reasonably steep terrain an altimeter may help. In wooded regions and other featureless places you can set a bearing on your compass and walk along it. As you follow the bearing you can count your paces either manually or using a pedometer and hence calculate the distance that you have travelled from a known point. For this you need to calibrate the length of your normal paces by counting the number of paces you take over a known distance. The distance you have travelled along particular compass readings can be combined to produce transects or traverses (Section 10.5.1).

3.2 Scale of observation, where to start and basic measurements

Geological observations need to be made at a range of scales. Start at the large regional scale: this will provide the overall context. Then, consider the whole exposure, followed by units within the exposure and finally focus down to the hand-specimen scale.

3.2.1 Regional context

Before starting any fieldwork it is essential to research the regional setting, context and previous work. Aside from books,

Table 3.2 Possible places to search for exposures. In the case of animal burrows and where trees have been disturbed the subsoil type and small pieces of rock may give an indication of the underlying unit. This type of information should be directly compared with similar data collected from where the rocks are exposed.

Potential exposure sites

Natural exposures in upland, semi-arid and arid areas

All river and stream sections, especially where there is a gradient

Foreshore and sea-cliffs

Mine and quarry workings

Footings of construction sites

Animal burrows

Uprooted tree bases

Road cuts

Tunnels

Back walls of landslides

Lakeside cliffs

When counting paces if you count the times that you put down just one of your feet this will halve the chance of making a mistake arising from miscounting. If you have lots of pacing to do it might be worthwhile using a pedometer.

scientific papers and maps on the regional geology, web-based satellite image display systems such as Google Earth provide an easy way of investigating the general lie of the land and making preliminary observations on a large spatial scale and in some cases in more detail. A desktop regional study may be used to gather information on: access to the field locality and within it; the overall topography; the type and location of potential exposures; the general structure and strike of the beds.

3.2.2 Whole exposure

Arriving at a large exposure for the first time can be both exciting and daunting. It is often difficult to know where to start so, check whether the exposure is safe (Section 2.11) and then walk around and view it from different angles before making a decision.

One way to tackle a large exposure with different rock types and features is to first of all divide the exposure into ‘units’ based upon obvious features such as changes in colour and weathering characteristics. In most instances you are looking for somewhere between about 2 and 10 units (Figure 3.1), any more than this and it is hard to assimilate. If you have more than about 10 units you should try to group them together. Decide from a distance what the main characteristics of these units are and consider making a sketch to show these characteristics and their relationship to each other (Section 4.3) before completing more detailed observations close up.

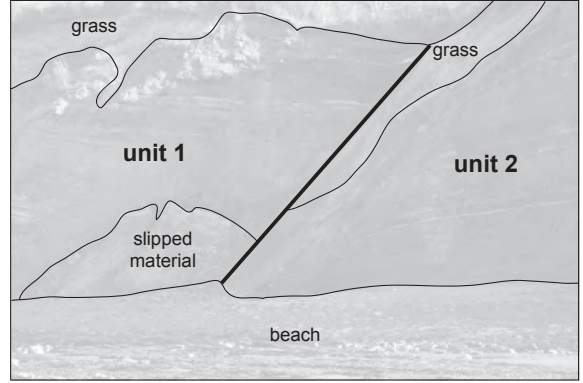
Your preliminary observations of the large-scale features in the exposure should include the following.

- *Nature of the contacts:* Note whether the contacts are gradational (e.g. colour change between units 2 and 3 and within unit 2, Figure 3.1d) or sharp (e.g. contact between units 1 and 2, Figures 3.1a and 3.1c) and whether they are planar (e.g. Figures 3.1a and 3.1c) or irregular (e.g. contact between units 2 and 3, Figure 3.1b and between units 1 and 2, Figure 3.1d). In the case of irregular contacts note the geometry.
- *Lateral changes in thickness:* Note the position and amount of any changes. These might relate to processes such as

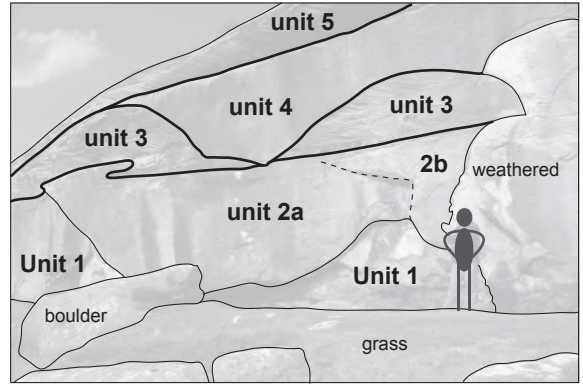
Figure 3.1 Four photographs and accompanying line drawings of different exposures showing how they might be divided into major units for recording and further examination. (a) Jurassic strata faulted against Triassic strata at Blue Anchor, Somerset, UK (height of cliff c. 10 m). (b) Carboniferous strata at Bowden Dors, Northumberland, UK. (c) Eocene strata exposed in the Clarence Valley, South Island, New Zealand. (d) Cenozoic strata at Choirokitia gorge, Cyprus. (a–d: Angela L. Coe, The Open University, UK.)



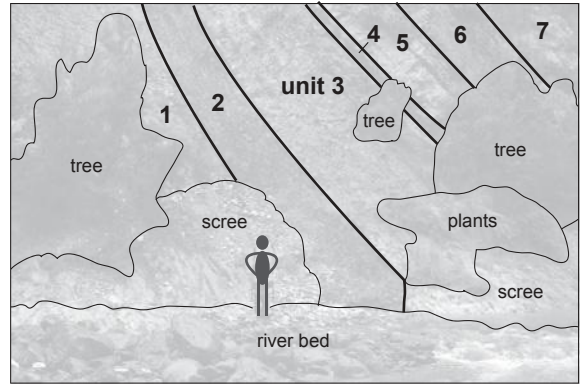
(a)



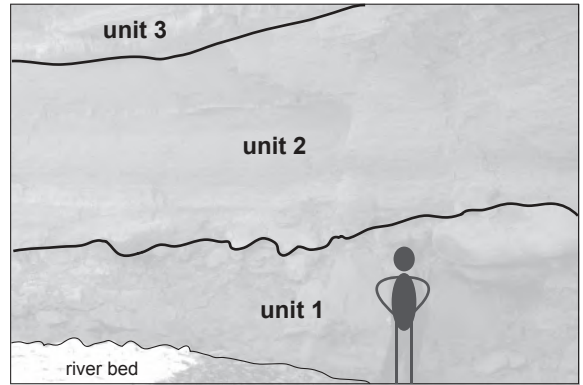
(b)



(c)



(d)



erosion, faulting, fluvial or submarine channels, thinning of a dyke or sill, changes in depositional conditions of sedimentary and extrusive rocks. Note which units change in thickness (e.g. unit 4, Figure 3.1b) and which are cut out (e.g. unit 3, Figure 3.1b).

- *Cross-cutting relationships*: Look for cross-cutting. For instance an igneous body cutting through older strata (Figure 7.1, p.140), erosional downcutting or an angular unconformity (e.g. Figures 3.1b and 3.1d).
- *Evidence of displacement and deformation*: Look for folding and faults (e.g. Figure 3.1a). Note any general trends in orientation angles and scale.
- *Angular unconformities*: Look for a change in the rock type associated with a change in the bedding orientation.

The large-scale weathering features of the units you are looking for are:

- whether any of the units stick out from the cliff or weather back (e.g. Figure 3.1c, unit 5 compared with unit 4);
- whether any of the units are massive, i.e. structureless (Figure 3.1b, units 1, 2 and 4);
- whether any of the units break into slabs or are crumbly (Figure 3.1c, units 1–3);
- whether there any notable changes in vegetation that may be associated with changes in lithology (e.g. Figure 3.1c units 1 and 4 are supporting trees), i.e. depending on mineralogy and permeability different rock types support different plants or have different moisture contents;
- whether the change in weathering matches with a change in colour, which together imply a change in lithology.

Once you have defined the main units, examine each one, in turn, close up, collecting the data that are appropriate to the objectives of the fieldwork. Some exposure surfaces do not reveal much, whereas other surfaces (e.g. where weathering has etched out the bedding or a fabric) may be more revealing. Don't worry if you cannot identify a rock type or geological feature straight away. If possible examine the rock or features in different parts of the exposure (e.g. natural vs. quarried, stream cut vs. wind etched) and its relationship to enclosing rocks or other features, its nature and identity may become apparent over the course of time. If not, record the features carefully in your notebook and with a camera and use the literature, or ask another geologist, to help identify them. Only if it is necessary and appropriate (Chapter 13) collect a sample.

When you have gathered enough of your own information to understand the basic relationships and rock types you are ready to complete more detailed studies, collect samples and, if appropriate, compare and correlate your subdivisions and observations with published information.

3.2.3 Hand specimens

When you select a loose sample, or an area of the unit to examine closely, check that it is representative of the unit being examined and that it has at least one very fresh surface. Loose specimens can be hammered to obtain a fresh surface. Only hammer off a small chip from an exposure if it is absolutely necessary and first ask yourself whether hammering will deface an exposure badly. To select a representative part you should consider the main features of the unit. For instance if 80% of the unit is sandstone and the other 20% is a muddy sandstone then ensure that you have a specimen of the main sandstone. Once you have examined the fresh surface you should supplement your observations by examining the weathered surface. In some rocks, for instance limestones and metamorphic rocks, differential weathering processes leave some minerals or grains sticking out of the main surface where they are easier to identify.

The questions and notes overleaf provide some points to consider when deciding whether the rock is igneous, metamorphic or sedimentary. As well as the composition and texture of the rock, its context should provide a good indication of the category that the rock type belongs to. Table 3.3 provides an overview of the checklists, rock-forming mineral tables and textural and classification diagrams provided elsewhere in the book and in the appendices. Commonly several of the units within an exposure are related to each other, so once you have described one hand specimen you should consider if it is possible to describe the others by simply noting differences between them. Often in sedimentary

Table 3.3 Reference guide to checklists, figures and tables elsewhere in the book and in the appendices (prefixed A) for rock description.

	Description	Common minerals	Textural	Classification
Sedimentary	Table A6.1	Table A6.2	Figures A6.1–A6.4	Section 6.2.1, Figures A6.8, A6.9, A6.11–6.13
Igneous	Section 7.3	Table A7.2	Section 7.3	Figure A7.1
Metamorphic	Sections 9.1 and 9.2	Section 9.3.1, Table A9.1	Section 9.2	Section 9.3.3

successions, but also with igneous bodies, it is the changes and differences between the units that provide clues about how the processes within the succession have changed.

Some questions to think about when deciding whether a rock is igneous, metamorphic or sedimentary:

- Is the rock made up of interlocking crystals, or made up of crystals in a fine-grained groundmass, or made up of grains within a matrix? If it is composed of grains then it is likely to be a siliciclastic rock or a carbonate but it could also be a pyroclastic rock. If it is crystalline then it could be igneous, metamorphic or one of the less common sedimentary rocks such as an evaporite or recrystallized limestone.
- What are the major minerals in the rock? There is only a limited range of minerals in sedimentary rocks and certain minerals are diagnostic of metamorphic conditions.
- Does the rock body show layering? In many cases this is bedding and it indicates sedimentary rocks, lava flows or pyroclastic rocks. Be aware though that a few metamorphic and plutonic rocks can also show layering which may be mistaken for bedding.
- What is the geometry of the rock body? Both igneous and sedimentary rocks can form dykes and sills but these are relatively uncommon in sedimentary rocks.
- What is the overall context of the rock body? Metamorphic rocks either form distinct, concentric zones around an igneous body if they are due to contact metamorphism, or more extensive outcrops if they were formed through regional metamorphism.
- Does the rock show a mineral foliation (Section 8.3)? If it does it is probably metamorphic, although some igneous rocks show such fabrics.
- Does the rock show distinct cooling joints? These form only in igneous rocks (Section 7.2.2), although they can extend into the adjacent country rock.
- Fossils are absent from igneous rocks except for the occasional occurrence in pyroclastic deposits. Fossils are only rarely preserved in low-grade metamorphic rocks and are not found in high-grade metamorphic rocks.
- More complex bedding structures such as cross-stratification and ripples are confined to sedimentary and pyroclastic rocks.

- Sedimentary rocks show a range of porosities whereas plutonic igneous and metamorphic rocks have a very low porosity.
- Metamorphic and igneous rocks have a higher density than most sedimentary rocks.

3.3 Overview of possible data formats

The objectives of the fieldwork will determine the most appropriate format for the data collection. Chapters 5 to 9 cover specific types of data collection relating to fossils, structures and different rock types. It can also be useful to transfer techniques between different rock types, so the range of field methods are briefly reviewed here.

- *Sketches*: Sketches on a range of scales both in plan view and cross-section to show the geometric relationships of rock bodies are used in all aspects of geological fieldwork. They are covered in detail in Section 4.3.
- *Graphic logs*: These are graphic representations of a stratigraphic succession of rocks, including information on the facies, boundaries between different units, bed thickness and lithostratigraphy. Graphic logs are commonly used for recording changing facies in sedimentary rocks (Chapter 6), but they are probably the best means of recording any stratigraphic information whether it is changing rock types along a cutting, the stratigraphic succession of fossils (Chapter 5), or the features of pyroclastic rocks (Section 7.2) or even a succession of lavas (Chapter 7). The construction of a graphic log is covered in detail in Section 6.3.
- *Cross-sections*: Field sketches of cliffs and exposures provide one type of cross-section. Another type that is worth sketching when in the field is a generalized cross-section of the inferred subsurface geology. This can be particularly useful where the strata are folded and/or faulted. A sketch cross-section helps to focus the task and think about different possibilities. Cross-sections are covered in Sections 4.3, 10.4.3 and 10.6.2.
- *Maps*: Sketch maps (Section 4.3.4) and base maps (Section 10.5.2) provide an invaluable plan view of the geological features showing the geometrical relationship between the units and the location of large-scale geological features.
- *Stereonets*: For structural studies and also palaeocurrent measurements in sedimentary successions it is often

For geological fieldwork it is a good idea to get used to estimating distances, angles and directions both for approximate readings and so that when you do measure something you can mentally check whether the reading is reasonable or not. This enables you to rule out the possibility that you have used the measuring device incorrectly or whether it has malfunctioned.

necessary to collect large amounts of orientation information on the different features. These are best summarized and analysed in the form of a stereogram, which provides a means of easily comparing the data and assessing where the main orientations lie. Stereographic projection is briefly outlined in Appendix A8.

- *Quadrats*: Quadrats (i.e. a set area or volume of rock) are useful for providing a means of gathering a quantitative snapshot of objects on a plane that is statistically representative of those objects (Section 5.4.2). They are often used to record the type, size, preservation and orientation of fossils. However, they are also useful for characterizing coarse-grained sedimentary deposits such as pebble beds or even phenocryst variation in igneous rocks.

4 The field notebook

Angela L. Coe

4.1 Introduction: The purpose of field notes

The field notebook forms the main record of the data you gather in the field. In particular, it should contain notes on where the data were collected, the relationships between the different rock bodies, their compositional and textural characteristics, and internal features. It usually also records the location of any samples collected, the position and orientation of any photographs taken, cross references to published information and notes on any ideas that you have for interpretation or questions raised by your observations. In addition the field notebook usually links together any other components that you might have used to record data and ideas in the field. For instance, an electronic database held on a piece of geophysical equipment, field maps, annotated figures and graphic logging sheets.

One way to think of your field notebook is as an ‘academic’ diary, i.e. a record of *all* of your observations, ideas, interpretations and questions over the fieldwork period. Often field notebooks include less academic notes, for instance the weather, someone you met that day, where you stayed or ate, if you were ill or your mood. This is because all of these serve as an *aide memoire* when you come back to your notes, provide information for future trips and can help you to assess how good your notes might be for that particular day.

The choice of a suitable field notebook was covered in Sections 2.8 and 2.9. This chapter concentrates on the type of information that you need to collect in the field and suggestions for organization of the data. The principles are equally applicable to both an electronic notebook and a hardcopy notebook. A few features may need to be adapted for electronic use: for instance, use of sequential and logical file names rather than page numbers, creating an index and/or files with preliminary information. One of the main challenges of

using an electronic system is finding a suitable means of easily making detailed sketches (Section 4.3).

4.2 Field notebook layout

Designing and using a good field notebook layout adapted to suit *your* needs and style will enable you to be systematic in the notes that you take. This will help ensure that you do not forget major components and that the information you collect is much more accessible and therefore more readily useable. Fieldwork can be strenuous and difficult particularly when, for instance, it is raining, windy, very hot, very cold, at high altitude, or the locality is difficult to access. Quite often the time available to complete crucial data collection is limited due to transportation, the hours of daylight, tidal and weather conditions and the overall expense of completing fieldwork. All of these constraints mean that designing an efficient means of collecting data in the field will maximize your output.

4.2.1 Preliminary pages

When you start to use a new notebook ensure that you put your name, address, email and any other contact details in a prominent place on the cover or immediately inside just in case you should lose it. We suggest that you set aside up to 10 pages at the front of the notebook where you can insert a table of contents and useful general information. For the table of contents two to four pages are usually sufficient with a column for page numbers. Other useful information for these preliminary pages may include copies of rock classification figures (such as those in the Appendices of this book), checklists (to ensure you do not forget to take a crucial measurement or record an important observation), abbreviations and symbols used, photocopies of geological or topographic maps of the areas you will visit, information on who you need to contact to gain access to the area (e.g. quarry manager or landowner) and any other information that you might find useful in the field. In remote and semi-remote areas where accommodation is limited it can also be useful, either at the front of the notebook or in the daily entries (see below), to include brief details of suitable accommodation and places to eat/buy provisions, etc., for return visits.

4.2.2 Daily entries

The daily entries will form the bulk of the information in your field notebook. Example pages for the start of a daily entry are illustrated in Figure 4.1.

YORKSHIRE S260 ROCKS
 RS20 TSJ.
 'Elland Flags' micaceous fine-grained sst, 3-8 mm laminations of sand interbedded with sub mm laminations rich in plant debris. Occasional ripples and small scours.

From Rand & Asquith (Acelandale Ltd)
 Tel 01484 719263 Spoke to Steve Rand
 Fax 01484 401420

Office: Tuck Royd Quarry
 Halifax Road
 Brighouse
 West Yorkshire
 HD6 2PL

Quarry manager Paul Rand
 Quarry SE 128 214 Lower Edge Road
 (between Kestrick & Elland)

- very obliging took 'crazy paving slabs' i.e. poor flags for rX specimens & thin sections
- 2 pieces Ashlar - Flag contact with ripples & syn sedimentary dewatering structures. Polished.
- Plant, mud and mica rich flags - enough for HS at SS Os Landranger Map N° 104

For general info see SCRUTTON, C. 1994. Yorkshire Rocks and Landscape. Yorkshire Geological Society

(a)

INSIDE SILICIC CALDERAS 7-18th July '99

Themes: tectonism, hydrovolcanism, deep sections thru calderas.

7th July 1999 SNOWDONIA

Ordovician volcanism into the Hekla basin. Subsequent deformation and alteration. Marine caldera within a rifted extensional basin. Magmatism concentrated along basement fracture pattern. Early Ord rift in northern Snowdonia in volc's, this switched off before moving to 435 Ma (Coradoc) northern Snowdonia. Only relative dates not absolute. One of P's queries: how long could this sort of system be active? Margins of the basin: sinistral extensional.

Nonextensional rifted basin.

"flower structure" geometry with magma plumbing the basement discontinuity ① and facilitating upper crustal weaknesses.

SW NE

basaltic volcanoes developed on subaerial, rhyolitic emergence.

Trap-door subsidence to the N allowed thick units to be preserved within the caldera.

Intercaldera fill (LRT)

disruption of Potts Head bluff (unit beneath LRT)

(b)

Day: 1 Date: 29.06.1989

Aims: Reconnaissance of eastern end.
 Region: East of SWA: around Doughterard. (to N)
 Weather: Sunny w. light breeze
 Health: J.T. tired - still recovering from journey, otherwise OK.

Locality 1. TONWEE ROE NE

A long, fresh drainage trench through a field reveals 20 cm of dark brown turf lying on top of a red-orange boulder clay.

Sketch of one side of the trench.

(c)

15/7/07 SEATON SLUICE ①

SUNNY & DRY
 N# 339768

- ① Identify Rock Type - Sandstone
- ② Examine Sed structure - Trough Cross Strat
- ③ Identify Sed structure - ↓
- ④ Determine palaeocurrent direction westerly

(d)

Figure 4.1 Four examples from notebooks of the first page relating to a particular day's field activities.

(a) Visit to a working quarry to collect rock samples. (Notebook of Angela L. Coe, The Open University, UK.)

(b) Field trip to Snowdonia, UK with introductory notes. (Notebook of Tiffany Barry, The Open University, UK.)

(c) Geological mapping in Ireland. (Notebook of Kate Bradshaw, The Open University, UK.)

(d) Field trip to Seaton Sluice, Tyne and Wear, UK to examine the sedimentary deposits. (Notebook of Paul Temple, Open University student.)

The initial information should include the following type of information, although the exact details will depend on the purpose of the fieldwork.

- Date and day of field visit (Figure 4.1).
- A prominent heading containing the name of the general area and/or locality or localities to be visited (note this is clearly shown in upper case in a box in Figure 4.1a and b).
- Aims of the fieldwork (Figures 4.1c and 4.1d) or a summary of the general hypotheses that are to be tested (Figure 4.1b).
- Notes on the weather and any other information that will help you to recall the field day (Figures 4.1c and 4.1d). This might also be a prominent feature in the landscape or your means of access.
- The name(s) of your field partner or the other members of the team of people you are working with (Figure 4.1a top right).
- Any notes on access restrictions, permission, logistical arrangements and discrepancies between the topographic map and reality on the ground (Figure 4.1a).
- More detailed location information as appropriate. This may take the form of reference to the literature (Figure 4.1a), a grid reference (Figures 4.1a and 4.1d), longitude and latitude, reference to a detailed topographic map (Figure 4.1a) and/or a sketch map. Sketch maps are particularly useful for the area immediately adjacent to the field site(s) where you need information at a high spatial resolution (see Section 4.3.4 for further information).

The bulk of the information in your notebook is likely to be in one of the following forms: (1) field sketches including maps, cross-sections and diagrams of cliff faces and individual features (Section 4.3); (2) written notes or tables of the data collected; (3) written notes detailing the interpretation and ideas of yourself and others (Section 4.4.2); (4) systematic information on samples collected and photographs taken (Section 4.4.1, Chapters 12 and 13); and (5) reference to other data sets used in the field (such as field maps and published literature).

4.2.3 General tips

- *Cross referencing*: Number the pages of your notebook; this will allow you to cross reference, indicate where notes and figures might be continued, provide references to other documents and produce a list of contents for ease of access to information at a later date.

- *Use of space:* Space your notes out so that there is room to add further notes if you revisit the locality or to record the location of samples. Extra space is also helpful if you wish to add interpretation later on, or a discussion that you have had with colleagues about the data at a later stage. Space also makes the notes easier to follow (Figure 4.2a, p. 58).
- *Organization:* Use headings and subheadings as they make the notes much easier to find (e.g. Figure 4.1). Devise a system to show the hierarchy of these headings. For instance use a box around the main heading and an underline for the others (e.g. Figure 4.1a). Record ideas and points of interpretation in a different manner, for instance in a separate column or in a 'cloud' (Figure 4.2a). Another tip is to use a coloured pencil/waterproof pen to pick out particular notes that are important to the task in hand: for instance, sample numbers or locality numbers or photographs (Figure 4.2b) or strike and dip data. Information can also be organized by ordering it into columns (Figure 4.2b).

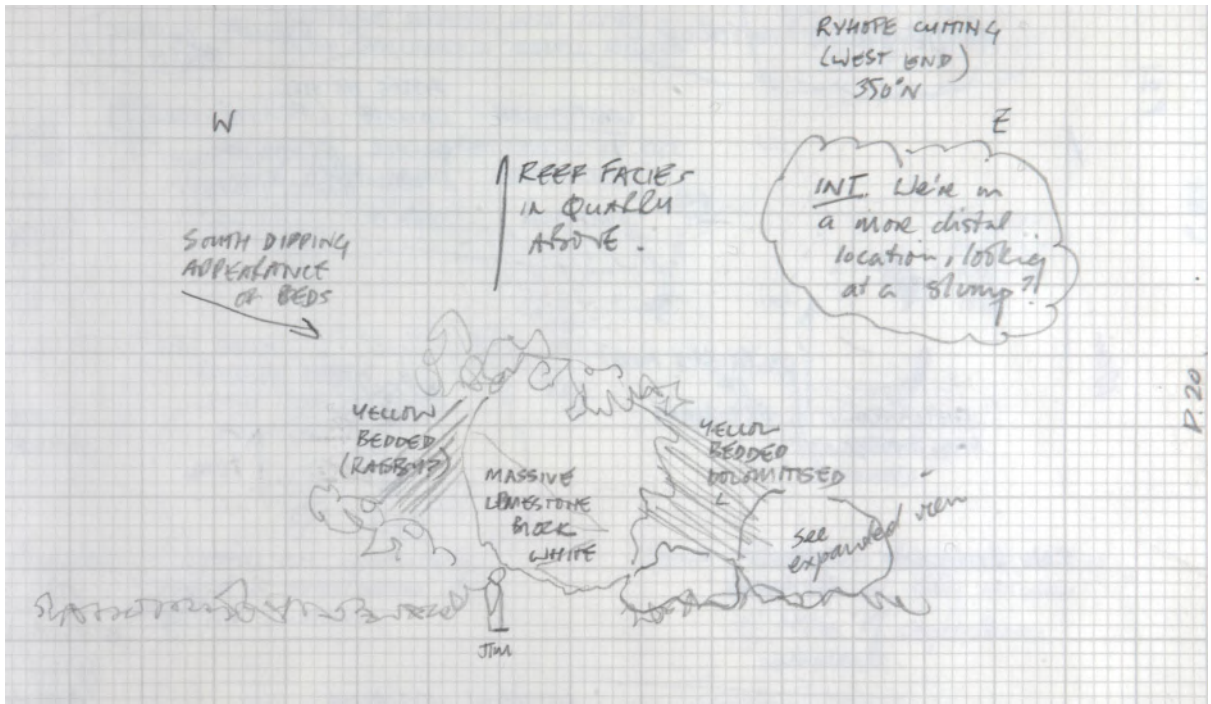
A few coloured pencils are useful for sketches in the field and for distinguishing different parts of the field notes.

4.3 Field sketches: A picture is worth a thousand words

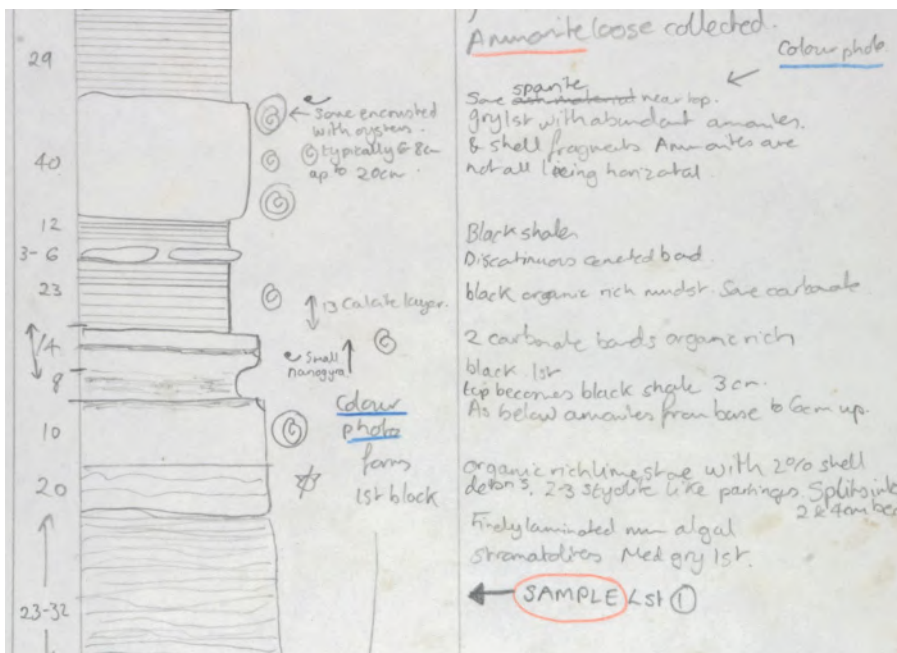
Sketches form a vital part of all geological field notebooks. They include: diagrams of cliffs or quarry faces; sketches of individual features such as a fossil, mineral or sedimentary structure; sketch maps; cross-sections; and sketches showing ideas for interpretation.

Sketches are one of the best ways of recording and conveying geological information. This is for two reasons: (1) They provide a shorthand means of conveying information in an easily accessible form. For example, it is much quicker to draw the form of an irregular contact between two beds than to describe it. Because geology is mostly about the relationship between different rock bodies and their three-dimensional geometries, irregular shapes and contacts are common, and it is much easier to convey this in detail in a figure than it is in words. (2) The very act of producing a good sketch involves carefully observing the features, units and the relationship between all of them. If executed properly, sketches can convey much more of the key geological information than a photograph because the author has to pick out the important geological features that relate to the objective of the fieldwork more clearly, add labels to show where other data have come from, and add a certain amount of interpretation.

It is worth bearing in mind that the human eye is much more sophisticated than any camera. In almost all instances a good



(a)



(b)

Figure 4.2 (a) Sketch from a field notebook showing good use of space, a method of separating interpretation (shown in the cloud at the top right) from the observations. (Notebook of Brian McDonald, Open University student.) (b) Part of a graphic log showing effective use of colour to pick out samples (red) and photographs (blue). (Notebook of Angela L. Coe, The Open University, UK.)

geological field sketch is a combination of a simple line drawing of the relevant geological features you can observe and your initial geological deductions. Thus photographs are *not* a replacement for sketches because they are neither selective nor deductive and you cannot add labels and cross references. Professional geologists regularly use a combination of photographs and sketches. Producing field sketches is the notebook skill that most students of geology and even some professionals find very difficult, but it is a skill that is well worth developing.

Figure 4.3 (p. 60) shows a range of different types of sketch and styles. They all record geological data. Simple two-dimensional sketches can provide an effective summary of many different features at a variety of scales (Figure 4.3a–d). In contrast, three-dimensional sketches of sedimentary structures are complex and difficult to execute (Figure 4.3e). In this case the author has also bravely tried to show the shape of the sandstone block the structure was preserved in. This type of sketch is not generally recommended because: (1) it is hard to draw and (2) the sedimentary structure is confused with the shape of the weathered surfaces; (3) the shape of the block is also irrelevant to the purpose of the exercise which was to record the sedimentary structure. Simple sketch cross-sections showing the topography, exposures and main geological units (Figure 4.3d) are useful overviews. Where the relationships between different rock units are complex a sketch will help to focus observations (Figure 4.3f). Figure 4.3f also shows effective use of colour and an inset box to show more detail of one part.

4.3.1 General principles: Aims, space and tools

Before you start sketching you should decide on the aims of the sketch. One way to do this is to start by writing down the title or caption of the sketch encapsulating the aims. Sketches are usually drawn freehand in pencil (i.e. not with a ruler). Drawing in pencil is advantageous because it allows you to erase mistakes and/or redraw part of the sketch. With a pencil it is also easier to draw lines of different thickness and boldness as well as shading part of the figure to bring out different features (Figure 4.4, p. 62). A minority of people sketch directly in pen but this is not recommended because it is impossible to correct mistakes or make improvements, so the accuracy is compromised. Most sketches look better on plain paper, although some people find that lined or graph paper is useful for scaling.

Here are some ideas for producing a good sketch; these are also summarized in Figure 4.4 (p. 62).

- *Space*: Allow plenty of space in your notebook for the sketch so that there is room to add labels summarizing observations, scale and orientation, detailed drawings of pertinent parts (insets), cross references to later sketches or other written notes, and labels summarizing points of interpretation. It is also much easier to sketch at a larger scale; if you are not good at sketching it may be tempting to push the sketch into one corner of a page of the notebook but this is making it far more difficult for yourself. So, take your time and use a whole page or even two facing pages for the sketch and labels. Don't spoil a good sketch with too many labels though or place labels on the sketch so that they obscure parts of it. Figure 4.2a (p. 58) shows good use of space but it could have been improved by placing the labels that are on top of the line drawing off to one side with tag lines in a similar manner to Figures 4.3c and 4.3f.
- *Scale*: All sketches should include a scale. How accurate the scale of the sketch is will depend on the purpose of the fieldwork. However, it is important to get the features into proportion. For sketches of cliffs, hillsides, etc., once you have established a scale for a small portion (e.g. from the height of a person (Figure 4.2a) or size of a vehicle) use your thumb held at arm's length to estimate the scale for the remainder of the sketch.
- *Orientation*: All sketches should include an orientation relative to north and a clear indication as to whether it is a plan view, oblique view or cross-section (e.g. cliff). The simplest and most straightforward way of adding an orientation is to use a north arrow for any plan views and to label the ends of cross-sections with the nearest compass points, e.g. NW–SE or NNW–SSE. Alternatively, you can label your viewpoint to the centre of the sketch, e.g. looking due southeast or looking towards 135°. The latter method is popular for views of oblique surfaces but is not recommended for cliff sections because it is not as clear.

Figure 4.3 Example sketches from different authors' notebooks showing features on a wide variety of scales. (a) Simple cross-sectional sketch showing wavy lamination in a sedimentary rock. (Notebook of Paul Temple, Open University student). (b) Zoned phenocryst showing shape of crystal zones. (Notebook of Kate Bradshaw, The Open University, UK.) (c) Labelled cross-sectional sketch of pebble bed. (d) Large-scale sketch cross-section across a hillside in Argentina. (c and d: Notebook of Angela L. Coe, The Open University, UK.) (e) Complex three-dimensional sketch of trough cross-stratification in a block of sandstone. (Notebook of Kate Bradshaw, The Open University, UK.) (f) Sophisticated sketch of the geological relationships of various rock bodies in a kimberlite complex, South Africa. (Notebook of Richard Brown, The Open University, UK.)

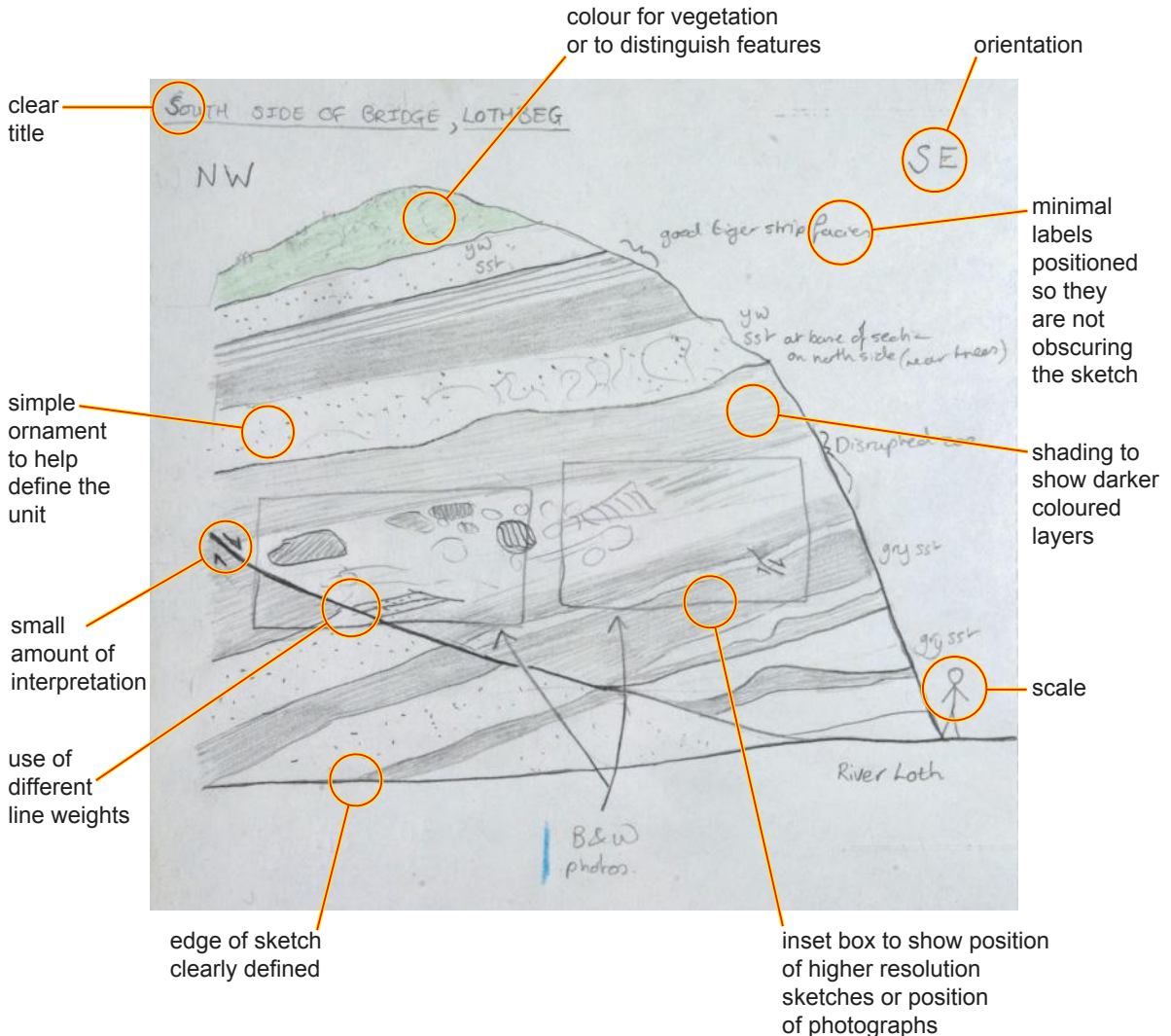


Figure 4.4 An annotated example of a field sketch showing some of the key features that can usefully be included in a sketch. This sketch is of Kimmeridgian rocks exposed in northeast Scotland. (Notebook of Angela L. Coe, The Open University, UK.)

- Angles and geometry:** Boundaries between units and features within units (e.g. cross-stratification or folding) are best shown at approximately the correct angle of dip. This will not only make the sketch look more realistic, it will be more accurate and make the features easier to identify. In general people tend to exaggerate angles (i.e. make them steeper). A simple technique for obtaining a good estimate of the angle is to put your compass-clinometer into the clinometer mode (Figures 2.6 (step 2) and 2.7 (step 3)) and then holding the compass-clinometer at arm's length with

the long edge at the same angle as the features whose dip you are trying to estimate, read off the apparent dip.

- *Inset boxes for detail:* In some cases the geological feature repeats itself on the small scale, or there is one particular part of the cliff that you want to collect data on in more detail. So rather than putting the detail in for the entire cliff face one useful technique is to draw the main features on the sketch and then add a box to indicate the area where a photograph has been taken or a more detailed sketch has been constructed (Figures 4.3f and 4.4, pp.60 and 62). This also enables you to draw the detailed part at a larger scale if appropriate.
- *Colour:* A green coloured pencil can be useful for showing the vegetation and clearly separates it from the geological part of the sketch (Figure 4.4). A red or blue coloured pencil is useful for cross references, particular items or key features (Figures 4.2b and 4.3f, pp.58 and 60).

4.3.2 Sketches of exposures

Sketches of whole, or representative parts of, exposures such as sea-cliffs, road cuts and quarry faces are commonly used to observe and show one or more of the following:

- the main units and the geometric relationship(s) between them;
- large-scale (metres to tens of metres) structures such as folds, faults and angular unconformities;
- the position of more detailed measurements (e.g. samples or a graphic log; see Section 6.3 and Chapter 13) so that the exact location can be easily relocated.

In most instances it is best to take up an entire page, or even two facing pages, of a hardcopy notebook when constructing a sketch of a cliff or quarry face. Also consider the orientation of the notebook; would the subject matter be best captured with the notebook page orientated landscape (i.e. wider than it is taller) or portrait (i.e. taller than it is wider)? Long cliff faces are usually best landscape whereas a vertical profile through a cliff might be better portrait. Figure 4.5b–f (pp.64–65) shows how you might build up a sketch of the cliff shown as a photograph in Figure 4.5a. While these instructions are divided into suggested steps it may be necessary to amend the order depending on the subject matter, or go back to a previous step to add or amend the detail. The aim of the exercise in the case of Figure 4.5 is to summarize the main rock units and the relationship(s) between them.

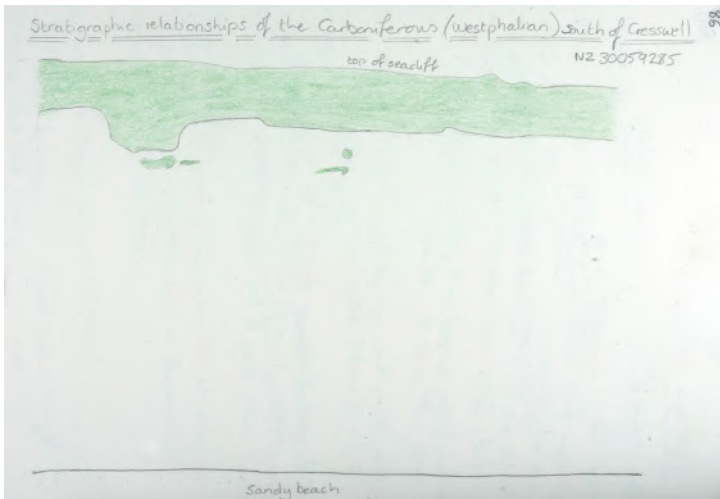


For shading, a softer (HB or less) conventional type of pencil rather than a mechanical pencil is better. Hold the pencil so that the side of the pencil lead is in contact with the paper to execute the shading. Varying the amount of pressure results in different depths of shading. Gently rub the tip of an index finger over the shading in a circular motion if you wish to smooth the shading out further.



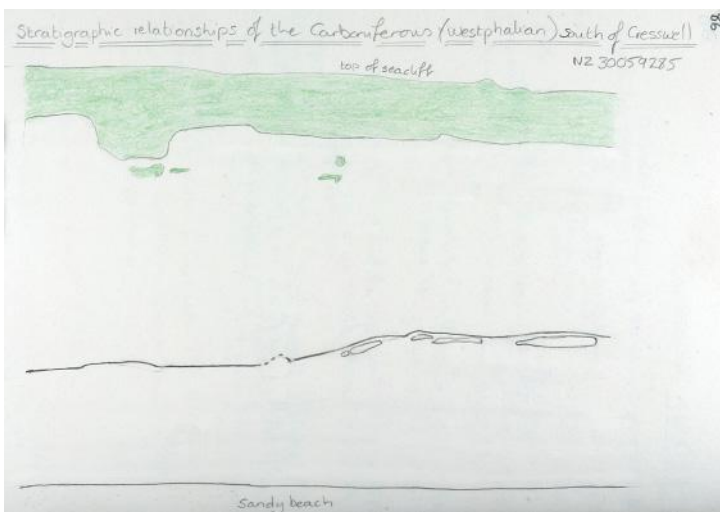
1. Assess the units

Spend some time looking at the exposure and deciding how many units there are (Section 3.2.2). Look for any major features such as cross-cutting relationships or displacements. Choose a representative part of the cliff to sketch (shown by the yellow box in this case).



2. Draw the outline

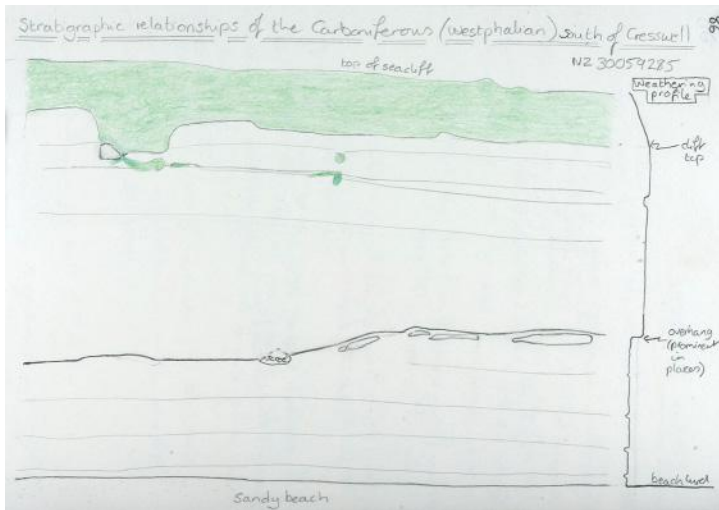
Decide on the best orientation of your notebook for the sketch (in this case landscape). Put a title/caption at the top of the page, detailing the subject of the sketch and the aims. Draw the outline of the area first, i.e. the bottom and top of the cliff, and extend the sketch laterally to the edge of the chosen area. If there are areas of vegetation add at least the main ones as points of reference.



3. Draw the major geological boundaries

Draw the major boundaries between the units. As you sketch in the boundaries pay particular attention to whether the boundaries are sharp, or gradational, undulatory or planar. Use a thick, bold line for where the boundary is sharp and distinctive, and a medium density line for those that are gradational. Use your compass-clinometer to estimate apparent angles (Section 4.3.1) and your thumb held up in front of you at arm's length to estimate the relative thicknesses. Ensure that the boundaries between the units are continuous for their entire length; if the boundary is obscured by vegetation or slipped material mark this in.

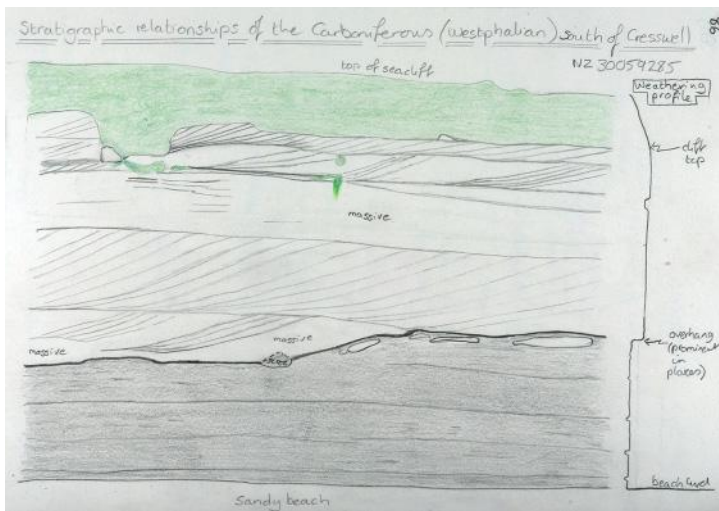
Figure 4.5 Photograph of Carboniferous-age strata near Cresswell, Northumberland, UK and series of sketches showing how a field sketch of this exposure might be gradually constructed. Note that features of no interest such as the large cracks have been ignored because they would detract from the geological features of interest.



4. Draw the boundaries of any subunits and a weathering profile

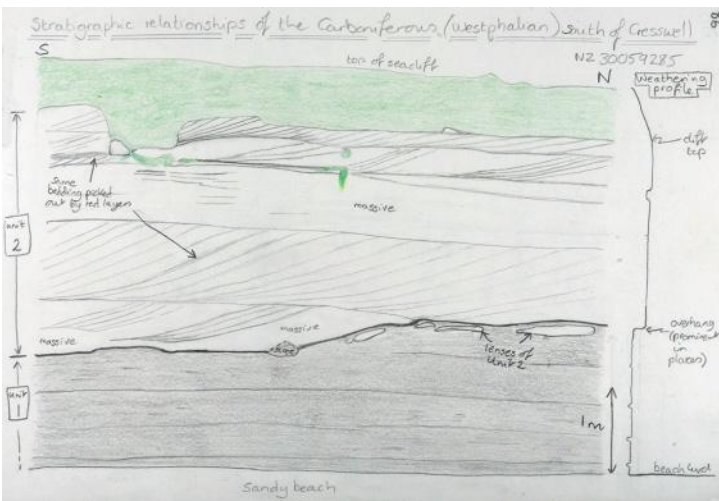
Where there is differential weathering of the rock units it can be helpful at this stage to draw a weathering profile at the side of the sketch that is directly related to each of the units. This can be used to relocate your position on the sketch particularly if there are many units.

Draw in the boundaries of any subunits using lines of appropriate weight and thickness. If appropriate, add other features such as scree, and further details on reference points such as vegetation to help you locate the different parts of the sketch but ensure that these do not detract from the main part of the sketch.



5. Sketch the detail within each of the units

Observe each of the units in turn and add the following: shading for any darker coloured units (using different densities of shading as appropriate); any detail within each of the units/subunits using thin lines, e.g. thinner beds, sedimentary structures, folds, etc. Ensure that as you add to the sketch the boundaries between the main units remain clearly defined. If for part of the sketch there are features that are hard to distinguish, or you do not have time to add the detail, label the sketch accordingly (e.g. features not shown, massive).



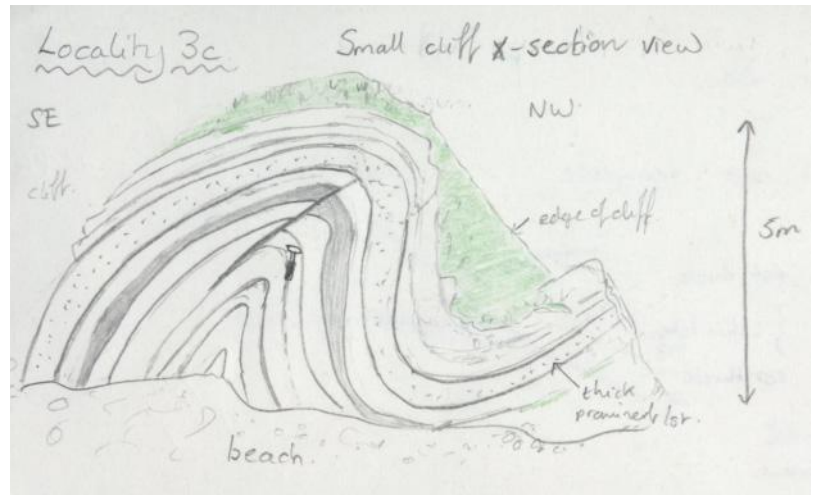
6. Add the finishing touches

Add a scale, orientation and number/name the units so that you can refer to each of them in your further notes. Complete a detailed sketch of any key parts and mark how these relate to your main sketch.

Figure 4.5 Continued The rock face is depicted in the sketch as if it has been projected on to a two-dimensional vertical plane. (Notebook of Angela L. Coe, The Open University, UK.)



(a)



(b)

Figure 4.6 (a) Photograph and (b) sketch of a fold near Berwick-upon-Tweed, UK illustrating the technique of tracing several key beds through the structure in order to illustrate its overall form. (Notebook and photograph of Angela L. Coe, The Open University, UK.)

A few other tips:

- If the exposure is composed of many thin beds with no really distinct units, concentrate on one or two beds and use them to depict the overall structure in the cliff (e.g. Figure 4.6).
- If the face is structurally complex you may have more than one possible interpretation. Show this by either completing more than one sketch, or completing a sketch and adding several small cartoons to show the different interpretations or using different colours to depict alternative interpretations.

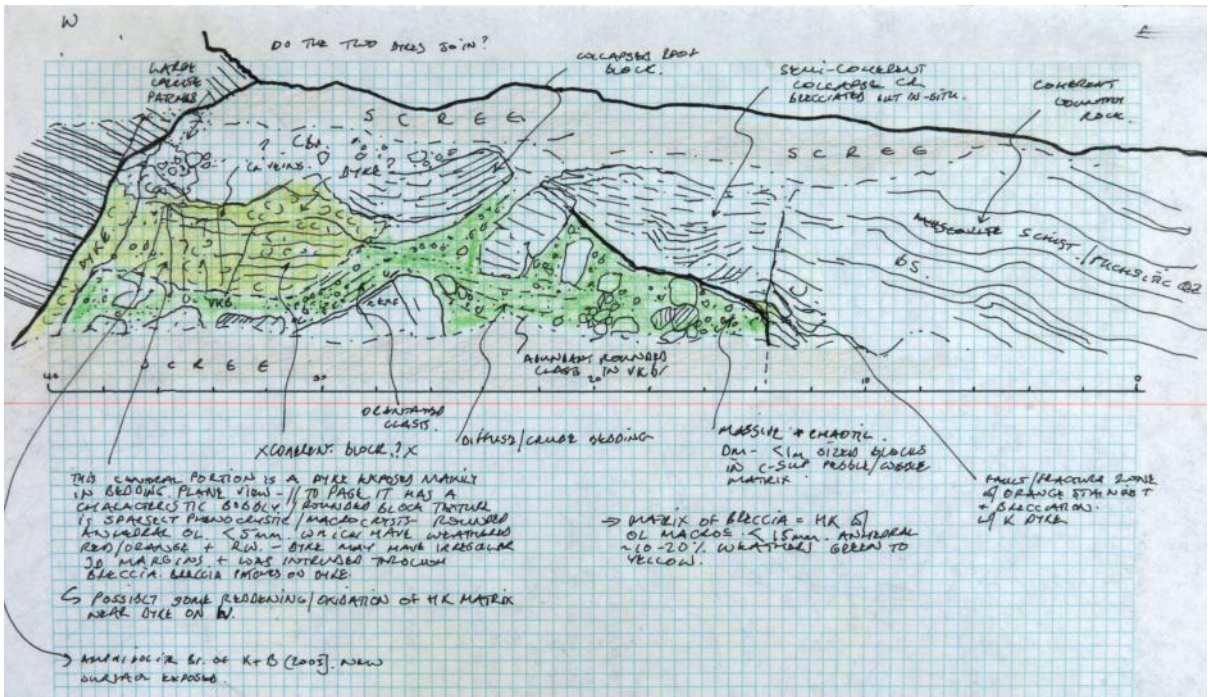


Figure 4.7 Detailed sketch of part of a kimberlite complex, South Africa illustrating use of an accurate horizontal scale in addition to good use of colour, clear labelling that does not interfere with the sketch and distinct boundaries between the different units. (Notebook of Richard Brown, The Open University, UK.)

- Use different line weights to distinguish between distinct and gradational boundaries. Use shading to pick out darker coloured units.
- Do not try and draw the three-dimensional nature of the face (e.g. Figure 4.3e, p.60). This will make it very complex. Imagine instead that the beds are projected onto a flat plane (Section 4.3.3). If necessary draw a sketch map to relate different two-dimensional faces to each other.
- If the sketch is to cover a laterally extensive area add a horizontal scale and consider breaking the sketch into scaled panels (Figure 4.7).

4.3.3 Sketching metre- and centimetre-scale features

All geological features occur in three dimensions, whether they are due to rock deformation, sedimentary processes or intrusion processes. Whilst a small minority of people are capable of drawing clearly in three dimensions, most of us are not. For some features such as faults and bedding a two-dimensional representation is sufficient.

However, where more difficult three-dimensional features need to be recorded such as folds or sedimentary structures there are two simple solutions depending on the feature being recorded.

- Draw two or three sketches of faces that are approximately at right angles to each other to illustrate the three-dimensional characteristics. It is important in this case to choose the most representative faces.
- Record the features as a small-scale map and cross-section (for instance the anticlines and synclines* in Figure 4.8).

Another useful technique when sketching structures is to ensure that the geometries are drawn at the correct angle. This means checking the apparent angle of any dipping surfaces and drawing them to within about 5° (see Section 4.3.1 for how to do this with a compass-clinometer) as well as showing the geometric relationship between the different parts correctly. For instance in cross-stratified deposits the beds generally dip at between about 10° and 25° and never higher than 40°; the individual layers in cross-sets do not cross-cut each other; and the base of the beds run in tangentially to a bottom surface that represents true bedding (e.g. Appendix A6; Figure A6.14a and b). Fossils are often best also recorded with photographs. Sketching has the advantage of making the geologist observe the features, but fossils are often so complex that a photograph is quicker and easier. If the fossil is partly obscured or has a complex three-dimensional form (e.g. some burrows), or you need to show the overall context, then sketching may also be necessary to show the overall form and how the different parts are related (see also Section 6.2.2). This ensures that you have a record of the interpretation of how the different parts fit together to enable the photographs to be put into context.

Tracing the structure: A simple technique that can help with the recording of more complex features is to trace a lamination or bedding plane through the structure with your finger or hand. This can help to give a better sense of the geometry and to split the structure into its component parts.

4.3.4 Sketch maps

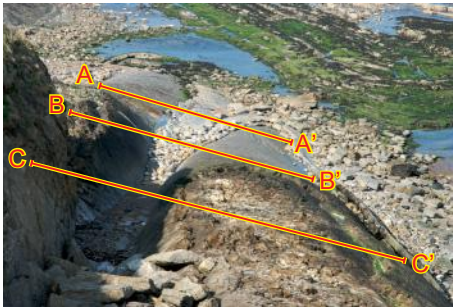
Sketch maps can be constructed to show areas of interest at a high spatial resolution so that the area can be relocated at a later date, or to remind you how the different data sets that you collected are related laterally. They can also be used to depict geological relationships schematically that cannot be shown on a single sketch. Sketch maps need only to be roughly to scale; they should, however, include an approximate scale and a north arrow. You should include sufficient topographical features, such as the edge of a cliff face or buildings or the sea, as well as the access route in order to put the specific geological material into context.

Figure 4.9 (p. 70) shows a number of examples of different styles of location maps from field notebooks. Remember that

*The terms anticline and syncline imply that the folded strata are the correct way up (i.e. younging upwards). The terms antiform and synform refer simply to whether the fold closes downwards or upwards no matter which way the younging direction lies.

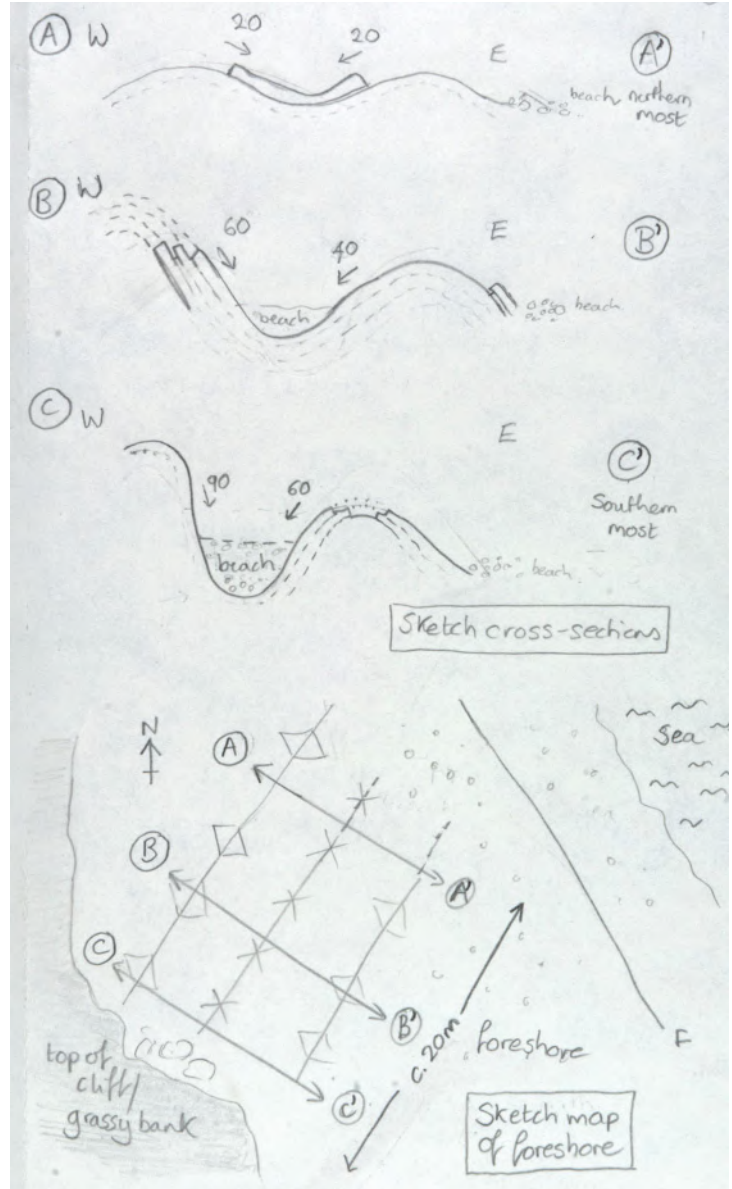


(a)



(b)

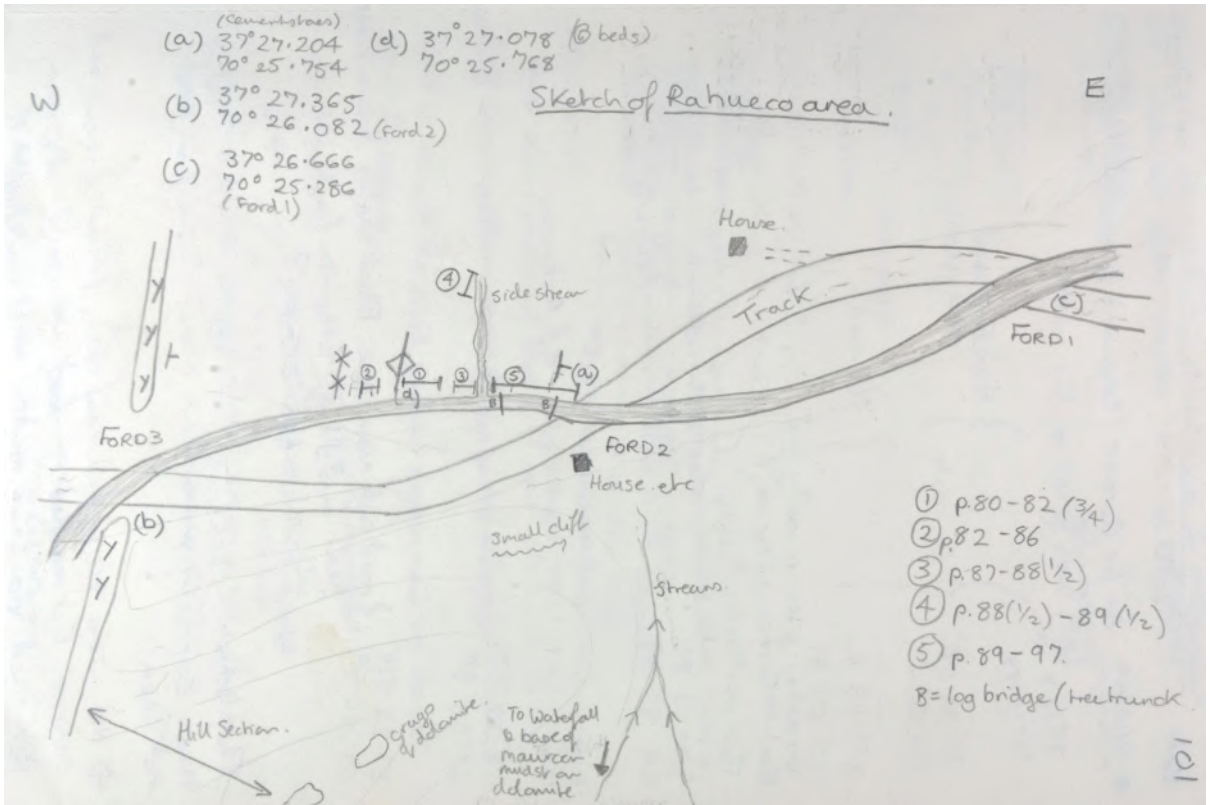
— line of section in (c)



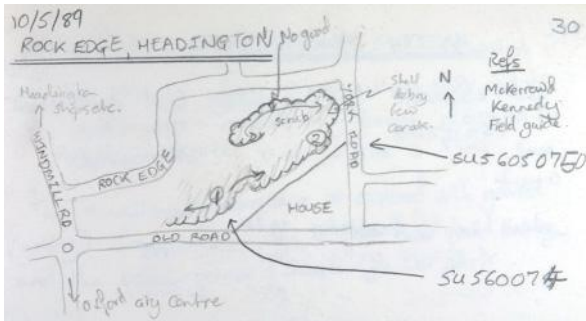
(c)

Figure 4.8 (a) Photograph of several plunging folds near Berwick-upon-Tweed, Northumberland, UK. (b) Detail of (a) showing lines of cross-sections in (c). (c) Series of simple sketch cross-sections and a sketch map from a field notebook showing how the three-dimensional characteristics of these folds might easily be recorded in two dimensions. The map could be improved by adding a numerical value for the strike direction of the axial traces. (Photographs and notebook of Angela L. Coe, The Open University, UK.)

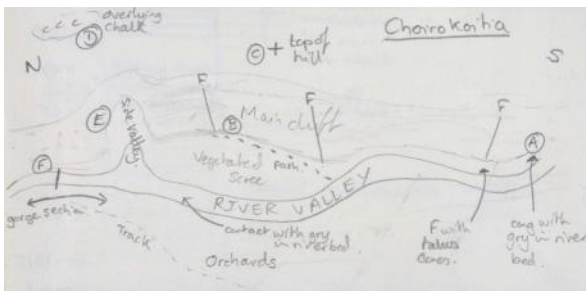
there is no point in reproducing detailed topographical maps that are already published and which you can annotate instead. The sketch map should add something new and useful. If you need to produce an accurate geological map then your



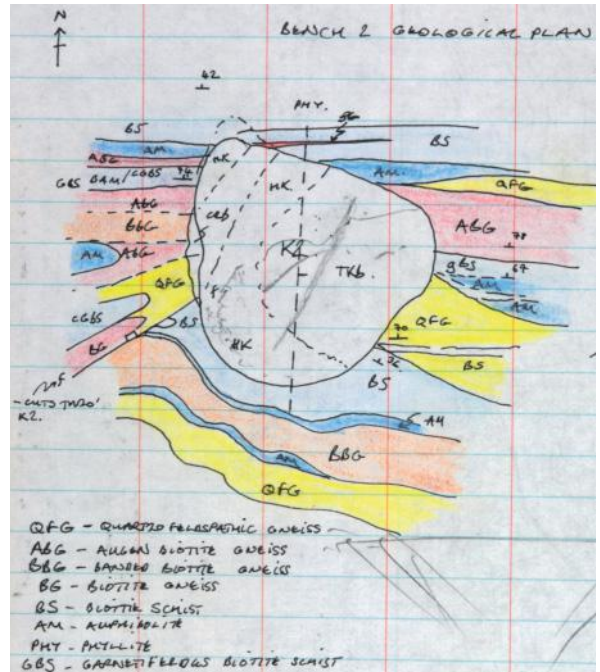
(a)



(b)



(c)



(d)

recordings should be plotted precisely on a topographic field map or aerial photograph (Chapter 10). Occasionally the hard-copy accurate base map is not at a large enough scale and, in these cases, it may be useful to draw an expanded map in your notebook and to add other topographical features (Figure 4.10).

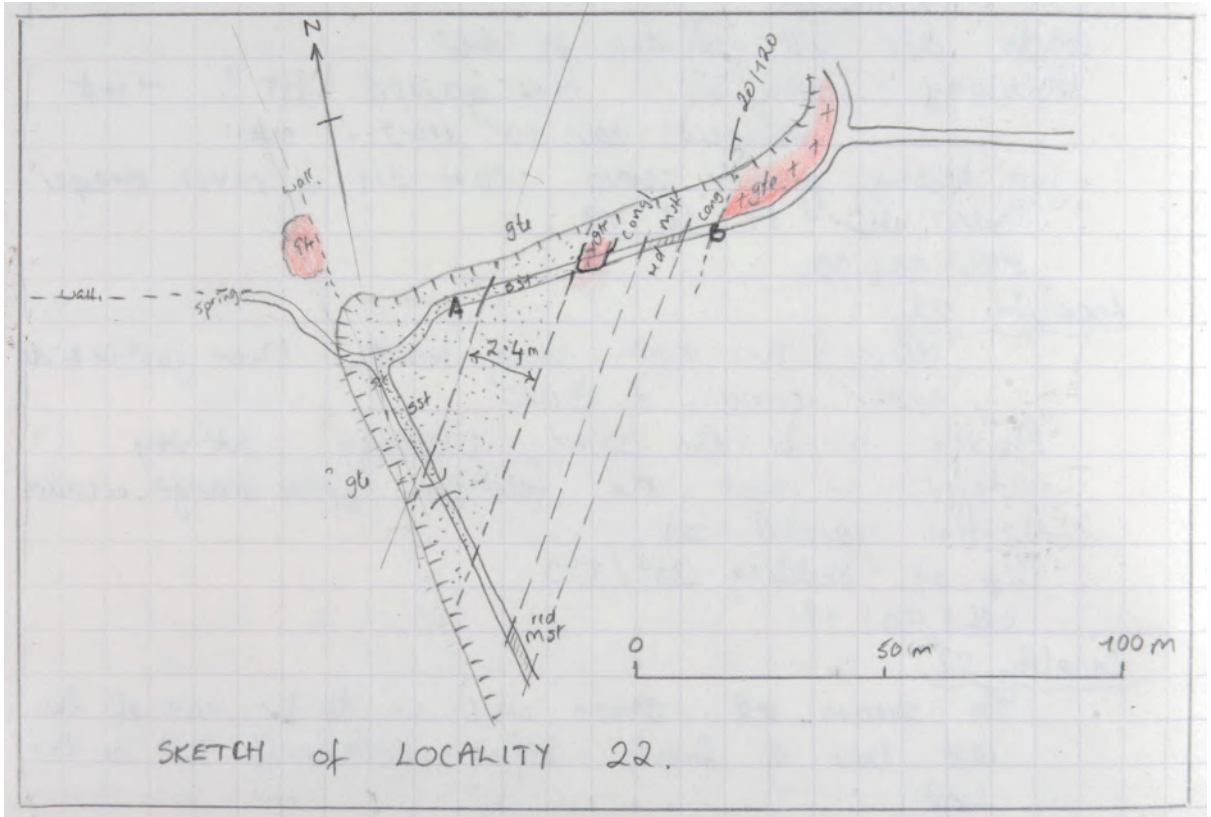


Figure 4.10 Example of an enlarged, to scale and orientated detailed map produced in the field at a higher resolution than the field map to show the details of several thin beds. Note that the main topographical features have been included along with the orientation and scale. (Notebook of Kate Bradshaw, The Open University, UK.)

Figure 4.9 Examples of different types of sketch map constructed to show the position of important geological information. (a) River section in Argentina to show the location of a series of graphic logs. Note the GPS readings for key topographical features (a, b, c, etc.) and cross references to notebook pages where the graphic logging notes are located. The map would have been better with a north directional arrow rather than the E and W because these make it look like a cross-section. (b) Simplified map of a disused quarry, Oxford, UK showing the location of the two different sections that were measured (1 and 2). (c) Sketch map of Choirokoitia gorge, Cyprus showing the main topographical features and the relative position of further notes (A to F). (d) Detailed sketch map of about 400x400m of the floor of a kimberlite mine, South Africa showing the relationship between the different rock types. Colour and abbreviations for the rock classification have been used very effectively to distinguish these complex relationships. (a to c: Notebook of Angela L. Coe, The Open University, UK; (d) Notebook of Richard Brown, The Open University, UK.)

If you have access to a photocopier then a large-scale base map could be produced, but this is often not possible and may not be foreseen before you go into the field.

4.4 Written notes: Recording data, ideas and interpretation

4.4.1 Notes recording data and observations

Written notes on the raw scientific data and observations that you collect can range from rock and fossil descriptions, to structural measurements, to more detailed notes on the relationship between rock bodies (Figure 4.11). These observations and data should be short notes rather than full sentences because these take longer to write and can detract from the main point. Bullet points, clear subheadings or numbered lists are a useful style to adopt for field notes as this encourages brevity and makes it easier to assimilate the individual points. If a lot of numerical information is being collected it is best presented in the form of a table. This will make it easier to assess at a glance whether all the necessary information has been recorded, and also aids its conversion into an electronic format. It can also be useful to develop your own abbreviations for features that are commonly used.

Given that the constraints on fieldwork tend to change frequently it is useful to regularly review the progress made and construct a list of further tasks (Figure 4.12a and b, p. 74). It is also common to compile a summary list of the samples collected (Figure 4.12c) and/or photographs taken (Figure 4.2b, p. 58). This helps to ensure that each sample has a unique number, places the information in a readily accessible form and allows other information to be added (e.g. grid references; Figure 4.12b, p. 74).

4.4.2 Notes recording interpretation, discussion and ideas

As well as new data, you should also record ideas, possible interpretations and questions when you are in the field to help you test competing theories (Figures 4.13 and 4.14, pp. 75–76). This might be in the form of a list, a figure, or even a series of cartoons illustrating a geological history (Figure 4.14a). It is often useful to record the whole thought process (Figure 4.14b) so that you can reanalyse this at a later stage. Frequently, when collecting field data, different possible interpretations come to mind because you are totally immersed in the information; this is particularly true when working with a field partner or as part of a team. The interpretation and ideas that you record should

Garnets - crystals 2-4mm found
in mica zones (red)

Mica - shiny, platy banding with
fine foliation. Garnets
present along the bands,
foliation wraps around garnets.

Quartz - large elongated ~10cm
1.5cm thick lenses evident
in veins.

Muscovite - silvery in appearance
Tormaline - green in colour.

(a)

Locality 54 Large outcrop from downstream.
- dip of bedding: 5°/110.
- lithology same as @ 53. fossils also, apart
for an occasional strophomenid.
- Also has calcite nodules - rather more
rounded here than @ 53.
- KRL/90/40

(b)

S ₃	L ₃ (sill)
88/356	68/079
68/357	30/075
	17/058
73/013	46/083 (sp)

→ SW on qtz beds
kfs megacrysts.

S ₃	L ₃ (qs)
66/327	04/055
67/331	09/058

→ SW on L_f sill fibres
kfs, Gnt megacrysts

L _f (sill)
12/049

(c)

COMPOSITION: QUARTZ / QUARTZ CEMENT 4 MAIN COLOURS OF GRAIN
LIGHT COLOURED (SANDSTONE) - BLACK/GREEN : WHITE/RED.

TEXTURE: MEDIUM TO COARSE GRAINED USING SANDSTONE CLASSIFICATION
GLASSY (WATER/MARINE) QUARTZ ARENITE.
WELL-SORTED - EQUIDIMENSIONAL
SUB TO ROUNDED.
MODERATELY HIGH SPHERICITY
NO PREFERRED ORIENTATION
GRAIN FABRIC GRAIN SUPPORTED.
RANDOM

FOSSILS: NO FOSSILS
NO EVIDENCE OF BIOTURBATION.
COMPOSITIONALLY MATURE / POTR ORGANIC ENVIRONMENT

(d)

Figure 4.11 Extracts from field notebooks showing examples of written data styles. In all cases the data are clearly laid out and easy to find. (a) List of the main minerals in an igneous rock and the characteristics of each of the minerals. (Notebook of Paul Temple, Open University student.) (b) Main observations at one locality in an area that was being mapped. (Notebook of Kate Bradshaw, The Open University, UK.) (c) Ordered and systematically recorded structural data of both planes and linear features with the dip recorded as a two-digit number and the strike as a three-digit number. Note: S₃ = main foliation, L₃ = main stretching lineation, L_f = fault lineation; the other abbreviations refer to minerals. See Section 8.1.1 for structural notation. (Notebook of Tom W. Argles, The Open University, UK.) (d) Description of a sedimentary rock based on a checklist of compositional and textural characteristics (see Appendix A6, Table A6.1). (Notebook of Brian McDonald, Open University student.)

Planning in the evening:
Objectives:

1. Finish measuring D, skim thru' rest of D. (1/2 - 1 day).
 Fiammé aspect ratios X
 Sample imbrication
 Photograph sheath flds + imbrication
 poss. add. brecciated flow front of TL2.
2. TL (East)
 Complete sheath fld study. @ Carboneras Wed
 (1 day) add sheath flds to section.
 inc. recy VI.
3. VI
 needs full recy.
 Complete sheath fld study. } → apparently 2 lineations. (1 day). Thurs.
4. Tidying up in Carboneras. Could do a bit on D! Stop day. Fri

(a)

TO DO

1. Finish off Yenkit traverse ✓
2. Walk inland from BK along village wadi
3. Back up to eastern schist exposure - what are the limestones doing?
4. Further up shear wadi - do we cross the OPIOP As sifan boundary?
5. Measure Tertiary
6. Yenkit eastern wadi - follow fist sq 3 (thin bit) contact to east and continue to top.

(b)

- Specimens List - 53

No.	Locality	Grid Ref.	Remarks
KEL/90/1	2	703436	Oughterard granite (pink)
KEL/90/2	3	705438	Derrylava Formation, Red conglomerate.
KEL/90/3	10	085434	Oughterard granite, (greenish - white)
KEL/90/4	11	086437	"Flow-laminated", or rather very fractured green granite.
	5	070420	Amphibolite with white feldspar alternations (+ vein?)
	6	070420	Semi-pelite + quartz + feldspathic psammite cut by a granite vein.
	7	118438	Strophomenid shells and other brachiopods - orcnids + probably spiriferids
	8	118438	Shows way up, & that most shell test convex side up.

(c)

Figure 4.12 Extracts from field notebooks showing examples of checklists. (a) Tasks to be completed and possible timing. (Notebook of Tiffany Barry, The Open University, UK.) (b) Simple 'to do' list. (Notebook of Clare Warren, The Open University, UK.) (c) Example of a rock sample list. (Notebook of Kate Bradshaw, The Open University, UK.)

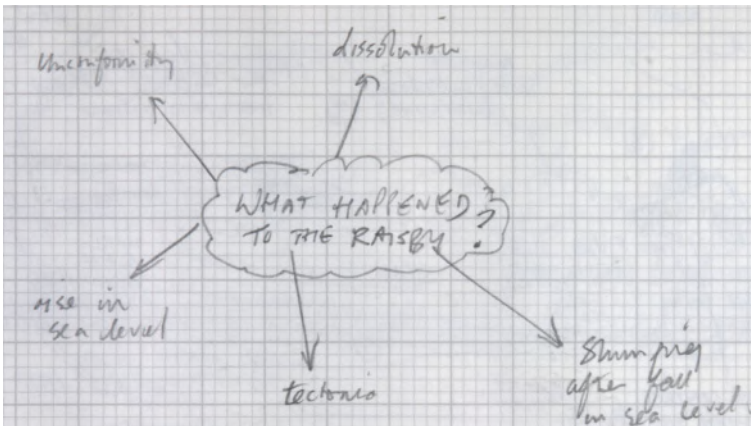
Interpretation (own)

Fining up sequences, stacked on top of one another.
 Look like Bouma sequences caused by turbidity currents
 but no very coarse layers seem to be present.
 Does this mean that this section is very distal and
 so only the finer material has reached this far??

Group Discussion

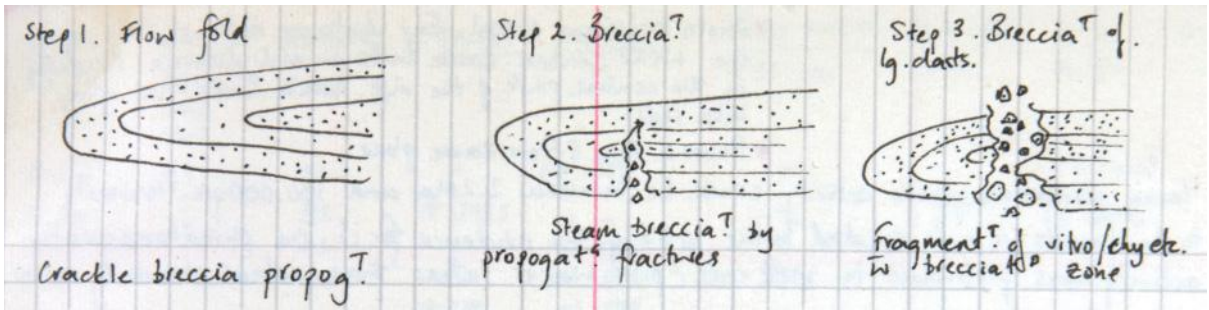
Beds are v. laminated, and of variable thickness
 Beds fine up, with sharp bases.
 Bouma sequences caused by turbidites. Location in deep water.
 [Siliciclastic turbidites can travel 60-70 mph]
 Coarse material settles first, then finer.
 Bouma sequences churn up lower deposits so can
 cause delamination.
 Whole cliff face could have been deposited within a
 few months
 'Orange layer' fizzes with acid → former volcanic ash

(a)

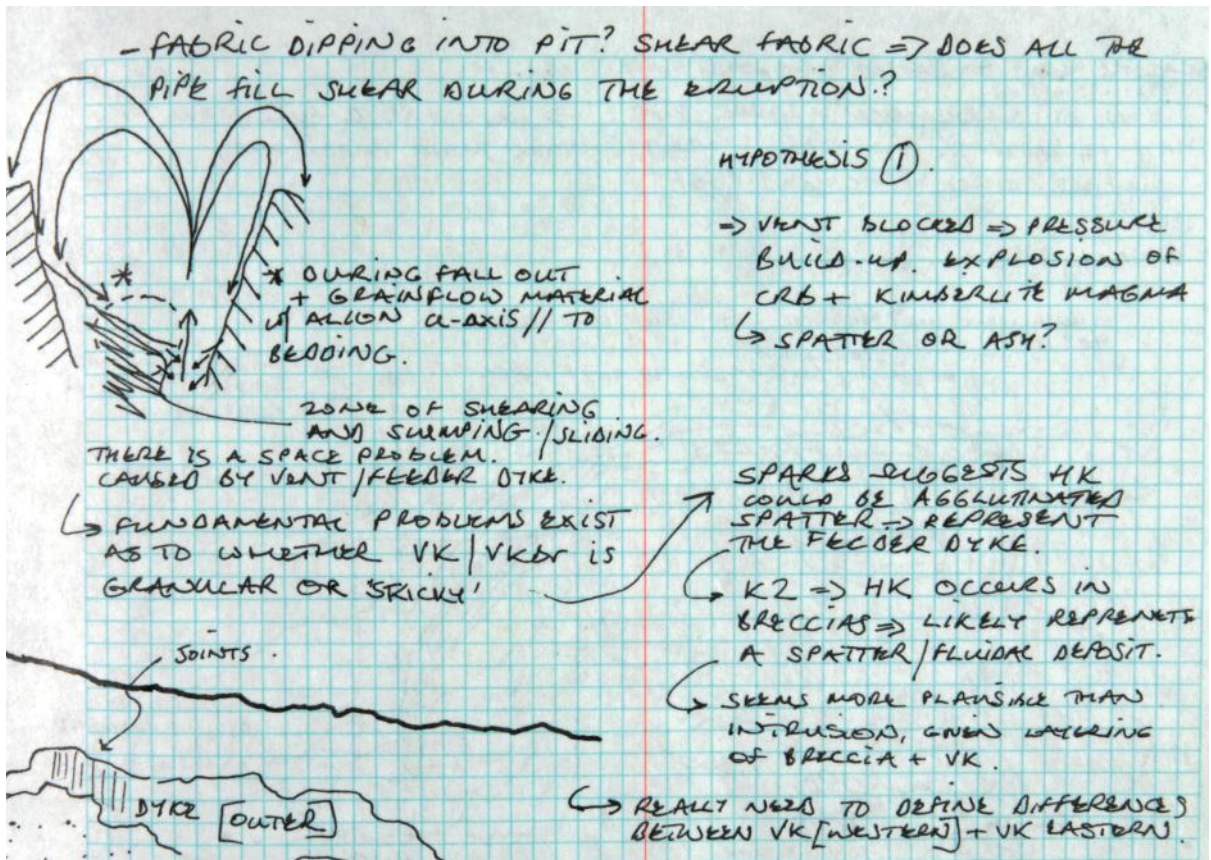


(b)

Figure 4.13 (a) Written interpretation in note form with clear indication of the source. (Notebook of Susan Ramsay, University of Glasgow, UK.) (b) Simple figure to summarize different interpretations of an observation. (Notebook of Brian McDonald, Open University student, UK.)



(a)



(b)

Figure 4.14 Examples of how interpretation might be recorded in the field. (a) Three cartoons to illustrate a possible interpretation of a fold with a cross-cutting breccia (Notebook of Tiffany Barry, The Open University, UK.) (b) Cartoon and notes interpreting a kimberlite deposit, South Africa. Excellent example of recording the hypothesis, evidence and questions that it raises. These type of notes will form a good *aide memoire* when the work has to be written up and as a basis of any further discussion (Notebook of Richard Brown, The Open University, UK.)

not just be the ‘perceived correct answer or that of the group leader’, because new data may change the interpretation. Also the recording of other ideas and interpretation can help to confirm which of several hypotheses is correct and determine what other observations need to be made. Ensure that you separate data from interpretation, in addition to noting the origin of the interpretation (Figure 4.13a, p.75).

Geological fieldwork relies on good observation of an incomplete record. The observations that you make are just as important as those of others.

4.5 Correlation with other data sets and interpretations

Correlation of new field data, either with data sets that you have previously collected or with those published in the literature, is a key part of many geological studies. This is because it enables us to integrate data and obtain a much more complete picture from different lines of evidence, thereby advancing our understanding. There are now very few rock exposures on Earth that have not been visited by geologists unless they are new (e.g. on a recently erupted volcano, road cut, railway cut or excavation) or were previously covered by other material such as ice sheets. There are, however, many reasons to revisit exposures and areas studied previously: (1) new techniques become available; (2) exposures change; (3) the exposures were used to test or erect a model or hypothesis that is now being called into question; (4) more resources are available to study the site; (5) samples analysed from the site yielded interesting results that are worthy of further investigation; and of course (6) to simply learn about geology.

Correlation between your own data sets even if they were collected during different field seasons should be fairly simple provided you kept good field notes! However, correlation with the data sets and interpretations of others can, at times, be challenging. There are two main reasons for this: field notes, where the direct evidence and location can be gathered, are not generally published; and exposures change. To focus the analysis and integration consider the following steps.

1. Read the publication(s) and identify the data. Make a note of any questions the interpretation raises that might be answered by further fieldwork or the application of new field techniques.
2. Take the relevant part of the literature (i.e. the data) into the field and attempt to re-identify the units from which the data were collected. First, find the main units/features using the location information. Then correlate what you can observe with the more detailed information.

As indicated by the following quote this can be challenging.

‘... it is evident that their bed 8 is my bed 1, their bed 6 is my bed 5, their bed 5 is my bed 6. Therefore their bed 7 can only be my bed 3 (with 2), and I have no doubt that the thickness “8 to 1 ft 0 in” originally appeared in their notes as “8 to 10 ft”...’

Arkell 1936a.

3. Check on any inconsistencies or differences and make a note of them.
4. Devise a method of linking your new field data with the publication. If it is a description of different beds it might, for instance, be as simple as adding a column to your notebook page for cross reference to the published bed numbers/units.
5. If the integration of the data is essential, and it is unclear from the publications how to correlate, consider contacting the author(s) of the publication(s).

5 Recording palaeontological information

Robert A. Spicer

5.1 Introduction: Fossils are smart particles

Unlike many sedimentary particles, such as quartz grains, each fossil has a story to tell that goes beyond its composition and the way in which it was transported and deposited. A body fossil represents the remains of a once living organism that had a life history, a certain environmental tolerance, and a defined range in terms of its geographical and stratigraphic distribution. Body fossils may be large, as in the case of a complete mummified mammoth, or microscopic, such as a pollen grain. Trace fossils represent impressions that an organism made in sediment, such as a footprint, or the disturbance of sediment as the animal went about feeding, or burrowing to create a living space. Fossils can also provide evidence of their decay process (including post-mortem scavenger behaviour), burial and tectonic history, all of which provide information on ancient environments. Moreover fossils occur in assemblages that may reflect predominantly life communities or processes of transport, deposition and decay that can also inform on past environmental conditions. Fossils are ‘smart particles’.

Fossils are smart particles so they are worth noting in detail. Not only do they yield information about energy levels and provenance like other types of sedimentary grain, they are also sensitive to factors such as climatic conditions, time and water depth.

5.1.1 Why are fossils important?

The occurrence of fossils in most sedimentary rocks, and more rarely in extrusive igneous rocks such as basalt lava flows and ash deposits, can be used to obtain stratigraphic, environmental and evolutionary information. Fossils can provide:

- a wealth of information on ancient life forms and thus are important in understanding the history of life on Earth and our place within it;
- data on ancient ecosystems and palaeoecology that have relevance to managing our planet today and in the future;

- qualitative and quantitative data on ancient climates, and a method of testing the applicability of climate models for a range of climatic modes;
- the basis of relative dating and correlation of rock units; some megafossils* are currently the only method by which rocks can be given a relative age in the field (other than superposition and cross-cutting);
- information on the biotic and chemical conditions following the death of the organism, at the time of burial and subsequently through its burial history – these data are important for determining, for example, the hydrocarbon potential of a rock unit.

5.1.2 Collecting fossil data

For fossils visible to the naked eye careful observation of morphology, preservation mode, orientation, context in terms of other fossils (assemblage characteristics), stratigraphic position and relationship to the entombing sedimentary deposits are all fundamental to successful palaeontological interpretations. The three-dimensional nature of both body and trace fossils often presents a challenge in recognizing the type of fossil. It is important to record the orientation and to become familiar with the characteristics of a variety of sections through the fossil. The best items of field equipment for recording fossils are:

- a notebook in which to make sketches;
- a hand lens to examine detail;
- a camera.

In general, fossils, rather than being removed, are far more valuable left in place for others to see and interpret. The location and sedimentary context of a fossil is of paramount importance. Fossils with no contextual or provenance information are of little value except for their aesthetic qualities. The term ‘provenance’ here includes not only the geographical location, but also information on the stratigraphic position as well as the nature of the sedimentary succession and individual sedimentary facies that surround it. Ideally this should mean constructing a sedimentary log of the succession with fossil data included (Section 6.3).

*The term megafossils indicates large fossils that are easily distinguished with the naked eye (compared with microfossils which are not easily distinguished). Megafossils are also sometimes termed macrofossils but, technically, the term macro only refers to length so it is incorrect.

If you do need to collect you will need to consider the following.

- *Is the site protected by law?* Many ‘classic’ fossil localities are now under legal protection. The exact nature of legislation differs from country to country but protection is usually granted for a good reason, for example to conserve the site. Written permission to collect is required or you will be breaking the law.
- *Is the site on publicly owned land?* Many fossil localities are on privately owned land where access is controlled. In the case of quarries and/or mines there are also specific safety and legal issues. Written permission should always be obtained when intending to collect on private land. When seeking permission you should outline: (1) why you are interested in the site; (2) what you intend to do at the site (e.g. make a thorough record of the lithology, sedimentary features, collect specimens, etc.); (3) when you propose to arrive and how long you intend to stay; and (4) how many will be in the field party. When visiting working quarries and/or mines you will be required to obey specific local rules usually related to safety issues. It is a good idea to follow up your visit with a note of thanks outlining what you have achieved.
- *Can the fossil be removed safely with the tools to hand without destroying it or endangering the collector and those in the vicinity?* Safety is paramount in the field (Section 2.11). Never put yourself or others in a dangerous position and always leave sites in a safe condition.
- *Is collection really necessary to aid understanding?* Collecting fossils should be regarded as a privilege and not a right. Apart from anything else, you should not put at risk for no good reason, by the collecting process or by using the wrong tools or method, a fossil that has been part of the Earth’s natural archive for millions of years.

If you intend to collect a specimen it is worthwhile photographing it before you attempt to remove it from the entombing matrix. The process of removal can damage the specimen and the photograph not only records the pristine state of the fossil, but also aids in any subsequent mending.

Collecting is sometimes necessary for detailed scientific study and in particular when new species are being described or the range of key species is being extended. This is because under the International Codes of Botanical and Zoological Nomenclature (ICBN and ICZN) a *type specimen* (preferably with other examples) has to be conserved in a museum to serve as reference material.

Recovery of large remains (e.g. dinosaur skeletons) requires mechanized equipment and materials for protecting the fossils during transport back to the laboratory. If you are lucky enough to find such remains do not try to extract any material yourself. Instead contact appropriate experts, for instance at the local museum, who will have the knowledge and resources to recover the fossils safely and, as far as possible, intact.

If you don't know the names of the fossils you find, give them temporary names (type 1, 2, 3, etc.). If these are accompanied by detailed descriptions, sketches and/or photographs they can be identified later by reference to specialist sources such as books and museum collections.

5.2 Fossil types and preservation

5.2.1 Body fossil classification

The chances are that in the field you will not be able to identify every fossil you find. Actually you don't need to. A lot can be deduced about the organism in the field by careful observation and you can make up a working classification based on simple observation of, for example, symmetry (Figure A5.1). Even if we know nothing of the taxonomic identity of a fossil (which is often the case with newly discovered species) we can infer a lot about its mode of life and palaeoenvironment by examination of its architecture and context within the entombing rock (e.g. Worked Example 5.1, p.84).

Plants invariably fossilize as dispersed organs (leaves, fruits/seeds, pollen/spores, trunks and roots) and most of the time we don't know which parts belong together to make a specific extinct species. For this reason each organ has a Latin name of its own. Try to record as accurately as possible the morphology of each plant part including shape, size and ornamentation; in the case of leaves, margin details and venation are also important (Figure 5.1).

Microscopic body fossils (microfossils) can rarely be identified in the field and collecting is often carried out without knowing if the sample will contain them. Section 5.3 provides notes on maximizing the likelihood that samples are fossiliferous.

5.2.2 Body fossil preservation

The way that a body fossil is preserved indicates a great deal about its transport, deposition and burial history as well as the chemical and tectonic history of the entombing sediment. Recognizing and recording the mode of preservation is important to understanding the processes during deposition and burial. (See Figure 5.3, p.85, and Appendix A5, Table A5.1 for common preservation modes.)

Preservation modes are not mutually exclusive and all of them can be affected by compression over time. If the body parts are inherently resistant to compression and/or are permineralized/petrified soon after burial, 'flattening' may be minimal. The extent of flattening relative to the compaction of the entombing sediment indicates the timing of mineralization relative to burial and sediment loading. More lateral distortions are invariably due to tectonics and can be useful in understanding the structural history of an area. In conjunction with observations on the phases of mineralization a history of the changing chemical environment over time can be reconstructed.

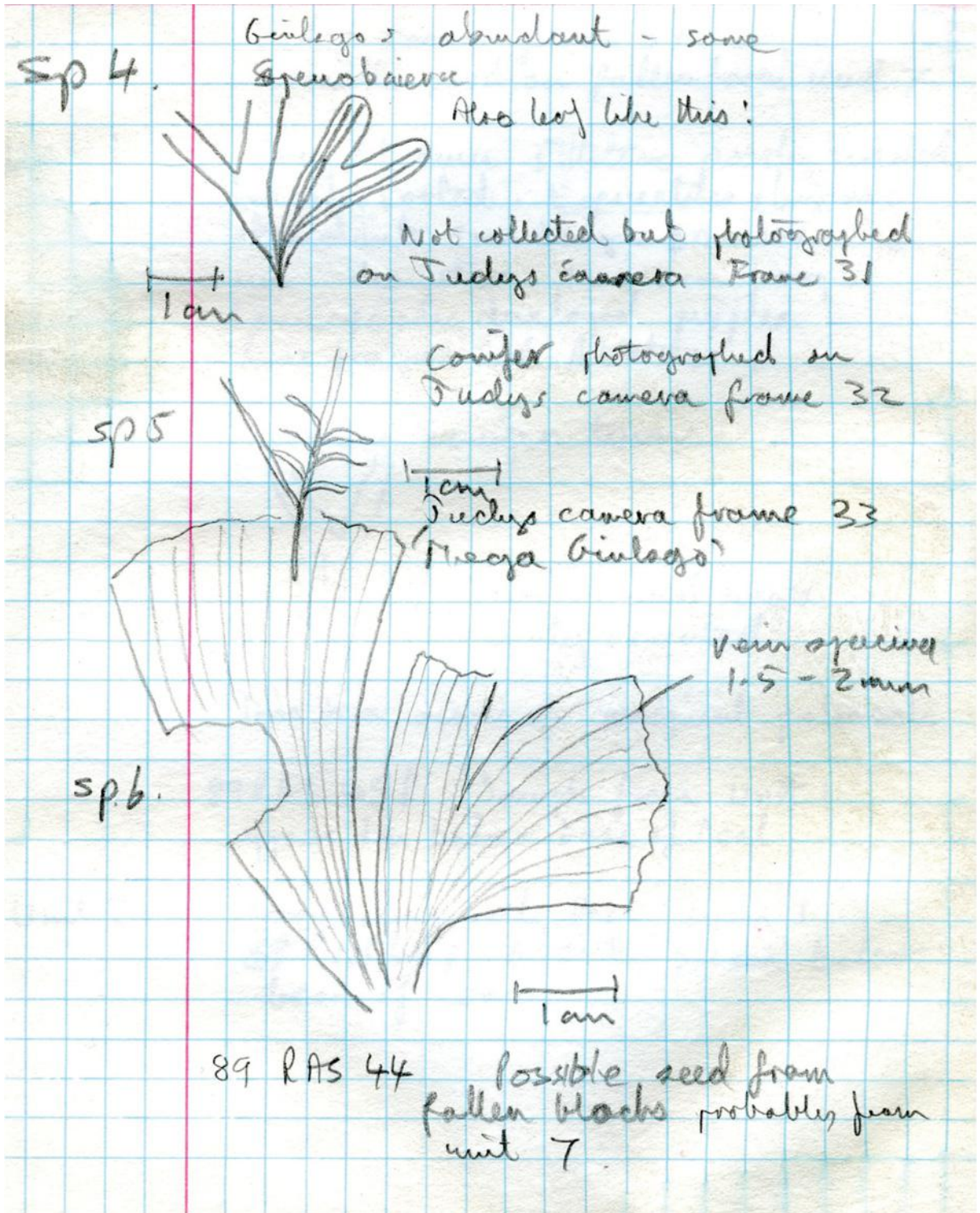


Figure 5.1 Part of a field notebook page showing sketches of leaves. Note scale, careful attention to venation and references to accompanying photographs, sedimentary units and specimen numbers. (Notebook of Robert A. Spicer, The Open University, UK.)

Worked Example 5.1 Using morphological observations to infer mode of life

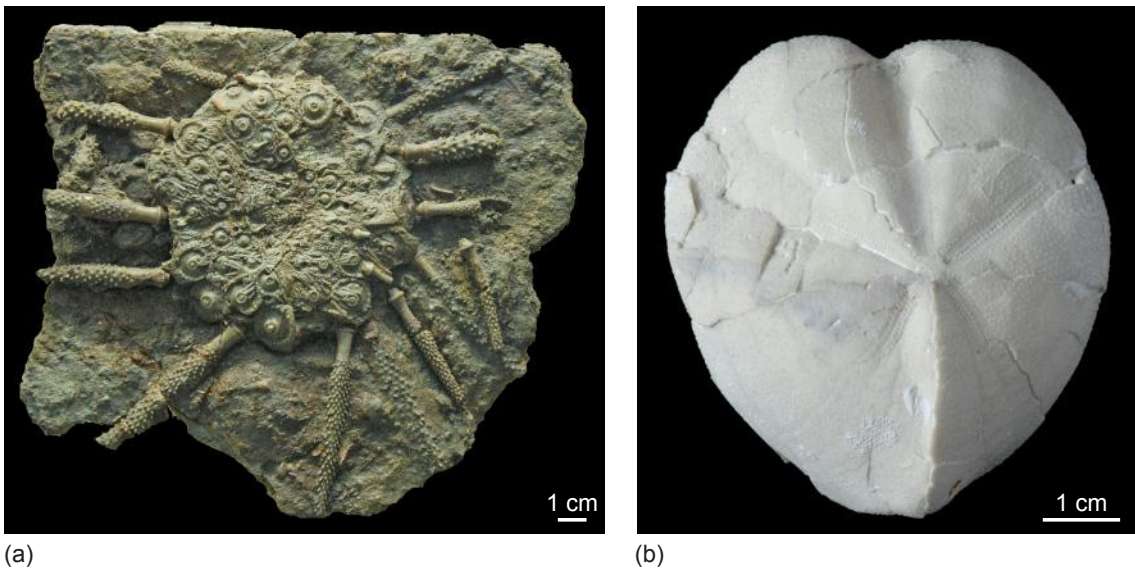


Figure 5.2 Two echinoid specimens with distinctly different morphologies. (a) *Archaeocidaris* (Robert A. Spicer, The Open University, UK) and (b) *Micraster* (specimen from Peter R. Sheldon, The Open University, UK).

In Figure 5.2 two echinoids are shown, one (taxon A) with a heavily armoured shell and another (taxon B) with a smoother and more streamlined shell. These morphological characteristics can be used to determine which of these is most likely to be infaunal (i.e. live within the sediment).

In the case of taxon A the possession of large spines would generate considerable drag if the organism were to attempt to burrow in sediment. It would be reasonable to surmise that taxon A was more likely to live on the surface of the

sediment (epifaunal), while the smoother and more streamlined taxon B was more likely to burrow in the sediment (infaunal). This is not to say that all epifaunal organisms are heavily armoured with spines (some are smooth) but it is true to say that no burrowing organisms will have rigid projections that would impede passage through sediment. Similarly, fossils representing organisms that live in shallow water above the fair-weather wave base typically are more robust than those living in quieter conditions at depth.

The likelihood that an organism will be preserved in the fossil record depends on: (1) where it dies relative to a depositional environment (and thus the length of the transport path to that environment); (2) the nature of that environment (most importantly its chemistry and the extent to which oxygen is lacking); (3) the rate of sedimentation and therefore the speed of burial; (4) the nature of the sediment (fine-grained sediment excludes oxygen better than coarse-grained and better protects fine surface detail); and (5) the mechanical strength and chemical composition of the organism itself. Animals lacking

hard parts will be less likely to be preserved than those with some durable components. Thus, vertebrate bones and thick calcareous shells from invertebrates have a high preservation potential. Some plant parts such as pollens and spores have outer coats made of an organic polymer known as sporopollenin and this is extremely biologically and chemically resistant. Thus pollens and spores have a high preservation potential. Wood and leaves are more likely to decay but even these can have their preservation potential increased dramatically by being charcoalified by partial burning prior to burial. Surprising as it may seem charcoalification preserves detail even at the subcellular level while simultaneously rendering the remains biologically inert by reducing them to almost pure carbon. Some of the best three-dimensionally preserved early flowers are in the form of fossil charcoal (fusain).

5.2.3 Trace fossils

Although the body parts of organisms that make trace fossils are almost always missing, the trace shape and context can tell us a lot about environmental conditions at, and after, the time the trace was made. Trace fossils have the advantage over body fossils in that they cannot be reworked, although they can be disrupted or destroyed by later trace fossils. Trace fossils fall into several categories based on behaviour (Appendix A5, Figure A5.3).

Trace fossils do not occur randomly but are repeatedly found in recognizable associations with particular sediment types. These associations form ichnofacies that can indicate a lot about the conditions under which sediment was deposited. In the field, using photographs and sketches, record the following:

- the size distribution;
- geometries (including working out which are different cross-sections through the same type of trace fossil);
- associations with other trace fossils;
- characteristics of the sedimentary deposits (Chapter 6);
- frequency and density (Section 5.5);
- presence/absence of burrow wall linings (e.g. made up of organic matter, shell fragments or different sediment types, etc.) – the infilling of burrows is also important to note in



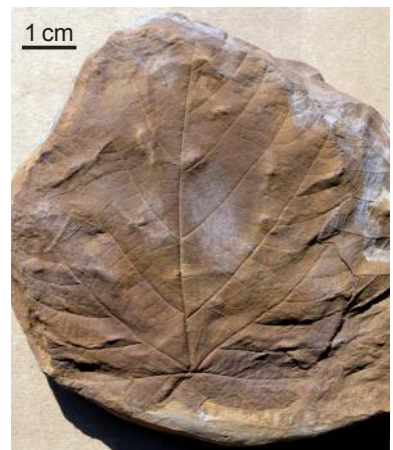
(a)



(b)



(c)



(d)

Figure 5.3 Modes of fossil preservation: (a) Mummified body of a young mammoth found in Siberia; (b) polished transverse section of a permineralized (petrified) tree fern stem; (c) cast of a tree fern trunk; (d) leaf impression from the north slope Alaska. (a–d: Robert A. Spicer, The Open University, UK.)

When looking for trace fossils on bedding planes do not forget to look up at the underside of overhangs. These are often cleaner and less abraded than bedding planes that may have been walked over and so the fossils are easier to see and better preserved.

respect of sediment type(s) compared with the sediment burrowed, and any geometries associated with the infill (simple collapse versus structures that indicate deliberate backfilling by the organism);

- look for tiering, i.e. the pattern of trace fossil types vertically in the sediment (Appendix A5, Figure A5.4), in relation to a given horizon marking a change in sedimentation – some burrows are typically formed in shallow sediment depths while others penetrate deeper, and loss of shallow tiers can indicate erosion;
- cross-cutting relationships indicating successive colonizations of the sediment and changing conditions through time.

While trace fossils carry information on how ancient organisms move, and thus their biology, information also can be gleaned about sediment deposition and erosion (e.g. Figure 5.4). Burrows may be filled with sediment quite unlike that into which the burrow is made, or that overly it, suggesting sediment was deposited and then eroded. Often this may be the only evidence of an unconformity. Trace fossils with defined geometries relative to the ancient sediment surface (e.g. vertical U-shaped burrows) can also be used as ‘way up’ structures. Any displacement from the normal orientation will indicate rock movement and/or deformation.

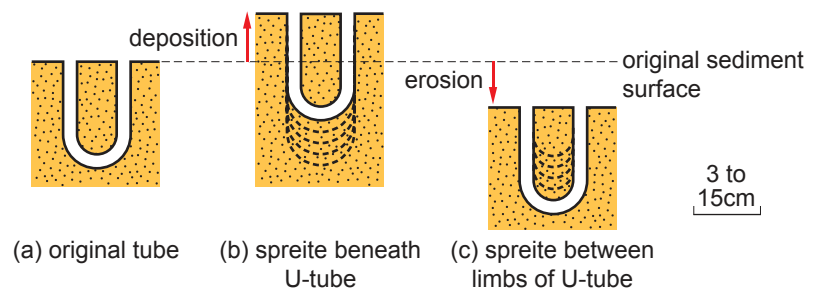


Figure 5.4 Sketches to show a variety of spreiten patterns in the trace fossil *Diplocraterion* formed in response to deposition and erosion. (a) Stable situation where no sediment deposition or erosion is taking place. In (b) sediment has been deposited causing the organism to migrate upwards leaving traces of the original burrow as disturbed sediment below. In (c) erosion has caused the organism to burrow deeper leaving disturbed sediment (spreiten) between the vertical burrows. Figures 6.3e and 6.3f (p. 113) show fossilized *Diplocraterion*.

5.2.4 Molecular fossils

The usual fate of any dead organism is to decay to such a degree that nothing remains of either the life morphology or the traces it left as a result of its activities. However, even in these cases it may leave behind its chemical signature. In the best circumstances whole, or partial, DNA molecules may be preserved, but usually only remnants of molecules characteristic of a particular group of organisms survive. When these are found we can infer something about evolution and even environments. An example is the occurrence of cyclopentane rings derived from the membrane lipids of marine plankton. The number of such rings correlates with sea-surface temperature (average annual or perhaps seasonal) and forms the basis of the TEX₈₆ palaeotemperature proxy. When collecting such samples (Chapter 13) extra care needs to be taken not to cross-contaminate between samples or to introduce contaminants from the sampling and wrapping material.

5.3 Fossil distribution and where to find them

Initially the best way to look for fossils is to examine loose pieces of rock material ('float') derived from the exposure. Float has the advantage of exposing a large number of bedding surfaces that can be examined for fossils. If fossils are visible the next step is to try and relate the lithology of the fossil-bearing float to lithologies that are in place, for example, in the adjacent cliff face. This lithology can then be examined for *in situ* fossil material. If fossils are not obvious on the float bedding surfaces, expose further bedding planes by splitting the blocks parallel to the bedding using a chisel or the chisel end of a hammer.

Preservation of organic body fossils is most likely to take place in sediments deposited in low oxygen conditions where dispersed organic matter is also easily preserved. This usually means in dark coloured fine-grained sedimentary deposits, typically mudstones. However, they are also preserved where the sedimentation rate is high, the conditions are conducive to rapid mineralization, or the chemistry limits dissolution of shells or bones (Section 5.2.2). Here are some other features to look out for.

- *Carbonate fossils*: Body fossils composed of carbonate tests or shells, as well as bones, are most likely to be found in carbonate-rich rocks such as limestones and chalks. They can also be found in siliciclastic rocks provided that they have not been in acidic conditions during deposition and subsequent burial.

- *Siliceous fossils*: Fossils with silica tests or frustules (diatoms and radiolarians for example) survive best in low pH (acidic) environments because silica is soluble under high pH (alkaline) conditions. It is therefore unlikely that diatoms and radiolaria will be found in carbonate-rich rocks; but note that even in chalk it is common to get localized variations in chemistry at the time of deposition, leading to the preservation of silica-rich fossils (e.g. sponge spicules in flint).
- *Colour*: Colour changes can also be a clue to finding fossils. Look at reduction spots (typically grey or green spots in otherwise red/brown sedimentary deposits) as these indicate locally oxygen-poor conditions and may be associated with organic remains or their derivatives.
- *Change in sedimentation rate*: Changing grain size and/or an increase in sedimentation rate can also be a clue to finding fossils. Post-mortem oxygen exclusion is related to the speed of sedimentation. For example leaves accumulating on the fine-grained sedimentary deposits at the bottom of a lake will often be destroyed by invertebrates, fungi and bacteria unless buried quickly. In such cases, look for fossils just below increases in grain size or other indicators of rapid sediment deposition.
- *Hydraulic equivalence*: In situations where water is flowing (streams, rivers and marine tidal flow environments) an important clue as to where to find fossils is the concept of hydraulic equivalence. Hydraulic equivalence equates the hydraulic characteristics (settling velocity, velocity of entrainment, etc.) of a fossil to that of a quartz grain. So, for example, a large dinosaur bone or a waterlogged tree trunk are broadly hydraulically equivalent to a large quartz pebble or small boulder. It is no surprise then that such fossils are commonly found in the basal lags of river channels. Similarly, leaves commonly occur in fine-grained fluvial siltstones.



Figure 5.5 Trees stranded in a shallow river in Alaska showing similar orientation. River flow is from right to left. Trees are about 10m long. (Robert A. Spicer, The Open University, UK.)

5.3.1 Transported or life position?

When you find fossils it is important to determine if they are preserved *in situ* (autochthonous), transported to the burial site from where they lived (e.g. Figure 5.5), or even reworked from an older deposit (allochthonous). Land plant fossils such as fossilized wood within deep marine sedimentary deposits clearly indicate transport. This could be over very long distances because, unless the wood is very abundant, its presence does not indicate proximity to land as floating logs can circumnavigate the Earth, driven by ocean currents. In

some other cases, whether or not transportation has occurred may be less clear. Coals (preserved peats), for example, can either be allochthonous or autochthonous. Autochthonous coal will have roots extending from its base and will lie directly on a palaeosol, whereas allochthonous peats will not. In the case of fossilized upright tree bases it is important to note whether the roots penetrate into a palaeosol (fossilized soil) because tree bases may well be transported in an upright position.

If any fossil is found broken, abraided or disarticulated then some pre-burial transport is likely to have occurred. If the fossil has attached or included sediment not found in the entombing rock then re-working should be suspected. An exception to this is breakage *in situ* during compaction of the rocks, but this is easily identified as all the parts will be in close proximity.

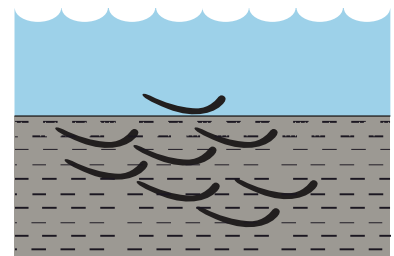
Also important is the fossil orientation. In flowing fluids (usually air or water) allochthonous body fossils may become oriented in relation to that flow post-mortem. This is most commonly seen in elongate remains such as belemnites or tree trunks. Often in the case of tree trunks branches become snapped off during transport but roots are more resilient. Stranding of the roots on the bed of the shallow parts of rivers will cause the remaining trunk to swing round and point downstream (Figure 5.5). If trees are blown down by wind, by a volcanic pyroclastic flow or lateral explosion, then the tips of the trunks will again point in the direction of flow away from the source.

Orientation is also an important indicator of life position. For example many bivalves live in the sediment, so often get preserved in that position. If the two shells (valves) of a bivalve are attached and closed then there is a good chance that the remains have not undergone any significant post-mortem transport. Careful inspection of the deposits may well indicate other remains in the same orientation and, if so, they are likely to be in life position (Figure 5.6).

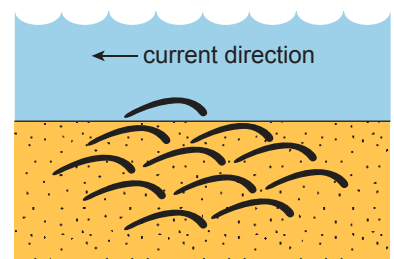
If single valves of bivalves or brachiopods are found then clearly they have undergone some disarticulation and transport after death, even if the distances involved are short. In this case it is useful to record which way up they are lying. When populations of single valves are found concave side up then it is likely that they were at some time suspended in the water column (e.g. by storm action) and then subsequently settled out of suspension to rest on the sediment surface in that position. Alternatively, if the valves are all oriented convex side upwards this would suggest that prior to final burial the shells were subject to horizontally flowing current that has flipped over the shells (Figure 5.7).



Figure 5.6 Infaunal bivalve in life position from the Jurassic, near Scarborough, UK. (Angela L. Coe, The Open University, UK.)



(a) Unstable: Settled from suspension



(b) Stable: Deposited under lateral flow

Figure 5.7 Sketch to show single valves oriented (a) concave up as a result of settling from suspension and (b) convex up as a result of lateral current flow.

5.4 Sampling strategies

Palaeontological sampling is aimed at determining the nature of the population of fossil remains contained within a given suite of sedimentary deposits, and from this to derive some information about the ancient living population and environment. Sampling strategies employed to achieve these objectives must be at an appropriate resolution and carried out efficiently in order to provide valid data.

5.4.1 Sampling for biostratigraphic or evolutionary studies

For biostratigraphy and/or evolutionary studies a succession of samples collected vertically through the deposit usually takes precedence over investigating lateral variations (compare Figure 5.8a with 5.8b and 5.8c). Over geological time different fossils are important for biostratigraphy (Figure A5.5). Many studies incorporate more than one fossil group. In addition the sampling strategy needs to be appropriate for the type of biozonation that is used for the fossil group or period of geological time (Figure A5.6). It is important with microfossils to limit the risk of contamination (Chapter 13). The two types of sampling are spot and continuous.

- *Spot sampling* can be performed at regular distance intervals and/or targeted to different lithologies. The advantage of spot sampling is that it is relatively quick and minimizes the amount of material collected. Using this technique, however, can easily miss small-scale or subtle variations in deposition, as well as potentially important non-visible events. As a general rule each lithology should be sampled at several locations in order to determine if there are any lateral, as well as vertical, variations in fossil abundance and assemblage composition. The appropriate

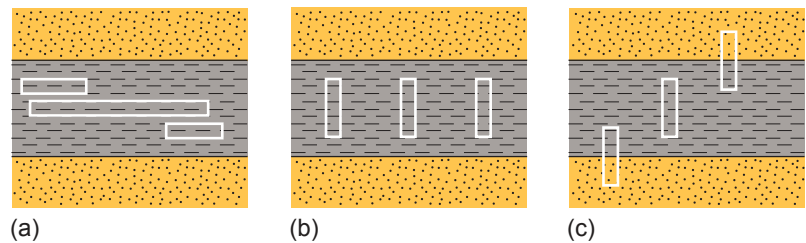


Figure 5.8 Three different patterns of continuous or channel sampling. (a) Overlapping samples parallel to bedding. (b) Repeat samples at right angles to bedding within a lithology. (c) Samples at right angles to bedding representing the stratigraphy, with short overlaps for cross-correlation purposes.

vertical sampling interval will depend upon lithological variations, sedimentation rate, proximities to suspected boundaries, suspected or known cyclicity, resolution necessary for the purpose of the study, resources and field constraints (Chapter 13).

- *Continuous sampling*, sometimes known as channel sampling, has advantages over spot sampling for high resolution studies if resources allow. Typically an exposure is first trenched to reveal fresh rock surfaces and then overlapping short lengths of rock are taken throughout the section under study (Figure 5.8c). The advantage of channel sampling is that there is a continuous record for later laboratory studies and the resolution of the study can be modified. Conservation issues and sampling restrictions must, however, be taken into account. The disadvantage of continuous sampling is the large amount of material that will be collected. This needs to be assessed against spot sampling where instead targeted samples can be collected, for instance along megafossil shell beds, rather than collecting material with no useful samples for the aims of the study.

Some planar fossil material such as leaves and fish can be viewed only by exposing bedding surfaces. On a wave-cut platform this is usually not too much of a problem, but in a cliff-face trenching is often the only option (Figure 5.9). Throughout the section spot or continuous sampling can be employed, but this needs to be done in such a way as to expose large areas of bedding surfaces. In this case trenches several metres square in horizontal dimensions might be required so that successive bedding surfaces from top to bottom of the section can be revealed.

If the aim of fieldwork is to correlate between different sections fossil occurrences should be recorded in stratigraphic context by means of a graphic log (Chapter 6 and Figure 5.10, p.92). Record the fossil appearances, disappearances and changes in abundance (frequency) as well as sedimentological information. Near a boundary such as a break in sedimentation or a suspected extinction event, sampling at close intervals is often required to pinpoint the boundary precisely. In the case of extinctions the last occurrence of a taxon is unlikely to be recorded because the fossil record is always incomplete. Similarly the origin of a taxon is difficult to pinpoint. The problem becomes more acute the rarer the taxon. The net effect is that even a sudden extinction will appear gradual. To minimize this effect (the Signor–Lipps effect) more frequent and larger samples are required near any boundary. What constitutes ‘near’ will depend on the size and abundance of taxa being studied.



Figure 5.9 Example of a trench through diatomite in China. Successive samples were obtained as the trench was dug. (Robert A. Spicer, The Open University, UK.)

Mark sample sites with fluorescent tape as you collect (fixed with rock or a nail) so that at the end of sampling you can log and photograph the exact sample locations. Remove the tape and nails before you leave the site.

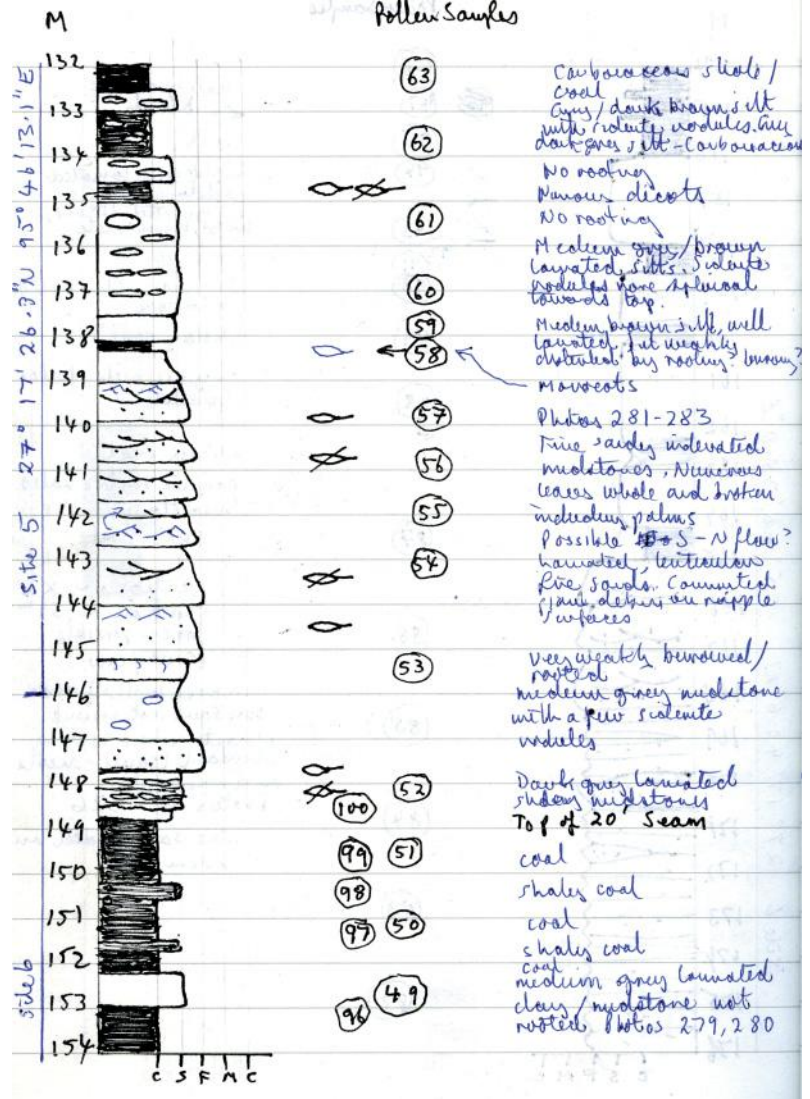


Figure 5.10 Example of a field notebook page showing the position of fossiliferous layers and pollen samples on a graphic log. The log and samples are for a section in Assam, India. (Notebook of Robert A. Spicer, The Open University, UK.)

5.4.2 Sampling of bedding surfaces and palaeoecology

Access to large bedding-plane surfaces presents opportunities for a greater variety of fossil sampling strategies and possible studies. The analysis of the distribution of fossil remains over a single bedding surface is usually done by recording fossil remains that occur in a defined area. Usually this area, known as a quadrat, is a square or rectangle that is of a size appropriate to the material and project under investigation. Quadrats are usually distributed in such a way that each is independent of all other quadrats as well as any pattern within

the sampled population. This usually means that their distribution is random. A random arrangement is best achieved by using random numbers as the basis of positional coordinates. Because invariably not all the fossil assemblage is accessible, subsequent statistical processing of the data has to be robust: placing minimal reliance on individual variables possessing normal (Gaussian) distributions, or, preferably, by being non-parametric. The biota within a quadrat either need to be recorded through measurements and sketches in the field or by taking detailed photographs. The latter method has the advantage that the image analysis software can be used to analyse the biota and there is a permanent record.

Three-dimensional sampling

While exposure of a single bedding plane may yield high-resolution data, there are numerous limitations to its application in practice. Inevitably the splitting properties of the rock matrix will preclude the exposure of large planar areas without the likelihood of cutting across several bedding surfaces. Also, full excavation of individual specimens damages adjacent bedding surfaces and breaks down the sampling regime on those surfaces. A more realistic approach is to accept the fact that single bedding planes cannot be excavated reliably and attempt instead to sample volumes of sedimentary rock. In this method blocks of rock can be excavated in the field. Where conditions and permission allow, cut from the rock using carbide-tipped chainsaws (Figure 5.11), or for small volumes a disc rock saw. In order to minimize loss of sampling resolution the bedding-plane package sampled must fall within an interval of sediment that was deposited under essentially constant physical conditions, sometimes termed a 'sedimentation unit'.



Figure 5.11 Cutting volumes of clays containing fossils using a carbide-tipped chainsaw. The advantage of this technique is that the samples can be taken back to the laboratory for detailed analysis. (Robert A. Spicer, The Open University, UK.)

Determining quadrat size – rarification or species/area (or volume) curves

Fossil size and distribution pattern determine quadrat size. If the quadrat dimensions are larger than those of the fossil remains then sampling will be meaningful (Figure 5.12a, p. 94). Suitable quadrat sizes can be determined for the particular fossil by constructing taxon/area (or volume) curves (Figure 5.12b). Usually this curve is constructed from a pilot study and may not be applicable to all parts of the fossil assemblage. For this reason a reasonable safeguard is to double the minimum size for the main investigation.

Pattern

Figure 5.12c represents three extreme two-dimensional distribution patterns of a taxon. The density is the same in each case. Quite different assessments of abundance will be obtained, using a quadrat of the dimensions shown, depending on the distribution and number of samples taken.

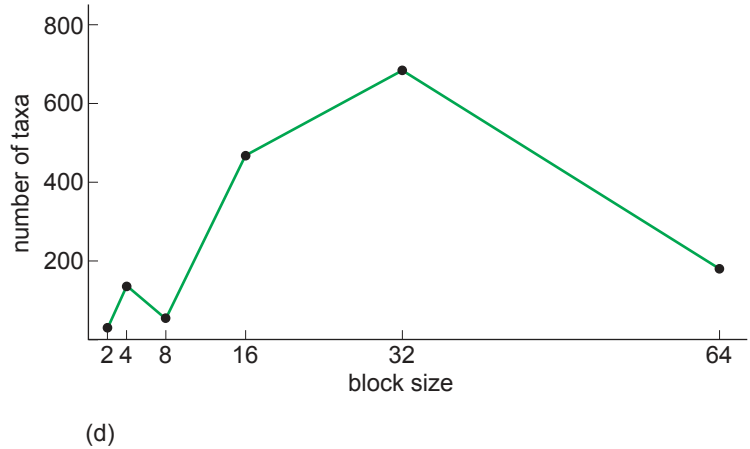
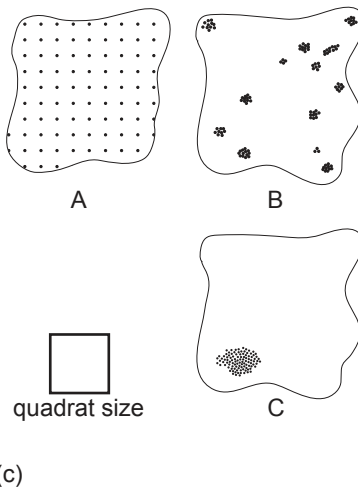
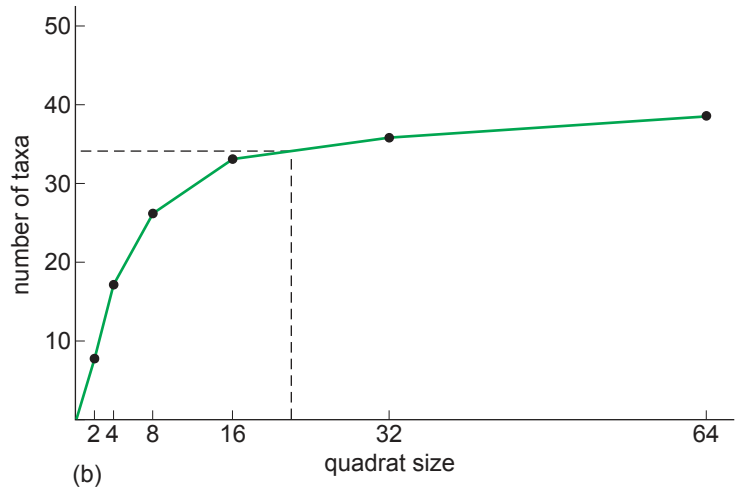
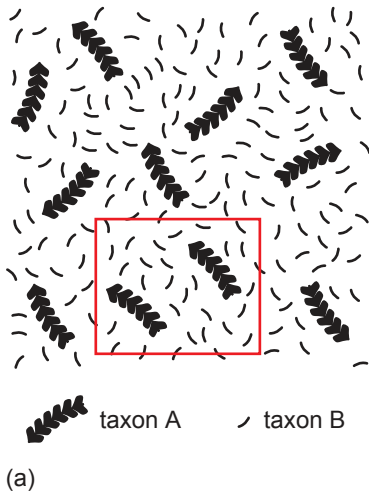


Figure 5.12 (a) The dependence of abundance estimates and, in particular, percentage frequency on the size of quadrat used in relation to the plant fragment size. If a quadrat of the size shown (small red square) were used to sample this bedding surface there would be a marked discrepancy in estimated abundance for the two taxa, irrespective of their actual relative abundance, because the quadrat size is similar to that of one of the taxa. (b) A rarefaction curve showing increasing numbers of taxa with successive doublings of quadrat size. As the quadrat size is increased more taxa occur within the quadrat, but above the point where the curve flattens out larger quadrat sizes become an inefficient way of sampling. The dashed line indicates the minimum quadrat size for this population, in which something in the order of 34 taxa might be expected to occur within each quadrat. (c) Quadrat size in relation to distribution pattern. A–C represent three forms of pattern that a taxon might exhibit: A, regular; B and C, clumped distributions of different sizes and distribution. In each area the number of specimens is the same but if a quadrat of the size shown were used for sampling very different estimates of abundance would be obtained. (d) Detection of contagions (clumping) within an assemblage. If the quadrat size is increased and the mean square (variance) is plotted, the peaks reveal the scales of clumping.

The situation becomes more complex when several taxa are involved which, because they may represent parts of the community or possess similar fluid dynamics characteristics, consistently exhibit positive or negative associations ('clumping'). If the exposure allows (e.g. bedding planes

exposed on a wave-cut platform) clump size can be assessed by laying out a grid of contiguous quadrats. Increasing 'quadrat' sizes are then built up by blocking adjacent quadrats in twos, fours, eights, etc. A graph can then be constructed of mean squares (variance) against block size. Peaks in the graph correspond to the mean clump sizes. An example is shown in Figure 5.12d in which there are two clump sizes: one at 4 block (quadrat) size and one at 32. In practice there may be severe constraints on laying out a contiguous grid of quadrats and the use of this technique is likely to be limited. Nevertheless pattern analysis of this kind can prove particularly rewarding in autochthonous assemblages.

Edge effects

Inevitably some specimens will intersect quadrat boundaries. The smaller the quadrat size the more important these edge effects become because a greater proportion of the sampled material will be represented by intersected specimens. Similarly the perimeter length to area (or volume) ratio of the quadrat will also be important. Quadrats approximating to circles or spheres would reduce edge effects to a minimum but these shapes are impractical. Squares or cubes (or approximations to them controlled by bed thickness and lithological factors) are the conventional choice. A possible exception here might be the sampling of elongate specimens that are flow oriented. An elongate, rectangular quadrat arranged so that its longest axis was parallel to the flow alignment would minimize edge effects.

A common practice is to include within the sample any individual (specimen) that has more than half its area within the quadrat and exclude the others. This approach biases the sample because it is influenced strongly by the size of the specimens (small specimens will intersect the boundary less frequently than large specimens). The actual area of the specimen falling inside the quadrat could be included in cover estimates (Section 5.5.3), but this would preclude any statistics such as mean specimen size that might be related to transport distance and differential degradation studies.

An alternative strategy is to include 50% of specimens of a particular taxon that intersect the quadrat boundaries and measure the whole area of those specimens included. The 50% measured should be a random sample.

5.5 Estimating abundance

Abundance can be determined both qualitatively and quantitatively. The ease of measures of abundance, their accuracy and their relationship to sedimentological and ecological phenomena varies greatly. Abundance can be estimated or measured in the field but an alternative method is to

Table 5.1 Typical simple subjective abundance classes and their numerical equivalents.

Descriptor	Numerical scheme
Very abundant	5
Abundant	4
Frequent	3
Occasional	2
Rare	1

photograph the area and use the photograph(s). This allows both a more visual comparison between different areas for qualitative measures (Section 5.5.1) of abundance, and image analysis of the area to obtain a quantitative measure (Section 5.5.2).

5.5.1 Presence/absence and qualitative abundance estimates

The advantage of presence/absence scores is that they are easy to obtain, but this ease has to be weighed against a substantial information loss incurred because the amount of a particular taxon is not recorded.

Qualitative visual estimates of abundance are useful because they are simple and rapid to use (Figure A1.1). Their popularity has spawned a number of schemes designed to improve their accuracy and comparability. The simplest scheme consists merely of ranking the taxa within a sample into a series of abundance classes with a quasi-logarithmic numerical scheme (Table 5.1).

The main problems with such a scheme are that small taxa (fragments) tend to be underrated, consistency between different workers is lower in the frequent, occasional and rare categories, and clumping of taxa biases visual assessment. However, fully quantitative abundance measures have not been shown to be totally necessary or reliable, and may actually prove less effective in revealing an assemblage pattern than the consistent and reasonable objective use of visually assessed scales.

5.5.2 Quantitative measures of abundance

Frequency

The frequency of a taxon is a measure of the chance of finding it within any one sample within a given set of samples. It is usually expressed as a percentage. Sample size greatly affects the observed frequency and should be stated. Frequency is also particularly sensitive to specimen (fragment) size and distribution in relation to sample size.

Density

Density is a measure of the number of individual fossils (whether representing whole or fragmented organs or organisms) of individual taxa that occur within a sample. As such it is a direct, potentially accurate and relatively easy-to-measure expression of abundance. Density measures also contain a strong taphonomic component in that easily fragmented material will tend to be overrepresented. Therefore whole-body fossils should be counted separately from fragments.

Cover

Plant cover has been defined as ‘the proportion of a planar unit sample area, aligned parallel to the bedding, that is occupied

Worked Example 5.2 Measuring abundance

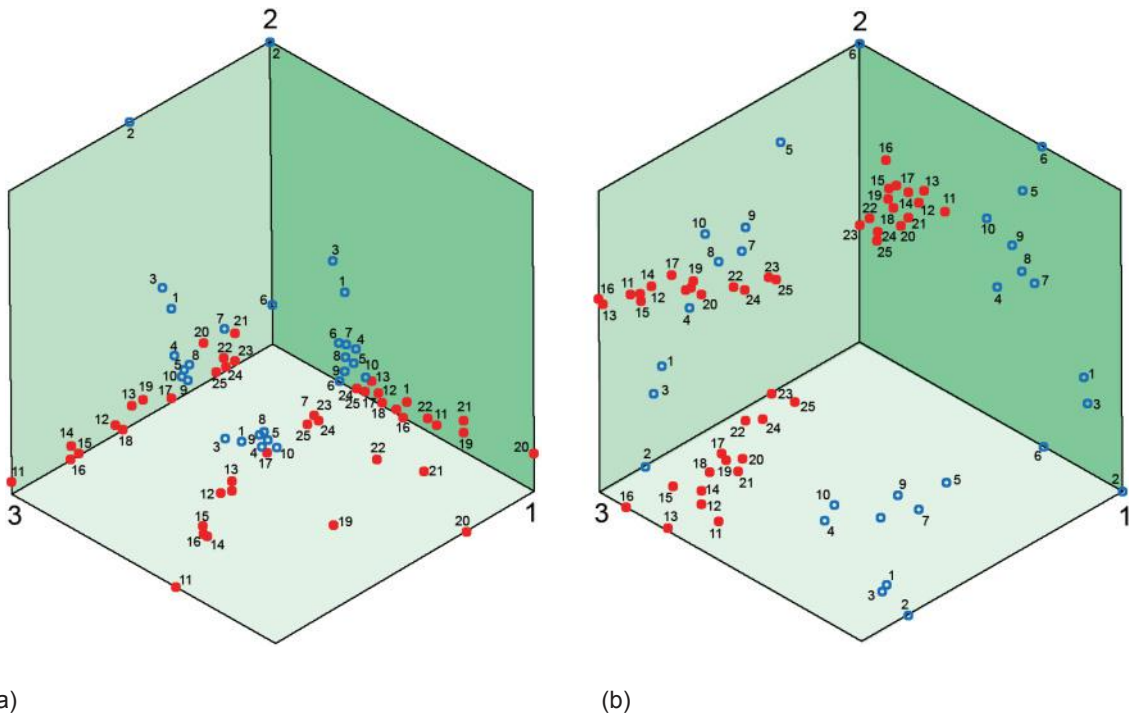


Figure 5.13 Correspondence analysis of samples from the Jurassic plant fossil locality at Hasty Bank, Yorkshire, UK. The diagrams show three faces of a hollow cube onto which the positions of samples are projected from three-dimensional space; this means that each plot has three times as many points as there are samples. The three sides of the cube represent the first three axes of greatest variation in the analysis. The sample points are numbered for cross referencing. Samples from siltstones are represented as open blue circles while closed red circles represent samples from claystones. (a) Abundance counts. (b) The same data but with abundance transformed into a logarithmic simple abundance class measure similar to that shown in Table 5.1. In plot (b) much of the ‘noise’ in the data has been removed and the pattern of plant associations in the two different sedimentary facies is more clearly displayed. (Modified from Spicer and Hill 1979.)

In the early 1970s Chris Hill excavated three vertical trenches to obtain contiguous samples through the Middle Jurassic plant beds at Hasty Bank, Yorkshire, UK. Sample volumes measured $0.5\text{ m} \times 0.5\text{ m}$ in area by $0.1\text{--}0.2\text{ m}$ depth in siltstones; where fossils were particularly abundant in claystones sample size was reduced to $0.25 \times 0.25 \times 0.2\text{ m}$. Within each sample every single plant fossil was identified and counted. In subsequent analyses all counts were normalized to $0.5 \times 0.5 \times 0.2\text{ m}$ volumes. Analyses were

conducted on the raw counts, logarithmically transformed counts and using a simple abundance class measure (Figure 5.13). Results were analysed by means of histograms and multivariate statistical analysis. The overall conclusion was that visually estimating abundance using a logarithmic scale as in Section 5.5.2 was more efficient and meaningful than absolute counts (Figure 5.13; see also Spicer and Hill 1979).

by a normal projection onto it of the individuals representing a species form that occur within that unit sample'. Cover estimates are usually obtained using a modification of the point quadrat method used in ecology. Typically a clear plastic sheet marked with 100 randomly distributed points is overlain on an exposed bedding surface (Figure 5.14) and the number of 'hits' of these points on various taxa are scored and expressed as percentage cover. It follows from this that a single bedding surface must be completely exposed over the sample area. Foreshores and some quarry floors provide the opportunities. However, in practice this is very difficult and some workers prefer to exhume blocks of matrix, each with a plant-bearing face exposed, and arrange these to form a sample area from which cover estimates are taken. The gaps between the blocks are scored as 'space'. Extra random points are then scored until the total score for plant material plus bare rock reaches 100.

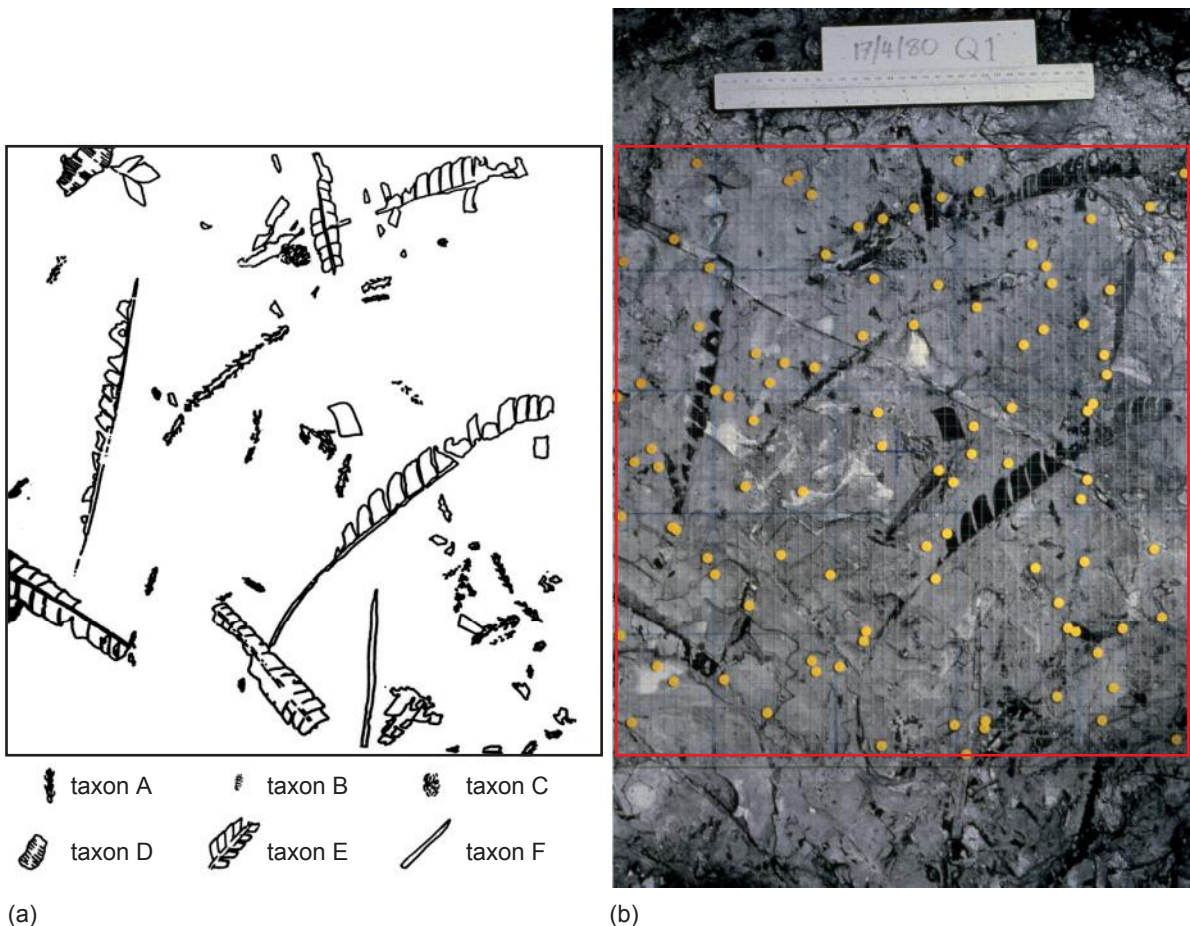


Figure 5.14 (a) Line drawing of Jurassic plant fossils from Cayton Bay, Yorkshire, UK, made from an exposed bedding plane with an overlain 0.5m × 0.5m point quadrat shown in (b). For purposes of visualization the 100 randomly distributed points have been expanded into yellow circles.

Percentage scores and other 'closed' measures

Whenever an abundance score is expressed as a proportion or a percentage any variation in the abundance of one taxon will affect the relative abundance of other taxa, even though their absolute occurrences may remain constant between samples. A rare taxon (few absolute occurrences throughout the population of samples) may have a high percentage score in a sample where it was the only taxon present, even though its absolute abundance within that sample is similar to that in other samples where it occurred with other taxa. Any closed measurement system, such as percentage scores, has to be used with great care.

Logarithmic transforms and the reduction of 'noise'

Adjacent samples often exhibit great variations in fossil abundance. This can be produced by the use of an inappropriate sample size, but such a pattern does seem to be a general characteristic of most allochthonous assemblages due to 'random' perturbations in fluid flow associated with the depositional process. This randomness also produces high levels of statistical 'noise' in the data that can swamp a palaeoecologically useful pattern. One way of overcoming this is to use a logarithmic transform. Abundant taxa will exhibit a greater variation in density than rarer taxa, and such variation can swamp any palaeoecologically useful pattern. By applying a log transform the pattern displayed by variations in the rarer components is retained while the noise associated with the less significant variations in abundant species is minimized (see Worked Example 5.2, p. 97).

5.5.3 How many samples are required?

It is often difficult to decide when sufficient samples have been scored to enable adequate investigation of a given assemblage. Certainly no generalizations can be made as every fossil assemblage is different. A guide to sample size may be obtained by constructing a graph in which the cumulative mean (of whatever abundance measure is being used for a given taxon) is plotted against sample number (Figure 5.15).

Wrap delicate fossils in tissue paper (not cotton wool) and then place in a protective box. Multiple specimens and boxes should be tightly packed in strong containers to prevent movement and abrasion during shipping. If possible try to keep the container weight to less than 10kg for ease of handling.

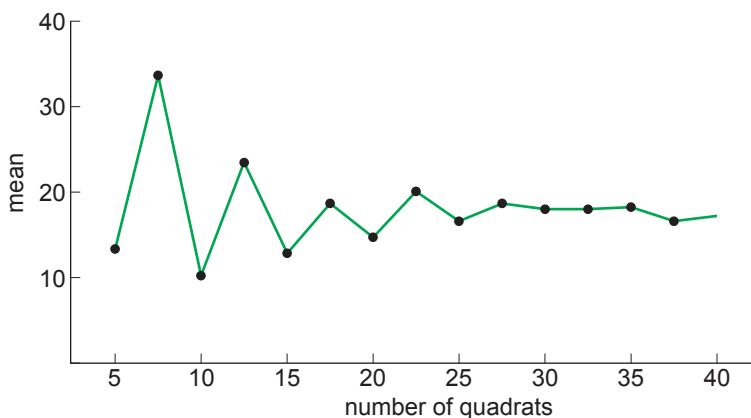
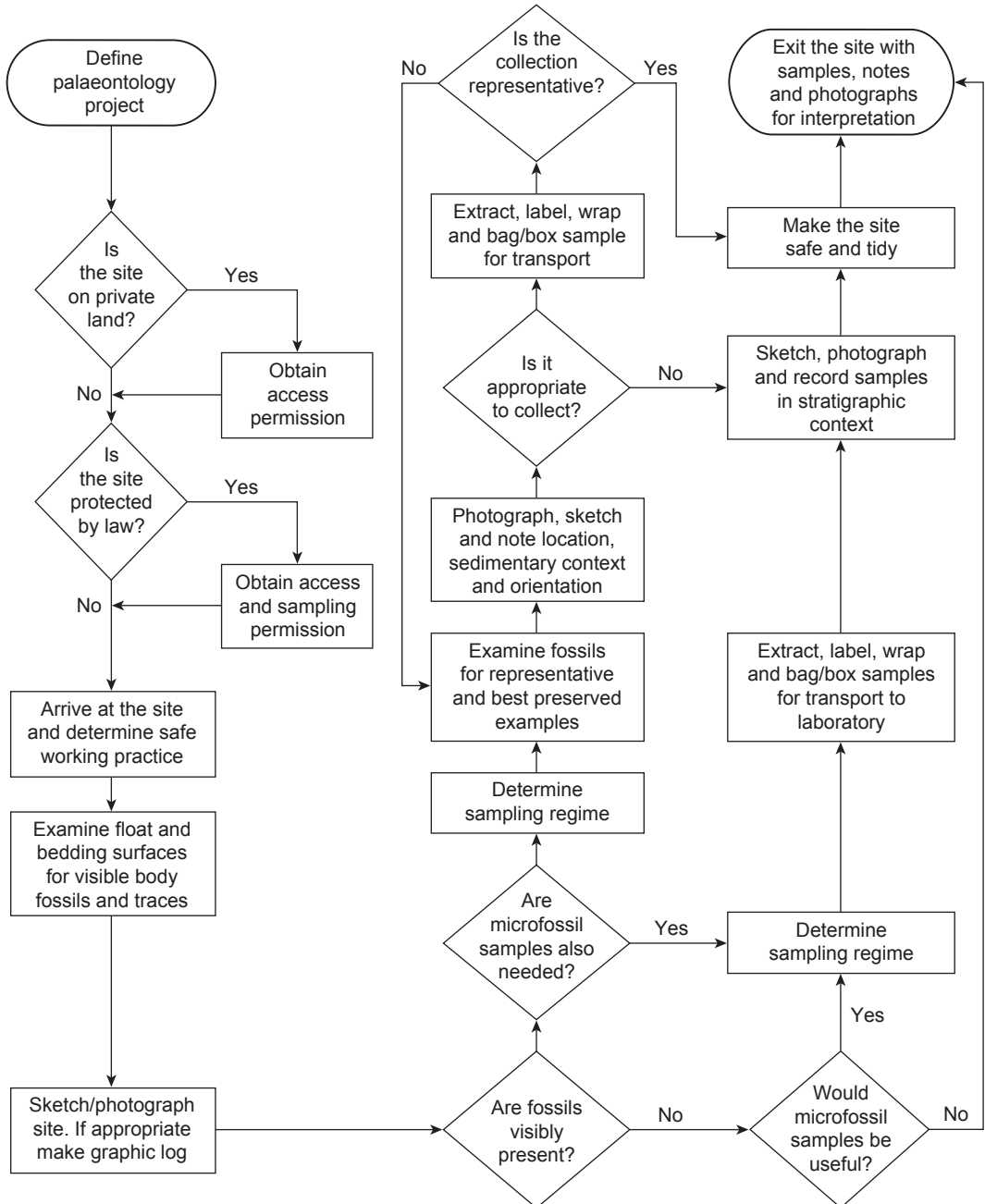


Figure 5.15 As the number of samples taken rises so the fluctuation in the value of the cumulative mean of the number of taxa will decrease. The point at which the variation stabilizes (in this case between 25 and 30) indicates the minimum number of samples required to investigate that population.

5.6 Summary

Every site is unique and no guide can be comprehensive and cover every eventuality. The importance of fossil sites for both amateurs and professionals has led to a wealth of guide books and websites specific to places and/or particular time periods or rock units. It is therefore worth searching the web and literature in advance of any palaeontological study as well as



getting in contact with local museums, however small, that may have collections and/or contacts. The flowchart opposite shows the main stages of most palaeontological investigations.

5.7 Further reading

- Benton, M. J. 2004. *Vertebrate Palaeontology* (3rd edition), Wiley-Blackwell, 472 pp.
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6 Recording features of sedimentary rocks and constructing graphic logs

Angela L. Coe

6.1 Introduction

Sedimentary rocks, particularly coarse-grained siliciclastic rocks, are rewarding to study in the field. This is because you can gain a lot of information about their mode of formation directly from field observations and start to make an interpretation (Figure 6.1) without the need to wait for thin-sections or geochemical analyses, which are required for many igneous and metamorphic rocks. Some carbonate successions and fine-grained mudstones can, however, be tricky to interpret in the field and their study can benefit greatly from follow-up microscope work and/or geochemical analyses.

Sedimentary rocks and the fossils they contain should always be considered together because, as ‘smart particles’ (Section 5.1), fossils provide vital clues on the processes and environment of deposition of the sedimentary deposits. Fossils, for instance, can provide immediate clues on whether the rocks are marine or non-marine, were deposited over a long or short period of time, what conditions were like on the sea or lake floor, as well as, in many instances, providing an immediate relative dating method.

There are a variety of specific reasons for collecting data from sedimentary deposits aside from the general ones of geological mapping or constructing a geological history for an area. These are to:

- *Understand sedimentary processes and depositional environments.* This leads to a better understanding of natural processes on the Earth’s surface.
- *Understand the potential of a sedimentary basin or unit for hydrocarbon recovery or for water resources.* An



Figure 6.1 An example of a small part of a section of sedimentary strata from which a lot of information about the depositional processes can be gained. The image shows cross-stratification produced by the migration of wave-formed ripples indicating that the sediments were deposited within wave base (less than tens of metres depth) by waves. Some of the ripples near the middle of the image are climbing, indicating high sedimentation rates. The image shows colour variation that is likely to reflect grain and/or compositional changes, which may relate to changing energy or sediment source. There are also several trace fossils indicating animal activity. Carboniferous-age strata exposed near Berwick-upon-Tweed, UK. (Angela L. Coe, The Open University, UK.)

understanding of where sedimentary rock types are situated in time and space, and how they vary vertically and laterally, enables the main reservoir rocks, seals and source rocks to be mapped out and fully exploited.

- *Reconstruct past periods of environmental change, particularly climate and sea-level change.* Fine-grained marine sedimentary deposits contain the most laterally extensive, complete and intact record of the changing chemistry of the Earth's oceans. Because of the interaction between the oceans and atmosphere, and that the oceans act like a large mixing pot, marine deposits are fundamental to understanding the Earth system in the past. The sedimentary deposits in caves and lakes also form a key part in the understanding of palaeoenvironmental change over about the past 2 Ma. Reconstructing sea-level change relies on examining and correlating both proximal and distal marine successions and looking for both gradual and abrupt changes in the type of sedimentary deposit.

- *Understand and exploit sedimentary building materials and mineral deposits.* Sedimentary rocks form important building materials. Sandstones and limestones are relatively easy to extract and shape because the natural bedding planes can be used to create blocks. Limestones are needed for cement production and agricultural uses, while mudstones are the raw component for bricks.
- *Refine the geological timescale.* The more continuous nature of the sedimentary record compared with that of igneous and metamorphic rocks, together with its fossil content, makes it important for the construction of the geological timescale. The sedimentary record is used for biostratigraphy, constructing magnetic polarity patterns, identification of Milankovitch and other regular cycles, radiometric dating of interbedded volcanic ashes, some direct radiometric dating (e.g. ^{14}C , U series and Re–Os isotope) and chemostratigraphy, all of which contribute a major part of the composite geological timescale.

In addition to the basic geological equipment (Table 2.1, p.4), it is useful for the study of sedimentary rocks to also have some of the optional equipment listed in Table 2.3 (p.6). In particular, ensure that you have a comparison chart for identifying grain size, shape, rounding and sorting (see also Appendix A6). A Munsell colour chart is useful if you are recording rocks where there is a significance to the variation in colour, or, where colour is the main distinguishing feature. A 1 lb (c. 0.5 kg) geological hammer and a cold chisel are usually sufficient to collect samples.

6.2 Description, recognition and recording of sedimentary deposits and sedimentary structures

There are four aspects that need recording in the description of sedimentary rocks: (1) the composition, which is relatively easy compared with igneous and metamorphic rocks as there are not many minerals that are common in sedimentary deposits (Appendix A6, Table A6.2); (2) the texture of the rock; (3) the sedimentary structures; and (4) the fossils within them. Composition and texture are taken together as lithology (Section 6.2.1), sedimentary structures are covered in Section 6.2.2 and the recording of fossils was covered in Chapter 5.

6.2.1 Recording sedimentary lithology

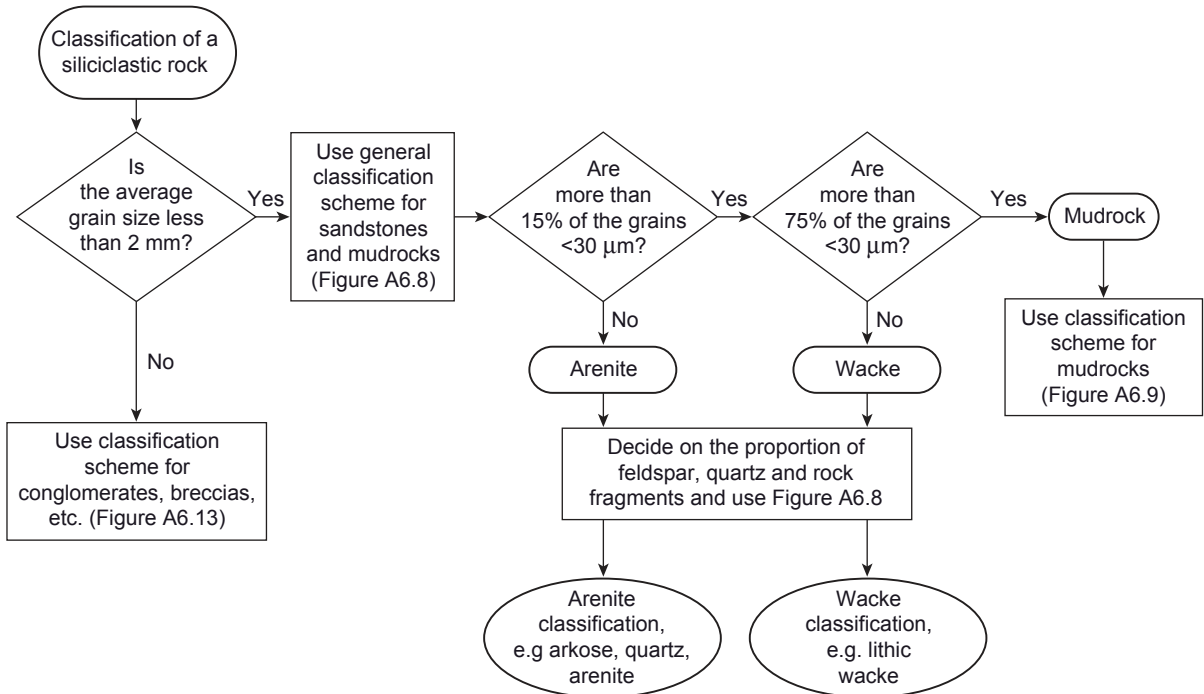
Assuming that the sedimentary section under study is divided into units (Section 3.2.2), the next task is to describe and classify the sedimentary rock type of the unit under

consideration. Classifying sedimentary deposits provides an approximate quantification of the rock components and therefore information on the depositional process, sediment source and environmental conditions. Use the following items in Appendix A6 to describe and classify the rocks: checklist (Table A6.1), table of properties of common minerals in sedimentary rocks (Table A6.2), textures (Figures A6.1–A6.4) and rock classification charts (Figures A6.11–A6.13).

Siliciclastic rocks

For siliciclastic rocks the classification scheme depends on the grain size and the composition of the major grains, except for conglomerates and breccias where the clast shape is also important. The general siliciclastic classification process is illustrated in the following flowchart:

To test for small amounts of quartz sand or silt in sedimentary rocks you can grind a small amount of rock between your front teeth. The quartz is gritty and impossible to break whereas siliciclastic clay minerals or carbonate become a fine-grained powder that feels like a smooth paste.



Mudrock (synonymous with mudstone) and coarse-grained siliciclastic rocks can be subdivided further than shown in Figure A6.6 and require slightly different observations than siltstones and sandstones. These features are covered in the following two subsections.

Mudrock

Fine-grained siliciclastic sedimentary rocks make up over 50% of the sedimentary rock record. They are more difficult to work with in the field than coarse-grained siliciclastic rocks because their features are harder to distinguish with the naked eye and the variations are subtle. Carbonate mudrock with negligible

siliciclastic content are covered by the carbonate classification schemes. Figure A6.9 provides a general classification scheme for siliciclastic mudrocks that is applicable to most successions. However, in some instances it may be necessary to devise a classification based on the particular succession that you are examining and the major components within it. To do this, decide what the major components are (e.g. clay minerals, carbonate, phosphate and silica) both visually and, if you are on a return visit, through chemical analysis completed before you return to the field. Then, using these results devise a classification scheme based on the average percentages of each component that it is possible to detect in the field. Listed below are some useful common features of mudrocks to look for in the field. As with all geological observations, use several different lines of evidence to form your interpretation. The features listed below are particularly useful for mudrocks:

Wet rocks, particularly mudrocks, are usually darker (have a lower value; Figure 2.17) than dry rocks. However, the moisture content tends not to alter the hue or chroma. If the colour is critical record either wet or dry rocks and avoid areas that are weathered.

Mudrocks rich in marine organic matter that have been buried and moderately heated, such as most Mesozoic strata, have a distinct bituminous smell when they are freshly broken. Those with a very high organic-carbon content are very light in weight due to their lower density.

- *Colour:* As for other sedimentary rocks this primarily reflects composition. Most marine mudrocks are various shades of grey. Use a Munsell colour chart and/or carry small rock chips of each of the major colours identified in the succession for comparison. Mudrocks with a higher carbonate or silica content, or less organic matter, tend to be paler. Mudrocks rich in organic matter (i.e. organic-carbon compounds) are a brownish grey (Figure 2.17d). Non-marine mudrocks are often red or green depending on the oxidation state of the iron; they can also be white and various yellows. Bentonites (montmorillonitic clays of volcanic origin) are a distinctive bluish or greenish grey when freshly exposed.
- *Fracture:* The fracture pattern also provides a clue to the composition and subtly changes with the composition. Mudrocks mainly composed of clay minerals have an even, blocky fracture. Increasing amounts of carbonate (e.g. marly clays and marlstones) tend to give the rock a conchoidal fracture pattern (Figure 6.2). Mudrocks with a high silica content are harder.
- *Fissility:* Mudrocks with a fissility (i.e. break into thin (millimetre-sized) layers) are termed shales. They can develop a fissility for two reasons: (1) laminae scale variation in composition; (2) compaction and weathering. Shales with compositional lamination often have a higher overall organic-carbon content and/or some coarser-grained material. Not all compositionally laminated mudrocks are fissile (e.g. Figure 2.19b).

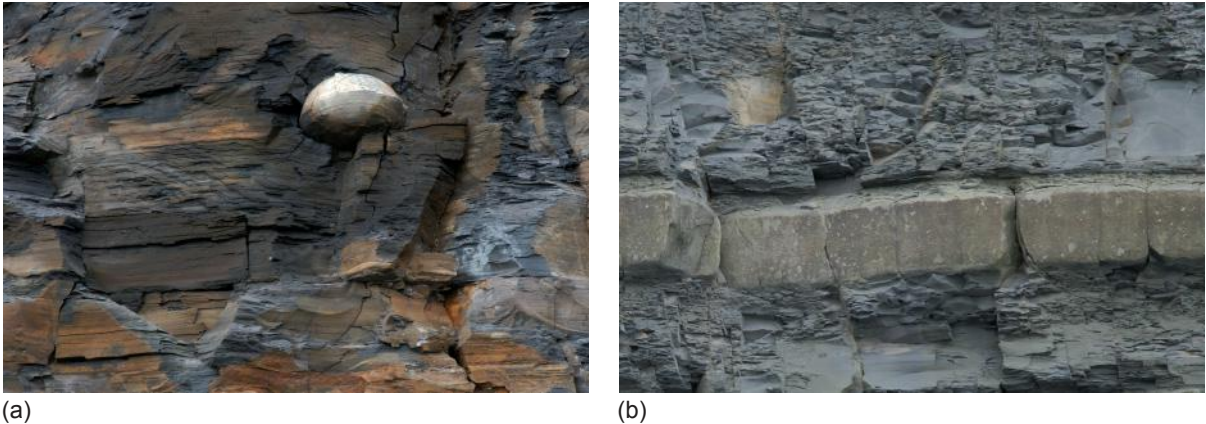


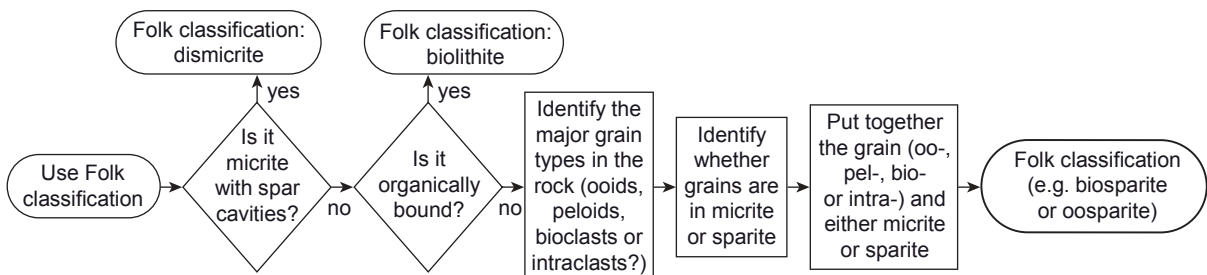
Figure 6.2 (a) Blocky fracture pattern of a siliciclastic mudrock mainly composed of clay minerals. (b) Conchoidal fracture pattern of a mudrock with a significant proportion of carbonate. (a and b: Angela L. Coe, The Open University, UK.)

Conglomerates and breccias

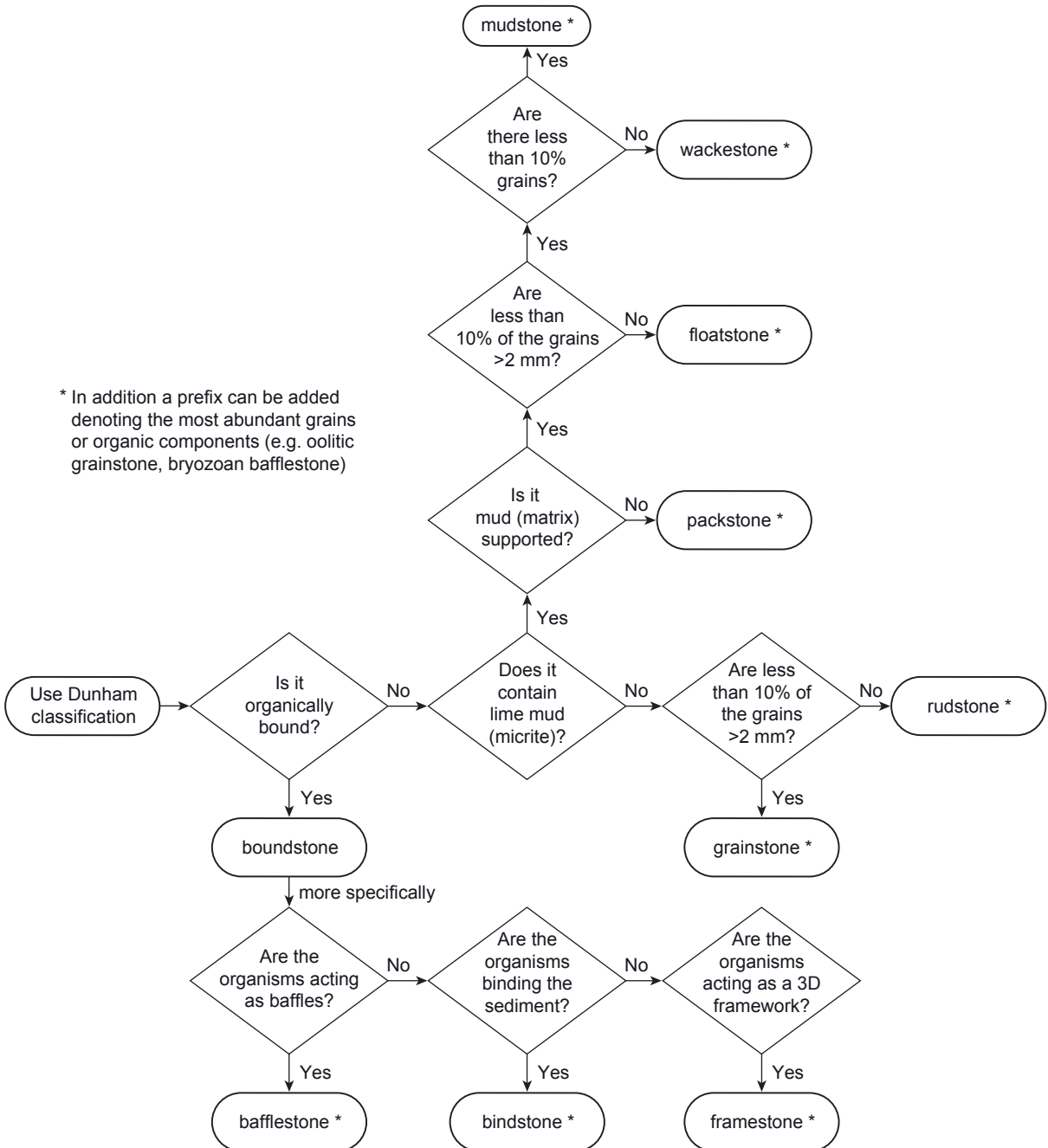
Conglomerates and breccias can be classified according to clast type and matrix properties (Figure A6.13). In complete contrast to mudrocks a ‘wide angle’ view of these coarse-grained sedimentary deposits is required to obtain representative data because of the potential large-scale variation. The quadrat method is useful for assessing and recording coarse-grained sedimentary deposits (Sections 3.3 and 5.4.2). A quadrat of 0.5 to 1 m square is appropriate for most deposits.

Carbonates

It is useful to look at both a weathered and a fresh surface of carbonate rocks. The carbonate grains tend to weather out making them easier to identify on weathered surfaces. There are two commonly used classification schemes for carbonates (Appendix A6, Figures A6.11 and A6.12). In both cases it is necessary to decide first of all whether the grains are bound together organically (i.e. whether it is a bioherm (reef) or not). The Folk classification scheme (Figure A6.11) is easier to use; it is based on the nature of the grains and whether these are within matrix or cement. The use of this classification scheme is illustrated by the following flowchart:



In contrast, the Dunham classification scheme (Figure A6.12) conveys information about the matrix or cement and the texture of the rock. The grain type(s) can be indicated by adding an adjective denoting the grain type (e.g. oolitic grainstone). The observations necessary to decide on an appropriate Dunham classification are illustrated by the flowchart below:



The other common types of carbonate are:

- *Dolomite*: Dolomite has three field characteristics that distinguish it from other carbonates: (1) it tends to be a pale yellowy-brown colour; (2) it reacts only slowly with dilute hydrochloric acid; and (3) if ground between the teeth its texture is softer than that of limestone and similar to that of royal icing.
- *Siderite*: This is most easily distinguished by its distinctive yellow-red colour (terracotta); it forms both bands and nodules, particularly in mudrock successions.

There is no well-established classification scheme for mixed siliciclastic/carbonate successions and a combination of the various classification schemes is typically used. The type of sediment, together with its depositional environment, governs the synsedimentary and post-sedimentary structures, and influences the preservation of associated features such as fossils. The common features of each sedimentary rock type to look for are summarized in Table 6.1 (pp. 110–111).

6.2.2 Recording sedimentary structures

Sedimentary structures are varied and complex. They are dealt with in detail in many geological textbooks and in specialist sedimentological textbooks (Section 6.6). A full coverage is beyond the scope of this book, so instead this section concentrates on how to: (1) record and describe them; (2) distinguish between structures that look similar; and (3) decipher cross-cutting relationships.

Sedimentary structures provide very direct clues about the processes responsible for deposition of a sedimentary rock, and the processes that occur after its deposition. In a number of cases they even provide specific information on the depositional setting, e.g. hummocky cross-stratification (HCS) is diagnostic of the offshore transition zone, which lies between fair-weather wave-base and storm wave-base, whereas swaley cross-stratification (SCS) forms close to fair-weather wave-base in the shoreface zone.

In the field you are likely to see structures that you don't understand; this may be because they are unusual, poorly developed, poorly preserved or exposed at a strange angle. So don't worry if you can't identify every sedimentary structure you see – this is not unusual. If you find something you don't understand, search around for other, possibly better/more revealing examples, preferably in the same unit but also in adjacent units. Then spend more time on the best examples first, returning to the more enigmatic ones later if there is time.

Table 6.1 Sedimentary rock types and the sedimentary structures and features that they are commonly associated with. Section 6.2.2 considers sedimentary structures more fully.

Sedimentary rock type	Depositional features and sedimentary structures	Post-depositional features and sedimentary structures	Commonly associated features
Claystones, mudrocks and marls	<p><i>Lamination</i>: millimetre-scale compositional variation giving fine-scale rock banding</p> <p><i>Fissility</i>: rock breaks easily into thin sheets parallel to bedding (may be related to lamination)</p> <p><i>Colour</i>: change in colour represents compositional variation, particularly iron minerals, organic matter and carbonate content</p> <p><i>Fracture pattern</i>: reflects compositional variation (see above)</p> <p><i>Weathering profile</i>: mudstones with a higher calcium carbonate content tend to stick out as they are often more resistant to weathering. Similarly, those with a high organic-carbon content tend to weather proud. When mudrocks are interbedded with sandstones or carbonates the mudrocks always weather back.</p>	<p><i>Nodules</i>: form below the sediment–water interface under particular geochemical conditions. Early diagenetic carbonate nodules can be used to help calculate the amount of compaction. In some successions they nucleate on fossils</p> <p><i>Cone-in-cone calcite</i>: calcite crystals that grow in cones perpendicular to the pressure during overpressuring of mudrocks</p> <p><i>Soft sediment deformation features</i>: common for high sedimentation rate interbedded mudrocks and sandstones due to density contrast of fresh sediment (mud holds c. 80% water whereas sand holds c. 50%)</p>	<p><i>Fossils</i>: the low energy of deposition, fine-grained and non-porous nature of mudrocks tends to be excellent for fossil preservation, both mega- and microfossils. Trace fossils are easy to detect if there is a colour change and the fine detail is often well preserved.</p> <p><i>Pyrite</i>: this is often associated with euxinic (free H₂S in the water column) depositional conditions</p> <p><i>Organic matter</i>: marine and terrestrial, which influences colour and can influence lamination. It indicates high productivity and/or suitable preservation conditions (e.g. anoxia)</p>
Siltstones and sandstones	<p><i>Sedimentary structures</i>: there is a wide range (see Section 6.2.2), many of which indicate the processes of deposition</p>	<p><i>Nodules</i>: as above. Late diagenetic nodules are more common</p> <p><i>Liesegang rings</i>: lines of iron concentration that form as later fluids move through the rock. Can appear at first glance to be sedimentary structures</p>	<p><i>Fossils</i>: often present but can be reworked under the high-energy conditions of deposition</p>
Carbonates (non-organically bound)	<p><i>Sedimentary structures</i>: there is a wide range (see Section 6.2.2), many of which indicate the processes of deposition</p>	<p><i>Stylolites and other pressure solution features</i>: carbonates are susceptible to dissolution. Reprecipitation can enhance, mask or destroy primary features</p> <p><i>Cementation</i>: the soluble nature of carbonates makes carbonates particularly susceptible to cementation</p>	<p><i>Fossils</i>: bioclasts are important in many carbonates and provide valuable information on the site and conditions of deposition</p>

Table 6.1 *Continued*

Sedimentary rock type	Depositional features and sedimentary structures	Post-depositional features and sedimentary structures	Commonly associated features
Carbonates (organically bound)	<i>Sedimentary structures:</i> often massive with distinct vertical relief. Usually closely associated with horizontally bedded units representing the lagoon and steeply inclined chaotic beds representing the bioherm debris	As carbonate (non-organically bound above)	<i>Fossils:</i> by definition these are <i>in situ</i> and can provide much information about the environment and palaeoecology
Conglomerates and breccias	<i>Clast types:</i> identify the rock types of the clasts, which gives a good indication of the source and sometimes the depositional processes <i>Sedimentary structures:</i> cross-stratification, bedding, etc. (see Section 6.2.2)	Compaction of matrix around clasts and cementation	<i>Fossils:</i> only the robust large megafossils such as vertebrate remains and large pieces of fossilized wood tend to survive intact
Coal	<i>Colour and shininess:</i> indicates type of organic matter and/or clay content (see also Appendix A6, Table A6.3)	Check for an underlying palaeosol that would indicate the coal is <i>in situ</i> and not derived. The coal itself may be interbedded with other sedimentary deposits	<i>Pyrite:</i> associated with high sulfur content Carbonate nodules in coals can preserve plant remains
Evaporites	Note distribution within sedimentary deposits and crystal shape. Large crystals and fibrous ones are recrystallized	Dissolution and reprecipitation common. Complete dissolution is quite common	Faults and folds due to the ductile nature of evaporites and their high solubility Associated with shallow-water deposits, particularly carbonates
Ironstones, cherts and phosphates	<i>Colour:</i> can reflect compositional variation and in the case of phosphates the amount of reworking (pink/buff when a precipitate, grey/brown and black when reworked)	<i>Banding:</i> these deposits are susceptible to dissolution and reprecipitation so the banding may be entirely post-depositional	Phosphates are indicative of high productivity areas. The silica for the chert may come from diatoms, radiolaria or sponge spicules. These indicate a wide range of depositional conditions so determining the origin of the silica is important



When recording and describing sedimentary structures try to view and record them in all three orthogonal faces if possible in order to help in their identification.

If you don't find other examples, take a photograph and make some notes so that you can show it to other geologists and/or compare it with other examples in the literature, but don't waste a lot of time on it.

Here are some suggestions for observing, describing and identifying sedimentary structures.

1. Examine the structure if possible in plan view and in cross-section, preferably in faces that cut through the structure parallel and perpendicular to the current direction. This is because different structures look similar or even exactly the same if only one view is taken. The three-dimensional morphology of sedimentary structures is often complex, because sedimentary structures are the result of the migration of three-dimensional bedforms, or of animals and plants disrupting the sediment. Figure 6.3 shows some common examples of how sedimentary structures look different depending on the orientation of the rock face.
2. Decide whether the structure is common in the succession or unusual. If the latter, is it important or an oddity that is not worth spending much time on?
3. Record the size (in all three dimensions where possible) and any systematic variation or repetition, both laterally and vertically.
4. If it is a large-scale structure that disrupts other beds and changes its nature along strike, record these details using photographs and/or sketches (see first part of Worked Example 6.3).
5. Record where the sedimentary structure is located within the bed. Is it at the base or top of the unit or in the middle?
6. If you cannot identify the structure, sketch and/or take photographs of it. Label the sketch with notes on the geometries and ensure that you have notes on whether this is a cross-section or plan view, and that you can relate different views of the structure.
7. Look for associations of sedimentary structures both laterally and vertically. For instance flute casts and tool marks are both formed through mass flow processes, and are likely to be found in the same succession. In addition, if you find flute marks look for other evidence of mass flow deposits, such as the pattern of sedimentary structures typical of a Bouma Sequence. In some cases sedimentary structures can subtly change through the succession from one form to another. For instance in coastal successions, HCS is likely to change to SCS as the succession records

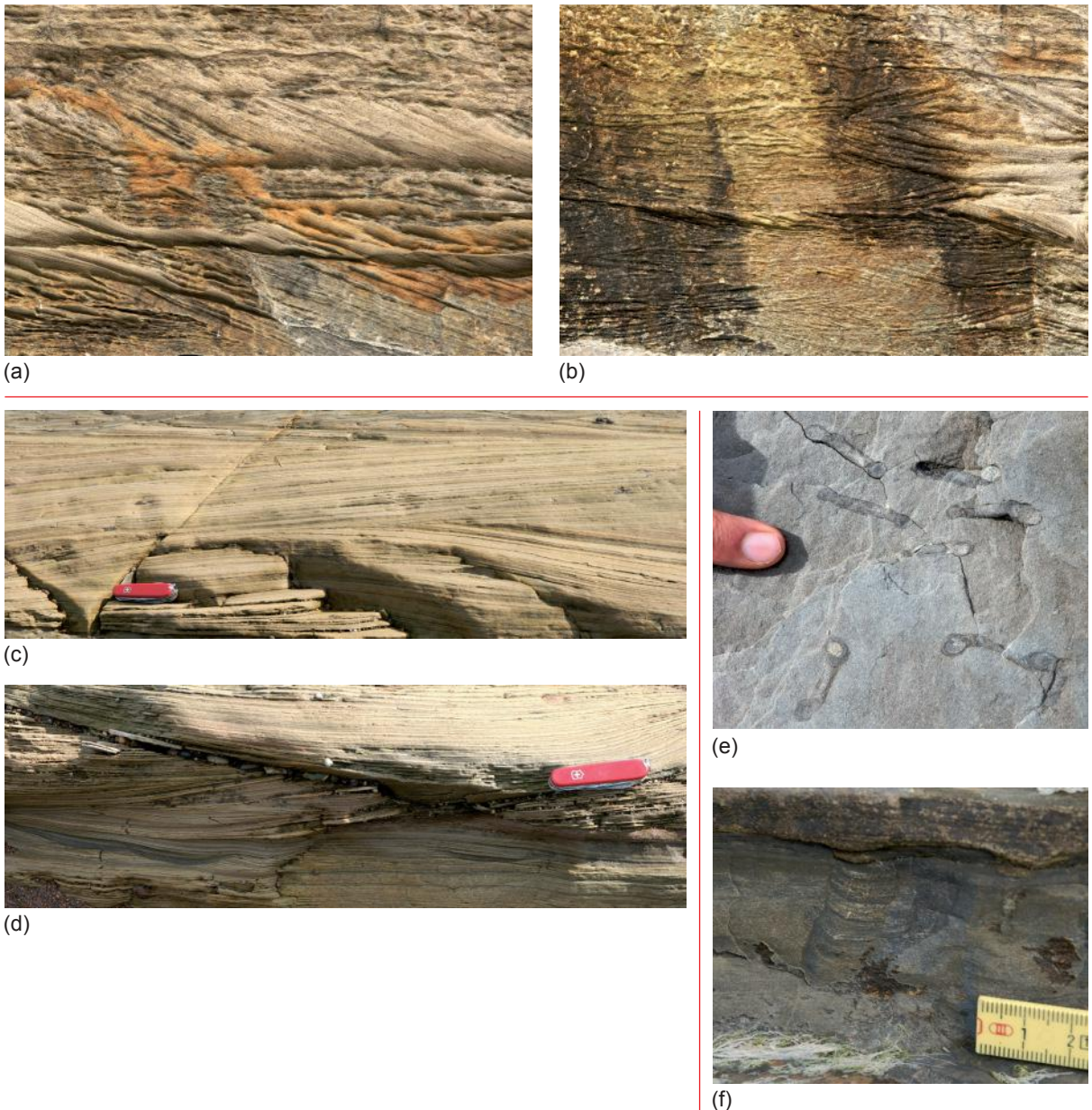


Figure 6.3 Paired photographs of sedimentary structures taken from orthogonal faces. (a) Cross-stratification. Note that from this one view it is impossible to tell whether it is trough or planar stratification. (b) This is from the same bed as (a) and shows distinct troughs indicating that (a) and (b) are part of a trough cross-stratified deposit. (c and d) Hummocky cross-stratification (HCS) showing that the structure is similar no matter which section is viewed. (e) *Diplocraterion* burrow showing the plan view of this vertical burrow. The circles are the top of the tubes and the lines joining them are the disrupted sediment in between. (f) Cross-section view showing the vertical U-tube and spreiten. This view is more typical of that illustrated in the literature. Figure 5.4 (p. 86) shows an idealized cross-sectional view of *Diplocraterion*. (a–f: Angela L. Coe, The Open University, UK.)

conditions that represent water depths closer to fair-weather wave-base rather than storm wave-base.

8. Determine, by examining the nature of the contacts, which of the conventional four categories the sedimentary structure falls into: depositional, erosional, biogenic (e.g. trace fossils) or post-depositional. Biogenic structures of both plant and animal origin are covered in Chapter 5 and Appendix A5. If the structure is post-depositional, and you are interested only in the depositional sedimentary structures, then you can ignore it. Tables 6.2–6.4 summarize the common depositional, erosional and post-depositional sedimentary structures and bedforms respectively.

Table 6.2 Some of the common depositional sedimentary structures, bedforms (marked) and their process of formation. Note: cross-stratification refers to both cross-bedding and cross-lamination with no scale implication. Figure numbers prefixed with an A can be found in Appendix A6.

Sedimentary structure or bedform	Thickness or size	Features to observe	Processes	Figure/Table
Lamination	Less than 1 cm	Continuity, variation, colour	Variation in composition or compaction	2.19b, 12.1, 12.2, 13.2b
Bedding	1 cm to metres	Continuity, repetitions, thickness variation	Varying conditions	3.1, 6.2b, 6.15, 6.16
Grading	Variable	Normal or reverse, gradational or restricted	Waning or waxing currents	A6.17s,t
Wave-formed ripples (bedform)	cm	Three-dimensional. Climbing or not, associated with HCS or SCS or other structures	Waves	6.1, A6.17k,l,m, Table A6.4
Current-formed ripples (bedform)	cm	Three-dimensional. Climbing or not, associated structures, palaeocurrent	Unidirectional currents	A6.17i,j, Table A6.4
Impact ripples (bedform)	cm	Size, orientation	Aeolian	–
Lenticular bedding	cm	Wave- or current-formed ripples? Vertical changes and whether it is part of a fining- or coarsening-upward trend	Fluctuation between deposition from traction currents and settling from suspension	A6.17
Flaser bedding	cm			
Dunes (bedform)	1–10s m	Shape of bedform	Wind and water	–
Current lineation	cm	Provides a direct measure of palaeocurrent. Check orientation with respect to other structures	Upper flow regime	2.9, A6.17r

Table 6.2 *Continued*

Sedimentary structure or bedform	Thickness or size	Features to observe	Processes	Figure/Table
Planar lamination	mm to 1 cm	Continuity, nature (compositional or grain size), presence of current lineation	Traction currents from currents or waves (upper or lower flow regime)	A6.17q
Cross-lamination	Less than 1 cm	Sedimentary structure resulting from current- or wave-formed ripples. Examine continuity and observe whether ripples are climbing	Migration of wave- or current-formed ripples	6.1, A6.17j,l,o
Trough cross-stratification	cm to several metres	Observe in three dimensions to confirm identification; provides palaeocurrent direction	Migration of curved bedforms at particular speed and depth	6.3a,b, A6.17c,d
Planar cross-stratification	cm to several metres	Observe in three dimensions to confirm identification; provides palaeocurrent direction	Migration of straight bedforms at particular speed and depth	6.11b, A6.17a,b
Hummocky cross-stratification (HCS)	m (but smaller than SCS)	Structure should look the same in all cross-sections; plan view and cross-section show a 1:1 ratio of antiforms and synforms	Storm waves	6.3c,d, A6.17e,f
Swaley cross-stratification (SCS)	m	Structure should look the same in all cross-sections; plan view and cross-section show mainly synforms	Fair-weather waves	A6.17g,h
Tidal bundles	cm	Note the orientation; look for associated tidal features (bi-directional cross-stratification, clay drapes) and consider possible tidal regime (diurnal or semi-diurnal)	Cross-stratification usually picked out by finer grained deposits with the cross-stratification surfaces in distinct groups of 7 that change from closely to widely spaced, representing neap and spring tide deposition respectively. Diagnostic of tidal currents	A6.17p
Desiccation cracks	cm	Look for evaporites, palaeosols and other evidence of subaerial exposure	Subaerial exposure	A6.17u
Pseudomorphs	cm	Geometrical shapes	Replacement of evaporite minerals after their dissolution	A6.17v

Table 6.3 Some of the common erosional sedimentary structures and their processes of formation. Figure numbers prefixed with an A can be found in Appendix A6.

Structure	Size	Features to observe	Processes	Figure
Flute casts	cm	Orientation provides palaeocurrent direction	Turbulent eddy of a turbidity current	A6.17y
Tool marks including groove casts	cm	Orientation of some provides palaeocurrent direction	Features produced by the erosion and entrainment of larger clasts by currents. The clasts are dragged, bounced or dropped on the surface. There are a wide range of structures from prod marks to grooves	A6.17x
Scours	m	Possible association with erosion surface	Erosion from currents or waves	A6.17w
Channels	10s m	Evidence for base-level fall; possible change from marine to fluvial or submarine incision	Large-scale erosion from flow	3.1b, 4.5, 6.12
Gutter casts	5–10s cm wide, length 10s m	Orientation provides palaeocurrent direction	Rip currents	6.12f
Glacial striations	cm to m	Orientation shows direction of ice movement	Ice-sheet movement	–

Table 6.4 Some of the common early and late post-depositional sedimentary structures and their processes of formation. Figure numbers prefixed with an A can be found in Appendix A6.

Structure	Size	Features to observe	Processes	Figure
Early post-depositional structures				
Nodules (early diagenetic)	cm–m	Size, composition. Early diagenetic nodules are flattened ovoids and the laminae or bedding become gradually wider apart near the middle of the nodule. Check if multigenerational due to reworking	Changes in the pore-water chemistry a few decimetres to metres below the sediment–water interface	6.2a, A6.17z,aa
Deformed/convolute bedding	cm–m	Extent, any sense of movement direction, possible erosion	Unstable sediments due to angle of deposition, high sedimentation rate, change in pore-water pressure or earthquakes or other structural disturbance	A6.17gg
Slumps and slides	cm–km			–

Table 6.4 *Continued*

Structure	Size	Features to observe	Processes	Figure
Sandstone sills, dykes and mud volcanoes	m–km	Direction of extension, associated features, whether the infill sedimentary deposits are part of the 'normal' succession	Synsedimentary movement. Often found close to faults	–
Dish and pillar structures	cm	Small concave-up shapes. Look for other associated dewatering features	Water escape structures form where sedimentation rate is high and the underlying sediments have not had chance to compact before more sediment is laid down on top.	A6.17dd,ff
Load casts	cm	Look for other associated dewatering features		A6.17cc
Ball and pillow	cm	Other evidence of high sedimentation rate		A6.17dd,ff
Late post-depositional structures				
Nodules (late diagenetic)	cm–m	Size, composition. Late diagenetic nodules have a high sphericity. They often preserve other sedimentary features	Change in pore-water chemistry 10s to 100s m below the sediment–water interface	A6.17bb
Pressure solution structures (e.g. stylolites, cone-in-cone calcite)	cm–m	Extent laterally and vertically	Sediment compaction and movement of fluids. Presence depends on the chemistry of the sedimentary deposits and pore waters as well as the amount of pressure	8.5
Leisegang rings	m	Other evidence for diagenesis	Late stage pore-fluid movement	A6.17hh
Dendrites	cm			A6.17hh

6.3 Graphic logs

The preceding section should have provided you with the tools to start recording the features of individual units that make up sedimentary rock successions in the form of written notes and also sketches of both large- and small-scale features. However, the standard way to record and summarize data on sedimentary rock successions is by using a graphic log (e.g. Figure 6.4, p. 118). This is an idealized and pictorial summary of each of the sedimentary rock units as they were laid down stratigraphically on top of each other and preserved.

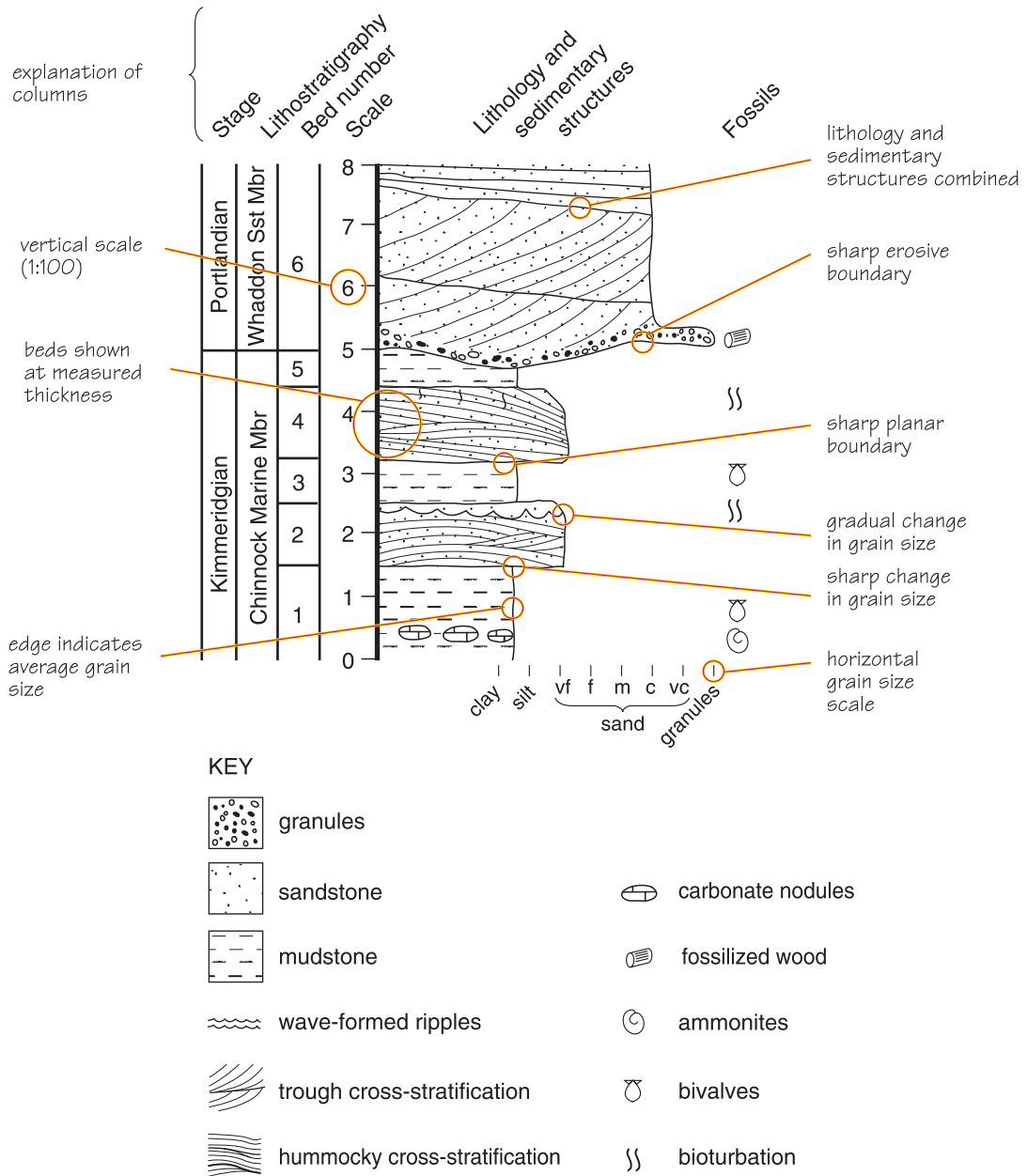


Figure 6.4 A neat version of a typical graphic log with some of the key features labelled. The field version should look very similar except it might not be drawn to scale vertically and there might be other columns with samples, photographs and links to more detailed notes on particular contacts and/or units. For examples of field graphic logs see Figures 4.2b, 5.10, 6.9b, 6.11 and the book cover.

Graphic logs have many advantages because they:

- are a succinct method of summarizing a lot of data;
- immediately give an impression of the vertical succession and can therefore aid in the identification of repetitions and major changes in the sedimentary facies;

- are a convenient way of testing and making correlations between sections of similar age from different places.

There are many variations on the style in graphic logs, with authors tending to develop a format according to the overall objectives and personal style. There are, however, several set conventions that are generally followed and these are discussed in Section 6.3.1 before some of the common types of graphic log and different conventions are illustrated. Section 6.3.2 explains the stages in constructing a graphic log.

6.3.1 Conventions for graphic logs

The set conventions for recording graphic logs can be summarized as follows.

- *The vertical scale:* This represents cumulative thickness, above a particular datum on the exposure (distance above datum increases upwards) or in the case of a borehole core the depth down from the top (distance below datum increasing downwards). Graphic logs can represent successions that range from centimetres to hundreds of metres depending on the scale of observation. The scale factor also varies. It is usual to choose a scale factor that is easy to work with, e.g. 1 m of rock = 1 cm on paper (1:100) or 10 m of rock = 2 cm on paper (1:500).
- *The horizontal scale:* For siliciclastic deposits this always represents the average size of the grains, and by implication deposition from high- or low-velocity currents or suspension (Figure 6.5a and b). Usually the grain size is shown increasing to the right. In the case of carbonate deposits the grain size is more complex because the size of the clasts is often a function of factors other than the energy (e.g. size of the biota producing the bioclasts or whether ooids or peloids or pisoliths are forming). Nevertheless the horizontal scale is based on decreasing amounts of carbonate mud towards the right (Figure 6.5c).
- *Lithology:* The rock type is represented by particular ornaments, e.g. stipple for sandstone, bricks for limestone.

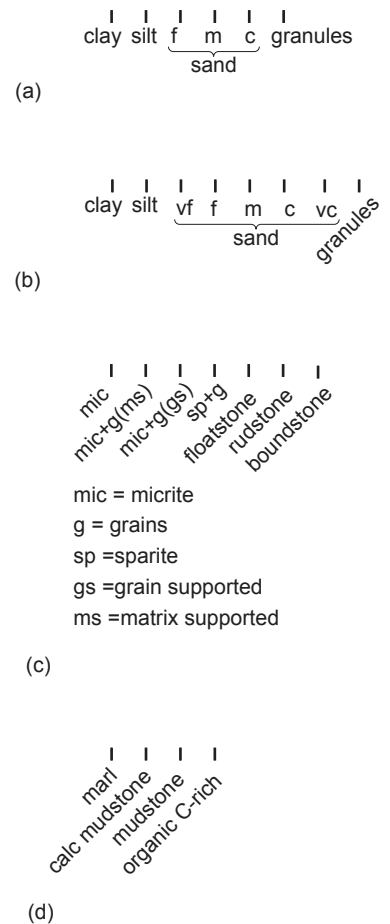


Figure 6.5 Variety of different grain-size scales. (a) Basic scale for siliciclastic rocks. (b) A more technically correct scale with each of the subdivisions representing a doubling in grain-size diameter for the sand subdivision (but this can be harder to distinguish in the field and does not necessarily add that much more information). (c) Grain-size scale for carbonate rocks. (d) Potential subdivisions based on composition for mudstone successions. For mixed siliciclastic carbonate rocks both grain-size scales are often added to the graphic log.

For the less common rock types, e.g. ironstones and evaporites, the ornament used may vary slightly. Some of the commonly used symbols for graphic logs are shown in Appendix A6, Figure A6.16.

- *Sedimentary structures.* The sedimentary structures are represented either by very idealized symbols or by a sketch (to scale) of the structures as seen. The latter has the advantage of not having to identify the structure immediately and/or showing the particular geometry of the sedimentary structure in that succession. For instance, the typical thickness of the cross-stratification sets or the variation in angle can be shown.
- *Other information:* Other information includes the lithostratigraphic nomenclature, fossils, biostratigraphic zones, sample and photograph information, bed numbers, palaeocurrent data and sequence stratigraphy. These are usually put into columns adjacent to the main log with the information aligned horizontally with the particular level that it pertains to. These columns are usually ranked in a logical order, e.g. for lithostratigraphy: group name, formation name, member name and bed number. If the data you have collected need to be compared with those of previous studies this is often also shown in a summary format. It is a good idea to work out the correlation in the field where a variety of features are more obvious and different correlations can be tested. This is essential if you are relying on previous data sets for biostratigraphic or geochemical information.
- *Stratigraphic order:* The rock units should, if possible, be examined and recorded in the notebook in stratigraphic order, i.e. with the notes on the overlying unit above the unit it supersedes. This enables the contacts between the units to be depicted graphically. Sometimes in the field, because of particular conditions, it becomes necessary to log the youngest units first and work down through the stratigraphy. In this case the units should still be recorded in the correct stratigraphic order in the notebook; this is easily achieved by working down from the top of the notebook pages.

Variations on the conventions for graphic logs

The common variations on the main conventions are:

- using the same or separate columns for the lithology and sedimentary structures – exactly the same information from Figure 6.4 is represented in a split column format in Figure 6.6;
- where the succession is mainly or entirely composed of carbonates, omitting the brick symbol used for carbonates (e.g. Figure 6.10, p. 126);

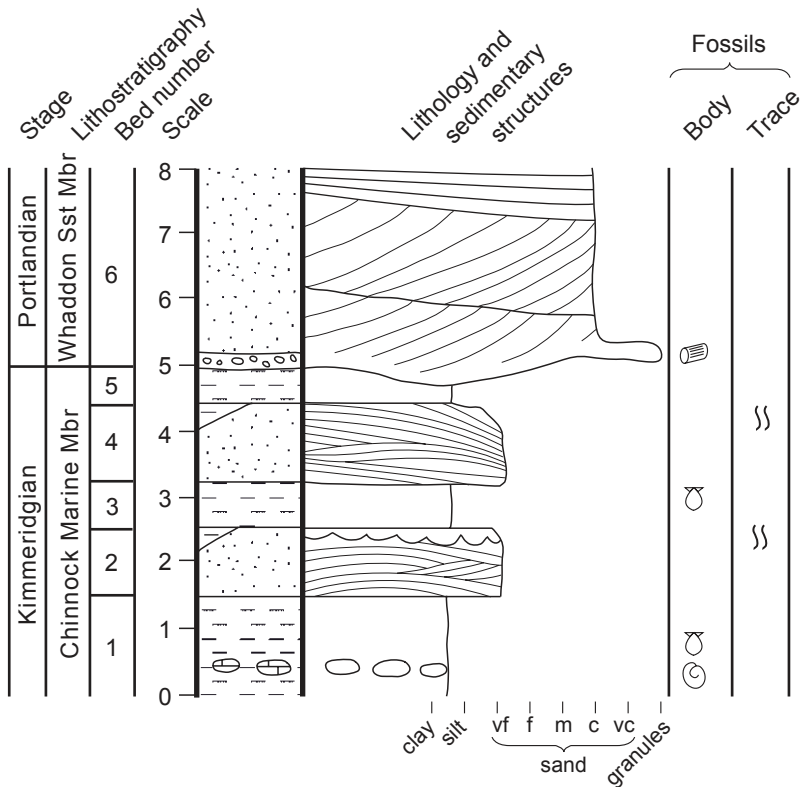
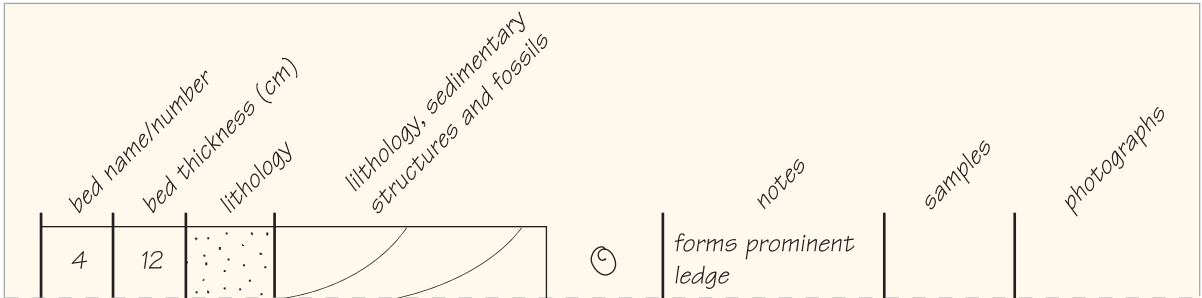
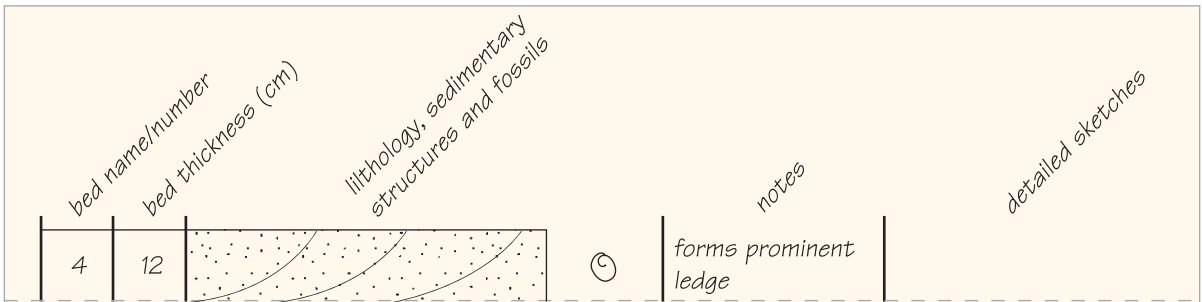


Figure 6.6 Same graphic log as Figure 6.4 but with the sedimentary structures and lithology in two separate columns.

- sedimentary structures are shown as idealized symbols only;
- note that colour is usually used on graphic logs only when it is one of the main defining characteristics (e.g. in a mudrock succession) or for visual purposes for oral presentations.
- completing the graphic log on a pre-formatted graphic logging sheet or directly into a field notebook (Section 6.3.2).

6.3.2 Constructing a graphic log

1. Prepare your notebook or graphic logging sheet(s). Divide up the notebook page with vertical ruled lines, both to order the data systematically and to serve as a reminder for what data need to be collected. If necessary use two facing pages for all the different columns pertaining to one unit. There are various options for the format according to personal preference; some examples are shown in Figure 6.7a (p. 122). Some people use preformatted graphic logging sheets (e.g. Figure 6.7b). If logging sheets are put onto standard quality paper the paper and large size of the sheet can be susceptible to damage under poor weather



(a)

Location:			Name:			
			Date:			
Bed name/no.	Bed thickness	Scale	Lithology and sedimentary structures	Fossils, other features & notes	Depositional area	Sequence stratigraphy

(b)

Figure 6.7 (a) Some options for notebook layout for graphic logging. (b) Header of an example graphic logging sheet.

conditions. There is more chance of losing one of a set of loose-leaf sheets than a notebook. Logging sheets are, however, particularly useful and extensively used for logging core (e.g. International Ocean Drilling Program (IODP) legs and petroleum companies), where they are easier to handle and the standard sheet ensures that different authors record the same type of information.

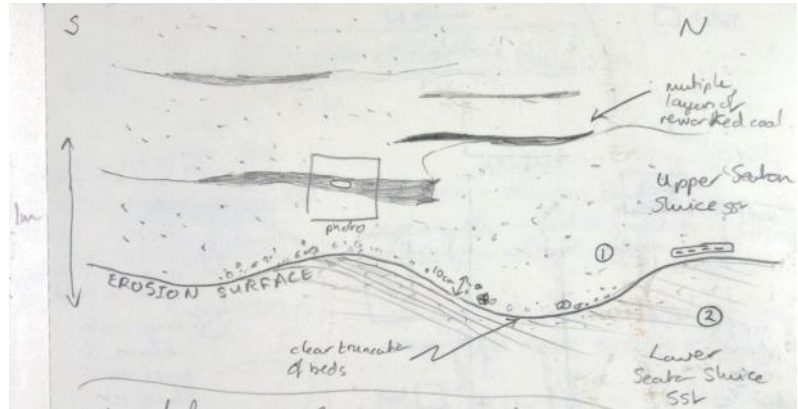
2. Decide on an appropriate vertical scale, taking into account the average and minimum thickness of the units to be

logged, the total thickness of strata to be recorded, the time available and the aim of the logging. Alternatively you could draw the log to a very rough scale in the field and then draw it to scale in the neat version. The advantages of not completing the log to scale in the field are that it allows you to put the details into very thin beds and to not take up too much space with thick beds that show few features; it is also much quicker. The disadvantage is that you do not have as good a visual record of the beds in the field.

3. Decide where exactly along the exposure you are going to make your measurements and observations. You need to ensure that you complete the logging somewhere that is representative, where you can access the stratigraphy safely and where beds are not covered by scree or vegetation. Many exposures are of dipping beds so it may be necessary to move along in order to examine all of the beds. As you construct your log you should note any major changes that occur laterally, for instance if one of the contacts is erosional and cuts out the underlying beds.
4. Record the nature of the boundary at the base of the section to be logged. Note whether it is gradational or sharp. If it is gradational record over what distance this occurs. You should also note whether the contact is planar or undulose. For undulose contacts the nature of the contact should be noted preferably in graphical form.
5. Decide where the upper boundary of the unit lies. The 'unit' is either a bed or set of beds depending on the nature of the succession and the scale of resolution required for the graphic log.
6. Measure the total thickness of the unit, ensuring that you measure perpendicular to the bedding surface.
7. Record the nature of the contact with the overlying unit.
8. Record the composition and sediment texture information (lithology) for the unit. Note any changes within the unit if that scale of resolution is required.
9. Record the sedimentary structures and fossils in that unit.
10. Record any samples or photographs taken.
11. Record any unusual features and/or topographic features that may help you relocate the unit.
12. Complete any correlation and comparison to previous work as necessary.
13. Repeat steps 5 to 13 for the next stratigraphically younger unit and so on, continuing on further pages of the notebook as necessary.

For any units or boundaries that are laterally variable or show a number of different features, use a sketch along with the graphic log to show the lateral variation or particular features (e.g. Figures 6.8 and 4.3c). Worked Example 6.1 shows an example of how the graphical logging technique was used to record a sedimentary succession.

Figure 6.8 Sketch of an erosion surface in the Carboniferous, Northumberland showing the large-scale topography on the surface and details of the laterally variable units above and below. (Notebook of Angela L. Coe, The Open University, UK.)



Worked Example 6.1 Construction of a graphic log of a shallow-water carbonate succession

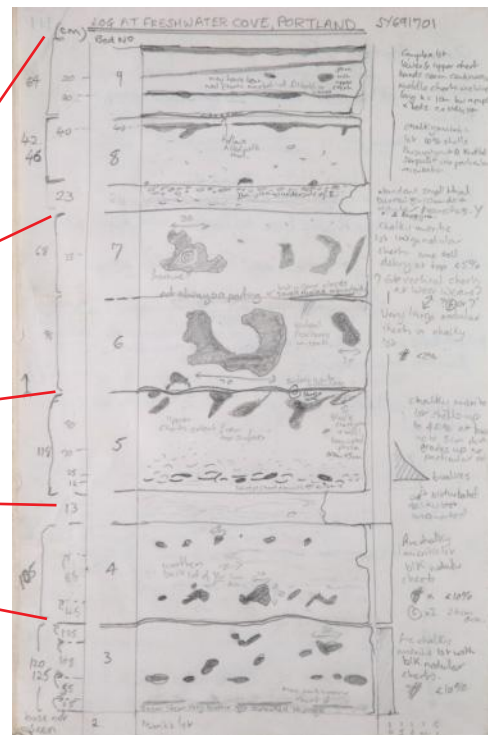
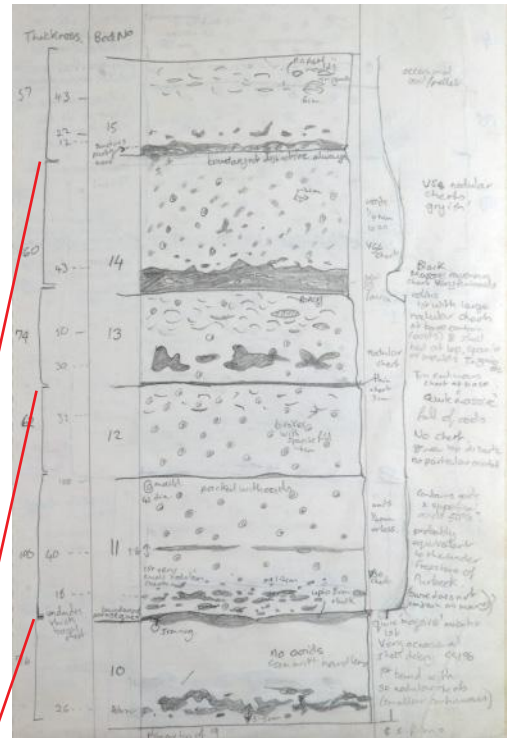
Figures 6.9 and 6.10 show photographs and the field and published version of a graphic log that was compiled to summarize the features of the Portland Beds at Freshwater Bay, Isle of Portland, Dorset, UK. This work was completed as part of a basin-wide study of the depositional history and sequence stratigraphy of the Portland Beds within the Wessex Basin, southern England. The graphic log in Figure 6.10 is one of a set that was constructed along a proximal to distal basin profile. Thin-sections were cut from the samples taken and these were used to confirm and supplement field observations. A facies model for the main depocentre was also constructed using many sections. Note that the black chert nodules that have formed around *Thalassinoides* burrows are drawn roughly to scale so that the beds can be easily recognized (Figure 6.9). There are notes on the occurrence of ooids; these change through the succession and

because of their shallow-water origin they are significant for the sequence stratigraphic interpretation. The thin beds are drawn relatively thickly in the notebook so that there is space for the details.

All of the ammonite biostratigraphic information was compiled from the literature. Particular note was taken of stratigraphic gaps evident from both the sedimentology and the biostratigraphy. The facies and the stratigraphic gaps were used to construct a sequence stratigraphic interpretation (Section 6.5.1). The surface marked P2 (Figure 6.10) is a sequence boundary that corresponds to an incised fluvial valley cut into marine deposits on the basin margins and is therefore interpreted as a forced regression. Surface P3 is also a sequence boundary associated with more minor marine incision.



(a)



(b)

Figure 6.9 Field data. (a) Photographs of part of the exposure at Freshwater Bay, Isle of Portland, UK. (b) Two pages of a field notebook showing part of the graphic log constructed in the field. Note that the field log is drawn only to an approximate scale. (a and b: Angela L. Coe, The Open University, UK.)

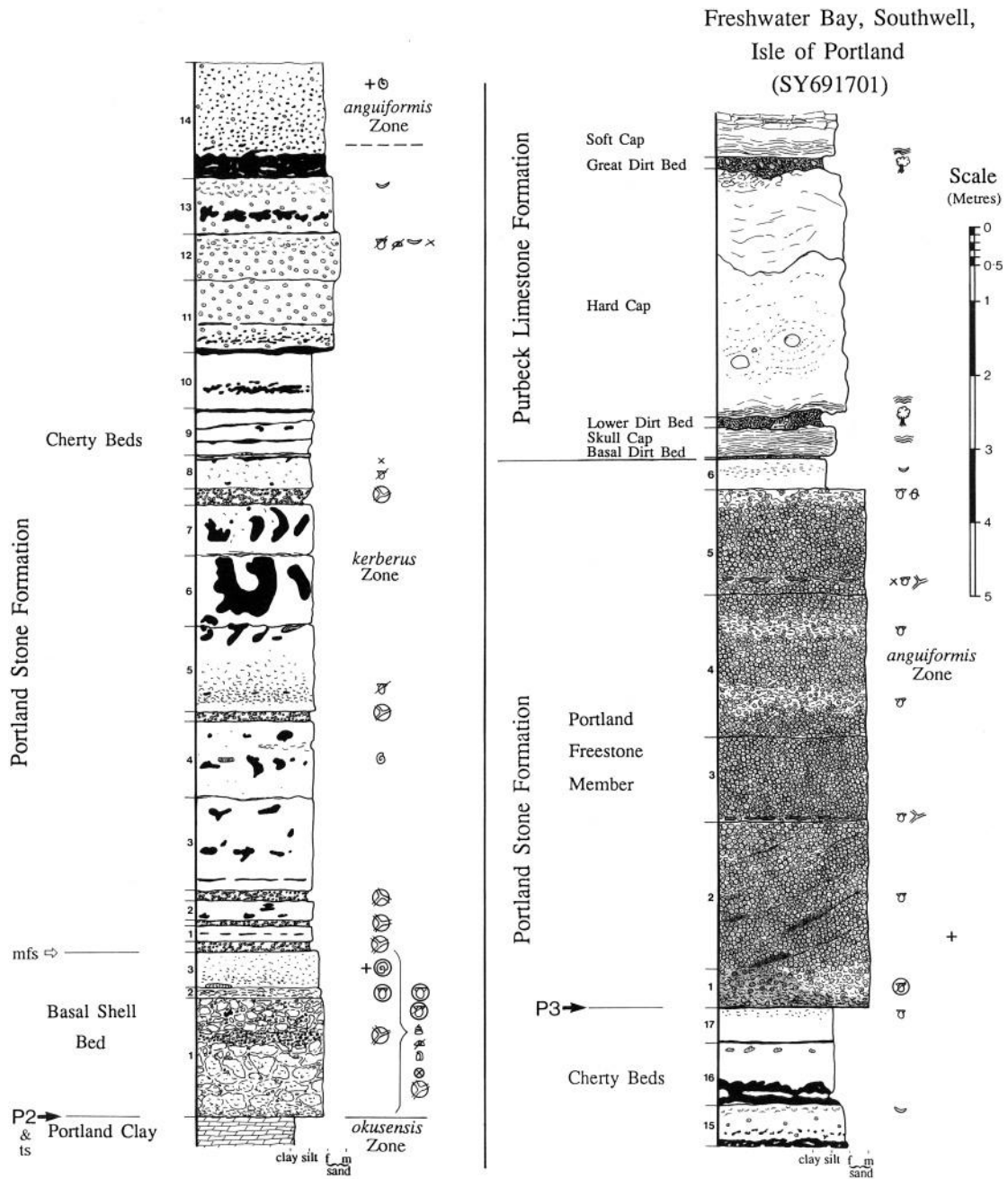


Figure 6.10 The published version of the graphic log from Freshwater Bay, Dorset including the data shown in Figure 6.9. (From Coe 1996.)

6.4 Rocks in space: Reconstructing sedimentary environments and their diagnostic features

A set of graphic logs in proximal and distal locations, together with sketches and other information, can be used to record and interpret the depositional environment(s) of the strata. The graphic logs should provide a summary of features to allow division of the succession into sedimentary facies (i.e. rock bodies with similar composition, texture, fossils and sedimentary structures that represent a particular set of processes and depositional conditions). Using Walther's Law, and knowledge of the different parts of depositional environments and the processes within them, the facies can be grouped together into architectural elements or facies associations. The construction of facies associations is particularly appropriate for depositional environments where there are large lateral changes, such as within a fluvial system. The elements of completing such a study are illustrated in Worked Example 6.2 (pp. 130–133).

For pilot projects, broad-scale regional studies or simply if time is short, generalized graphic logs recording the main sedimentary features to an approximate scale can be useful (e.g. Figure 6.11, p. 128). The advantage of this is that it is fast, allowing time to visit more locations and gain a better overview.

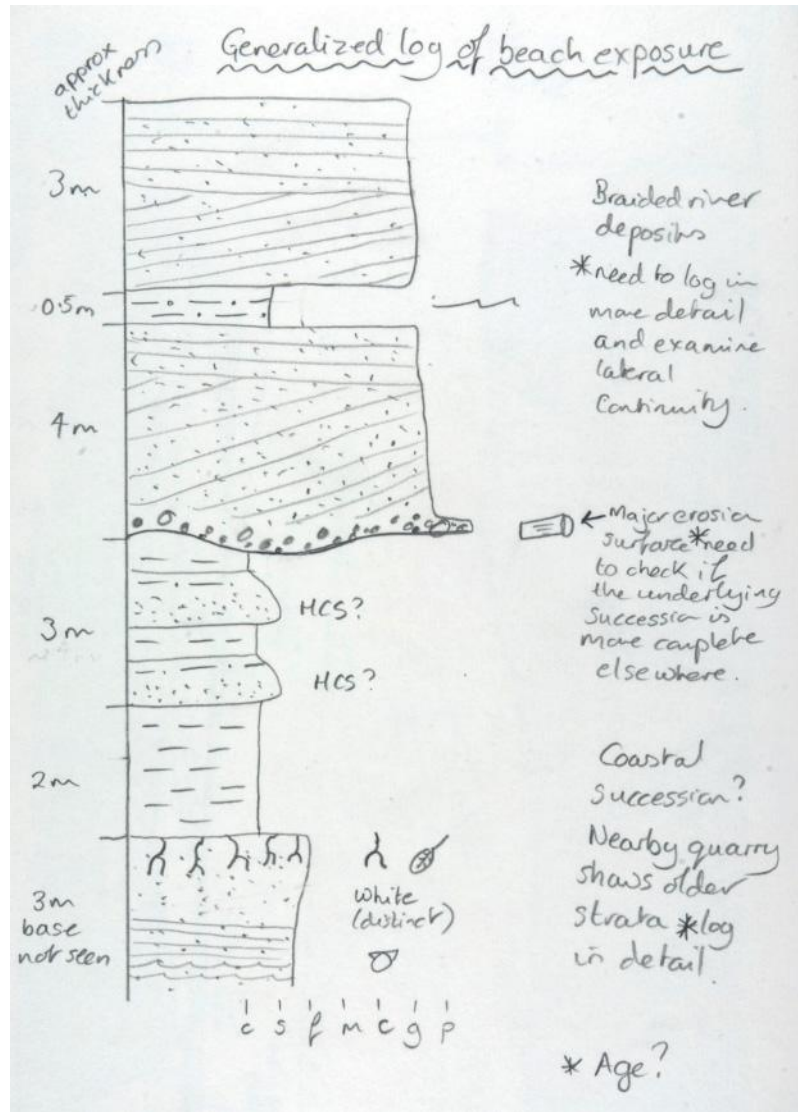
The benefit of carrying out facies analysis is that the facies patterns are then predictable and can be used to assess reservoir and source rock potential. In addition facies models underpin the interpretation of changes in relative sea-level, the establishment of stratigraphic gaps and can add to interpretation of long timescale changes in the climate, palaeolatitude and altitude.

Fine-grained hemipelagic and pelagic carbonate and siliciclastic successions tend not to vary for hundreds of metres or kilometres. Usually with this type of succession, because the variation in facies is so small, there is no need to define facies associations. The visual differences between facies in the field are often very subtle, but may well reflect large changes in parameters such as run-off, temperature and productivity.

In summary, facies analysis needs to consider the following.

- Is the area chosen for the graphic log and facies analysis representative?
- Are sections along a proximal to distal profile available (basin centre and basin margin)?
- Do the facies obey Walther's Law or not?

Figure 6.11 Example of a generalized graphic log from a field notebook incorporating, in part, the beds shown in Figures 6.4 and 6.6. (Angela L. Coe, The Open University, UK.)



- Are there key sedimentary structures and fossils that indicate relative water depth and/or processes of deposition (e.g. hummocky cross-stratification, non-marine fauna)?
- Are there any repetitions?
- Are there any large-scale features (e.g. river channels, intrabasinal highs, depocentres next to synsedimentary faults)?
- Is there lateral continuity of the facies and is the method of correlation robust?

A description of the typical facies in the range of possible sedimentary environments is beyond the scope of this book. A good summary is provided by Stow (2005) and most textbooks

on sedimentology (e.g. Section 6.6). Table 6.5 provides a list of some of the clues to look for when trying to decipher the depositional environment. The most robust interpretation comes from a wide range of evidence and no one set of observations should be taken in isolation. In addition, for coastal environments Appendix A6, Figure A6.14 shows the dominance of different processes and resulting variation in morphology.

Table 6.5 Summary of some of the processes/features and the sedimentary environments that they might represent. In all cases it is the combination of different lines of evidence that will help to determine the depositional environment.

Processes/ features	Possible environments
Water currents (current-formed ripples, cross-stratification, etc.)	Fluvial, lacustrine or marine
Waves (ripples, HCS, SCS, etc.)	Large standing body of water, i.e. large lake or the sea. Consider: lacustrine or marine environments (high water mark to wave base)
Large-scale cross-stratification	Aeolian, alluvial or movement of sand on the continental shelf or within an inlet by tides
Tidal features (e.g. mud-draped ripples, tidal bundles)	Marine environments near the coastline
Low diversity/brackish fauna	Restricted lagoon or estuary or coastal embayment
High diversity marine fauna	Shallow marine (or possible deep-marine condensed succession). Consider strandplain or delta or barrier island
Mainly or totally pelagic fauna	Deep marine (unless there is another factor to exclude benthic organisms such as evidence for anoxic conditions)
Abundance of fossilized plant remains	Delta or fluvial or possibly lacustrine
Numerous coals	Delta or aggrading fluvial system
Extensive evaporite deposits	Carbonate platform or lacustrine or aeolian
Fine-grained, laterally continuous beds over 100s km	Deep marine; pelagic/hemipelagic or large-scale lacustrine
Mass gravity features	Alluvial fan or submarine fan but also consider synsedimentary faulting and/or steep slopes such as at the edge of a carbonate platform
Wind features (frosted grains, large-scale high-angle cross-stratification, impact ripples)	Aeolian (but if the evidence is not laterally extensive consider backshore)
Cyclic successions	Any environment, but less likely to be regular in fluvial and aeolian
Turbidites	Anywhere in water where there is a slope of more than a few degrees. If they are extensive and associated with other deep-marine features and mass flow deposits, possible submarine fan. Carbonate turbidites will form off the edge of the carbonate platform due to the vertical build-up of reefs, etc.

Table 6.5 *Continued*

Processes/ features	Possible environments
Ooids, peloids, abundant bioclasts or bioherm/biostrome	Part of a carbonate platform. Consider position and distribution of different facies to determine the type of carbonate platform (ramp, rimmed shelf, isolated, etc.)
Sedimentary deposits of highly variable composition	Consider submarine and alluvial fans, glacial environments
Ice features (e.g. dropstones, glacial striations, hummocks, eskers)	Glacial environments
Large-scale lensoid sand bodies encased in fine-grained deposits	Meandering fluvial system or part of a submarine fan complex

Worked Example 6.2 Meandering river depositional environment: Burniston, Yorkshire, UK

Figure 6.12 shows the interbedded mudstones and sandstones exposed near Burniston, Yorkshire, UK. These sedimentary rocks form part of the Long Nab Member and are Middle Jurassic in age. The sea-cliffs and foreshore together provide an opportunity to record the three-dimensional nature of these laterally variable sedimentary deposits. Many publications have been written on these deposits and the material presented here shows only some of the findings. The research that was conducted on these deposits was of particular interest not only for understanding the architecture of a meandering river system, but also because it provided an analogue for petroleum reservoir rocks in the North Sea, offshore UK.

The deposits at this exposure require a combination of different techniques because of their variable nature. These include the construction of sets of graphic logs with the positions of the logs carefully chosen so that they recorded the overall variability, mapping of the geometry of the sandstone bodies using aerial photographs of the foreshore at low tide (Figure 6.13) and sketching the geometry of the sand bodies. From these observations a facies model could be constructed (Figure 6.14).

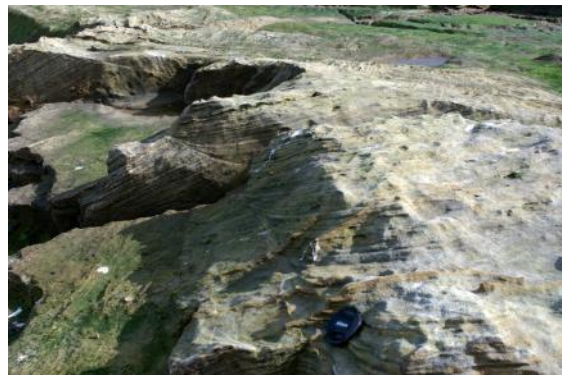
Figure 6.12a illustrates a typical view of these (and other) meandering river deposits with a

lensoid sandstone body (the river channel fill) encased in floodplain mudstones. The sand to clay ratio will vary with the energy of the river, sediment source and its proximity to the centre of the channel. Figure 6.12b shows a tabular cross-stratified quartz arenite that is interpreted to have been deposited as a subaqueous sand bar near the centre of the fluvial channel. Figures 6.12c and 6.12d show the lensoid point bar that is laterally equivalent to this channel sand bar. The succession also contains thin, fairly laterally continuous, sandstones with rootlets (Figures 6.12e). This distinctly different sandstone facies represents crevasse-splay deposits. Some of these sandstones have gutter casts at the base (Figure 6.12f) from which palaeocurrent measurements could be taken to ascertain the orientation of the channel. Figure 6.12g shows an abandoned channel filled with plant-rich mudstones. It probably represents the sediment fill of a small ox-bow lake.

In addition to the sedimentological interest the low-energy overbank environment provided ideal conditions for the preservation of plant fossils. Plant fossils from these deposits have been used to reconstruct the Jurassic vegetation at that time and to gain an understanding of the climatic regime (Figure 5.14, p. 98).



(a)



(b)



(c)



(d)



(e)

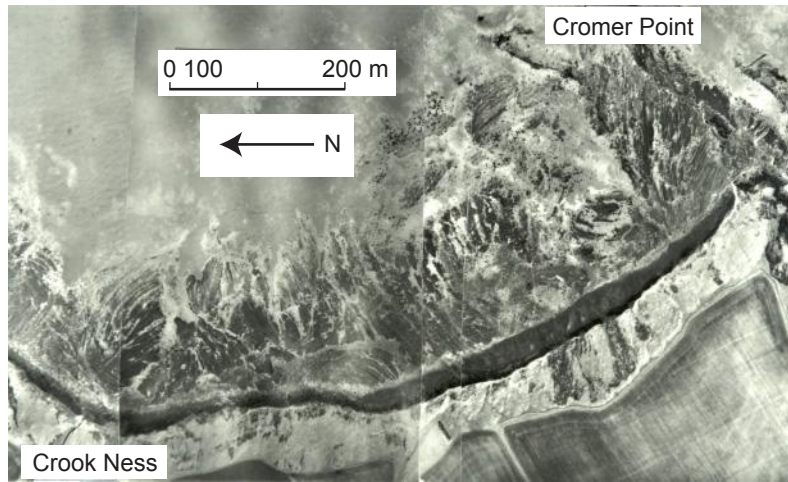


(f)

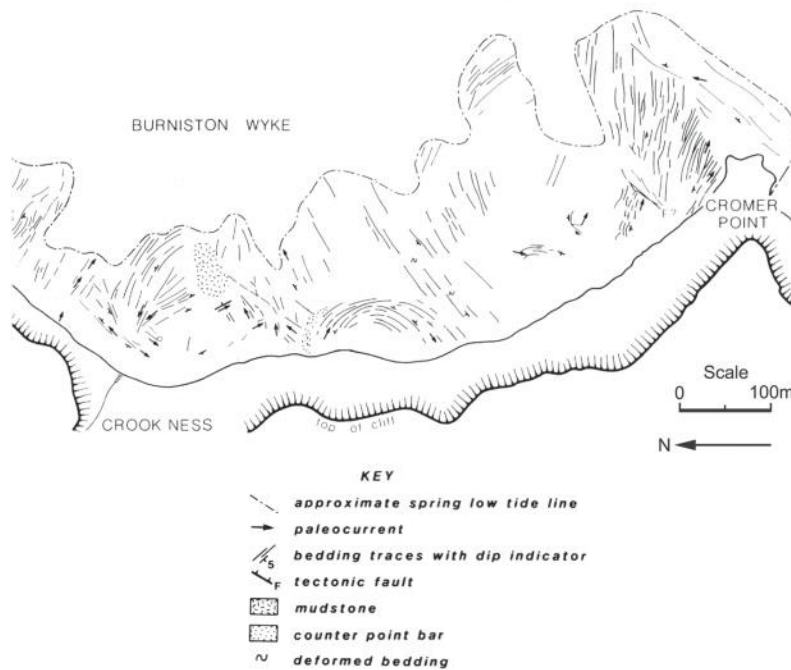


(g)

Figure 6.12 Photographs of the exposure near Burniston, Yorkshire, UK, showing the highly variable nature of the deposits. (a) General overview showing a channel sand body encased in floodplain mudstones. (b) Trough cross-stratified clean sandstones of the river channel. (c and d) Cross-cutting nature of a point bar. (e) Roots in a crevasse-splay sandstone facies. (f) Gutter casts at the base of the crevasse-splay sandstone. (g) Interbedded mudstones and sandstones interpreted as overbank deposits and crevasse splays. The dark-grey bed is a plant-rich mudstone interpreted as an ox-bow lake sediment plug. (a–g: Angela L. Coe, The Open University, UK.)

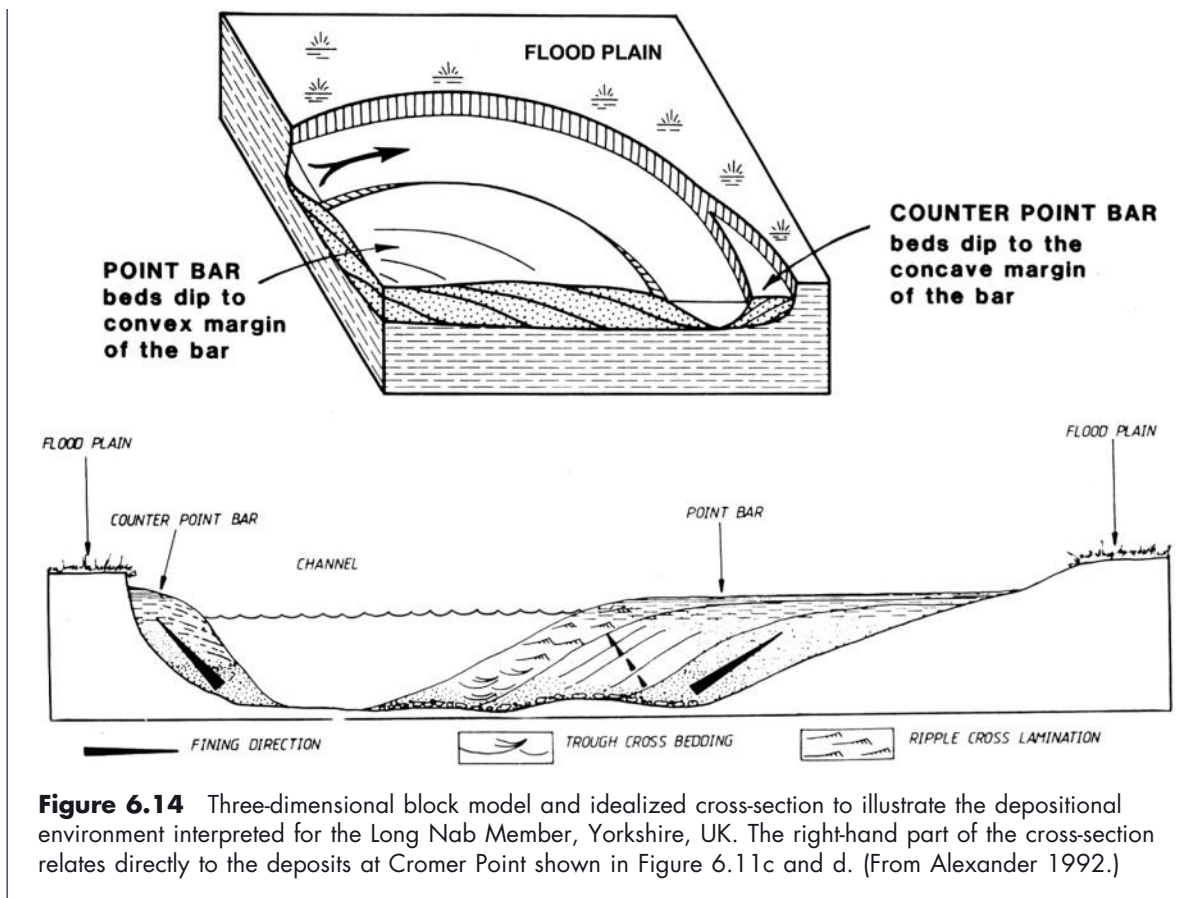


(a)



(b)

Figure 6.13 (a) Extract of part of an aerial photograph of the foreshore at Burniston, Yorkshire, UK and (b) part of a line drawing showing the foreshore in (a) with the distinct curved features interpreted as point bars and counter point bars. (From Alexander 1992.)



6.5 Using sedimentary rocks to interpret climate change and sea-level change

Marine and lacustrine sedimentary records are unique because below storm wave-base in the oceans and in lakes sedimentation can be fairly continuous over hundreds of thousands and even millions of years. This continuous record can be correlated with the usually less complete nearshore and terrestrial records. Together these sedimentary records enable us to collect information on how the Earth's surface environment has progressively changed over time. The processes that occur on the land surface and near-shore environments affect those in the ocean. The position of sea-level influences both land and ocean processes because

changes in topography or sea-level will cause the system to change its equilibrium profile. By piecing together evidence from terrestrial, shallow-marine and deep-marine successions deposited at the same time we can gain a more complete understanding of Earth processes.

6.5.1 Climate change

Long-term climatic indicators include the presence or absence of the following: coals, evaporites, palaeosols, plant megafossils (Chapter 5), palynomorphs, foraminifers, diatoms, corals and particular animal taxa that are latitudinally dependent. Three main types of sedimentary rock are used to study and construct short-term changes in climate through time : (1) fine-grained marine sedimentary rocks deposited on the continental shelf below storm wave-base or in the deep ocean; (2) fine-grained lake deposits; and (3) other non-marine deposits such as fine-grained wind-blown sediment (loess) and cave deposits. These deposits are used because in general sedimentation is continuous and fairly constant so they contain a fairly unbroken record of past changes. Sedimentary deposits of the same age can be used to determine, for example, the temperature gradient over latitude or altitude. Because the climate affects the chemistry and biota of the rocks laid down, a range of geochemical proxies (e.g. C-, O-, Sr- and Os-isotopes, Mg/Ca ratios and CaCO₃ content) has been developed to obtain an indication of the changes in the climatic variables. Sections 6.2.1 and 13.1.3 provide information on obtaining a record from this type of succession for these purposes.

6.5.2 Sequence stratigraphy and relative sea-level change

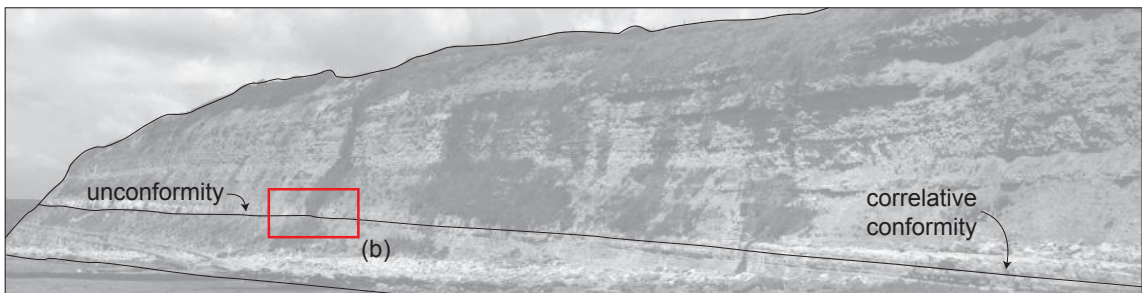
The facies patterns, unconformity surfaces, geometry and preservation of many shallow-marine and non-marine sedimentary rock successions can be used to interpret changes in relative sea-level. This works particularly well when it is possible to correlate, with certainty, between shallow-marine and deep-marine facies and even into non-marine successions across sedimentary basins or wide regions. Sequence stratigraphy provides a conceptual model for the detection of past changes in relative sea-level change by predicting the geometry and composition of sediment packages and surfaces that form during a single cycle of relative sea-level change. Sequence stratigraphic analysis is used widely to predict facies distributions, to examine the sea-level history over a period of time, to understand the genesis of the rock succession and predict where gaps and condensed sections may be present. For

the theory of sequence stratigraphy and examples of its application see suggested further reading in Section 6.6. Listed below is the typical data set and general methodology for a sequence stratigraphic interpretation.

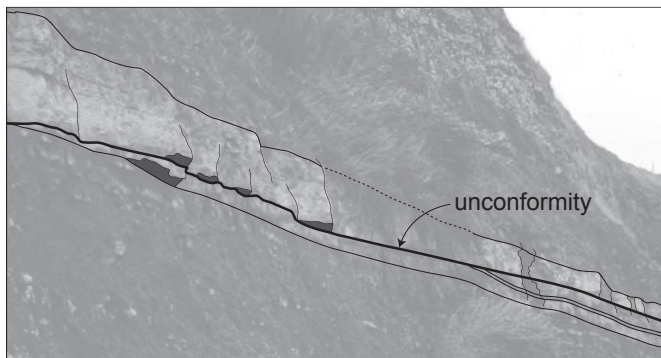
1. Record the vertical and lateral changes in the sedimentary succession along a proximal to distal profile of the depocentre. This is usually done through the graphic logs of exposures and/or seismic sections and borehole information. The sedimentological and palaeontological data all need to be integrated.
2. Incorporate any other published information (e.g. evidence for subaerial exposure, biostratigraphy, fossil assemblages).
3. Interpret the facies in terms of facies models so that it is obvious where facies that are juxtaposed obey Walther's Law and where they do not.
4. Construct, or integrate into the data set from the literature, a robust 100 thousand year to million year resolution relative timescale for each of the sections to enable correlation.
5. Identify patterns and repetitions within the succession with a view to interpreting the parasequences, their stacking patterns and the systems tracts. The transgressive systems tract is unique in containing retrogradational parasequences so this is sometimes the easiest systems tract to identify.
6. Identify major unconformity surfaces (one or more sequence boundaries) and trace them laterally in a distal direction to find the correlative conformity. Identify condensed sections that might represent the maximum flooding surfaces and the transgressive surfaces.
7. Integrate the data on the sediment packages and key surfaces in order to construct a sequence stratigraphic interpretation identifying all of the systems tracts and key surfaces.

Examples of sequence stratigraphic interpretations are beyond the scope of this book but Worked Example 6.3 (pp. 136–137) illustrates data collection along a sequence boundary and Worked Example 6.1 (pp. 124–126) also shows some sequence stratigraphic interpretation. More extensive examples in a range of depositional settings can be found in Coe (2003), Emery and Myers (1996) and Catuneanu (2006).

Worked Example 6.3 Set of photographs and sketches to illustrate a key sedimentary contact



(a)



(b)

Figure 6.15 (a) Photomontage of the cliff at Bran Point, Osmington Mills to show the erosive nature of the unit near the middle of the cliff and line drawing showing the erosive surface. Inset box shows position of (b). (b) Detail of the downcutting from near the middle of the section and line drawing showing the truncation. (a and b: Angela L. Coe, The Open University, UK.)

The sea-cliffs at Osmington Mills, near Weymouth, Dorset, UK show a marked facies change from micritic limestones (biomicrite) to oolitic grainstones (oosparite). The base of the oolitic grainstone facies is erosional and down-cuts towards the west. The objective of this field exercise was to gather evidence for the erosive nature of the contact and to interpret its possible origin. The photographs show both an overview (Figure 6.15a) and a close up view along the section (Figure 6.15b). Accompanying sketches

or line drawings (Figure 6.15) can be used to show the large-scale geometry of this important surface. A graphic log was constructed (Figure 6.16) where this section was interpreted to be at its most stratigraphically complete. This erosive contact has been interpreted as a sequence boundary on the basis of the erosion at this location, and others across the basin, together with evidence from sections in the Cleveland Basin to the north, where there is also a sharp facies change.

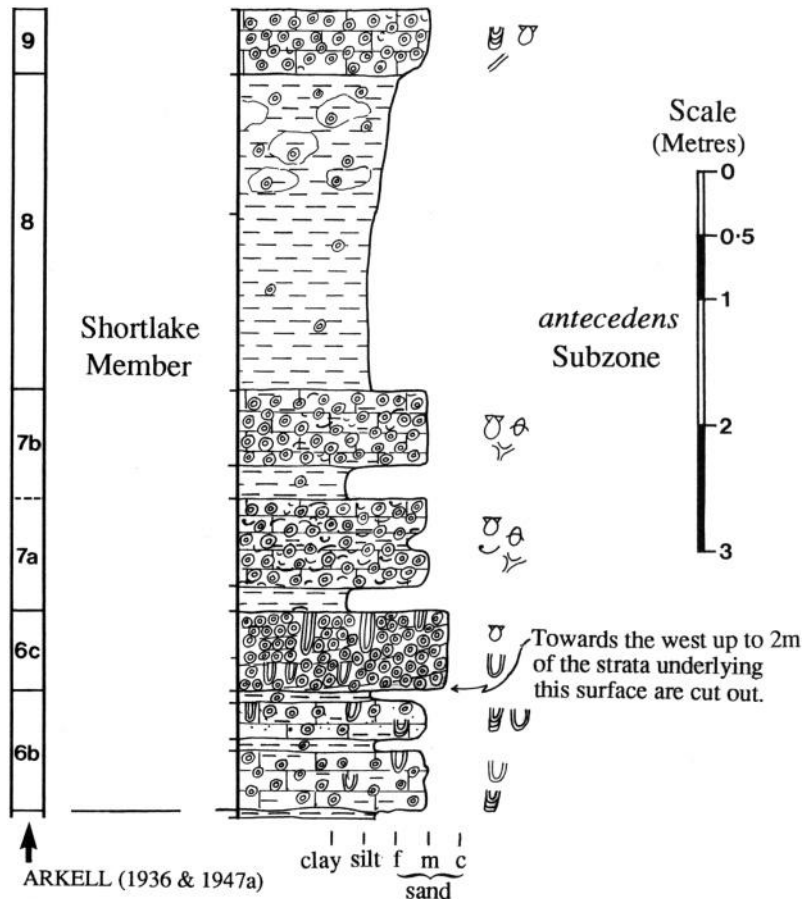


Figure 6.16 Extract from a published graphic log of the most complete part of the succession across the sedimentary contact shown in Figure 6.15. (From Coe 1995.)

6.6 Further reading

Alexander, J. 1992. Nature and origin of a laterally extensive alluvial sandstone body in the Middle Jurassic Scalby Formation, *Journal of the Geological Society, London*, **149**, 431–441. [Summary paper of the Middle Jurassic succession described in Worked Example 6.1]

- Catuneanu, O. 2006. *Principals of Sequence Stratigraphy*, Elsevier, 375 pp. [In-depth coverage of a wide range of sequence stratigraphy models.]
- Coe, A. L. 2003. *The Sedimentary Record of Sea-level Change*, Cambridge University Press and The Open University, 287 pp. [Textbook on sequence stratigraphy.]
- Collinson, J., Mountney, N. & Thompson, D. 2006. *Sedimentary Structures*, Terra Publishing, 292 pp.
- Emery, D. and Myers, K. 1996. *Sequence Stratigraphy*, Blackwell Science, 304 pp. [The first comprehensive textbook on sequence stratigraphy. Wide coverage of subsurface data.]
- Miall, A. D. 2010. *The Geology of Stratigraphic Sequences*, Springer, 480 pp. [In-depth textbook on sequence stratigraphy and various controversies.]
- Nichols, G. 2009. *Sedimentology and Stratigraphy*, Blackwell Science, 432 pp. [Good book covering the basics of sedimentology and stratigraphy.]
- Parish, J. T. 2001. *Interpreting Pre-Quaternary Climate from the Geologic Record*, Columbia University Press, 348 pp. [Excellent reference text on interpreting climate change from the geological record.]
- Prothero, D. R. and Schwab, F. 2003. *Sedimentary Geology*, W. H. Freeman, 600 pp.
- Stow, D. A.V. 2005. *Sedimentary Rocks in the Field*, Manson Publishing, 320 pp. [Excellent in-depth textbook on describing sedimentary rocks in the field. Richly illustrated with 425 colour photos of sedimentary features and many useful summary tables.]
- Tucker, M. E. (ed.) 1988. *Techniques in Sedimentology*, Blackwell Scientific Publications, 404 pp. [Chapter 2 is devoted to field techniques.]
- Tucker, M. E. 1991. *Sedimentary Petrology*, Blackwell Scientific Publications, 260 pp. [Long running and very popular textbook on sedimentology.]
- Tucker, M. E. 2003. *Sedimentary Rocks in the Field*, Blackwell Scientific Publications, 244 pp. [Well respected book now in its 3rd edition summarizing sedimentary rocks and how to record them in the field.]

7 Recording features of igneous rocks

David A. Rothery

The study of igneous rocks in the field relies on many of the skills already established in this book. Modern volcanic eruptions are well documented and some individuals have been privileged to have experienced one, but most igneous processes lie further from the realm of commonplace experience. Nobody has actually seen a granite intruding into its country rock, or witnessed a pyroxene crystal growing within a magma, so these processes are impossible to observe directly. Thus, it is crucial to make field observations in the light of general understanding of igneous processes, backed up by laboratory studies.

The main reasons to study igneous rocks are to: (1) understand volcanoes and the hazards they pose to life on Earth; (2) understand processes beneath the Earth's surface that drive plate tectonics and that contributed to the evolution of Earth and other planetary bodies; (3) understand the distribution of ore minerals; and (4) for chronology.

7.1 Equipment, basic tips and safety

If igneous rocks that you intend to study are in contact with other rock types, you should carry the basic equipment for general geological fieldwork listed in Table 2.1 (p.4). For igneous rocks a geological hammer is usually important so that you can obtain a fresh surface to examine the mineralogy. Additions and refinements for working on active volcanoes and young lava surfaces are discussed in Section 7.4.

Depending on the nature of your field project, you may already know (or suspect) that the rock at a particular locality is igneous. When visiting an *unknown* exposure, you first need to form at least a working hypothesis as to which parts of it are likely to be igneous, as outlined in Section 3.2. Confirmation, or revision, will come from observations of field relationships (Section 7.2) and also of mineralogy and texture (Section 7.3). It is good to explore field relationships early, but it is usually

worth making a preliminary assessment of mineralogy and texture (to confirm that you are indeed looking at what you think you are!) before studying the field relationships in detail.

7.2 Field relationships of igneous rocks

This section is concerned with studying igneous rocks exposed by natural erosion or quarrying. Active volcanoes and young lava flows that retain exposed original surface morphology (up to tens of thousands of years in arid regions) offer different opportunities and are discussed in Section 7.4.

7.2.1 Relationships with surrounding rocks

The most fundamental attribute of a body of igneous rock, and one that you should try to ascertain as soon as you can, is whether it is intrusive (e.g. Figure 7.1) or extrusive. You may wish to classify an intrusion according to the scheme given in Appendix A7, Table A7.1, but more important than this is to try to deduce how it was emplaced, based on as wide a variety of evidence as you can assemble.

Figure 7.1 A dyke of Cenozoic age cutting discordantly across complexly folded wackes (Augrim quarry, Co. Down, Northern Ireland). The dyke is the 2-m-wide reddish feature, passing nearly vertically up the rock face behind the person in the foreground. (Richard Warner, British Geological Survey and Donald Fay, Open University Geological Society, UK.)



If you can see an exposed contact between the igneous rock and the adjacent rock (which might also be igneous), then simple observation may make it apparent that the edge of your igneous body cuts across the fabric of the neighbouring rock (Figures 7.1 and 8.22b). If so, then this discordant nature of the contact points very strongly to an intrusive relationship. If the shape of the contact is complicated (Figure 7.2) this would be very clear evidence for discordance, but some discordant contacts look straight (or nearly planar if they can be determined in three dimensions). In such a situation you need to rule out the alternative possibility that the two rock units have been brought into contact by a fault (Section 8.2).

Weathering, soil and vegetation sometimes conspire to make intrusive contacts, especially into sedimentary rock, frustratingly poorly exposed. Crucial details may be hidden, so that the geometric relationship between the intrusion and country rock cannot be easily assessed. In such a situation, comparing your best estimate of the strike and dip of the contact with the strike and dip in nearby exposures of country rock is a useful pointer. Unless the two planes are similar, the contact must be discordant (or a fault). You will need to judge how close ‘similar’ needs to be according to your particular circumstances. Factors to bear in mind include:

- If the contact is poorly exposed your best estimate of its attitude could easily be wrong by more than 10° either way.
- You can often measure the strike and dip of sedimentary bedding at any one place to better than $\pm 5^\circ$, but is that representative of the local average strike and dip?
- Attitude may vary locally because of folding, so how far apart are the measurements that you wish to compare?

Table 7.1 (p.142) suggests how to pin down a contact that is unexposed, but manifested because of differences in resistance to weathering and erosion, in chemistry, or in permeability between an igneous body and its country rock.

Having established the geometry of the edge of your discordant intrusion, you should ask yourself ‘where is its other edge?’. This is easy if you are dealing with a narrow curtain of intrusive rock (a dyke) because these are mostly less than a couple of metres wide. Except in very poorly exposed regions, if you can see one edge of dyke you can usually see its other edge (Figures 7.1 and 7.3). A pipe-like volcanic neck will be typically tens of metres across, but if you are at the margin of a pluton the other side may be many tens of kilometres away. Coarse grain size, and lack of chilling at the contact, are good clues that you are dealing with a pluton (Section 7.3).

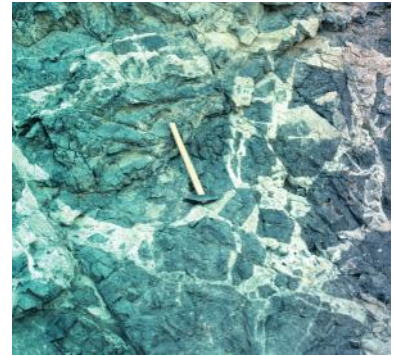
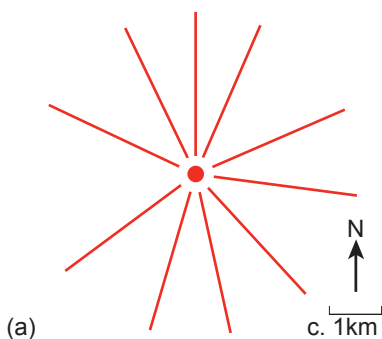


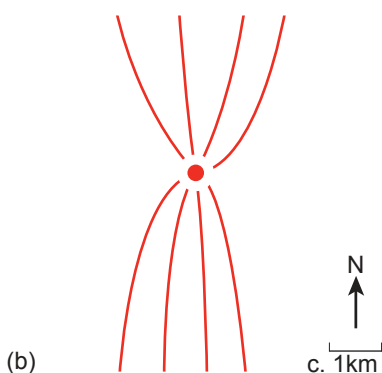
Figure 7.2 A complicated intrusive contact between a pale intrusive rock and a darker country rock (Oman, Arabia). In this example, the intrusive rock (here a plagiogranite or trondhjemite) has made space for itself by the process known as ‘stoping’, in which blocks of the country rock (dolerite, in this case) are plucked away and engulfed within the intrusion (where they may then become assimilated). (David A. Rothery, The Open University, UK.)



Figure 7.3 A near-vertical dyke cutting bedded sedimentary rocks (Howick Bay, Northumbria, UK). Both edges (margins) of this 1-m-wide dyke are clear. (Angela L. Coe, The Open University, UK.)



(a)



(b)

Figure 7.4 Schematic plan view of the possible outcrop pattern of radial dykes around a volcanic centre: (a) in the absence of regional stress and (b) with east–west extension.

Table 7.1 Possible landscape clues to the location of an unexposed contact.

Aspect	Possible features
Topography	Break in slope; trough (or ridge); general change in landscape
Weathering	Contact may weather back and erode more than average
Vegetation	Change in type (related to soil chemistry) or lushness (related to drainage) across contact

It is often particularly informative to measure strike and dip of discordant contacts, especially if there are other examples in the area. Measurement principles are the same as those laid out in Section 2.3.1. When it comes to making a map (Chapter 10), an obvious example is the strike and dip pattern of dykes, which will tell you whether you are dealing with a generally parallel dyke swarm, or radial dykes coming from a common centre (Figure 7.4), or cone sheets (circular or elliptical in outcrop pattern but dipping inwards) or ring dykes (similar but dipping outwards; Figure 7.5). If the edge of your igneous rock body lies parallel to the stratification of the country rock (a concordant contact), then it may be extrusive (lava) or a layer of pyroclastic rock. However, it could still be intrusive.

Intrusions into foliated metamorphic rock commonly exploit the foliation, though in places they can sometimes be seen to cut across it discordantly. In a migmatite, the leucosomes (layers or lenses of sweated-out igneous material) form coevally with the overall fabric, and so are generally concordant.

If you suspect that a concordant contact may be the top or bottom of a sill (Figure 7.6), you should try to find the opposite contact. Sills are tabular bodies, typically intruded between beds of horizontal (or gently dipping) strata. Although they may extend horizontally for tens of hundreds of kilometres, most sills are only a few tens of metres thick, so the evidence needed to confirm the concordant nature of both contacts may not be far away.

When an intrusion is emplaced into wet, poorly consolidated, sedimentary rocks, then water–rock reactions can lead to margins that are locally brecciated, unlike the almost planar contact in Figure 7.6. This texture is called peperite, and may look like an inverse version of a stoped contact (such as Figure 7.2), having angular lumps of igneous rock enclosed within the country rock instead of angular fragments of country rock enclosed within the igneous rock.

It can be particularly tricky to distinguish a sill from a lava flow, but you will be in less doubt if you can see (or deduce

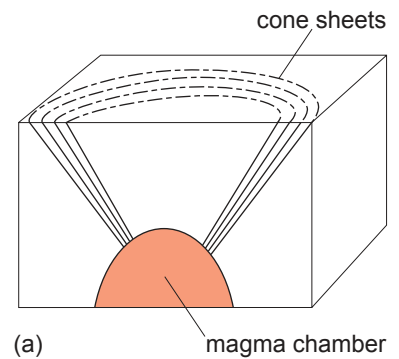
BEWARE! A concordant contact must be parallel to the stratification of the country rock in three dimensions, so be sure that you are not misled by looking only at one surface in a specific orientation.

from mapping) a place where either the top or the bottom of the sill steps up or down the stratigraphy (Figure 7.7, p. 144). A lava flow cannot do this (but beware of a lava flow emplaced unconformably onto a tilted and eroded sedimentary succession; Figure 7.7b). You should be alert for such local discordances in a sill. These may give clues to the large-scale shape of the body; in particular, major sills intruded into sedimentary deposits tend to be saucer shaped, by virtue of discordant steps that allow them to be both thicker and deeper towards their centres.

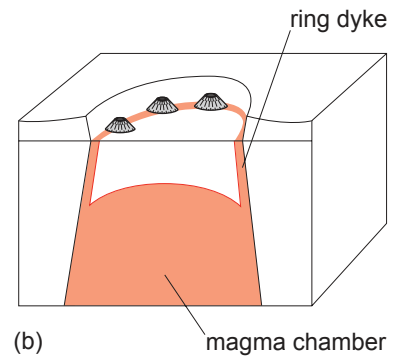
A lava flow may be emplaced over a previously weathered surface, and in turn its top may have been weathered before it became buried by a subsequent lava flow or by a pyroclastic or sedimentary deposit. Although a sill may be intruded along a previously weathered horizon, the top of the sill itself cannot become weathered (except if it is subaerially exposed sometime after intrusion). Therefore, a weathered (typically reddened, maybe even developing into soil) top to a concordant igneous sheet is strong evidence that it is a lava flow.



Figure 7.6 The base of a sill (Teesdale, Co. Durham, UK). Buff coloured fine-grained sandstones occur below the level of the person's shoulder. The base of the sill is not actually in the obvious recess at head-height where, especially on the weathered surface, the colour changes. This is a thin siltstone layer overlain by a further c. 1 m of sandstone. Close study in the field with the aid of a hand lens reveals that the base of the sill is at the level indicated by the arrows. (David A. Rothery, The Open University, UK.)



(a) magma chamber



(b) magma chamber

Figure 7.5 Block-view of (a) cone sheets and (b) a ring dyke, showing their typical outcrop pattern and relationship to a magma chamber (which would solidify to form a pluton). The ground surface shown in (b) has not yet been eroded, and the circular depression bounded by the ring dyke is a volcanic caldera.

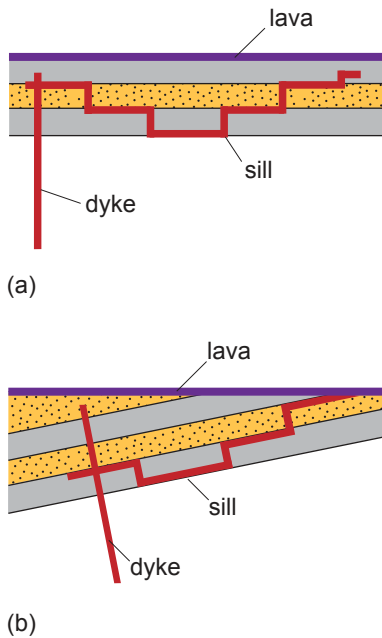


Figure 7.7 (a) Sketch cross-section showing the typical relationship between a sill (in this example fed by a dyke on the left) and horizontal strata intruded by it. The sill is generally concordant, but is locally discordant where it steps up or down between strata. The lava flow is concordant. (b) As (a) but in this case the strata into which the sill and dyke were intruded have been tilted. At a later date lava flowed over the area. In this case the lava flow is discordant.

Other ways to distinguish between lava flows and sills depend on medium- and large-scale textural features, which we here refer to as ‘internal architecture’ to avoid confusion with crystalline, petrographic texture (Section 7.3).

7.2.2 Internal architecture: Joints and veins

The pattern of jointing in a flow can be used to deduce its cooling and crystallization history (it may also tell you about the local palaeotopography), and should be documented by sketches or photos of both vertical and horizontal faces.

The most obvious kind of ‘internal architecture’ characteristic of some igneous rock bodies is columnar joints, which are generally attributed to thermal contraction during cooling. Columnar joints develop perpendicular to the cooling surfaces of tabular igneous bodies. This can happen in dykes (Figure 7.8), in which case the columns are horizontal when they form, but columnar joints tend to be much better developed in sills and in thick (>5 m) lava flows that formed extensive, evenly cooling, sheets (Figure 7.9). They can also be found in some welded ignimbrite deposits, which were very hot when emplaced and cooled in a similar fashion.

Lava-flow columnar joints can form a monotonous pattern of vertical columns called a ‘colonnade’ in the lower third to half of a flow (where cooling tends to be slowest and most uniform), above which there is usually a sharp change to more slender columns with a less well-ordered orientation. This zone, called the ‘entablature’, may persist almost to the flow top, or there could be an upper colonnade. Colonnade columns are between 0.3 m and 2 m wide, but within a single colonnade the range of widths is much more limited.

Unlike within lava flows, columnar jointing in sills rarely if ever develops into an entablature. Another distinguishing feature of sills is that their colonnade joints may penetrate a metre or two above and below the sill into the country rock, which was heated by the intrusion and then cooled with it. Columnar jointing is apparent in the sedimentary rock below the sill in Figure 7.6 (p. 143), but the evidence in this one photograph is insufficient to prove that this is a sill because columnar joints can also penetrate into country rock below a thick lava flow.

Plutons can have joints too. If you find ore minerals or zeolites coating joint surfaces, this is a clue that the joints formed during cooling, when aqueous magmatic fluids were still circulating.

Joints in igneous rocks are not necessarily open fractures; they may have been completely filled by crystallization of an



(a)



(b)

Figure 7.8 Columnar joints developed perpendicular to the margin of a near-vertical dyke, Hvalfjörður, Iceland. (a) General view. (b) Close-up. Coin for scale. (David A. Rothery, The Open University, UK.)



Figure 7.9 The Fingal's Cave flood basalt on Staffa, Inner Hebrides, Scotland. The cliff is nearly 40 m high. The base of the flow is the thin, slightly rubble horizon at the bottom of the columns (at the roof of the cave). Columns are remarkably regular in the colonnade forming the lower 15 m of the flow, above which the joints of the entablature are more closely spaced and fan out into a variety of orientations. The original flow was probably virtually horizontal, but has been tilted by about 3° to the east (right). (David A. Rothery, The Open University, UK.)

Table 7.2 Distinguishing characteristics of veins in igneous rock.

Type of vein	Description	Significance
Pegmatite	Coarse crystals, mineralogy similar to or more felsic than the host rock, may also contain large crystals of exotic minerals such as apatite, tourmaline, beryl	Crystallization of last, volatile-rich, fraction of the magma. If zoned (mineralogy in the middle differing from the edges), this indicates evolving chemistry as the joint expanded
Aplite	Fine-grained, sugary, felsic veins, common in granites	Crystallization of last fraction of silica-rich magma, possibly triggered by sudden escape of volatiles when joints were initiated
Hydrothermal vein	White quartz or calcite, sometimes containing metallic sulfides, epidote or fluorite. Sometimes the wall-rock is altered, but little or no material is precipitated. Tendency to penetrate further into country rock than other veins	Chemically charged aqueous fluids, circulating between igneous body and country rock. Could reflect hydrothermal circulation as a pluton cools, or could be younger and unrelated



Figure 7.10 A wave-eroded exposure cut into the colonnade of the Fingal's Cave flow (about 200m to the right of Figure 7.9). Note the clear shapes of the columns. (David A. Rothery, The Open University, UK.)

Just because you *can* measure something, doesn't mean that the measurement will actually be *useful*. Don't let yourself be distracted from scientific observation into collecting a large number of easy-to-make measurements unless you can foresee a use for them.

aqueous or late-stage magmatic fluid to form veins. Veins in igneous rocks may be much younger than their host, as they can be in any rock type, so it is important to try to determine the significance of any veins that you find. Table 7.2 summarizes distinguishing features.

It is often very easy to determine the strike and dip of individual joints, and in situations such as those shown in Figures 7.8 and 7.10 a large number of measurements could be made. However, you need to consider whether this is necessary and what the aim of collecting all these data might be. Beware also that some joints, or sets of joints in certain orientations, may result from tectonic process or release of confining pressure during exhumation, and therefore be irrelevant to the igneous history of your exposure.

7.2.3 Internal architecture: Other exposure-scale fabrics

Other features to seek out and record in ancient lava flows include:

- *General morphology and texture.* Are there any pillows (indicative of eruption into water or under ice)? Is there a rubbly top or base, suggesting emplacement on land as an 'a'a (Figure 7.11). Are there glassy 'hyaloclastite' fragments above or below, or a peperitic base (also indicating water)? If you find a peperitic top, this cannot be a lava flow; it must be a sill intruded into wet sediment.

- *Flow architecture.* Did the flow arrive in place with the full thickness you now see, or was it ‘inflated’ by a series of pulses? Look for signs internal to the flow bearing on this matter, but also study the flow top. If you can find either pahoehoe texture or several-metre-high mounds that may have been tumuli, then the flow probably grew by inflation, implying a relatively slow but prolonged effusion rate.
- *Vesicles.* Concentrations or layers of vesicles within a flow (Figure 7.12) may record pauses in inflation of the flow. Non-spherical vesicles may indicate either shearing during flow or later flattening. Vesicles in general, especially if concentrated towards the top, are a good indicator of a lava flow rather than a sill. Mineral infill of vesicles (turning them into amygdales) is a consequence of post-emplacement fluid percolation. Identifying these minerals may help to define metamorphic grade (Section 9.3).

Vesicles in lava and in volcanic bombs can preserve a record of the history of bubble nucleation and expansion in the magma (e.g. Worked Example 7.1, p. 148). This may have occurred in several stages (e.g. during ascent, during storage at depth, during ejection from the vent, after emplacement). In the field, use your eyes and brain to weigh up the possible information conveyed by vesicles, but be aware that thorough analysis of the size distribution of bubble populations requires measurements in the laboratory (based on measuring large numbers of bubbles, often in thin-section).

Lava flows too thin to develop columnar jointing tend to have a massive interior but sometimes a rubbly base. In basalts, the top will be especially rubbly if the flow was emplaced as an ‘a’a (Figure 7.11). If emplaced as pahoehoe, it may be possible to find distinctive relicts of pahoehoe lobes or ropes on the upper surface. A thin flow is unlikely to pass from subaqueous to subaerial, so if there are pillows the whole flow is probably subaqueous (Figure 7.14, p. 149), a definition which includes eruption under ice.

Chilling and chilled margins

A minor intrusion such as a dyke or a sill is likely to have been emplaced at a fairly shallow depth into relatively cold country rock. You should therefore expect to find its grain size decreasing close to the contact, forming a ‘chilled margin’.

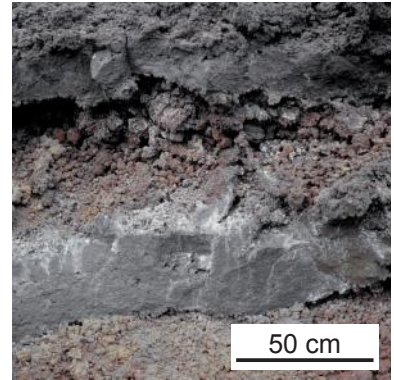


Figure 7.11 The side of a road-cutting exposing the massive interiors and rubbly tops of ‘a’a flows in Hawaii. (David A. Rothery, The Open University, UK.)



(a)



(b)

Figure 7.12 Vesicles within an ‘a’a lava flow, seen in cross-section. (a) General view, showing how vesicles become larger towards the top of the flow. (b) Close-up within the grey, central, part of the flow revealing that millimetre- and centimetre-scale vesicles are very abundant. Mount Etna, Italy. (a and b: David A. Rothery, The Open University, UK.)

Worked Example 7.1 Impact vesiculation

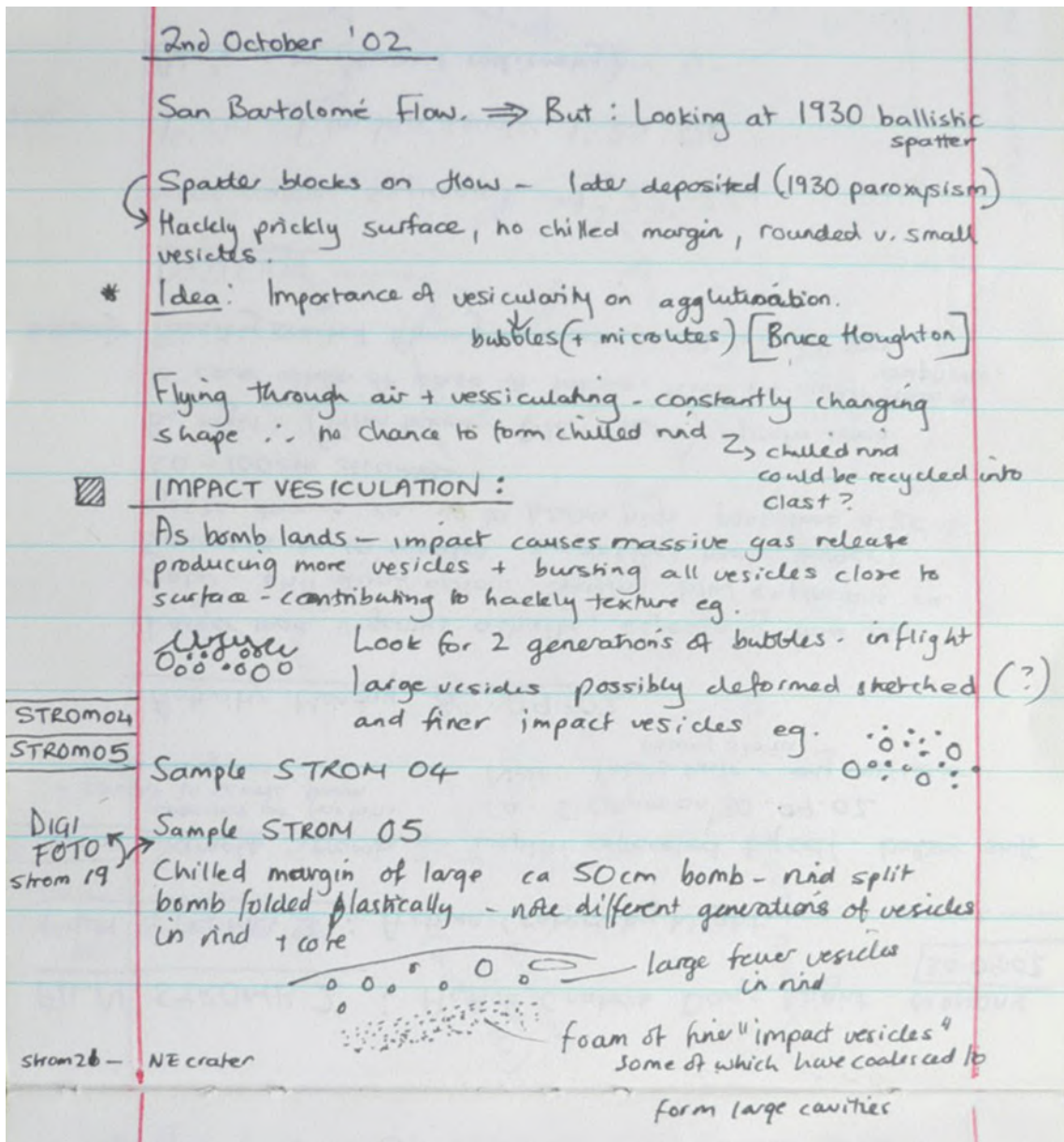


Figure 7.13 Page from a field notebook recording observations and ideas that were later tested in the laboratory. These are good notes but there is no scale to go with the sketches. (Notebook of Janet Sumner, The Open University, UK.)

In 2002, observations of the vesicle patterns within basaltic spatter bombs thrown 1 km during the 1930 eruption of Stromboli led volcanologists to speculate that some of the vesicles began to grow as a result of the bombs

hitting the ground (Figure 7.13). The viability of this process, termed 'impact vesiculation', was later demonstrated by experiments in the laboratory that caused bubbles to form in silicate magma subjected to impact shock.

Usually the effects of chilling extend inwards no more than a centimetre or two. The very edge may be glassy, lacking groundmass crystals of any size, but with groundmass crystals becoming larger and thus more clearly visible further away from the contact.

To spot a chilled margin from a metre or so away, look for variation in darkness or colour of the rock (Figure 7.15, p. 150). A fresh basaltic rock with a chilled margin will be grey in its interior, becoming darker as the feldspar in the groundmass becomes smaller and more transparent, and ending up almost black at the glassy contact. Later alteration and/or weathering can obscure things, but the story may still be visible as, for example, a gradual change from green to red at the chilled margin. Use a hand lens to verify grain-size changes and to try to confirm any initial diagnosis based on tone or colour.

Chilling can affect only the groundmass. If the magma contained phenocrysts, some of these may occur in the chilled margin, surrounded by glass. Likewise, any chilling at the contact cannot manifest itself in the grain size of an intrusion that was emplaced as a crystal-rich mush (as hypothesized for some granites). If you find an intrusive contact that lacks any signs of chilling, you should ask yourself whether the intrusion was emplaced as a mush, or whether it was emplaced at depth and/or into country rock that was too hot to cause rapid chilling.

When an intrusion occurs into a rock of the same composition and same average grain size as itself, chilling at the contact enables the relative ages to be deduced, even if there is no other evidence (e.g. Worked Example 7.2, p. 151). The rock that is chilled must be younger than the rock that it chills against. Close to the contact, there will be a gradual (over a centimetre or two) change in tone, colour or grain size within the younger rock, but there will be no such changes as you approach the contact from the other side.

It is exceptional to find chilled margins inside a pluton, but there are commonly contacts between batches of magma that had slightly different composition. These are discernible from a distance by different tone or colour, and evident at close range by differences in the abundances or crystal size of the main minerals. Particularly for felsic magmas, viscosity inhibits mixing, so that the sharpness of the contact between magma types may be limited only by the size of the crystals.

Pyroclastic rocks

Pyroclastic rocks are a special subset of volcanoclastic rocks. The latter consist of fragments of volcanic rock, fragmented by *any* process and transported by *any* agent. However, the contents of a pyroclastic deposit must by definition have been

BEWARE! In ancient rocks the shapes of pillows may have been deformed, making them hard to confirm, and spheroidal weathering can lead to a pillow-like appearance in unpillowed massive basalt.

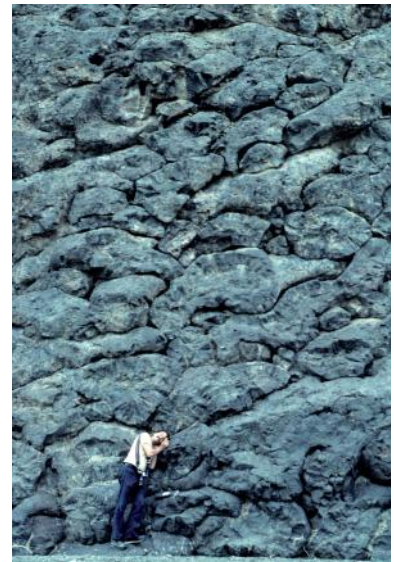


Figure 7.14 Unusually well-preserved and easily distinguished pillow lavas. Oman, Arabia. (David A. Rothery, The Open University, UK.)

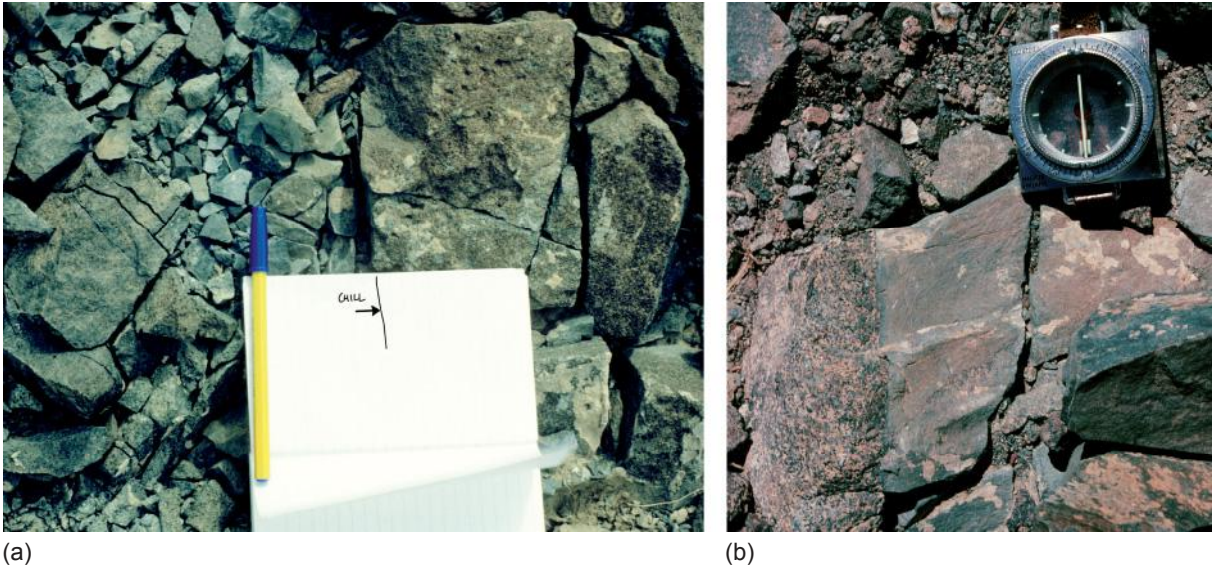


Figure 7.15 Dyke chilled margins. (a) The chilled margin runs from top to bottom of this view parallel to the pen. Its location is indicated by the arrow drawn in the deliberately positioned field notebook. This exposure is weathered and fragmented, but there is a slight darkening on fresh surfaces from left to right towards the chilled margin. To the right of the chill, the intruded rock is the interior of another dyke. (b) Chilled margin of dyke (right) against gabbro (left). Note the inclusion of the compass in the photo, to show the strike (Oman Ophiolite, Arabia). (a and b: David A. Rothery, The Open University, UK.)

fragmented and transported as part of the eruptive process. When interpreting a volcaniclastic rock look for contextual clues to try to establish whether it is truly pyroclastic. (A fall deposit from a volcano counts as pyroclastic, unless it has been reworked by wind or water.)

Pyroclastic rocks may contain textural evidence of their nature and mode of emplacement. Fragments of spatter from around a vent (hitting the ground as ‘cow-pat’ bombs) may have become welded together in such a way that their integrity can no longer be determined, but scoria that was more chilled by the time it accumulated may preserve its original texture. Fragments of lava encased in ash, or ash or lava or both found in association with blocks up to tens of metres in size of other rock types (either related igneous lithologies or country rock), have traditionally often been regarded as ‘vent agglomerate’, denoting a deposit that filled a volcanic vent or fissure following explosion or collapse. If you find such an occurrence this is a good working hypothesis to start with, but you would do well to consider other possibilities too. Look for evidence to help you choose between alternative explanations such as a lahar or a debris avalanche deposit, or a proximal fall deposit extending beyond the confines of a vent. Mapping out the field

Worked Example 7.2 Chilling statistics in Cyprus

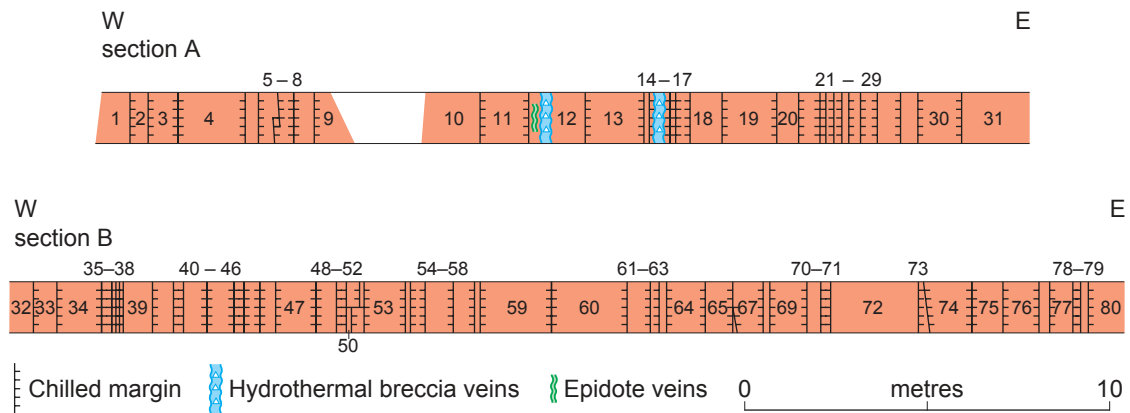


Figure 7.16 Schematic diagram of an east–west traverse across sheeted dykes in Oman (similar to those in Figure 7.15). The tick on the chilled margins shows the direction of chilling. Numbers identify dykes, but not their order of intrusion. The east end of section A and the west end of section B are separated by a 20m fault zone of poor and confused exposure. There is another fault zone between dykes 9 and 10. (From Lippard *et al.* 1986.)

In the early 1970s, the sea-floor spreading origin of ophiolites was gaining support, but was not yet fully accepted. Rupert Kidd and Joe Cann (1974) studied chilled margins in the sheeted dyke complex of the Troodos Ophiolite (Cyprus), in places that consisted of nothing but dykes, striking approximately N–S. They argued that the absence of non-dyke ‘host rock’ means that this unit must have been formed by 100% spreading, and they cited evidence from chilled margins for additional support. They found that usually the chilled margin of one dyke abutted against the chilled margin of its neighbour (so that their relative ages could not be told), and reasonably explained this as a younger dyke being injected along the edge of a previous dyke. However, they observed that about one dyke in ten had been split by a younger dyke, which

must have been injected into the interior of the older dyke.

They documented the direction of chilling in these split dykes, and found that there was a statistically significant preponderance of chilled margins in which chilling was towards the east. From this, they argued that the eastern halves of split dykes were more common in the ophiolite than western halves of split dykes, and hence that the Troodos Ophiolite as a whole represents ocean floor that formed on the east of the spreading axis.

Conversely, in the Oman Ophiolite, where the sheeted dykes also strike roughly N–S, there is a preponderance of chills towards the west (Figure 7.16), suggesting derivation from the west side of a spreading axis.



Figure 7.17 Accretionary lapilli in this fall deposit are recognizable by their spheroidal shape and (where exposed) their concentric internal structure. (Peter Francis, The Open University, UK.)

relationships may help, but sometimes you may be left with significant doubts.

Rock consisting largely of tuff (consolidated volcanic ash) brings you into the realm of techniques more familiarly used to study sedimentary rocks (Chapter 6), even if it is truly pyroclastic rather than more broadly volcanoclastic in origin. Ancient fine-grained ash deposits that settle to the sea floor can look very much like marine mudstones (even including the presence of lamination and pelagic fossils) and their true nature may remain unresolved. Features to look for include their distinctive colour when fresh (white, bluey grey or greeny grey), sharp contact, possible grading and (if they have degraded to montmorillonitic clays) their soft texture.

Identification may need to be confirmed using thin-sections or geochemical analysis. More proximal fall deposits may include accretionary lapilli a few millimetres to about 2 cm in size (Figure 7.17). These are originally spherical but may become flattened during compaction. They typically form by airborne nucleation in wet conditions, and in cross-section may reveal a diagnostic concentrically ringed pattern.

Often, the most useful record that you can make of a pyroclastic deposit in the field is a graphic log (Section 6.3). Fall deposits may show significant grain-size variations. You are likely to notice these first at a distance, appearing as sedimentary layers. Individual clasts will be visible, at least in the coarser-grained horizons, when you get close. In a pyroclastic flow deposit, cross-stratification may be apparent in addition to variations in the size and composition of clasts. When making a graphic log of a suspected pyroclastic deposit, aspects to look out for in particular include:

- *Grain-size variations.* A coarse-grained base fining upwards suggests a discrete explosive eruption, with fine-grained material taking longer to fall out. Possibly there will be a succession of such events, yielding fining-upwards units with sharp coarse-grained bases separated by hard-to-quantify time-gaps. On the other hand, if you find grain size coarsening upwards and then decreasing again (which may happen repeatedly) you may suspect a sustained eruption whose strength waxed and waned. If the deposit is unconsolidated, take samples from different layers to sieve for grain-size analysis. This can be diagnostic of many subtleties in the conditions of eruption and/or emplacement.
- *The nature of clasts.* This is most clearly distinguished in larger fragments. They may be pumice (representing frothy magma, evidencing the escape of volatiles that powered the

eruption), lumps of dense rock (ripped from the walls of the conduit) known as ‘lithic fragments’, or fragments of single crystals. Particularly in welded deposits, such as many ignimbrites, significant compaction may have occurred while the deposit was still hot. When this happens, the pumices become squashed (and are called *fiamme*; Figure 7.18) but the lithics and crystals retain their shape much better. If you find *fiamme*, you can tell that the deposit was hot when it came to rest.

- *Cross-stratification*. Record this carefully, in the same way you would for a sedimentary deposit (sections 6.2 and 6.3). In pyroclastic rocks it usually implies a ‘surge deposit’ from a low-density flow (Figure 7.19), and does not occur in fall deposits. Look out for localized disruption of the cross-stratification, lamination or bedding, which could be caused by upward escape of steam and other volatiles when a hot pyroclastic flow came to rest over damp or vegetated ground.
- *Flow banding*. There may be some macroscopic ‘flow banding’, for example resulting from downhill creep after welding began in a hot pyroclastic deposit (Figure 7.20, p. 154). In ancient or deformed rocks such a ‘rheomorphic tuff’ may be hard to distinguish from a unit with cross-stratification or primary layering, so you should be aware of all possibilities and look for additional evidence to distinguish between hypotheses.

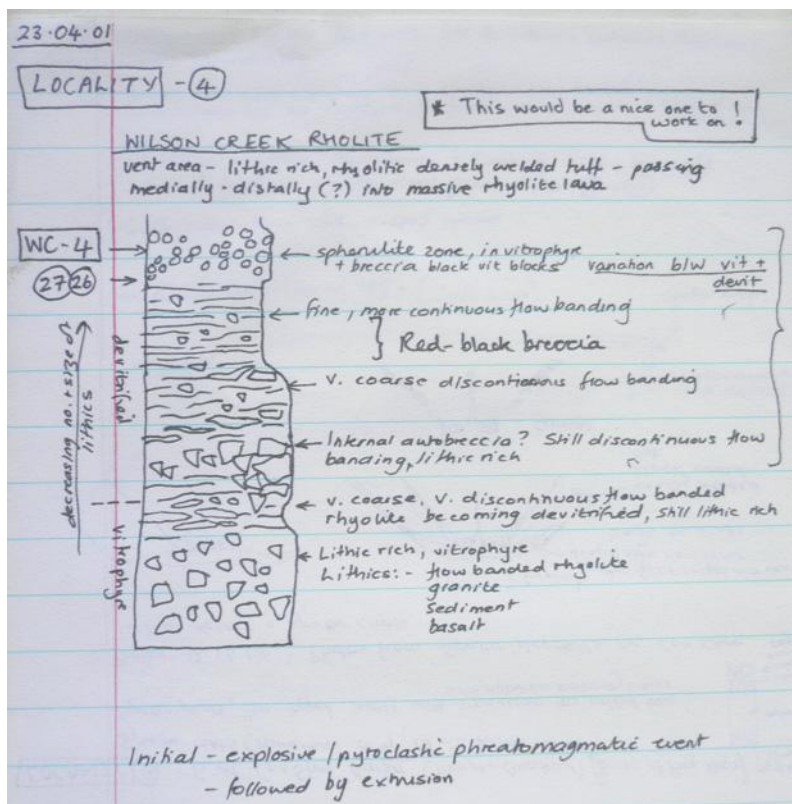


Figure 7.18 Squashed pumice clasts (dark) within the paler ash matrix of the Bandelier Tuff, a 1.14 Ma ignimbrite erupted from Valles caldera, New Mexico. (Peter Francis, The Open University, UK.)



Figure 7.19 Cross-stratification in a pyroclastic surge deposit, including clear variations in clast size. This example is only weakly cemented, and the holes are where geologists or other animals have dug away at the rock face. Campi Flegrei, Italy. (David A. Rothery, The Open University, UK.)

Figure 7.20 Part of a field notebook, containing a log with preliminary interpretation of a near-vent section of the 11.4Ma Wilson Creek Ignimbrite, Snake River Plain, Idaho, USA. The scale (given elsewhere in the notebook) is 1 m per ruled division on the page. (Notebook of Janet Sumner, The Open University, UK.)



- *Relationships between ash and large fragments.* Is the 'ash' made of the same stuff as the large bits? Are the largest clasts supporting one another (rather than floating in an ashy matrix)? If the answer to both is 'yes', you should think along the lines of a 'block-and-ash-flow' produced by collapse or explosive fragmentation of a lava dome.

Another discriminator between fall deposits and pyroclastic flows is that fall deposits mantle the topography, whereas pyroclastic flows are much thicker in, or entirely confined to, valleys. Thus, you should try to document any thickness variations and their relationship with palaeotopography.

7.3 Mineralogy and small-scale textures of igneous rocks

Here we consider diagnostic mineralogical and textural evidence that can be seen in the field with the unaided eye for

coarse-grained rocks, easily with a hand lens for medium-grained rocks, but with difficulty even with a hand lens for fine-grained rocks.

7.3.1 Petrologic type

For any crystalline igneous rock, you should attempt to identify the rock type on the basis of its mineral content. You will find this easier if you have already had some experience diagnosing hand specimens with the aid of accompanying thin-sections. In the field, you are unlikely to be able to go much further than the simple classification scheme provided in Appendix A7, Figure A7.1. More advanced classification depends on petrography done using thin-sections and geochemical analysis. Here are probably the three most useful tips:

- In medium- or fine-grained rocks, pyroxene and amphibole can be particularly difficult to tell apart. Don't worry – it doesn't matter much. More than 40% of any mafic mineral means your rock is mafic; 20–40% makes it intermediate.
- In igneous rocks quartz crystals are usually clear (unlike quartz in veins, which can be milky), but feldspar is often altered so that it looks white. If the plagioclase is still fresh it can be clear like quartz. However, on a freshly broken surface of a hand specimen some of the fractures in plagioclase will be flat cleavage planes that will catch the light as you turn the specimen, whereas all fractures in quartz will be irregular and curved.
- Most igneous rocks contain some plagioclase feldspar. If you can identify this, estimating its percentage will help to determine the rock type.

7.3.2 Mineral texture and fabric

You should of course check that your rock has an igneous texture. Except for glassy lava and the matrix in pyroclastic rocks, this means the rock should have interlocking crystals. However, it is not true, despite what some texts suggest, that igneous rocks must necessarily lack foliation. In fact, you should look carefully for signs of mineral alignment or arrangement in planes. This may be more subtle than in metamorphic rocks, but if present it can tell you a lot about the emplacement process.

'Flow banding' or 'flow foliation'

This is a result of shear in pyroclastic deposits (Figure 7.20) or viscous lavas such as andesite, dacite or rhyolite, so that crystals (or, in obsidian, the glassy fabric defined by microlites, bubbles,

isolated crystals and/or colours in the glass) become aligned with the direction of flow. In the field the clearest manifestation of this may be simply in the way the rock fractures or weathers. Look out for fiamme to distinguish pyroclastic rocks from flow-banded lavas. You should be on the look out for flow banding in plutons too, especially granite that may have been emplaced as a crystal-rich mush, although it is surprisingly rare.

Cumulate layering

This was once thought simply to result from crystals settling to the floor of a magma chamber, but it has been shown that similar textures can result from crystal growth against magma chamber walls. Occasionally, cross-stratification is evident. Cumulate layers occur on a centimetre scale (Figure 7.21) and may be evidenced by variations in mineral abundances. For example, in a gabbro alternating layers of 60% :40% versus 40% :60% plagioclase and pyroxene is called 'ratio layering'. The appearance and disappearance of a particular mineral phase is called 'phase layering'. An example of the latter would be a gabbro having alternating layers with and without olivine. Cumulate layering can be recorded by means of a graphic log (Section 6.3), paying attention to whether changes are gradual or sharp (e.g. Worked Example 7.3).

Other attributes of mineral texture can provide insights on the sequence of crystallization. Isolated crystals larger than the groundmass are probably phenocrysts that began to grow early (perhaps during magma storage). When one crystal encloses

Figure 7.21 Cumulate layering in a gabbro in the Oman Ophiolite, Arabia. Dark olivine-rich layers with sharp bases gradually become more felsic upwards, repeated in a scale of a few centimetres. On this weathered surface, the felsic layers are reddened. As can be seen from the orientated compass-clinometer, in this example the layers strike approximately 060° and dip steeply northwards. (David A. Rothery, The Open University, UK.)



Worked Example 7.3 Dyke rooting and overlapping spreading centres in the Oman Ophiolite

The Oman Ophiolite is a 350 km long, well-preserved tract of Cretaceous ocean floor, thrust over the northeast coast of Arabia. Studies in the 1980s (Rothery 1983) and early 1990s (Macleod and Rothery 1992) made the crucial field observation of places where dolerite dykes from the sheeted dyke complex could be traced downward into 'high-level gabbro' of identical composition but coarser grain size (e.g. Figure 7.15b). This gabbro was interpreted as the upper part of a magma chamber from which the dykes were fed, and indeed it was possible to find chilled margins of gabbro against gabbro, representing the roots of individual dykes. Integration of mineral texture and fabric observations with these broader field observations proved its worth when it was found that, next to and below dyke rooting zones, the 'high-level gabbro' often has a weakly lineated fabric. This is expressed by orientation of pyroxene crystals consistent with generally upward flow towards the overlying dykes, although sometimes this fabric has been destroyed by recrystallization during

hydrothermal alteration (when pyroxenes were largely replaced by amphibole).

Equally important, elsewhere (within a few tens of kilometres) the dykes from the sheeted dyke complex could be traced into cumulate gabbros, where they cut across the cumulate layering. Dykes could not have been fed from these places, so it was argued that they must have been injected along strike from a nearby magma chamber. About half a dozen of these 'penetration zones' were identified, and it was suggested that they marked segmentation of the spreading axis at which the Oman Ophiolite was created. Such segmentation was consistent with overlapping spreading centres like those that began to be identified on the East Pacific Rise in the late 1980s (and subsequently in many other places, including marginal basins) rather than segmentation defined by transform faults. Although mid-ocean ridge magma chambers have subsequently come to be regarded as small and/or ephemeral, the important distinction between dyke rooting and dyke penetration remains valid.

another the enclosed crystal must have grown before the enclosing crystal, and well-formed crystals probably grew before badly-shaped crystals that appear to be filling in spaces. In the field, such evidence can be assessed only for coarse-grained rocks, and even for those it is better to study thin-sections under the microscope.

Pegmatites

You may find exceptionally coarse intergrown crystals in parts of a pluton, or coarse patches within an otherwise medium-grained sill. This is probably pegmatite (Table 7.2, p. 146), in which the size of the crystals is nothing to do with cooling rate, but was instead controlled by the availability of nucleation sites and/or the abundance of volatiles in the last residue of the melt. Pegmatites usually occur in veins or lenses. Things to note in particular are the shape of the pegmatite body and the clarity of its edges. Does it appear that the main igneous body was solid and brittle, or mushy and ductile, when the pegmatite was active?

'Enclaves'

Sometimes within an igneous rock you may find patches (or 'enclaves') with a different texture or mineralogy, but which are not greatly coarser (in fact they may be finer) and so are not pegmatite. These enclaves may be so obviously different (and large enough) that you can spot them from a distance. Examine them carefully in order to decide between competing possibilities that could explain them.

- *Xenoliths?* These would be fragments of country rock that were engulfed in the igneous magma (e.g. by stoping: Figure 7.2) and transported within it. If so, they may not be igneous in origin. The most exotic xenoliths come from the mantle. Edges of xenoliths tend to be well-defined, and their shape can be angular. At its smallest, a xenolith may consist of no more than a single exotic crystal, in which case it is known as a xenocryst. Beware of misidentifying an aggregation of phenocrysts (known as a 'glomerocryst') as a xenolith.
- *Magma of different composition that has somehow avoided total assimilation into the main magma?* These, sometimes referred to as autoliths, may be blobs that were injected into the main host rock while it was still partly molten (Figure 7.22). They tend to have a rounded shape, and their edges may be diffuse. This is really just a small-scale variety of the incomplete magma mixing described in Section 7.2.2.



Figure 7.22 Autolith, 60cm long, in the Shap Granite, Cumbria, UK. On close examination, it turns out that the autolith is not mafic (as would be implied by its colour). It is a microgranite, with a higher proportion of biotite than the coarse-grained granite that encloses it. (David A. Rothery, The Open University, UK.)

7.4 Recent and active volcanoes

Active and recently active volcanoes allow you to see igneous rocks in the making, or at least before they have been changed by weathering, burial or other processes. They are places where processes can be studied on scales ranging from molecular chemistry (when volcanic gases mix with the atmosphere) to the deformation of a stratocone volcano under its own weight. There is space here to mention only a few general principles.

7.4.1 Equipment and safety

Your safety equipment should include a hard hat even if you do not intend to work close to any cliffs, to offer head protection if an explosive eruption occurs. The ground may be unstable (especially on fresh pahoehoe and on 'a'a of any age), so it is wise to carry a long stick for support and (if necessary) probing. You should also wear tough trousers and gloves of suitable material for protection against cuts and burns, and which will not melt when exposed to heat (Figure 7.23). If you expect to be working near fumaroles you should carry a gas mask capable of filtering out acid gases such as sulfur dioxide.

You should NEVER risk putting yourself in either of the following situations, but here is some advice that might save your life if you get caught.

- If volcanic bombs start falling towards you, do not turn and run. It is better to stand and face the bombs, preferably somewhere where you can dodge without tripping over. Watch the bomb-fall carefully, and if you are sure that one is headed for you, step aside so that it misses you.
- If a pyroclastic surge is coming your way, you will not be able to outrun it, although you may be able to escape sideways out of its path. If not, cover as much of your body as you can, especially your face, and get down as low as you can in a hole or behind a large rock. While the flow is passing, hold your breath for as long as possible so you don't sear your lungs by inhaling hot gas and ash.

Sampling and measuring equipment will depend on the nature of your study. Infrared thermometers can record temperatures for studying vent processes or lava flow rates (Figure 7.24, p. 160), there are various ultraviolet or infrared sensors for studying volcanic gases, and of course you may wish to collect samples of rock. Downwind of an explosive vent, something as simple as an aluminium baking tray can usefully be laid out to catch scoria fall-out, for studies of crystallization and vesiculation changes during the course of an eruption.

You need to take special care and be extra vigilant when working on or near an active volcano.



Figure 7.23 The shelly skin of this recent pahoehoe flow gave way under the weight of this volcanologist. Wisely, he is wearing long trousers (rather than shorts) that would have protected his shins if he had stumbled into the sharp, glassy rim (Kilauea, Hawaii). A far worse accident would have been to have broken through the roof over an active lava tube. (David A. Rothery, The Open University, UK.)

Figure 7.24 Two infrared thermometers and one infrared video camera have been set up to look into this skylight on an inflating pahoehoe field, to record variations in the rate of flow in a lava tube on Kilauea, Hawaii. (David A. Rothery, The Open University, UK.)



7.4.2 Access

You should expect to face considerably greater access challenges than normal (Section 2.5). Some pristine volcanic landscapes (especially those where eruptions are rare) are protected by legislation that restricts access to certain areas. During an eruption, the authorities may prohibit entry – for your own safety and also so that resources do not have to be diverted from protection of local inhabitants. Conversely, on volcanoes in virtually continuous low-level eruption (e.g. Stromboli) there may be a well-established system of local guides, leading tourists on lava-watching hikes. To obtain permission for a serious scientific (rather than touristic) visit to an active volcano, it is advisable to make contact with any relevant park authorities or the nearest volcano observatory, which can be found via the World Organization of Volcano Observatories (WOVO).

7.4.3 Observations

Techniques involving specialist geophysical and geochemical equipment for monitoring active volcanoes are beyond the scope of this book. However, equipped merely with your own senses on an erupting volcano you can, for example, log the times and locations of discrete explosions or measure the speed of a lava flow (throw a rock onto it to act as a marker). Here we note some observations that can be made safely in young volcanic terrain when there is NO eruption and NO LIKELIHOOD of imminent eruption.

- *Examine lava flow morphology.* Identify the individual lava flows making up a lava field. If the lava is basalt, look for pahoehoe (which comes in many varieties; Figures 7.23 and 7.24) and 'a'a (Figure 7.12a). See if you can find a pahoehoe flow that turns into 'a'a where it passed onto a steeper slope so that the flow rate was forced to increase. In a pahoehoe flow field, look for tumuli (mounds), where lava was squeezed up from below. Lines of tumuli can indicate the track of a lava tube. If the tube has emptied, you are absolutely sure it is safe and you can find a way in, it may be worth exploring to look for 'tide marks' on the wall left by the waning flow. Study a flow front; where would it have gone next if the supply of lava had not run out?
- *Can you find any volcanic bombs?* Were they completely fluid, or crusty, or fully solidified when they hit the ground? Do they represent magma, or wall-rock ripped out of the vent?
- *Has there been a recent pyroclastic flow?* This may be a good chance to see the damage that one can do. In the proximal region the deposit may be vanishingly thin (and so virtually unrecognizable in ancient examples), but it may have scoured away soil and previous ash deposits.
- *Is there fresh fall-out ash still in situ?* Is it on steep slopes, prone to being washed away during heavy rain to generate a lahar? Which areas are at risk?
- *Are any vents accessible?* Features such as scoria cones, tuff rings, maars and tuff cones that can be hard to interpret when found in cross-section in ancient rocks are easier to make sense of in a modern setting.

7.5 Further reading

- Francis, P.W. and Oppenheimer, C. 2003. *Volcanoes*, Oxford University Press, 536 pp. [A nice account of volcanism in general.]
- Gill, R. 2010. *Igneous Rocks and Processes*, Wiley-Blackwell, 480 pp. [A lengthy review aiming to give students the skills and confidence to identify igneous minerals and interpret igneous rocks.]
- Le Maitre, R. W., Streckeisen, A., Zanettin, B., Le Bas, M. J., Bonin, B. and Bateman, P. (eds) 2008. *Igneous Rocks, a Classification and Glossary of Terms: Recommendations of the International Union of Geological Sciences Subcommittee on the Systematics of Igneous Rocks*, Cambridge University Press, 256 pp. [Formal, detailed account of the systematic classification of igneous rock types.]
- McPhie, J., Doyle, M. and Allen, R. 1993. *Volcanic Textures*, Centre of Ore Deposit and Exploration Studies (CODES), University of Tasmania, 198 pp. [Excellent photographic atlas of volcanic rock textures. Reprinted in 2005.]
- Rothery, D. A. 2010. *Volcanoes, Earthquakes and Tsunamis*, Hodder Headline, Teach Yourself Books, 288 pp. [A basic introduction to

active volcanoes, earthquakes, tsunamis and the relationships between them.]

Schmincke, H.-U. 2004. *Volcanism*, Springer-Verlag, 324 pp.

[Beautifully illustrated account in colour.]

Thorpe, R. S. and Brown, G. C. 1991. *The Field Description of Igneous Rocks*, Geological Society of London Handbook Series, Blackwell Scientific Publications, 160 pp. [Further information on the field description of igneous rocks and more of the theory.]

8 Recording structural information

Tom W. Argles

Our planet is an active one, with tectonic plates in constant motion. Its crust and mantle are subject to changing stresses that cause rocks to deform, either by breaking or by bending/stretching (brittle or ductile deformation respectively).

Although we may glean some information on this deformation from sophisticated seismic methods probing the Earth's depths, or by measuring infinitesimal ground motions using satellites, the most detailed record is preserved in deformed rocks exposed at the Earth's surface.

Measuring brittle structures provides information on how and why the upper crust in particular deforms, specifically the orientation of regional and local stresses, and the direction of motion on faults. Such data help us understand why, how and where earthquakes occur. Understanding fracture systems is also critical in exploiting oil, gas, coal and mineral resources efficiently; rock structures provide not only challenges, but also opportunities (such as hydrocarbon traps). Movement of fluids through the upper crust is strongly influenced by fractures, so structural geology plays a crucial role in a wide range of related fields, including groundwater studies, pollution control, geothermal schemes and carbon dioxide storage and sequestration. Major engineering schemes (e.g. reservoir dams, barrages, motorways, tunnels) are literally founded on structural geology. Section 8.2 illustrates some important brittle structures, to help you recognize them, measure them and interpret the resulting data.

Ductile deformation dominates strain deep in the crust and in the mantle, so measurement of ductile structures provides information on fault motions and stress orientations at depth, giving insights into regional deformation patterns. Section 8.3 illustrates some of the commoner ductile structures.

8.1 Equipment and measurement

Structural geology is the study of geometrical features (e.g. planes, lines, surfaces, ellipsoids) produced by deformation. We describe and measure the orientation and dimensions of these geometrical elements to better understand how and why they formed, in terms of rock movements (kinematics) and stresses (dynamics). Hence, structural fieldwork may require some of the optional and specialist equipment (e.g. binoculars, pocket stereoscope; Table 2.3, p.6) in addition to the basic equipment for geological fieldwork (Table 2.1, p.4). For accurate measurement of azimuths, dips and plunges, a specialist compass-clinometer (e.g. Brunton-type; Section 2.3) is recommended.



A long pencil is useful in some cases as an extension of the line, if the feature itself is awkward to measure with the compass-clinometer.

8.1.1 Structural measurements and notations

Section 2.3 introduced the compass-clinometer; measurement of the strike and dip of an inclined plane was covered in Section 2.3.1, Figures 2.6–2.8. Section 2.3.2, Figures 2.9 and 2.10, described how to measure linear features such as fold axes, lineations and striations, which are at least as important as planes in structural geology. Gathering orientation data is a critical part of structural work, so it is a good idea to develop consistent, efficient strategies for measurement in the field.

Because many structural studies require copious measurements of different lines and planes, it is important to record the data in a concise, organized and logical manner in your field notebook (e.g. Figure 4.11c, p. 73). Separate the structural data from other notes (perhaps even by colour), and arrange them in tabular form. Abbreviations for different features (e.g. Lc = crenulation lineation) are a useful shorthand, but ensure that you are consistent in their usage, and include a key in each notebook, for instance on the inside cover. As explained in Section 2.3 it is important to follow the convention for recording azimuths and dip (or plunge) values:

Azimuth (strike; trend of linear feature)	three-digit number	076
Dip or plunge (inclination from horizontal)	two-digit number	76

This convention should avoid confusion between the two numbers, regardless of the style of notation used (Table 8.1). This is especially important, because many structural geologists use a short notation for planes of ‘dip angle/dip azimuth’, rather than the longer ‘strike azimuth/dip angle + dip direction’. This saves space, but means that notebook records of planes and lines look very similar, and therefore should be

Table 8.1 Notations for structural orientation data.

Description	Notation	Type	Comments
PLANE striking on a bearing of 047°, and dipping at 23° towards the SE	047/23 SE	Strike, dip, dip direction	Less likely to confuse with plunge and plunge direction measurement of linear feature. Strike can be plotted directly onto map sheet
	23→137 or 23/137	Dip, dip azimuth	Shorter, fewer elements to forget or mis-record. Strike must be calculated to plot onto map sheet
LINE plunging 23° towards 137° (line of maximum dip on above plane)	23→137 or 23/137	Plunge, plunge azimuth	Possible to confuse with plane orientation recorded in dip, dip azimuth notation; label carefully

labelled carefully to identify what they are. Because the strike of a plane is easier to measure accurately than the dip direction with the Silva-type compass-clinometers, the ‘strike azimuth/dip angle + dip direction’ notation tends to be more popular among non-structural geologists.

8.2 Brittle structures: Faults, joints and veins

During the study of brittle features it is better to focus first on their orientation, before looking at more detailed clues to the direction and sense of past movements on those features, and their relationships with associated structures.

Remember that a degree sign (°) for angle or azimuth can be mistaken in a handwritten notebook for an ‘extra’ zero, leading to confusion – it is better to omit these altogether. Clear identification of the data, and use of the three-digit convention for strike or azimuth and the two-digit convention for dip or plunge, will avoid ambiguity.

8.2.1 Planar brittle features – orientation

The attitudes of faults are strongly influenced by the orientations of the three principal stresses (σ_{\max} , σ_{int} and σ_{\min}). Faults that we define as normal, thrust and strike-slip commonly have steep, gentle and subvertical dips respectively. Fault dip can be roughly estimated in the field, or from maps and satellite images (Figure 8.1, p. 166), by observing whether the fault trace cuts sharply across topography (steep dip) or follows the land’s contours (gentle dip). Many faults are obscured in the field by vegetation, soil and other superficial deposits, so look for indirect clues to their presence (Table 8.2 and Figure 8.2, p. 167). General features of faults are shown in Figure A8.1 (Appendix A8).

The dip and strike of simple, planar fractures are easily measured using the compass-clinometer. For uneven surfaces a clipboard or book can be used to smooth out the unevenness (Section 2.3.1 and Figure 8.3a, p. 168). If the plane is highly

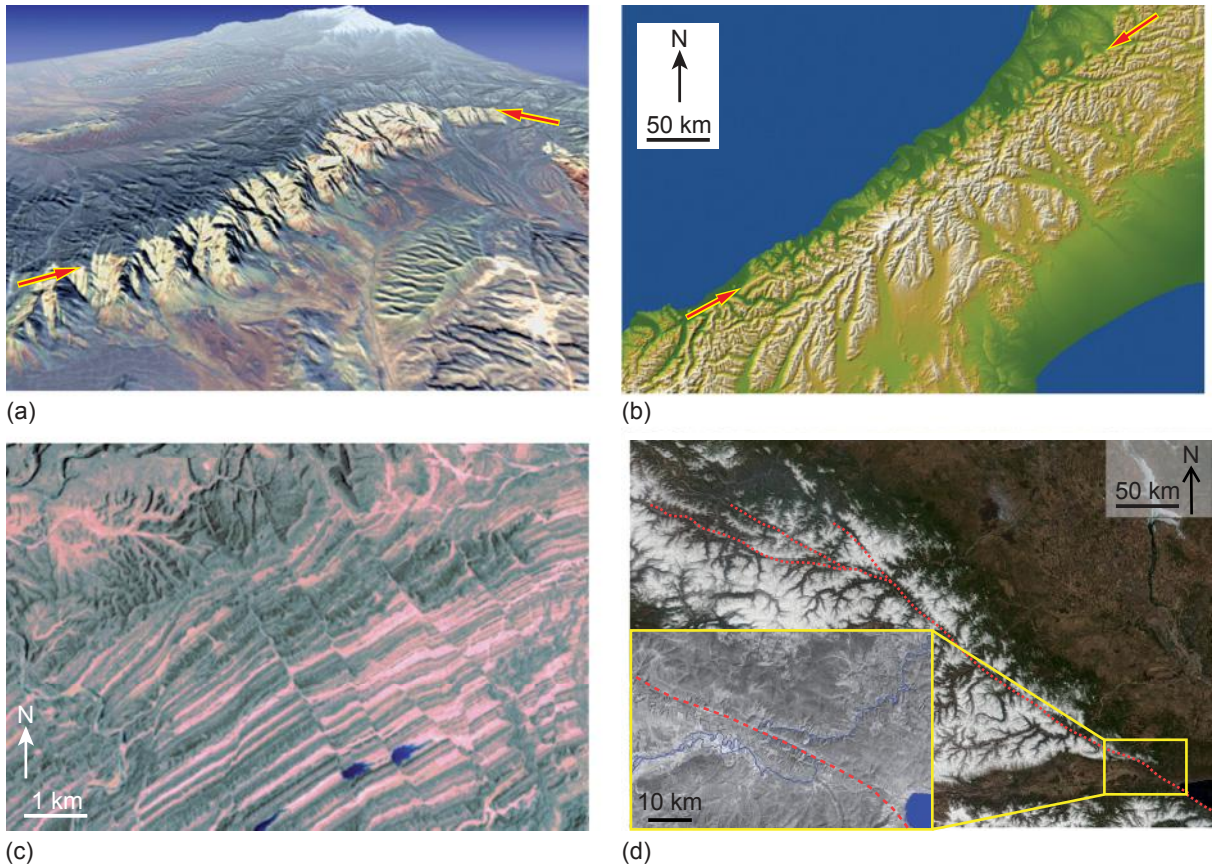


Figure 8.1 (a) Perspective view of a gently-dipping thrust plane (arrowed contact between dark strata in hanging wall and pale strata in the footwall) which follows topographic contours: Keystone thrust, Nevada, USA. Distance between arrows is about 20km. (b) A major strike-slip fault (arrowed) cuts across topography in this image showing relief on the South Island of New Zealand, generated using radar from the Space Shuttle. (c) Steep faults offsetting tilted strata in this satellite image, southern Pakistan. (d) River valleys aligned along faults (dashed red lines) in this satellite image near Lake Baikal, Russia. Inset is a modified Landsat image that highlights the pronounced offset of a river (blue) across a strike-slip fault (dashed red lines). (a: Generated from U.S. Geological Survey Landsat image and National Elevation Dataset; b and c: courtesy of the U.S. Geological Survey /NASA images; d: Modified from U.S. Geological Survey / NASA MODIS and Landsat images.)

irregular or inaccessible the orientation may have to be estimated by sighting along the plane with a compass (Figure 8.3b, p. 168). If only the edge of the plane can be seen the recorded dip will be an apparent dip, lower than the true dip by an amount that depends on how inaccurate the strike estimate is. If possible, it is worth carefully excavating a small portion of the slip plane to measure.

With increasing depth, faults tend to widen into zones with multiple fractures, and then breccia or fault gouge zones contained within bounding surfaces (Figure 8.3c). Minor fractures within these fault zones may seem chaotic, but their

Table 8.2 Landscape clues to the presence of faults.

Aspect	Typical features
Topography	Break in slope (Figure 8.2a); trough or ridge (Figure 8.2b); scarp; river gorge; abrupt landscape contrast
Erosion	Ravine/gully/stream/river follows fault-line (easily eroded crushed rock); ridge (if fault mineralization is harder than country rock; Figure 8.2b)
Drainage	Springs, sag ponds (many fault rocks are impermeable; Figure 8.2c); sinkholes (limestone one side of fault); abrupt drainage contrast at fault
Vegetation	Sharp change across fault, due to soil and/or drainage change on different rock types (Figure 8.2d)
Offsets	Offset of linear feature (stream, ridge, dyke, road, fence, railway), especially for active faults (Figure 8.2e)



(a)



(b)



(c)



(d)



(e)

Figure 8.2 Landscape clues to faults. (a) Line of fault runs obliquely from left (just behind lambs) to right, marked by a break in slope and low scarp (with gorse), northeast England. (b) Hard, mineralized fault rock forms a ridge c. 10m high along the Highland Boundary Fault, Garron Point, Scotland. (c) A sag pond in a depression along the San Andreas Fault, Carrizo Plain, California. (d) A steep normal fault (arrowed) marked by vegetation contrast cuts across topography in southern Spain. (e) Wallace Creek, a stream offset across the San Andreas Fault (arrowed), California. (a and b: Angela L. Coe, The Open University, UK. c: Courtesy of the U.S. Geological Survey. d: Tom W. Argles, The Open University, UK. e: Courtesy of the U.S. Geological Survey; photographer Bob Wallace.)



(a)



(b)



(c)

Figure 8.3 (a) Measuring an uneven plane with the aid of a clipboard. Remember to ensure that any metal clips are not affecting the measurement. (b) Measuring the dip of an irregular fault by sighting using the compass-clinometer. Inset shows orientation of the compass-clinometer and detail of the line of sight. (c) A set of subsidiary fractures (thin arrows) with a consistent angular relationship to the main fault zone (thick arrows). These are Riedel fractures (Section 8.2.2), evidence that the fault downthrows to the right. (a and c: Tom W. Argles, The Open University, UK. b: Angela L. Coe, The Open University, UK.)

orientations are ultimately related to overall fault zone motion. Even if the bounding faults are not exposed, these fault sets may indicate both the orientation and sense of motion of the main fault zone (see Section 8.2.2).

The orientation of joints can also provide insights into the regional stress field. Shear joints commonly occur in conjugate sets, in orientations mirrored across σ_{\min} and σ_{\max} , forming characteristic ‘X-shaped’ patterns (Figure 8.4a); conjugate sets of normal faults are also quite common. Joint sets can be measured to yield information on either local or regional stress regimes (e.g. in a single fold structure, Figure 8.4b; or due to unloading of ice sheets or rock overburden, Figure 8.4c). When fractures are mineralized (forming veins), the mineral fibres

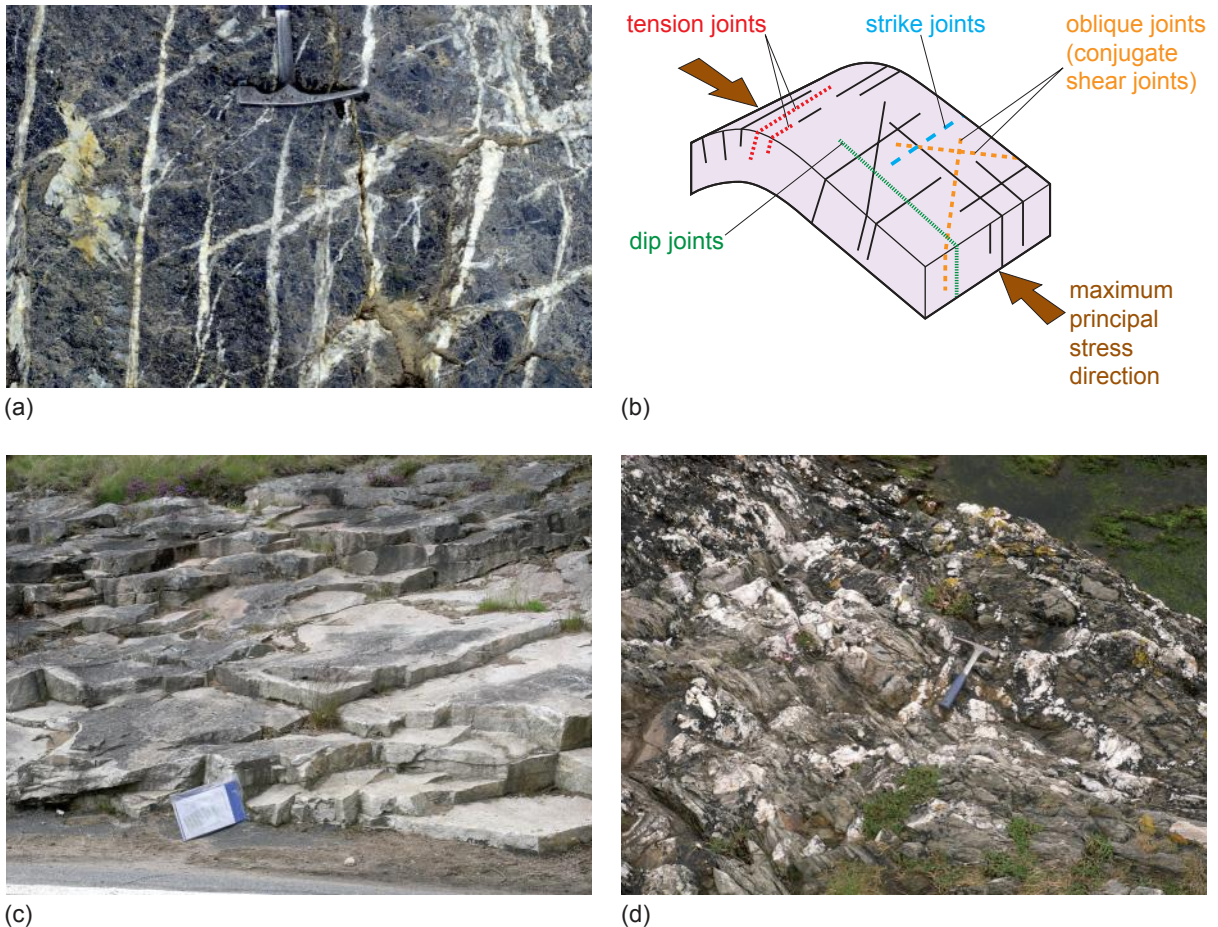


Figure 8.4 (a) Conjugate veins, with a characteristic X-shaped pattern and minor offsets (Switzerland). (b) Diagram of shear and extensional fractures on a fold (based on McClay 1991); (c) Unloading joints in granite exposure near Balmoral, Scotland, UK: two sets are subvertical, almost at right angles to each other, while the third set is roughly parallel to the land surface. (d) Chaotic veins in this exposure suggest hydraulic fracturing under high fluid pressure (Wales, UK). (a, c and d: Tom W. Argles, The Open University, UK.)

may provide valuable information on any past motion on the fracture. In some cases high fluid pressure locally dominates the regional stress field, so that cracks can open in any orientation (a process known as ‘hydraulic fracturing’), resulting in veins that criss-cross an exposure chaotically (Figure 8.4d).

Stylolites (Figure 8.5) generally form perpendicular to σ_{\max} , reflecting either sediment compaction (bedding-parallel) or regional tectonic stresses. They are generally more irregular surfaces than faults, and are a clue to rock composition as well as stress orientations, being typical of limestones.

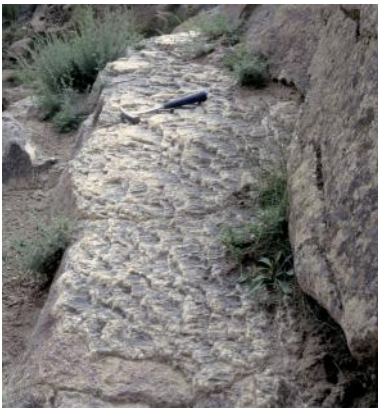


Figure 8.5 Stylolite picked out in white limestone by red, insoluble iron oxide. Scale = 5 cm. (Tom W. Argles, The Open University, UK.)

To determine the direction of movement of slickenfibres move your hand up and down parallel to the fibres. The slickenfibres feel smoothest in the direction of motion of the missing block.



(a)



(b)



(c)

8.2.2 Determining past motion on brittle structures

With any fracture, a primary goal is finding out in which direction the adjacent rocks moved, and how far. Accumulating such data builds a picture of local, and subsequently regional, brittle deformation that feeds into studies of earthquakes on major faults, especially in plate boundary zones. Many faults carry clues to their past motion. The following indicators are the most common:

- *Slickenfibres* (Figures 8.6a and 8.6b) are mineral fibres that grow during fault creep. The long axes of fibres are parallel to the fault slip direction, while steps in the fibres may reveal the sense of fault motion. The direction of motion is down the steps.
- *Slickenside lineations* (slickenlines) are grooves and striations on fault surfaces (slickensides) that also run parallel to fault slip direction (Figure 8.6c), i.e. down dip on thrust and normal faults, or subhorizontal on strike-slip faults. Slickenlines observed at an intermediate orientation between the dip and strike of a fault plane imply that the fault moved by oblique slip, a combination of dip-slip and strike-slip movement which is not uncommon. This interpretation assumes the fault to be in its original orientation. Note also that slickensides tend to record the latter stages of fault movement, which in some cases may differ from the main phase of slip on the fault.
- *Minor fractures* in fault zone breccias or gouges may also bear slickensides, which can be measured to build up a picture of movement throughout the zone.

In some cases, increments of slip (perhaps representing single earthquakes) may be recorded by lines or ridges at a high angle to the striations (e.g. the subhorizontal ridges in Figure 8.6c), and variations in slip direction can produce curved slickenlines, or multiple sets of slickenfibres with different orientations. Overlapping of these features can in some cases be analysed to construct a relative chronology of fault slip.

←

Figure 8.6 (a) Mineral fibres in this vein grew at right angles to the vein walls, showing that it is a dilational vein. Vein is 15 mm wide at top of image. Southwest Wales, UK. (b) Slickenfibres of quartz showing oblique slip (parallel to hammer shaft) on a minor thrust fault in the Himalaya, north Pakistan. Direction of movement of the upper block is right to left, parallel to handle of hammer. (c) Steep striations (i.e. slickenside lineations) on a fault in limestone in the Swiss Alps indicate dip-slip motion. Subhorizontal ridges may record successive slip episodes, but not the sense of motion. (a–c: Tom W. Argles, The Open University, UK.)

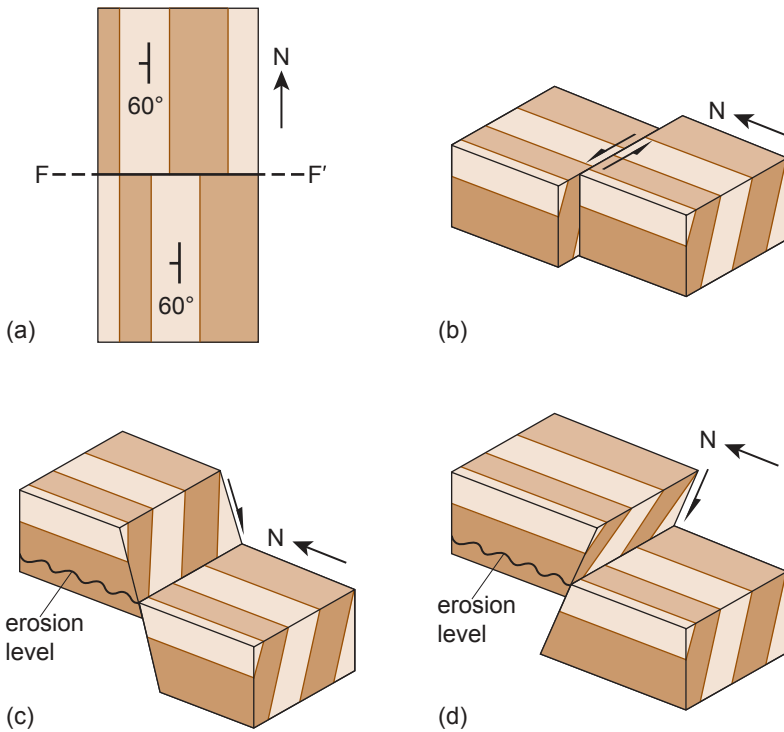


Figure 8.7 (a) This outcrop pattern of simple offset strata suggests a simple sinistral strike-slip fault, as shown in (b), but the pattern could also be produced by normal (c) or reverse (d) faulting.

Once the direction of motion on a fault has been established, the next question is: what is its sense of motion? There are numerous observations that can help answer this question, but first, a note of caution. Observations of shear sense *should always* be made parallel to the direction of motion (i.e. parallel to the slip lineations you have already recorded). If you cannot determine the direction of motion, then you cannot be sure of the significance of any shear-sense indicators you find. Simple offset features illustrate this point well (Figure 8.7); it is easy to misinterpret offsets of dipping beds if you haven't first determined the direction of fault motion.

The best indication of fault motion (giving both the sense and magnitude of displacement) is the offset of a linear feature intersecting the fault plane, visible as a 'piercing point' on both sides of the fault (Figure 8.8, p. 172). Imagine a buried pipe cut and offset by an active fault: you could match the two broken pipe-ends up on either side of the fault to see how far it had moved. However, linear features such as the pipe are rarely accessible, so evidence for relative fault motion should be gleaned from other kinematic indicators in the vicinity of the fault (Figure 8.9, p. 172).

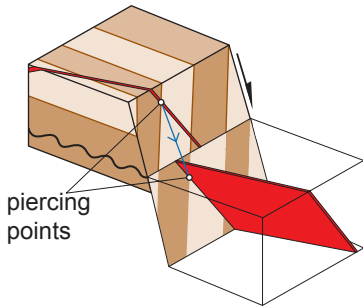
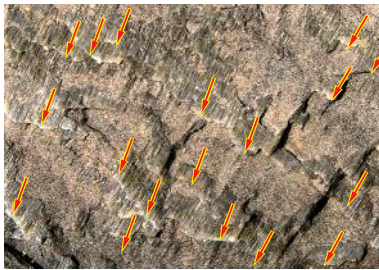
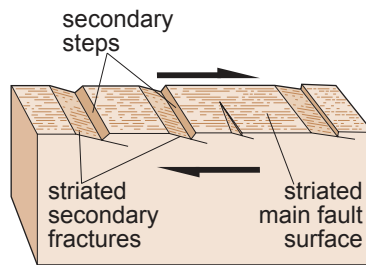


Figure 8.8 Matching corresponding piercing points, in this case where a dyke (red) intersects a lithostratigraphic boundary, is the best method for determining overall displacement on a fault. Linear features, such as a river channel in a sedimentary succession, are quite rare in the rock record. The most common type of situation is where two planar features intersect along a line, as here.



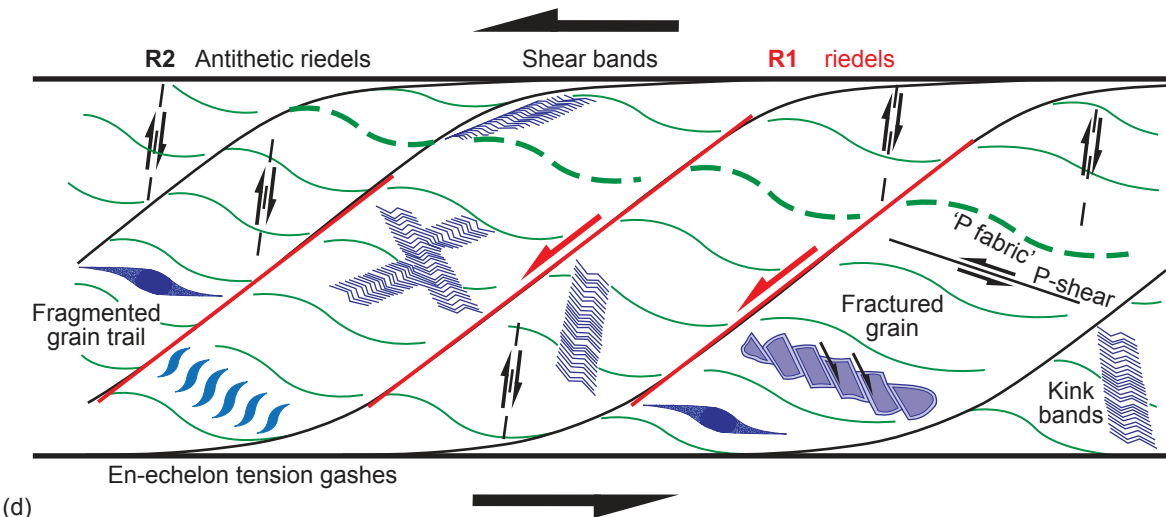
(a)



(b)



(c)



(d)

Figure 8.9 (a) Arrows mark individual steps and indicate slip direction of the missing block on this slickenside in southwest Wales, UK. Field of view 6 cm across. (b) Secondary fractures may develop that produce a stepped effect opposite to that in (a). (c) The pattern of en échelon vein arrays indicates relative shear sense, confirmed in this example by the deflection of dark solution seams through the shear zone that caused vein formation (southwest Wales, UK). (d) Some features within a wider shear zone that can be used to diagnose sense of shear (Riedel fractures, antithetic Riedel fractures, gouge fabrics, broken clasts). (a and c: Tom W. Argles, The Open University, UK.)

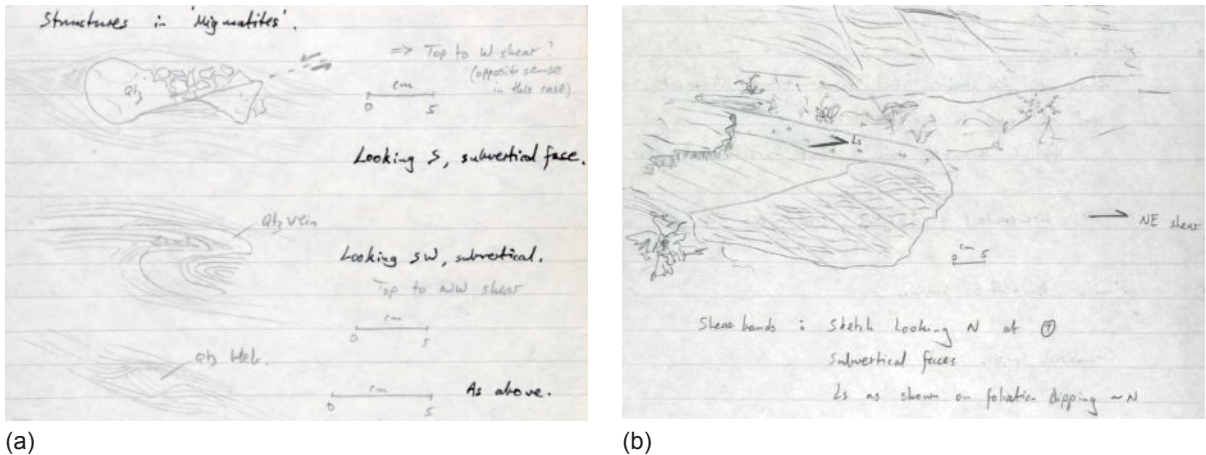


Figure 8.10 (a) Examples of orientated ‘thumbnail’ sketches of kinematic indicators from a field notebook. (b) An orientated sketch of structural features in a larger exposure. (Notebook of Tom W. Argles, The Open University, UK.)

For many kinematic indicators, a simple field sketch is an adequate record. Photographs are also useful, but sketches (Figure 8.10) can incorporate a level of interpretation that is lacking in a photograph. For any structural sketch or photograph, it is *essential* to specify:

1. orientation, using compass directions (e.g. ‘Photograph looking SW’, or SE–NW at either end of sketch);
2. the attitude of the surface depicted (e.g. subvertical cliff, gently-dipping slab).

For some features (e.g. Riedel fractures, gouge fabrics), measurements can provide more information, for instance the orientation of the overall fault zone, if this is obscure (Worked Example 8.1, pp. 174–175).

Without a visible piercing point, the actual magnitude of slip on a fault can rarely be determined in the field, because visible offsets can result from a range of fault displacements (Figure 8.7, p. 171). Juxtaposed beds in a well-documented stratigraphic section may allow you to determine the minimum throw (vertical displacement; Figure 8.14, p. 176) of the fault, which for dip-slip faults is a useful first-order comparison (major faults have large throws). Few fault planes are exposed enough to enable addition of incremental fault slip steps (Figure 8.6c, p. 170), or slickenfibre lengths (e.g. Figure 8.6b). Since the fibres generally record only a part of the motion history, measurement of the longest fibres observed will give at best a minimum estimate.

Worked Example 8.1 Investigating a fault zone in Andalucía

Figure 8.11 View looking ESE along a narrow outcrop of Neogene sedimentary rocks (underlying brown field) that separates coherent schists (steep slopes to right) from fault rocks (pale knoll left of centre). Near El Chorro, southern Spain. (Tom W. Argles, The Open University, UK.)

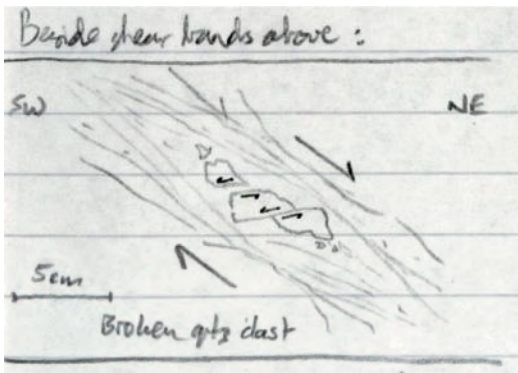
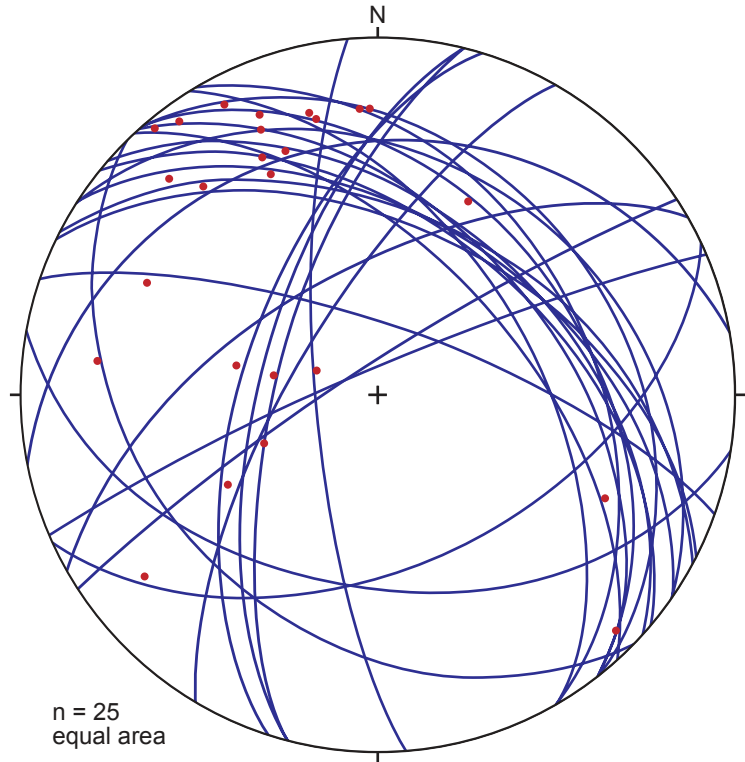


Figure 8.11 shows one of a number of exposures of crumbling, broken rock on the edge of a col between ridges of mica schist. The col is occupied by a narrow outcrop of Neogene sedimentary deposits, which it was suspected had filled the depression formed when erosion exploited a fault zone. Exposures of cataclasite with minor fractures and gouge zones confirmed that a major fault zone was present. Observations and measurements of minor fracture surfaces, gouge fabric planes and associated slickenlines were made in order to determine: (1) the orientation of the fault zone; (2) its direction of slip; and (3) its sense of motion.

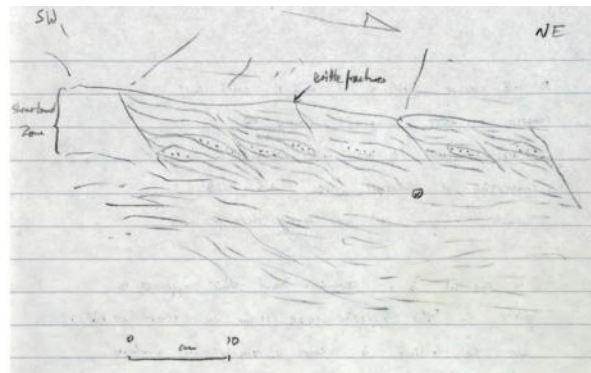
The data showed substantial variation of fracture and slickenline orientation within the fault zone, illustrated by the scatter of both sets

of data on this stereographic plot (Figure 8.12; see Appendix A8 for a note on stereographic plots). However, a large group of fractures and gouge fabrics dipped moderately to the NE, defining the attitude of the overall fault zone. Almost all slickenlines on these surfaces plunged gently between N and NW (implying oblique slip), and sparse kinematic indicators (Figure 8.13) suggested top-to-the-N shear sense. A minor subset of fractures dipping steeply W, with down-dip lineations, could represent Riedel fractures; their orientation would be consistent with the overall shear sense of the fault zone. This oblique-slip fault zone, downthrowing to the north, had helped thin the crustal section during the latter stages of its exhumation to the surface in the Betic orogenic belt.

Figure 8.12 Variable minor fracture plane data (blue arcs) and slickenside data (red dots) represented on a stereographic plot. The main group of fracture plane data is interpreted to approximate to the overall fault zone orientation (dipping moderately NE), while the main cluster of lineation data marks the overall slip direction (plunging gently NNW).



(a)



(b)

Figure 8.13 Kinematic indicators from the fault zone. (a) Broken clast of quartz vein within fault zone. (b) Suspected Riedel fractures near edge of zone. (Notebook of Tom W. Argles, The Open University, UK.)

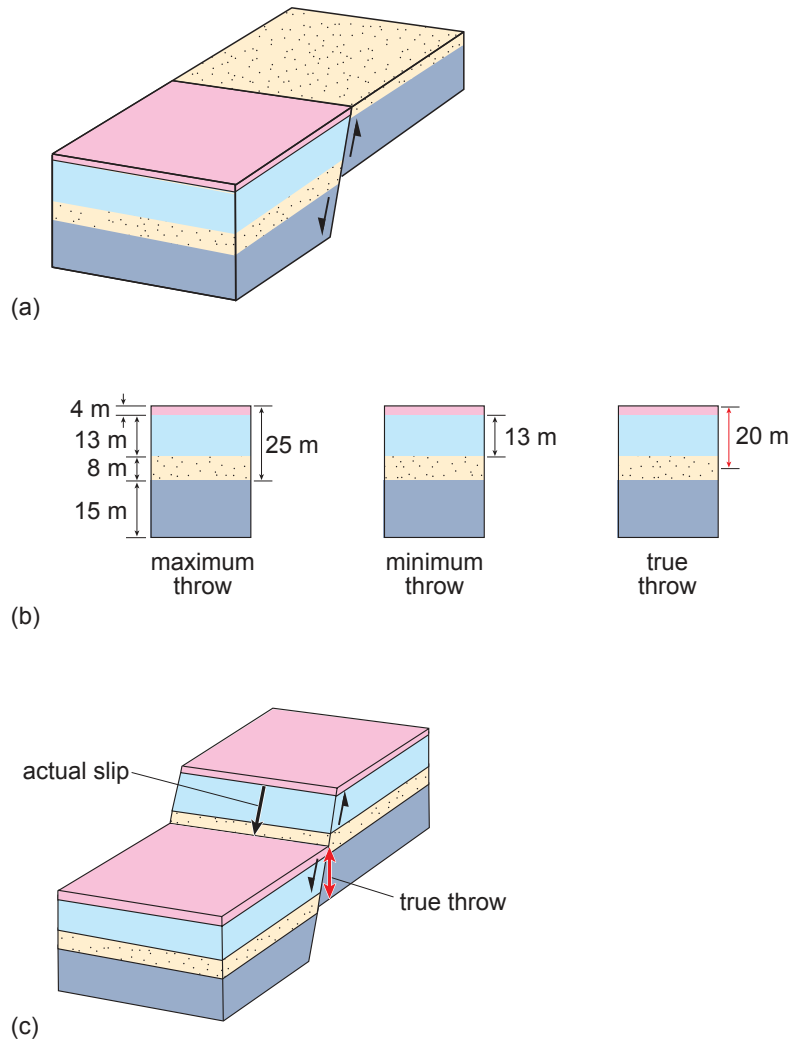


Figure 8.14 Estimating throw on a fault from known stratigraphy. (a) Two units are juxtaposed across a fault in the field. (b) Possible estimates of throw compared with true throw. (c) Block diagram representing theoretical situation if no erosion had acted on the faulted landscape.

8.3 Ductile structures: Shear zones, foliations and folds

Ductile structures tend to form at depth in rocks which, due to higher temperatures, can flow and buckle. Measuring these structures provides information on deformation deep in the crust and mantle, and stress regimes reflecting the large-scale tectonic forces that drive so much of the Earth system.

8.3.1 Orientation of ductile planar features

Tectonic fabrics (foliations) can be found in discrete shear zones (essentially, ductile faults), or they may occur

throughout the rock as regional planar fabrics. Many regional foliations form broadly perpendicular to σ_{\max} , in a response to regional tectonic forces, and vary with rock type and depth (i.e. increasing temperature, pressure). The following flowchart may help to discriminate between different foliations in the field.

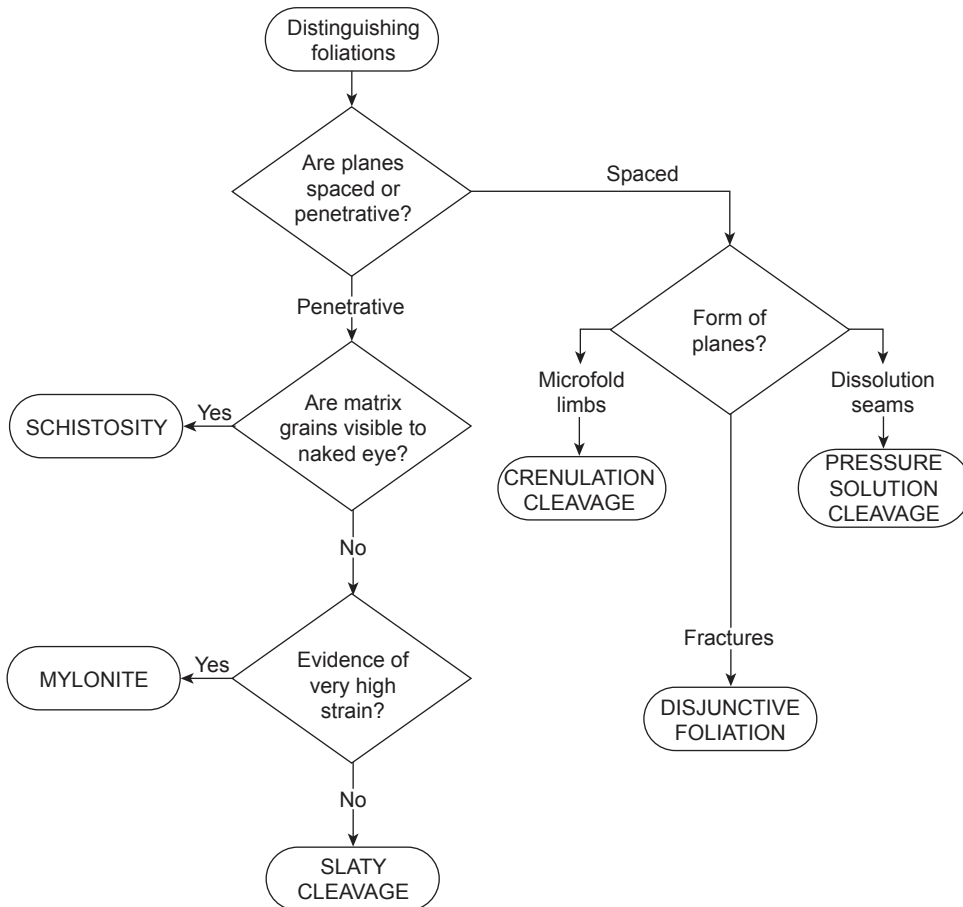


Figure 8.15 (p. 178) shows examples of different foliations to illustrate some of the differences between them, and Table 8.3 (p. 179) summarizes some characteristics of the main types of tectonic fabric.

Some mylonitic fabrics can be mistaken for slaty cleavage (or even fine-scale igneous flow banding). To confirm a mylonitic fabric, look for evidence of high strain, such as: strong stretching lineation (Section 8.3.2); strongly wrapped porphyroclasts with 'tails' (Section 8.3.3); boudinaged layers or grains; and intrafolial folds (Figure 8.16, p. 180). Original bedding structures are rarely preserved in mylonites, whereas beds are commonly traceable as folded bands of different colour and grain size in rocks with slaty cleavage. Slaty cleavage in



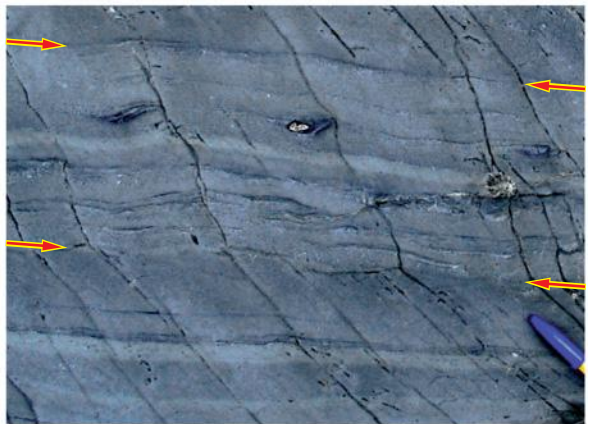
(a)



(b)



(c)



(d)



(e)



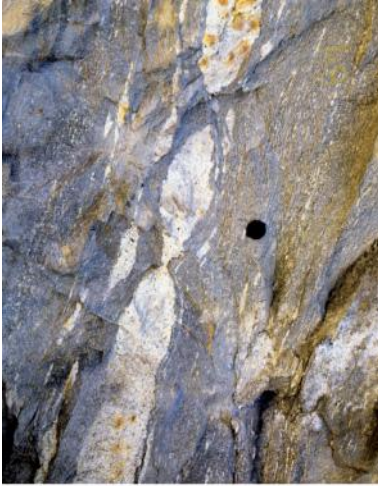
(f)

Table 8.3 Some common tectonic fabrics.

Fabric	Typical setting	Formed by	Clues in the field
Pressure solution cleavage	Upper crust, outer zones of mountain belts	Dissolution of soluble grains due to directed stress	Dark/pale colour striping; partially dissolved fossils, clasts; stylolitic surfaces
Slaty cleavage	Upper crust, outer zones of mountain belts; fine-grained rocks	Alignment of platy grains by rotation, dissolution and recrystallization during applied stress	Fine fabric that rock cleaves along; typically associated with folds
Fracture cleavage	Upper crust, outer zones of mountain belts; competent rocks	Tensional failure under high fluid pressure* in competent rock types	Spaced cracks in competent rock type
Mylonitic foliation	High strain faults and shear zones at all but shallowest depths	Extreme flattening and stretching in narrow, high-strain zones of shearing	Strongly planar fabric; other high-strain features (see text for examples)
Schistosity	Middle crust, inner zones of mountain belts; metamorphosed rocks	Mineral alignment under applied stress, during metamorphic crystallization	Visible mineral grains; millimetre- to centimetre-scale folia, rougher than slaty cleavage
Crenulation cleavage	Middle crust, inner zones of mountain belts; metamorphosed rocks	Microfolding of a pre-existing planar fabric (tectonic or sedimentary)	Microfold hinges, crenulation lineation (Section 8.3.5)

*Many of the mechanisms for cleavage formation (especially fracture cleavage) are a matter of debate.

Figure 8.15 Examples of tectonic foliations. (a) Mylonitic foliation, northwest Himalaya. High strain is indicated by the strong planar fabric and tightly wrapped porphyroclasts with tails streaked out into the fabric. (b) Slaty cleavage, visible as fine lines running from top left to lower right (two separate cleavage planes are arrowed). The cleavage cuts obliquely across bedding (dark/pale subhorizontal layers) in these fine-grained mudstones and siltstones from Cumbria, UK. (c) Spaced fractures (arrowed) cut across subvertical bedding in a limestone, southwest Wales, UK. This fabric is sometimes referred to as 'fracture cleavage'. (d) Pressure solution cleavage (thin, dark lines) in siltstones, west Wales, UK. Note also the cleavage refraction, where cleavage orientation changes abruptly across some bedding planes (arrowed), reflecting grain-size changes. There is also a very fine (barely visible) slaty cleavage parallel to the solution cleavage. (e) Subhorizontal crenulation cleavage in schist, NW Himalaya, showing clear microfold hinges. (f) Close-up view looking down on schistosity planes showing visible mineral grains, including mica. The surface of the sample cuts through numerous, irregular, millimetre-scale foliation planes. View is 4 cm across. (a–f: Tom W. Argles, The Open University, UK.)



(a)



(b)

Figure 8.16 High-strain features typical of mylonites. (a) Boudinage of a competent layer, northwest India. (b) Intrafolial folds, northwest India (view about 1.5 m across). (Tom W. Argles, The Open University, UK.)

Look closely in the hinge areas of mesoscale folds, and in 'strain shadows' where the main foliation wraps round rigid objects such as boudins and veins, for earlier fabric relationships that are commonly preserved there.

rocks of variable grain size may change orientation, gradually within a single layer, and abruptly across bedding planes separating beds with contrasting grain size. This phenomenon is known as cleavage refraction (Figure 8.15d, p. 178): in coarse-grained rocks, the cleavage tends to form at a high angle to bedding, but as the grain size becomes finer, cleavage planes may curve round until they are almost parallel with bedding. Slaty and disjunctive fabrics (pressure solution and fracture cleavage) are common in the outer zones of mountain belts, and their relationship with systematic, regional folding (Section 8.3.5) can be critical to understanding regional deformation. In the cores of mountain belts, the orientations of ductile foliations largely reflect regional tectonic stresses.

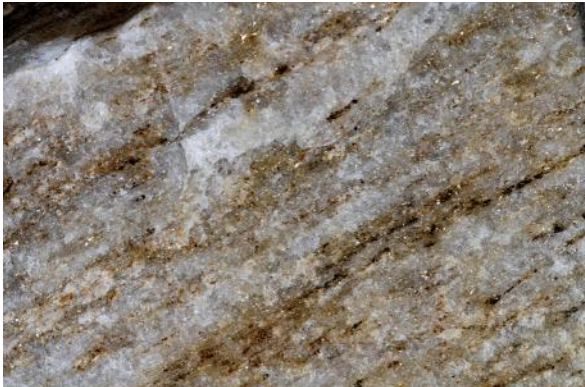
Some rocks that are affected by more than one deformation event may develop multiple fabrics. For instance, the crenulation cleavage in Figure 8.15e may retain evidence for the earlier, microfolded foliation, and in some cases the original bedding is also visible. The orientations of these earlier fabrics and associated lineations, and their relationships with later fabrics, can reveal detailed information on how the rocks were progressively deformed. In some cases, the latest deformation is so strong that any earlier fabrics are largely rotated into parallelism with the crenulation axial planes and cannot be traced, a process known as transposition.

Many coarse-grained, high-grade rocks have a planar tectonic fabric defined by aligned and/or flattened mineral grains, which has been termed 'gneissosity'. However, the same term has also been applied to centimetre-scale compositional banding in gneisses (Figure 8.17), and so is best avoided. Gneissic banding may reflect processes other than deformation (e.g. partial melting, metamorphic segregation, transposition of original lithological layering), whereas gneissic foliation is simply a coarser form of schistosity.

8.3.2 Direction of shear/stretching: Stretching lineations

When rocks deform, stretching tends to dominate in one direction, resulting in a preferred orientation of linear elements (e.g. stretched mineral grains, pebbles and fossils; or aligned elongate crystals). Lineations are most easily measured on foliation planes (if they exist: see Figure 8.18). Large areas of consistent lineations are likely to reflect regional stress orientations, whereas lineation trends in narrow zones generally indicate the direction of motion on those major shear zones. You should always record what defines a lineation (e.g. stretched quartz grains, aligned belemnites) at the same time as recording its orientation, as this may provide information on the metamorphic history of a deformed rock.

Figure 8.17 Gneissic banding: compositional layering on a centimetre scale in a coarse-grained gneiss, Bhutan. It is difficult to tell whether this banding has a sedimentary, tectonic or metamorphic origin without detailed petrographic or geochemical analysis (Tom W. Argles, The Open University, UK.)



(a)



(b)



(c)



(d)

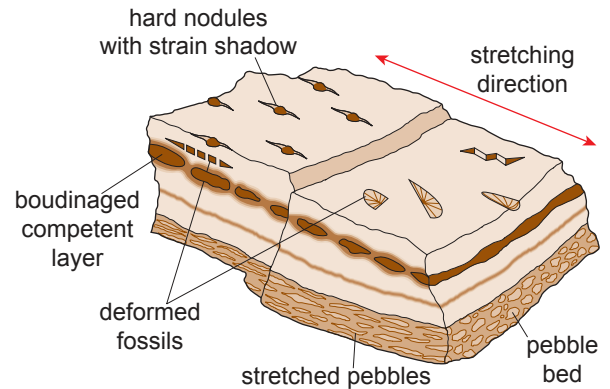
Figure 8.18 Stretching lineations. (a) Stretching lineation defined by stretched grains of quartz and biotite in a mylonitic quartzite (5 cm across). (b) Weakly aligned orthopyroxene grains roughly define the stretching direction in a mantle peridotite (base of sample is 10 cm across). (c) Stretching lineation defined by elongate amphibole crystals in an amphibolite that lacks foliation (base of sample is 8 cm across). (d) High-strain gneiss with orthogonal faces cut parallel (left face) and perpendicular (right face) to stretching lineation, which is faintly visible as colour streaking on the top surface (weathered foliation). Note that the left face (parallel to the lineation) appears much more sheared than the other cut face: this can be a useful feature to look for on an irregular exposure when searching for stretching lineations. Line on top surface is part of the marking originally used to orientate the specimen. (Right face is 5 cm across.)

You may be able to distinguish with a hand lens between stretched grains (stretching lineation) and elongate grains that have grown or been rotated into parallel orientations (alignment lineation). Some igneous rocks show weak alignments of elongate phenocrysts due to flow of magma (magmatic lineation).

Care is needed to distinguish stretching lineations from other lineations such as intersection lineations (Section 8.3.5) or striations (Figure 8.6c, p. 170). Examine the mineral grains with a hand lens to confirm their stretched nature, and corroborate your initial impression of the stretching direction with other clues, such as stretched pebbles, fossils, quartz lenses, boudinaged veins or layers, tension gashes and pressure shadows (e.g. around porphyroblasts or porphyroclasts). Some examples of features to look for as clues for stretching directions are given in Figure 8.19.



(a)



(b)

Figure 8.19 Clues to the stretching direction. (a) Dilational fractures perpendicular to a mineral lineation on this mylonitic foliation plane confirm the stretching direction, northwest India. (b) Composite sketch depicting clues to the stretching direction. ((a)Tom W. Argles, The Open University, UK.)

8.3.3 Sense of shear: Kinematic indicators

One of the most critical observations in zones of ductile deformation is the shear sense. Consistent shear indicators constrain the sense of motion on major ductile shear zones in the same way as faults, but the shear strain is commonly distributed across a wider area.

With kinematic indicators, it's always a case of 'the more the merrier'! You may find that not all the indicators share the same shear sense. Only if you find that *most* indicators are

When determining sense of shear, always observe features in a plane that cuts the foliation at a high angle, and *parallel* to the stretching lineation.

consistent should you infer a definite, non-coaxial shear sense.

In zones of strong non-coaxial (simple) shear strain, one shear sense dominates most, if not all, kinematic indicators. Some rocks may have been subjected to more than one episode of shearing, however, commonly under different conditions (pressure, temperature, fluid, etc.). Later shear fabrics and kinematic indicators may have partially overprinted earlier ones, so it is important to note which features you have used to deduce which sense of shear, as well as their orientations. Figure 8.20 provides some examples of common ductile shear sense indicators.

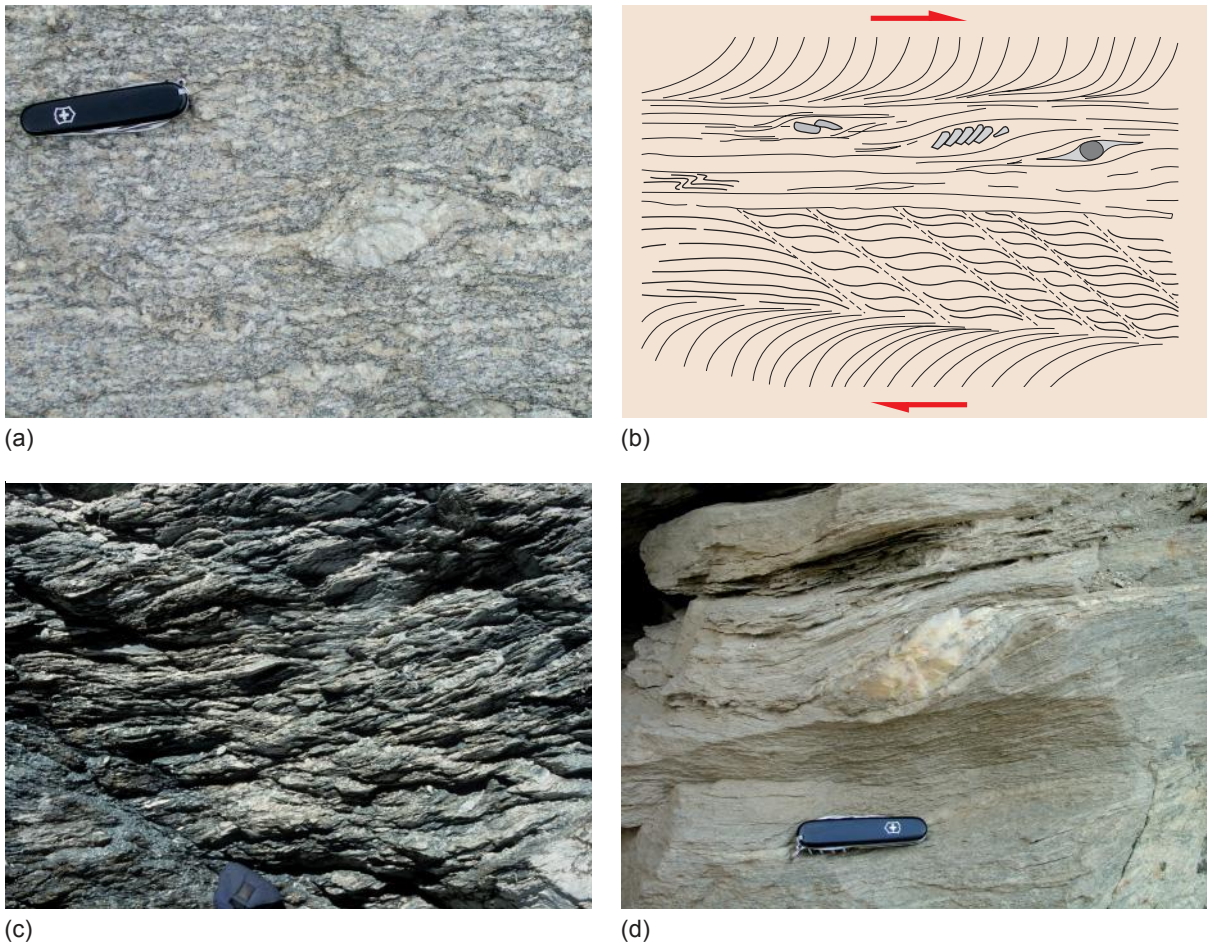


Figure 8.20 Ductile kinematic indicators, all indicating dextral ('top-to-the-right') shear sense. (a) Asymmetric tails on feldspar porphyroclasts in a mylonite, northwest India. (b) Composite sketch depicting various features used for determining shear sense (width c. 40 cm). (c) S-C fabric (shear band cleavage) in a mica schist, Switzerland. Camera case near the base is 25 cm across. (d) Asymmetric pressure shadows on a boudin in a gneiss, northwest India. (a, c and d: Tom W. Argles, The Open University, UK.)

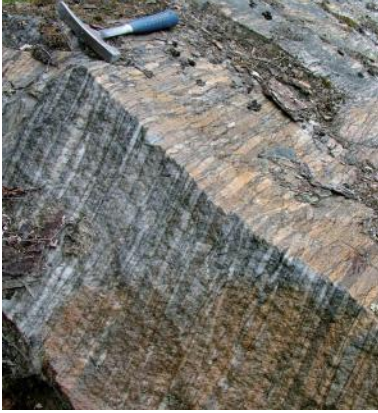


Figure 8.21 A deformed conglomerate showing flattening of pebbles that were probably much nearer spherical in the original sediment, Bhutan. (Tom W. Argles, The Open University, UK.)



(a)



(b)



(c)



(d)

Figure 8.22 Examples of different fold tightness. (a) An open fold in low-strain strata, near Minehead, Somerset, UK. (b) Tight folds indicating high strain are cross-cut by an undeformed (later) granite (top), Glen Gairn, Scotland. (c) Isoclinal folds show intense strain in metamorphosed mudstones (dark) and sandstones (pale brown), southern Spain. (d) Monocline in Carboniferous sedimentary rocks, Northumbria, UK. Hammer near centre for scale. (a and d: Angela L. Coe, The Open University, UK. b and c: Tom W. Argles, The Open University, UK.)

8.3.4 Magnitude of shear strain

Assessing how much strain a rock has undergone is seldom easy. In rare cases a deformed object can be compared with its known shape and size before deformation (e.g. a fossil). High-strain rocks tend to show strong parallelism of planar and linear ductile elements, while aspect ratios of more rigid objects increase at higher strains. Roughly spherical objects (e.g. ooids, pebbles, reduction spots) will deform into ellipsoids (Figure 8.21), with a ratio of long to short axes that can yield an estimate of the strain magnitude.

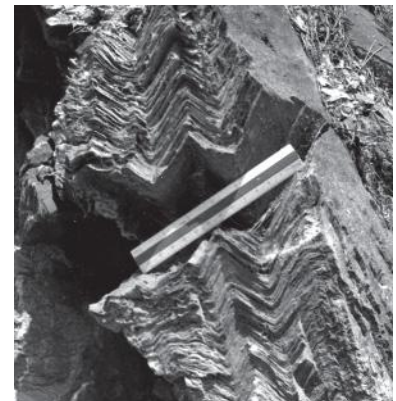
8.3.5 Fold analysis

Many rocks contain planar surfaces that bend during deformation, forming folds of diverse shapes. Describing and sketching fold types can yield useful information on their host rock and the conditions under which they formed (temperature, depth, strain intensity). The general anatomy of a fold is illustrated in Figure A8.2 (Appendix 8).

Size, shape and orientation should be considered in describing folds. Fold sizes can be summarized by recording their amplitudes and wavelengths (e.g. on a sketch). Folds occur at all scales, and minor folds superimposed on a larger fold occur commonly during a single deformation event. Fold shape is very variable, and can be described in a number of ways. You should note the direction of fold closure (antiform or synform?), and the interlimb angle (Figure A8.3), which gives a clue to the amount of strain the folded rocks have experienced. Open folds reflect relatively low strains, whereas isoclinal folds indicate high strain intensities typical of shear zones at depth in orogenic belts (Figure 8.22). The shape of the folded layer in the profile plane is also important; are the folds in a series of neatly stacked chevrons (Figure 8.23a), or are they disharmonic (Figure 8.23b)? Are successive layers parallel, or similar in shape (Figure 8.23c and d)? Fold shape reflects the relative competence of the layers at the time of fold formation.

In complex deformed zones such as orogenic belts, way-up evidence becomes important. Strata, and even whole structures, may be inverted. The younging direction of way-up features (e.g. erosion structures, graded bedding), determined parallel to

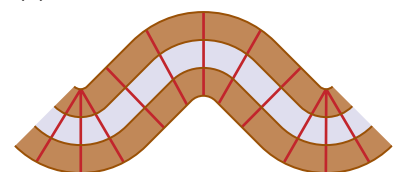
Folds are best observed (and sketched) in the profile plane, i.e. at 90° to the fold axis, if possible. This section through a fold represents its key characteristics (symmetry, shape, etc.) most faithfully.



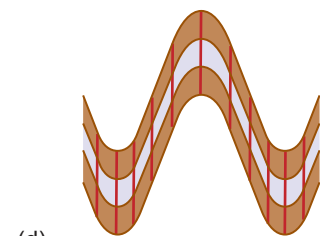
(a)



(b)



(c)



(d)

Figure 8.23 Examples of different fold shapes. (a) Chevron folds, common in uniformly layered strata at relatively shallow crustal levels, Tennessee, USA. (b) Disharmonic folds reflect contrasting rheologies of different layers. (c) Parallel folds imply competent layers. (d) Similar folds, with thickened hinge areas and thinned limbs, suggest weaker rocks that can deform easily. (a: Courtesy of the U.S. Geological Survey; Photographer W. B. Hamilton. b: Tom W. Argles, The Open University, UK.)

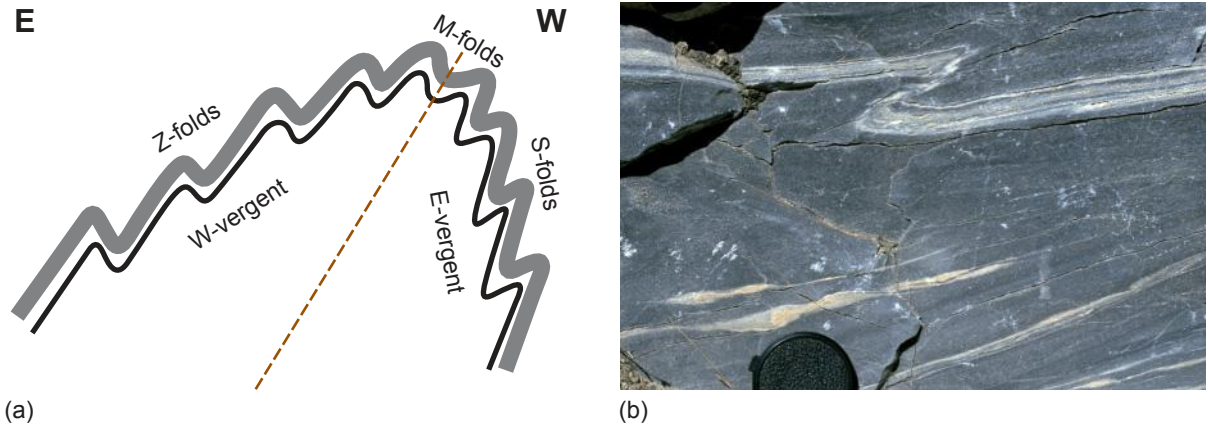


Figure 8.24 Information from fold asymmetry. (a) Schematic cross-section showing an example of how fold asymmetry (and vergence) changes across a fold axial plane (red line). (b) Isolated asymmetric fold in calcareous mylonite, implying dextral (top-to-the-right) shear, Switzerland. (Tom W. Argles, The Open University, UK.)

the fold axial surface, defines whether a fold is upward- or downward-facing. If you find the latter, this indicates that the fold has been affected by at least two distinct deformation events, a valuable deduction from an isolated exposure.

Symmetric folds have limbs of equal length that are mirror images either side of the hinge, but many folds are asymmetric (Figure 8.24). Fold asymmetry may help constrain the following:

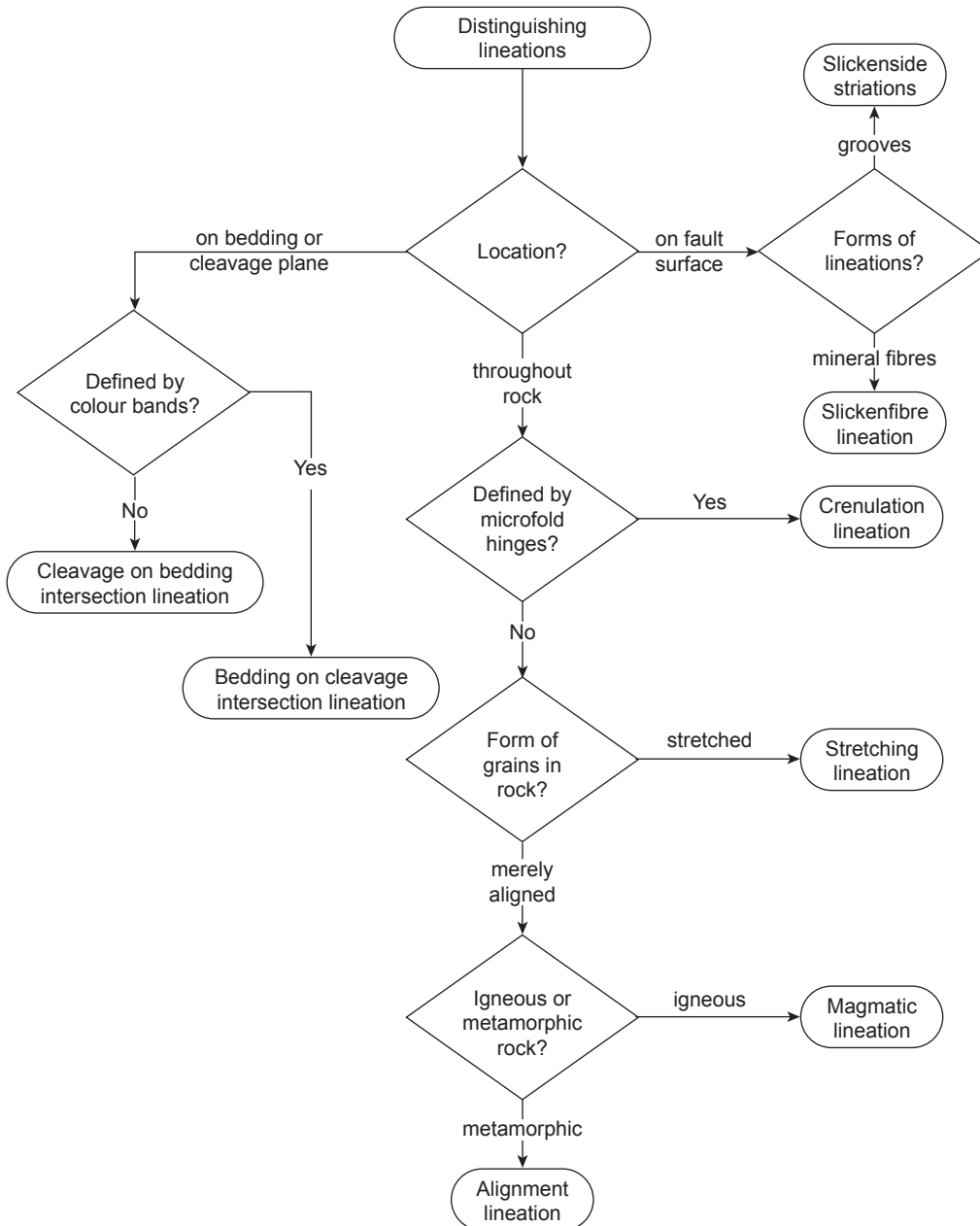
- for minor folds, their asymmetry changes across a major fold hinge – a useful aid in mapping (Figure 8.24a);
- asymmetric shear-related folds may be good kinematic indicators for shear zones (Figure 8.24b).

However, it is the *orientation* of folds (Appendix A8, Figure A8.4) that relates directly to either local or regional tectonic stresses, which raises the question of what exactly to measure. You should measure the following elements if possible (using your preferred notation; Table 8.1):

Fold axial plane	dip and dip azimuth	e.g. 83/147
Fold axis (hinge line)	plunge and plunge azimuth	e.g. 11/056

How are these theoretical elements measured? Fortunately, an associated axial-planar cleavage will be roughly parallel to the

fold axial plane, and can be readily measured. If the cleavage orientation is strongly affected by cleavage refraction (Section 8.3.1), estimate the overall orientation of the cleavage across several beds – this will approximate to the axial plane of the associated fold. If a later *transecting* cleavage cuts across folds, it is very unlikely to be axial-planar to them. Intersection or crenulation lineations may also be useful: the flowchart below shows how to discriminate between different lineations (see

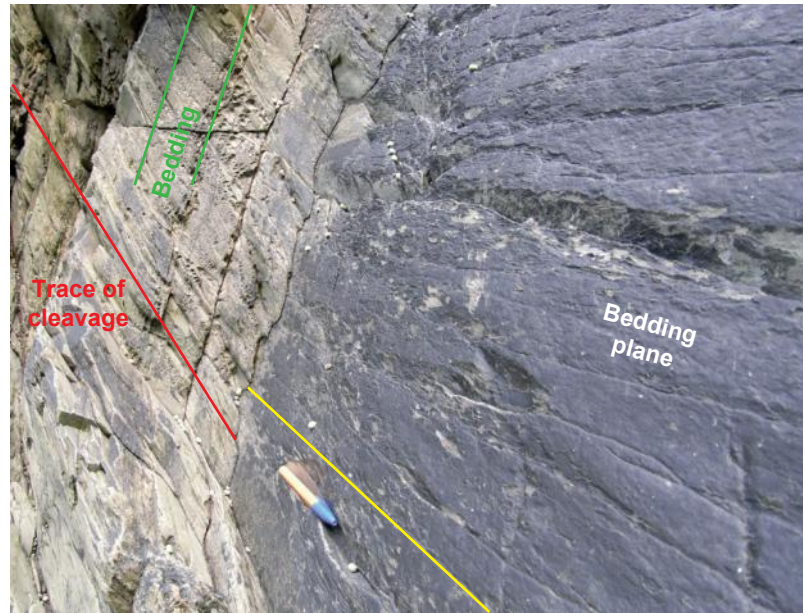


Where an axial-planar cleavage intersects a folded bedding plane, the resulting intersection lineation (Figure 8.25a) is parallel to the fold axis. These lineations are typically easier to find and measure than the corresponding fold axis, as they can occur anywhere on the fold (Figure 8.25b).

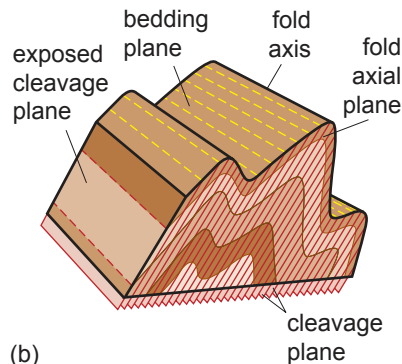
also Figure A8.5). In some cases the fold hinge line, which generally equates to the fold axis, may be easy to measure, but if a hinge is not accessible, the following tricks may help.

An intersection lineation of cleavage on bedding is typically visible in the field as thin, dark lines on bedding planes, whereas bedding on cleavage intersections tends to show up as stripes of different colour where successive beds intersect the cleavage plane. Hinges of minor folds formed at the same time as the major fold may also define a lineation that is parallel to the major fold axis. This is known as a crenulation lineation (Figure 8.25c), and is easily measured along the hinges of the minor folds. An example of how to separate different tectonic fabrics is provided in Worked Example 8.2.

Figure 8.25 Approximations to fold axes. (a) Thin grooves and lines (parallel to yellow line) on dark-grey bedding plane are the intersection of cleavage with bedding. Bedding plane dips steeply to the left. Cleavage traces (parallel to red line) are visible in the vertical joint surface on the left of the photograph, cutting through steeply-dipping sedimentary layers (marked with green lines); west Wales, UK. (b) Diagram showing relationship of intersection lineations with a major fold structure; folded beds are shown in shades of brown. Intersections of cleavage on bedding are marked by dashed yellow lines on the folded, mid-brown bedding plane; intersections of bedding planes on cleavage (marked as dashed red lines) are shown on the steep cleavage plane on the left-hand side. The two lineations are both parallel to the fold axis. (c) Crenulation lineation, defined by the hinges of millimetre-scale folds, on the limb of a larger fold that is not visible in the field; Strath Fionan, Scotland. (a and c: Tom W. Argles, The Open University, UK.)



(a)



(b)



(c)

Worked Example 8.2 Unravelling multiple tectonic fabrics and folding

A series of interbedded psammitic and pelitic schists displayed numerous folds, mainly with subhorizontal axial planes, and a dominant micaceous schistosity, also generally flat-lying. In many exposures, the main foliation lay almost parallel with the original bedding. However, in some exposures (e.g. Figure 8.26), this parallelism was shown to be a result of transposition, so the main foliation formed axial-planar to the abundant, flat-lying folds.

Further detailed study of the schists highlighted a few exposures of low-strain zones, in the hinge

areas of 10m scale folds and near quartz vein boudins (Figure 8.27), where the main foliation (S3) was revealed to be a crenulation of an earlier, coarse schistosity (S2).

On close inspection, this earlier schistosity appeared to be differentiated into mica- and quartz-rich layers, typical of fabrics formed originally by crenulation. This hypothesis was supported by the observation of an even earlier fabric (S1), oblique to S2, that was only visible as inclusion trails within albite porphyroblasts that grew during formation of S2 (Figure 8.28).

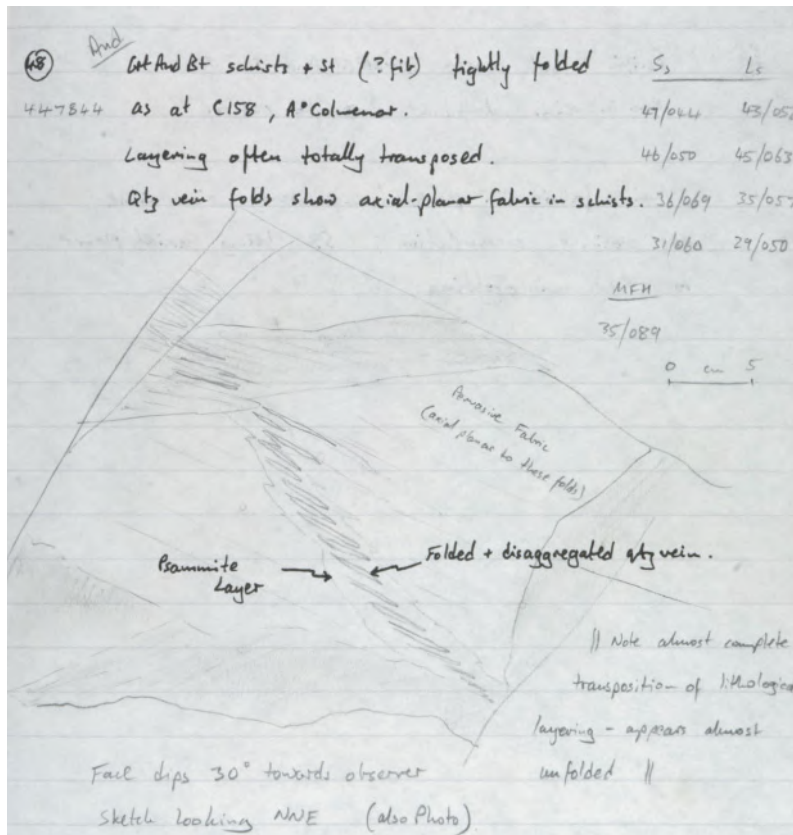


Figure 8.26 Page from a field notebook with sketch showing transposition of lithological layer in strongly deformed schists. (Notebook of Tom W. Argles, The Open University, UK.)

Figure 8.27 Sketch from a field notebook showing lower-strain zone near quartz vein where main foliation (S3) can clearly be seen to be a crenulation of an earlier schistosity (S2). (Notebook of Tom W. Argles, The Open University, UK.)

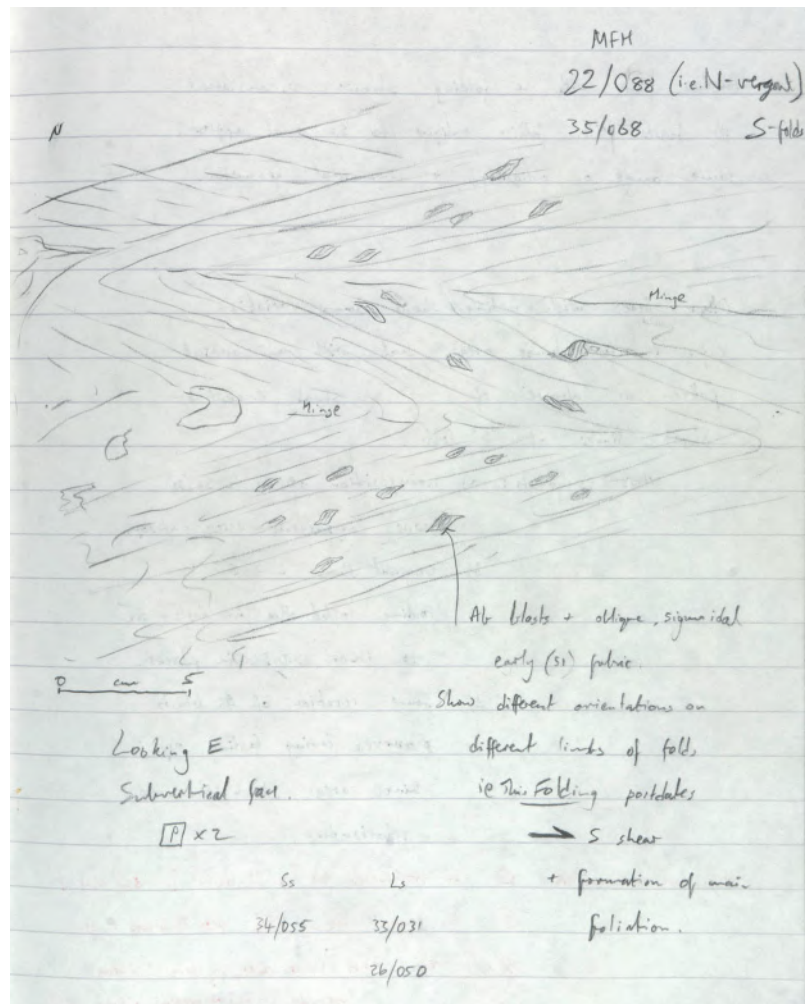
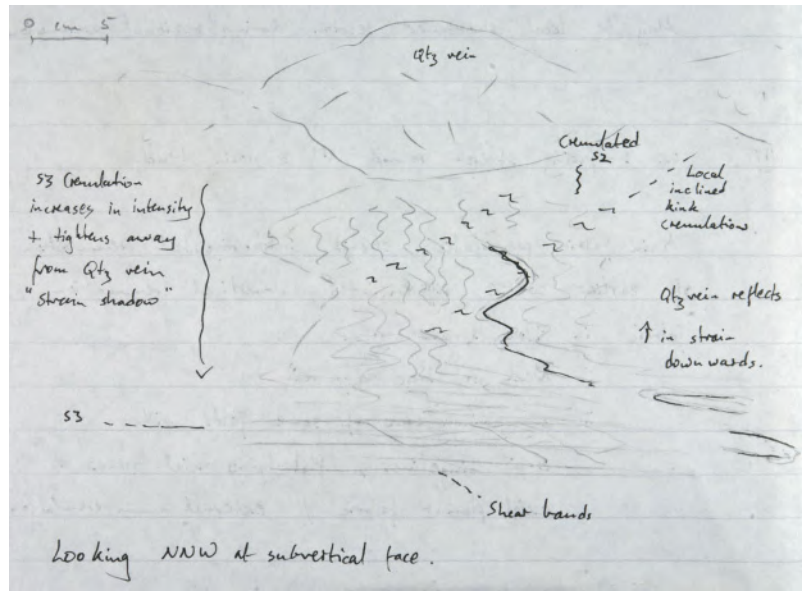


Figure 8.28 Sketch of albite porphyroblasts with curved, oblique included fabric, wrapped by foliation (S2) that is itself also tightly folded, with a weak axial-planar fabric (S3). (Notebook of Tom W. Argles, The Open University, UK.)

This relationship was very rarely visible in the field, and had to await confirmation following study of thin-sections.

A summary of the structural history was proposed based on the following observations.

- Formation of first tectonic fabric, a fine cleavage. Evidence was too sparse to determine whether this fabric formed during folding of sedimentary layers, or by burial and compaction.
- Microfolding of S1 cleavage to form S2, during heating and growth of metamorphic minerals (e.g. albite, staurolite).
- Folding of S2 crenulation cleavage to form numerous folds and a related, axial-planar crenulation fabric, S3. The flat-lying orientation of the fold axial planes and S3 foliation imply this deformation phase involved vertical thinning (and hence horizontal extension).

8.4 Further reading

- Davis, G. H. 2009. *Structural Geology of Rocks and Regions*, John Wiley & Sons, 635 pp. [Clear, readable text on structural geology and tectonics, with illustrations, explanation of techniques, and experiments.]
- McClay, K. R. 1991. *The Mapping of Geological Structures*, John Wiley & Sons, 168 pp. [A small-format book focusing on how to map, record and analyse geological structures.]
- Park, R. G. 1997. *Foundations of Structural Geology*, Routledge, 216 pp. [Good, simple, introductory-level text.]
- Ragan, D. 2009. *Structural Geology: An Introduction to Geometrical Techniques*, Cambridge University Press, 624 pp. [This book focuses on geometrical analysis of structural problems, including the use of stereographic projections.]
- Ramsay, J. G. and Huber, M. I. 1984. *The Techniques of Modern Structural Geology Volume 1: Strain Analysis*, Academic Press, 307 pp. [Rigorous and well-illustrated text covering all methods of strain analysis.]
- Ramsay, J. G. and Huber, M. I. 1987. *The Techniques of Modern Structural Geology Volume 2: Folds and Fractures*, Academic Press, 391 pp. [Rigorous, well-illustrated text on the analysis of folds and fractures (faults).]
- Twiss, R. J. and Moores, E. M. 2007. *Structural Geology*, W. H. Freeman & Co., 532 pp. [Attractive textbook with numerous diagrams and illustrations, covering both theoretical and practical aspects of structural geology.]
- Van der Pluijm, B. and Marshak, S. 2004. *Earth Structure – an Introduction to Structural Geology and Tectonics*, W. W. Norton & Co., 672 pp. [Illustrated textbook that uses examples and analogies effectively to explain structural geology and tectonics.]

9 Recording features of metamorphic rocks

Tom W. Argles

The environments in which metamorphic rocks form are a long way from our everyday experience: crushing pressures, baking temperatures, and stresses that stretch and distort rocks weakened by the high temperatures. Studying the textures and mineralogy of the rocks that have been exhumed to the Earth's surface is a fascinating window into these alien environments, and gives critical insights into how the Earth works, the processes operating in active mountain belts and subduction zones, and how crustal and mantle materials are recycled. Metamorphic processes play a key role in concentrating a number of useful elements into economically viable mineral deposits, so metamorphic studies are critical in the exploration and exploitation of such resources.

This chapter will consider common metamorphic textures and minerals, before examining how we can extract information about the timing of different metamorphic processes from metamorphic rocks in the field.

9.1 Basic skills and equipment for metamorphic fieldwork

Metamorphic study in the field needs little more than the basic equipment (Table 2.1, p.4). You will also find simple aids to mineral identification (e.g. a scratch/streak plate, a steel penknife and dilute acid) from the optional equipment in Table 2.3 useful. Field study of metamorphic rocks mainly requires keen observation at all scales, in particular of fine-scale textures (Section 9.2) using the hand lens, and mineral identification (Section 9.3).

9.1.1 Field relations and context

Before focusing in detail on an exposure, consider its wider context. Is the rock layered, massive or patchy in appearance? Are there cross-cutting relationships or contacts between

different rock-types? Is there an intrusion nearby? You should note such gross features, as they are likely to provide critical clues to the original, pre-metamorphic lithology of the rock (its protolith), and suggest likely associations of rocks that may be present. Considering the rock as a whole (e.g. colour, density, hardness, weathered aspect) may offer clues to its key minerals. For instance, a mafic rock is likely to contain dark-coloured, mafic minerals (biotite, amphibole, pyroxene, etc.). Worked Example 9.1 shows how diverse clues to a mineral's identity can be assembled.

Many metamorphic rocks are deformed, so familiarity with structural features (Chapter 8 and Section 9.4) is also a real asset in describing and interpreting metamorphism in the field.

Worked Example 9.1 Mineral identification in southern Spain



Figure 9.1 Dark grey prisms in a fine-grained schist from southern Spain. Sample is c. 15 cm long.

Figure 9.1 shows a hand specimen of fine-grained, grey schist with darker grey prisms of a porphyroblast mineral that is not easily recognizable; it could be one of several common minerals, including chloritoid, andalusite or amphibole. As a result, several clues were used to aid identification in the field:

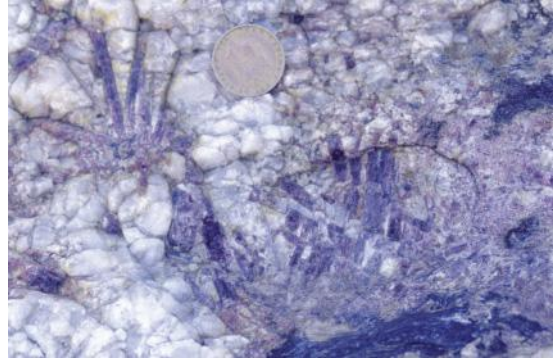
- prismatic shape, with roughly equidimensional end-sections;
- lithological association – a layered series of grey pelitic and beige sandy metasediments;
- metamorphic grade – finely crystalline, so most likely low to medium grade;
- associated minerals – garnet, biotite, muscovite (garnet zone);
- host rock – prisms abundant in grey, aluminous pelites, but absent from sandy layers.

Subsequently, abundant synmetamorphic veins throughout the study area were found to contain well-formed crystals of one or more of the aluminosilicate polymorphs (andalusite, kyanite and sillimanite; Figure 9.2). Mapping, combined with thin-section studies, showed that the Al_2SiO_5 minerals in the veins matched those in the host schists, defining a set of metamorphic

zones. In addition, textures in the veins confirmed the relative timing of growth of the three polymorphs, with early kyanite replaced by sillimanite or andalusite, depending on the temperature conditions.

In this example, the abundance of the grey prisms in this particular location is a final hint: this part of Spain is known as Andalucía.

Figure 9.2 Well-formed prisms in a synmetamorphic vein observed not far from the schist in Figure 9.1 show the characteristic pink colour of andalusite. These crystals lack the numerous graphite inclusions that give andalusite – and other porphyroblasts in the surrounding schists – a dull grey colour. (Tom W. Argles, The Open University, UK.)



9.2 Textures

Study of metamorphic textures should not be left until you have access to a petrographic microscope. Careful observation in the field can help build an early understanding of complex rocks, avoid misleading assumptions and help with both sampling and collection of field data.

BEWARE! Grain-size variation in metamorphic rocks may not be a reliable indicator of relict sedimentary layering, as grains may be enlarged or reduced during metamorphism (e.g. Figure 9.3).

9.2.1 Banding

Many metamorphic rocks contain tectonic fabrics (Section 8.3.1), but they may also preserve the compositional layering of the protolith (e.g. sedimentary bedding; Figure 9.3). The former will be defined by aligned or flattened mineral grains, whereas the latter is best distinguished by variations in colour and mineralogy. Look for relict sedimentary features in low-grade rocks (e.g. cross-lamination, sole marks) as confirmation.

A third class of banding is metamorphic in origin, involving segregation of minerals into adjacent bands. This may occur at low grades, involving preferential dissolution of some minerals to produce a spaced cleavage picked out by alternating bands of light (quartz, calcite) and dark (micas, insoluble oxides, clays) minerals (Figure 8.15d). In higher grade rocks such as gneisses, coarser bands (Figure 9.4a) may reflect different processes forming or enhancing the bands, such as crenulation of an earlier foliation, or incipient partial melting.



Figure 9.3 Interlayered metapelites and metapsammities, Spain. Metamorphic minerals have grown much coarser in the pelites (right half of view) than in the psammities (under lens cap), where quartz grains may even have been reduced in size due to recrystallization under strain. The relative grain sizes of the original sediments are thus reversed, and their colour and inferred compositions are much better guides to their protoliths than grain size. (Tom W. Argles, The Open University, UK.)



(a)



(b)

Figure 9.4 (a) Gneissic banding defined by alternating felsic (pale) and mafic (dark) bands on a centimetre scale, northwest India. Subtler colour variation on a larger scale (5–10 bands width) suggests that the original precursor was compositionally layered (sedimentary or volcanic). Field of view is about 5 cm across. (b) Cross-stratification in metaquartzite picked out by colour bands caused by concentrations of heavy minerals; original younging direction is therefore to the right. Penknife at base for scale. (a and b: Tom W. Argles, The Open University, UK.)

Distinguishing metamorphic banding from inherited sedimentary layering may be almost impossible in some gneisses where all sedimentary evidence has been erased. Look for evidence of compositional variation that is distinct from the dominant alternation of mafic and felsic gneissic bands – for example, in a series of pelitic or psammitic gneisses, layers

with calc-silicate or carbonate minerals (e.g. amphibole, diopside, calcite), which typically reflect calcareous beds in the original sediments. Many such compositionally distinct layers have contrasting competence to the other gneiss layers, and are commonly boudinaged. Gneisses formed from igneous precursors with phenocrysts of strong minerals (e.g. feldspar and pyroxene in granitoid and gabbroic rocks) typically display an augen texture unless very strongly deformed. The strong phenocrysts resist recrystallization better than the matrix, which wraps round the large grains so they appear eye-shaped. Augen may form through a combination of metamorphic growth and deformation in some metasedimentary gneisses, but original compositional variation between beds generally means that the abundance or even type of augen also varies. Gneisses derived from porphyritic intrusions tend to show little variation in character on a decimetre to metre scale.

9.2.2 Grain textures

A key observation is whether the rock displays orientated crystals (typical of deformed, regionally metamorphosed rocks), or granular texture. The latter may indicate contact metamorphism caused by a nearby igneous body (a hornfels; Figure 9.5a), a low-strain domain where metamorphic grain growth has dominated or erased strain features (Figure 9.5b), or post-kinematic crystal growth where regional heating has outlasted deformation (Figure 9.1, p.193).

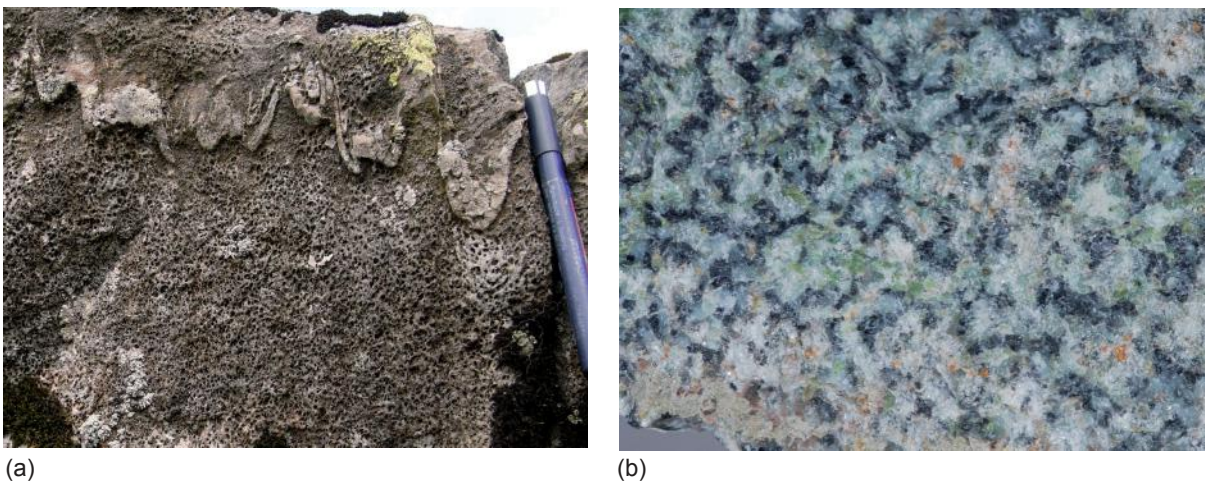


Figure 9.5 Grain textures. (a) Granular texture in a contact-metamorphosed hornfels, northern England. Cordierite grains have been weathered out, but the texture is preserved in the resistant quartz matrix. Field of view is 25 cm wide. (b) Granular texture in an eclogite-facies gabbro, where strain was partitioned into weaker rocks nearby; Switzerland. Field of view is 4 cm wide. (a and b: Tom W. Argles, The Open University, UK.)

Overall grain size tends to increase with increasing metamorphic grade, and is a good general guide for this (e.g. gneisses are typically coarser than schists; Figures 8.16–8.20). However, high strain can commonly *reduce* grain size (e.g. in mylonites). Moreover, some grains (typically of one particular mineral) may grow much larger than others, becoming porphyroblasts in a fine matrix (e.g. Figure 9.1). To determine metamorphic grade in the field, therefore, you need to consider mineral assemblages (Section 9.3.2) as well as grain size.

9.2.3 Reaction textures

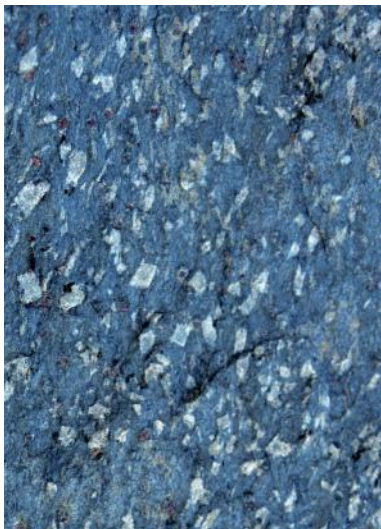
Textures recording reactions are valuable for piecing together the metamorphic history of a rock; some common examples are outlined below.

Pseudomorphs

Pseudomorphs are aggregates of new mineral grains that have formed by alteration or replacement of a pre-existing porphyroblast. In many cases, the aggregate retains the form of the original crystal precursor, which may be identified as a result (Figure 9.6a). New minerals within the aggregate may be identifiable using the hand lens. If either the original mineral or its replacement can be identified, the changes in pressure (P) and/or temperature (T) conditions may be inferred.

Coronas

Coronas may indicate partial replacement of a mineral by another, or represent a rim of new mineral formed at the interface between two others (Figure 9.6b).



(a)



(b)

Figure 9.6 Reaction textures in the field. (a) Pseudomorphs of fine-grained white mica and clinozoisite (Ca,Al silicate) after lawsonite in a retrogressed blueschist, Switzerland. The lawsonite is inferred partly from crystal shape (rhombs). Largest rhombs are 5 mm across. (b) Corona texture in an eclogite, Switzerland. Thin red garnet separate white pseudomorphs of talc (after olivine) from pale bluish zoisite (after plagioclase) and green clinopyroxene. (a and b: Tom W. Argles, The Open University, UK.)

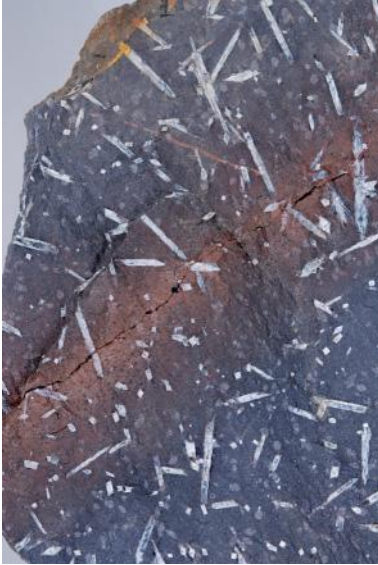


Figure 9.7 Metasomatic colour change (reddening) indicating fluid alteration either side of a crack. This rock was found adjacent to a fault zone with extensive reddening by haematite metasomatism. Field of view is 7 cm across. (Tom W. Argles, The Open University, UK.)

Many minerals in metapelites are crammed with inclusions of graphite, and hence look dark grey, regardless of their 'diagnostic' colour (e.g. andalusite in Figure 9.1).

Reaction zones

Zones marked by colour (and mineral) changes may reflect local metasomatism, for instance by hot fluids penetrating along cracks (Figure 9.7), or moving through the rock as a fluid front.

9.3 Mineralogy

9.3.1 Identifying common metamorphic minerals

Some minerals are easily identified in the field, but many minerals vary in their appearance from rock to rock. If in doubt about their identity, note their properties (colour, shape, lustre, cleavage, etc.) and sketch examples. You may need to adopt various strategies to collect the information, such as:

- describing the appearance of weathered grains (a weathered mineral may look very different – for instance cleavage may be picked out more clearly although the colour is dulled);
- noting the properties of minerals on a fresh surface (look for freshly broken pieces first before hammering);
- wetting a surface, which may help clarify colour and texture (or simply remove dust);
- concentrating on minerals that are abundant, porphyroblastic, fabric-forming or potential index minerals (Section 9.3.2);
- using mineral identification charts as necessary;
- noting the crystal shape and habit (this is a much better aid to identifying metamorphic minerals than colour, which can be variable and affected by other factors such as inclusions and alteration).

Table A9.1 in Appendix A9 lists the properties of many common metamorphic minerals. Figure 9.8 illustrates some reliable diagnostic features of common metamorphic minerals.

If you cannot identify a mineral in the field, you may need to collect a sample for further tests in the laboratory. Note any unusual characteristics of common minerals, and explain your identification of less common phases. As far as possible, note down the relative proportions of the minerals in the rock using the percentage charts in Appendix A1, Figure A1.1, to avoid later misinterpretation of composition or grade.

9.3.2 Using mineral assemblages

Identification of the minerals and mineral assemblages gives important information on:

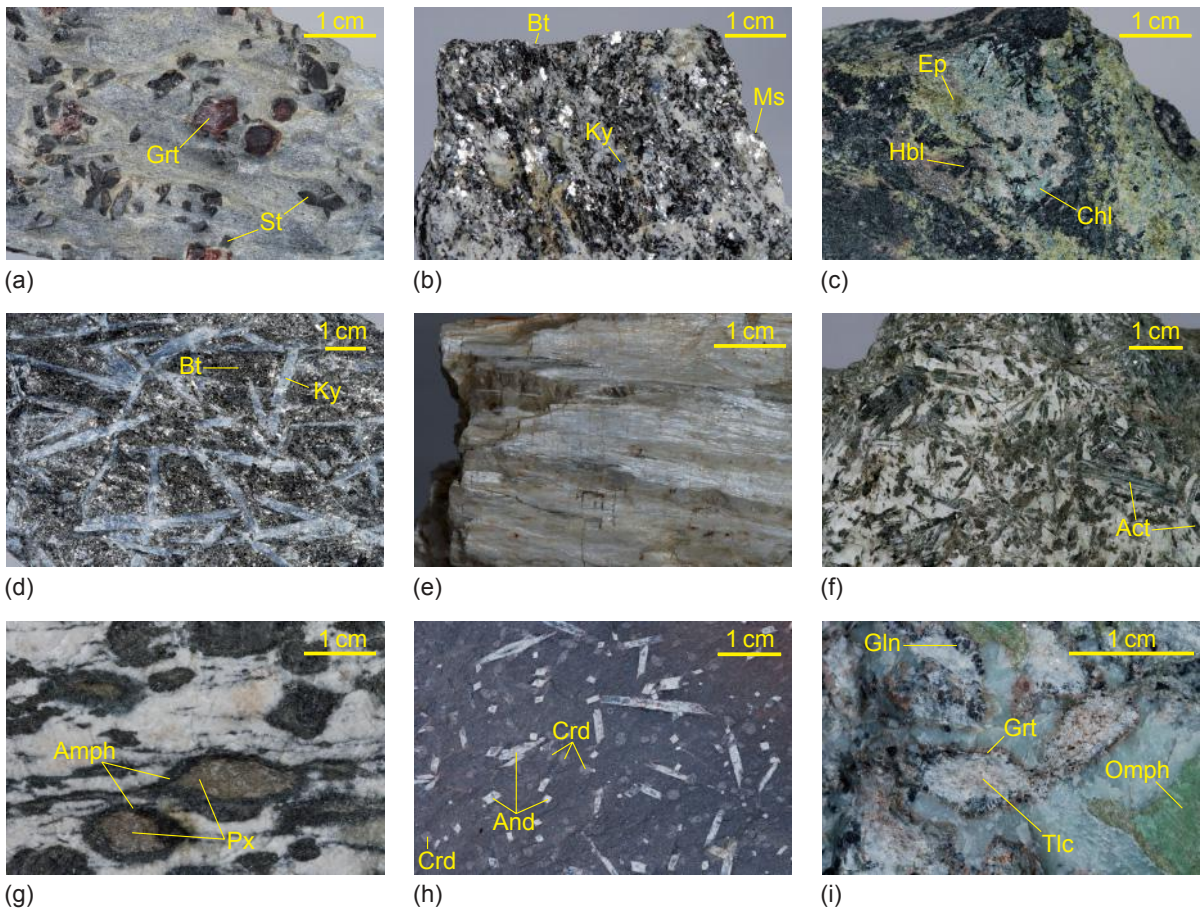


Figure 9.8 Examples of common metamorphic minerals. (a) Typical rounded crystals of dark red garnet (Grt), wrapped by a tectonic fabric. Dark prisms with pointed ends are staurolite crystals (St), appearing black due to graphite inclusions. The crystal shape is a better diagnostic feature than colour. Staurolite is characteristic of iron-rich metasediments. (b) Biotite (Bt) and muscovite (Ms) are common as shiny, elastic flakes defining the foliation, as in this gneiss. Bright blue grains are small kyanite (Ky) crystals. (c) Three green minerals are associated with pale pink, Ca-garnet in this metabasic rock. The characteristically yellowish green mineral is epidote (Ep), which commonly occurs as aggregates. The dark green (almost black) mineral is the amphibole hornblende (Hbl). The other bluish-green mineral is chlorite (Chl), common in fine-grained, low-grade rocks. (d) The bladed shape of kyanite (Ky) is a reliable diagnostic feature. However, the striking blue colour displayed in this kyanite–biotite schist is commonly pale or absent in other examples of the mineral. (e) Fibrous masses of sillimanite with a pearly sheen are intergrown here with quartz, but often occur with biotite. (f) Prismatic amphibole crystals may show rhombic cross-sections in well-formed crystals. Amphiboles are widespread, and abundant in many mafic rocks. This dark green amphibole is actinolite (Act), intergrown with white mica. (g) Pyroxene generally appears duller than amphibole, and may show square or rectangular cross-sections. Pyroxene is characteristic of high-grade rocks. In this sheared gabbro, olive-brown pyroxene crystals (Px) have been altered during deformation to dark coronas of amphibole (Amph), forming eye-shaped features known as augen. (h) Cordierite (Crd) is usually found as indistinct ovoid blobs as here, looking almost like grease-spots or raindrops. Contrast these with the sharp outlines of andalusite (And) porphyroblasts in this hornfels. (i) Talc is so soft that it feels soapy. Here, talc (Tlc) forms ovoid pseudomorphs with a pearly sheen after olivine in a metagabbro, with thin garnet (Grt) coronas (pink), dark glaucophane (Na-amphibole; Gln), bright green omphacite (Na-pyroxene; Omph) and a pale groundmass of altered plagioclase.

- protolith composition – what the rock type was prior to metamorphism;
- metamorphic grade – key index minerals, or mineral assemblages, may place constraints on pressure and/or temperature conditions of metamorphism;
- metamorphic history – how metamorphic reactions have progressed.

The appearance of quartzites and meta-limestones (marbles) can be very similar, but if the interlocking grains can be scratched by steel, then the rock is most likely quartzite. A clue to the rock composition can aid the search for appropriate index minerals in turn. Assigning a rock to a metamorphic facies or Barrow Zone (Figures A9.1 and A9.2) is not simply cataloguing; it can constrain the P and T conditions of metamorphism, perhaps very tightly, and these data improve our understanding of large-scale tectonic processes such as subduction and continental collision. Some minerals are characteristic of certain conditions (e.g. glaucophane suggests a relatively high P/T ratio; cordierite occurs at low pressures; chlorite tends to occur at low temperatures). However, composition and mineralogy are intimately linked, and mineral stability fields change in different rock types (e.g. garnet occurs at lower temperatures in Mn-rich metasediments). Some bulk-rock compositions do not contain enough of the elements required to grow useful index minerals. For instance, a metamorphosed sandstone may only develop quartz and perhaps some biotite, and these two minerals could coexist over wide P and T ranges. Table 9.1 (p. 201) lists some of the common minerals that are useful for constraining the conditions of metamorphism in different bulk-rock compositions at different conditions, and some that occur across wide P and T ranges and are therefore less useful (bottom row).

Minerals lose water with increasing temperature, so hydrous minerals such as chlorite and talc are generally characteristic of low-T rocks, whereas anhydrous minerals (pyroxene, garnet, feldspar, spinel) dominate in high-T assemblages.

Table 9.1 is a very simplified summary; recognizing a single metamorphic mineral may not constrain the conditions of metamorphism very well. Try to identify assemblages of minerals that have grown in equilibrium together, and as many minerals as you can in the field in order to refine your interpretations of metamorphic grade. Plotting the first appearance of index minerals on a map to construct isograds is a good way to summarize the metamorphic evolution of an area (see Section 10.3.2).

9.3.3 Classification of metamorphic rocks

The full complexity of a metamorphic rock can seldom be revealed by fieldwork, but classifying a metamorphosed rock guides observation and encourages systematic recording of observations. A good convention is to combine the key minerals with a textural term, for instance: 'kyanite–chlorite

Table 9.1 Key minerals in common metamorphic rock compositions: L, low; M, medium; H, high; P, pressure; T, temperature.

Pressure/ temperature conditions	Pelitic (mudstone)	Mafic (basalt)	Felsic (granite)	Ultramafic (peridotite)	Calc-silicate (impure limestone)
LT	Chlorite	Chlorite	Chlorite, epidote	Serpentine	Talc
LP	Andalusite, cordierite No garnet	Pyroxenes, olivine No garnet	Andalusite		
MP/T	Chloritoid, staurolite	Actinolite, epidote, zoisite		Talc (abundant)	Tremolite
HP	Kyanite, talc, rutile No plagioclase	Lawsonite, Na-pyroxene, rutile, glaucophane No plagioclase	Na-pyroxene, kyanite No plagioclase		Zoisite
HT	Sillimanite, spinel, orthopyroxene No muscovite	Clinopyroxene, orthopyroxene	Orthopyroxene, cordierite, sillimanite	Orthopyroxene	Wollastonite, Mg-olivine, Ca-pyroxene, spinel
Wide P and T ranges	Muscovite, biotite, garnet, quartz, plagioclase	Garnet, hornblende, plagioclase, biotite, quartz, titanite	Quartz, biotite, K-feldspar, plagioclase, muscovite	Olivine, chlorite, magnesite	Calcite, dolomite, plagioclase, Ca-garnet, hornblende, chlorite, epidote

schist or ‘andalusite hornfels’. Another convention, adding the prefix ‘meta-’ to a protolith name (e.g. metagabbro, meta-limestone), requires interpretation that may have to be revised following laboratory analysis. Any interpretation or inference on composition or protolith should be clearly noted, and justified by supporting evidence (e.g. preserved igneous textures; colour; mineralogy). For fine-grained rocks where mineral identification is impossible in the field, use textural names with other descriptive terms (e.g. purple slate, kinked grey phyllite, spotted hornfels, banded mylonite).

9.4 Unravelling metamorphism and deformation

As metamorphism is commonly closely related to deformation, many features in metamorphic rocks can be examined for clues to the relative timing of metamorphism and strain. The following sections highlight common examples of pre-, syn- and post-kinematic features that can be observed in the field.



Figure 9.9 Pre-kinematic staurolite crystals strongly wrapped by a strong schistosity (orientated vertically). Some porphyroblasts (e.g. large crystal in centre) are flanked by strain shadows, mainly filled by a pale mineral. View about 7 cm across. (Tom W. Argles, The Open University, UK.)

Porphyroblasts commonly offer the best chance of obtaining useful textural information in the field, and repay careful observation – and thumbnail sketches (Figure 9.10)!

9.4.1 Pre-kinematic features

Early porphyroblasts are commonly wrapped by later tectonic foliations (Figure 9.9), but larger bodies (e.g. boudins; Figure 8.16) may also show this relationship, preserving earlier fabrics and/or minerals in the boudin. They repay careful observation, recording and perhaps sampling so that the full history of the rock can be deciphered. Pre-kinematic grains or clasts may be cracked, bent or even pulled apart; this texture is common in mylonitic rocks. Inclusion trails in porphyroblasts should be sketched, if possible, as their form may reveal not only the relative timing of mineral growth, but potentially also kinematic information (Figure 9.10).

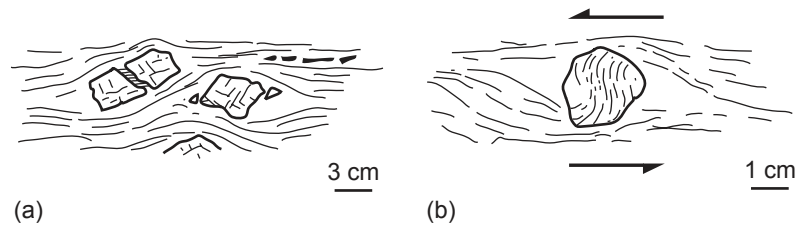


Figure 9.10 Sketches of mineral grains with different relationships to deformation. (a) Pre-kinematic, broken K-feldspar grains and a boudinaged tourmaline crystal (top right), wrapped by a high-strain foliation. (b) Syn-kinematic garnet with curved inclusion trails, showing inferred shear sense.

9.4.2 Syn-kinematic features

You should always record what mineral(s) defines the main planar tectonic fabric (Section 8.3.1), and any other fabrics too, especially if there is a distinct timing relationship between them (e.g. shear bands deforming an earlier foliation). Identifying the minerals that define different lineations can give valuable information on the metamorphic conditions during deformation. Careful observation of the lineation fabrics may indicate which minerals were stable at the time, as the following points indicate:

- mineral grains stretched in one direction (mineral(s) stable during deformation);
- elongate grains that have grown in an alignment (mineral(s) stable during deformation);
- elongate grains that have been passively rotated into an alignment (mineral(s) not necessarily stable);
- mineral X stretched and boudinaged, with mineral Y infilling boudin necks (mineral X may be unstable, mineral Y stable during deformation).

Syntectonic mineral growth in pressure shadows, fringes or pull-aparts may also give valuable information on P and T conditions during a certain tectonic event.

One indication of high strain in metamorphic rocks is the development of augen, where rigid clasts or grains have streaked-out tails of recrystallized mineral at either end. Generally, the tails are composed of finer grains of the same mineral, which suggests that the mineral was metamorphically stable under the conditions of shearing. In some cases the augen core reacts to form a new mineral, implying that the augen core mineral was unstable during shearing. The new mineral formed from the augen may provide clues to the changed P and T conditions at the time of deformation (Figure 9.11).

9.4.3 Post-kinematic features

Post-kinematic features generally show random orientation, indicating static, post-kinematic development. Undeformed coronas and reaction zones (Section 9.2.3) are a common example, as are pseudomorphs where the replacement mineral grains are randomly orientated (decussate). However, the most conspicuous example of post-kinematic metamorphism is where randomly orientated porphyroblasts overgrow an earlier fabric (Figure 9.1, p. 193). This is a common feature of contact metamorphic rocks (Figure 9.8h). Worked Example 9.2 shows how diverse observations can be used to reconstruct a metamorphic history.

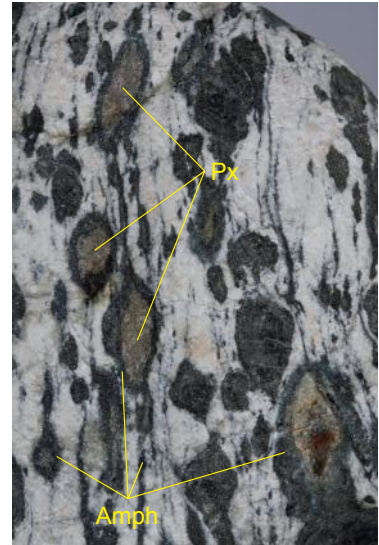


Figure 9.11 Augen of pyroxene in metagabbro, with rims and tails of amphibole drawn out into the strong foliation. View about 12 cm across.

Worked Example 9.2 Charting the exhumation of subducted oceanic crust

In the heart of the western Alps, near Zermatt, Switzerland a suite of metamorphosed mafic rocks has been studied by several researchers. The rocks have been interpreted to be a deformed portion of oceanic crust (an ophiolite), using field evidence such as the features shown in Figure 9.12, p. 204.

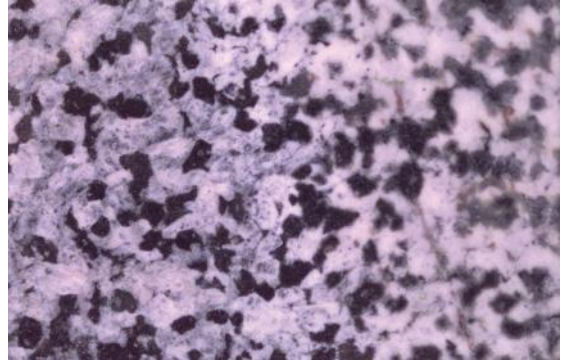
Different rocks within the ophiolite responded in contrasting ways to deformation during the continental collision that formed the Alps. Many gabbro bodies were scarcely deformed except near their margins, and some samples preserve the original igneous mineralogy and texture (Figure 9.12b). Other metagabbros also appear undeformed, but have recrystallized completely to mineral assemblages indicative of eclogite facies conditions, at depths implying they were metamorphosed during subduction (Figure 9.13a,

p. 204). The formation of eclogite facies assemblages seems to have been promoted by the presence of fluid during metamorphism, implying that the transition half-way across Figure 9.12b represents a fluid front. In some weakly deformed metagabbro samples (Figure 9.13b), the foliation is defined by blue amphibole (glaucofan), formed at lower pressures in the blueschist facies field as the ophiolite was exhumed towards the surface; in this case deformation aided metamorphic recrystallization.

Weaker metabasalts in the same area are generally more strongly deformed, either under blueschist facies conditions, or at even lower pressures and temperatures nearer the Earth's surface, in the greenschist field. These retrograde rocks are dominated by a strong foliation defined by green amphiboles, epidote and chlorite.



(a)



(b)

Figure 9.12 Evidence that the metamorphosed rocks in the Zermatt area were once oceanic crust. (a) Deformed lozenges in a metabasalt, interpreted as pillows formed in a basalt erupted under water. The mineral assemblage indicates that these rocks were metamorphosed to eclogite facies, at depths of around 90 km (lens cap for scale at base of exposure). (b) Igneous mineralogy (plagioclase and pyroxene) metastably preserved in a metagabbro from the same area as the metabasalts in (a). The right-hand half of the field of view appears blurred because in this domain the original minerals have been partially altered to eclogite facies minerals, including garnet (red). View is about 6 cm across. (a and b: Tom W. Argles, The Open University, UK.)



(a)



(b)

Figure 9.13 Metamorphic textures from rocks in the Zermatt area. (a) Eclogite facies metagabbro, with green crystals of omphacite (Na-pyroxene) and coronas of red garnet encircling talc-rich pseudomorphs (after igneous olivine). Pale groundmass is altered plagioclase. View about 9 cm across. (b) Eclogite facies metagabbro with a weak blueschist facies foliation defined by dark blue amphibole, which wraps around pre-kinematic omphacite crystals (green). View is about 7 cm across. (a and b: Tom W. Argles, The Open University, UK.)

From these field observations alone, the following history could be deduced:

- formation of oceanic crust including massive gabbros and basalts, some of which were submarine pillow basalts;
- subduction of this oceanic crust to great depth during continental collision;
- metamorphism of mafic rocks at high pressure in the eclogite facies, with massive gabbros resisting deformation while many metabasalts were deformed;
- initial exhumation of ophiolite, without significant further heating, overprinting many rocks with syntectonic blueschist facies mineral assemblages;
- further exhumation of ophiolite to shallower crustal depths, with formation of strongly sheared greenschist facies rocks.

9.5 Further reading

- Fry, N. 1991. *The Field Description of Metamorphic Rocks*, Blackwell Scientific Publication, 128 pp. [Useful aid to studying metamorphic rocks in the field.]
- Miyashiro, A. 1994. *Metamorphic Petrology*, UCL Press, 404 pp. [A good textbook covering many aspects of metamorphism.]
- Shelley, D. 1993. *Igneous and Metamorphic Rocks under the Microscope*, Chapman & Hall, 468 pp. [Invaluable aid for anyone studying igneous or metamorphic rocks using the polarizing microscope.]
- Vernon, R. H. and Clarke, G. 2008. *Principles of Metamorphic Petrology*, Cambridge University Press, 460 pp. [Modern text with numerous examples of features illustrating metamorphic processes.]
- Winter, J. D. 2009. *Principles of Igneous and Metamorphic Petrology*, Prentice Hall, 720 pp. [One of a number of textbooks dealing with both topics together.]
- Yardley, B. W. D. 1989. *An Introduction to Metamorphic Petrology*, Longman, 26 pp. [Excellent, readable introductory text.]

10 Making a geological map

Tom W. Argles

10.1 Principles and aims

A geological map is one of the most important tools of a geologist's trade. It shows how geological features (rock units, faults, etc.) are distributed across a region. It is a two-dimensional representation of part of the Earth's surface, scaled down to a size that is convenient for displaying on a sheet of paper or a computer screen. Information on the third dimension is incorporated by means of strike and dip symbols and other structural labels. Different rock units are usually shown as different colours (and/or ornaments) and are overlain on a topographic base map for easy location. Additional information on features such as structure, lithology and stratigraphy is also included, allowing interpretation of the subsurface. Increasingly, geological mapping data are stored with subsurface information in computer models that allow more sophisticated visualization and manipulation in three dimensions than is possible with traditional paper maps.

Geological maps are made for a variety of reasons and, depending on the region, these are to:

- record the position of particular geological features or exposures;
- help us understand the geological history of a region;
- locate natural resources, and understand the best way to exploit them;
- identify potential hazards (e.g. faults, volcanoes, unstable substrates, hazardous deposits);
- gain insights into the immediate subsurface environment, which governs soils, drainage, agriculture and ecosystems;
- provide a base for constructing a detailed geological cross-section to deduce and visualize strata below ground.

Geological mapping aims to distil data concisely onto a topographical base map, producing a clear, detailed

representation of the geology at the appropriate scale. The final fair copy map (with legend, etc.) should allow the geology of the area to be interpreted to a degree with no other aid – although maps are commonly published with an accompanying summary report outlining the features of the geological units shown on the map, along with horizontal and vertical cross-sections. This chapter will introduce the basic skills needed for producing geological maps and cross-sections. The fundamental principles of mapping apply whatever tools are used – be they pencils and paper, or the handheld computers that are increasingly favoured by geological surveys. The specific details of such electronic mapping methods are beyond the scope of this book.

10.2 Preparation and materials

Guidance on basic preparation and field equipment is provided in Chapter 2. The following sections look in more detail at how to prepare for geological mapping.

10.2.1 Base maps and other aids

Topographic maps

Good geological mapping depends on good base maps. You should find out what is available for the mapping area well before you start, so that you can assess which maps to use (and at what scale). Many governments produce good quality topographic maps based on a ‘National Grid’ designed specifically for that country; increasingly these are available digitally (e.g. for the UK, OS 1:10,000 Landplan maps; for the USA, 1:24,000 quadrangle maps). Digital topographic maps can be downloaded free, for instance from the U.S. Geological Survey website, for much of the USA. However, for some countries or regions good maps may be costly or impossible to obtain. In this case, a handheld GPS unit (Sections 2.6 and 10.2.2) is essential for recording your location in the field, supplemented by any maps that exist, and either aerial photographs or satellite images.

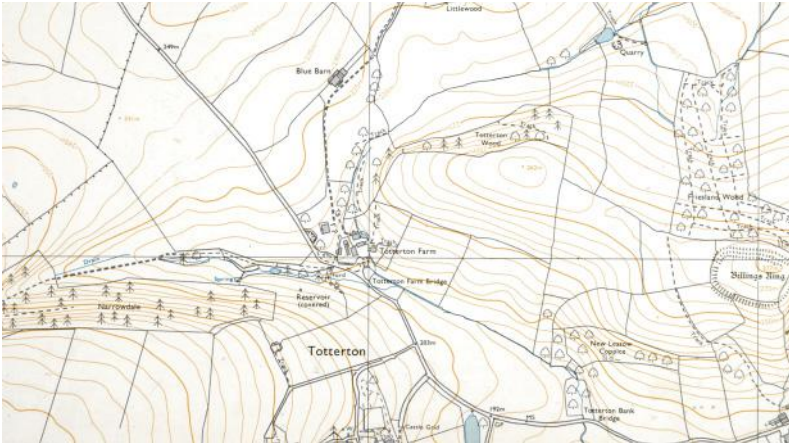
Base maps are generally drawn using a grid, typically a national grid defined for a particular country. In most cases, grid north on the map is nearly equal to true north (Earth’s rotation axis), but there may be a small difference, as described in Section 2.3 and shown in Figure 2.4 (p. 10). To compare any compass readings taken in the field with bearings on the map, the angular difference between grid and magnetic north must be corrected for, as this difference may be substantial depending on the area and year. Section 2.3 explains how to adjust your compass-clinometer for this before you use it for mapping.

If possible use good quality base maps printed onto thin card such as the 1:10,000 topographic maps available for the UK (Figure 10.1a). These will be more robust for extensive use in the field, and will not suffer from distortion produced by copying. Using one printed copy also ensures that all the data are in one place, making it easier to assess the different lines of evidence. Photocopies or photographs of field maps can be taken at regular intervals as insurance against loss, or a second hand drawn copy maintained. If the base maps have lots of features or colour, monochrome copies of base maps will show up geological data recorded in colour more clearly, although some information on the base maps may be harder to distinguish at a glance (e.g. contour lines, field boundaries). Figure 10.1 shows three examples of topographic maps. Figure 10.1b, a 1:25,000 Ordnance Survey map, includes several features that could be particularly useful for mapping (note that the 1 km eastings and northings are labelled in blue on the map extract):

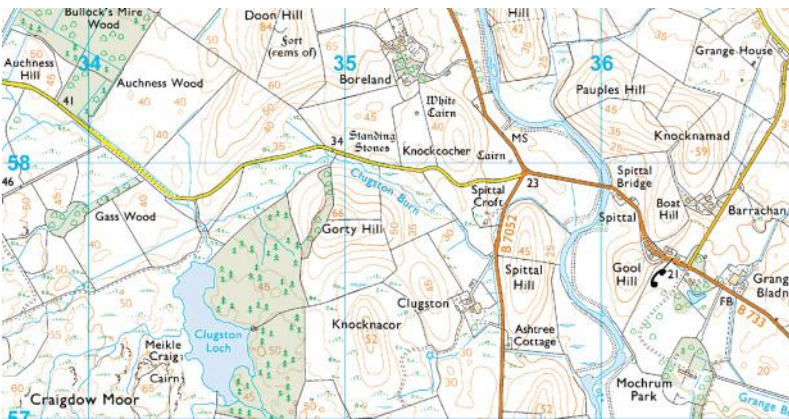
- topographic contours that define landforms in the landscape and give elevations;
- point features on which to take bearings (e.g. cairn on Meikle Crag at NX 342572, corner of coniferous plantation at NX 348579, corner of wall on top of Pauples Hill at NX 361583);
- linear features to check compass declination angle (e.g. wall running NE from minor road at NX 342580);
- spot heights to calibrate altimeter (e.g. road junction at NX 357580);
- location of specific exposures (e.g. on Craigdow Moor at NX 339572);
- indications of vegetation (e.g. marshland at NX 351575; scrub at NX 338575; rough grassland at NX 343574).

On this map extract bedrock is exposed mainly in the southwest corner, with a few rock exposures indicated elsewhere. However, other exposures such as those in streams or roadcuts may not be shown. The exposure symbols do not give a strong impression of the strike of strata in this case, but on many maps exposures are elongate in the strike direction. In the eastern half of this extract there are several distinct hills with oval outlines (e.g. Spittal Hill at NX 357576), with their long axes roughly aligned N–S. The lack of bedrock exposures and their smooth outlines imply these may be features formed from superficial deposits during the last glaciation, such as drumlins. One way in which this hypothesis could be tested is by examining the roadcut on the B733 at NX 362577, between Gool Hill and Boat Hill.

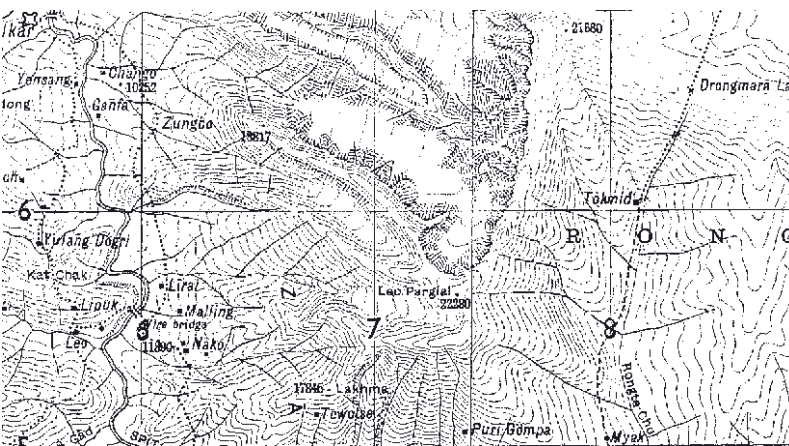
BEWARE! When copying base maps, avoid enlarging them too much. No precision is gained, because lines simply become thicker.



(a)



(b)



(c)

Figure 10.1 Examples of topographic maps. (a) Extract of a 1:10,000 British Ordnance Survey map of part of Shropshire, UK showing field boundaries, tracks and buildings in detail. (b) Extract from 1:25,000 topographic map of part of southern Scotland, UK, from the British Ordnance Survey (within 10km grid square NX(25)35). Grid squares are 1 km across, and contour intervals are in metres. (c) Photocopy of part of a much smaller scale map of northern India, dating from the 1940s. Grid squares are 10,000 yards across, and contour intervals are in feet. Details are sparse for this large area and out of date, but such maps may be the best available in remote regions. (a: Ordnance Survey 1:10,000 Sheet SO38NE © Crown Copyright. b: Ordnance Survey 1:25,000 Scale Colour Raster © Crown Copyright 2009. An Ordnance Survey/EDINA supplied service.)

Aerial photographs

Aerial photographs may be used for mapping, either using a transparent overlay (e.g. acetate, Mylar®), or mapping directly onto photographs enlarged to a suitable scale (e.g. 1:7000). Many are high enough resolution to be used at large scales (e.g. 25 cm resolution photographs are appropriate for 1:2500 scale mapping). Satellite images may also provide coverage of areas that are otherwise poorly mapped, but are generally lower resolution (e.g. 60 cm pixels for Quickbird; 15–30 m pixels for Landsat). Coverage and resolution of such imagery will no doubt improve, although availability (and cost) may remain subject to political and commercial pressures. Any map data drawn on the images must be carefully transferred to a map on return from the field, and will be subject to the various types of distortion inherent in such images. Table 10.1 assesses the relative merits of aerial photographs and satellite images.

Satellite images

Some low-resolution imagery (e.g. Landsat) is freely available online, but this is of limited use for detailed mapping, although it may help provide a regional context (Section 3.2.1). However, a range of data (maps, high-resolution satellite imagery, aerial photographs) is increasingly being displayed online, both in bird's eye view and three-dimensional perspective, via interfaces such as GoogleMaps™, Google Earth™, Microsoft Bing Maps™. These systems make available some of the visualization capabilities of a GIS to any internet user, and represent an invaluable resource when planning a

Table 10.1 Advantages and disadvantages of aerial photographs and satellite images for geological mapping.

Method	Advantage	Disadvantage
Aerial photograph	<ul style="list-style-type: none"> Clear depiction of landscape features May show more detail than map Landforms may be interpreted before mapping Clear features in photographs make it easy to confirm your location 	<ul style="list-style-type: none"> Limited global coverage Costly; rarely available for free May be old: landscape may have changed May be difficult to obtain for some areas Distortions must be corrected by processing No contours; slopes may not be obvious
Satellite image	<ul style="list-style-type: none"> Tend to show larger areas More readily available (e.g. Landsat) More sources of free images More information in different spectral bands: allows interpretation before mapping Newer images constantly being acquired 	<ul style="list-style-type: none"> Most are lower resolution than photographs Limited coverage of high-resolution images High-resolution images are costly Relief often less clear than in an aerial photograph May be old: landscape may have changed Distortions must be corrected by processing Clouds may obscure area

mapping season, especially to remote and poorly mapped areas (e.g. Worked Example 10.1). The image quality in some areas allows features such as roads, paths, streams and exposures to be resolved, providing useful logistical information that can guide mapping strategy in the field.

Additional data

Geophysical or geochemical data may be available for some areas, and maps of gravity or magnetic anomalies can provide valuable insights into large-scale subsurface structures that may influence the surface geology.

Worked Example 10.1 ASTER satellite mapping of rock units in southern Tibet

Accurate maps are not readily available for this region, so before starting a research project there, satellite imagery was viewed online, along with a false-colour, composite Landsat image (Figure 10.2a). ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) satellite images for specific areas were also acquired. Different rock types showed contrasting emissions, which were enhanced with further processing (Figure 10.2b). Comparing the images with existing, small-scale geological maps of Tibet suggested that the ASTER images could be used to define the

outcrop extent of certain units, because vegetation is sparse.

During two subsequent field seasons, rock units were recorded in the field, and their distribution compared with different colours on the ASTER images. Making observations in the field that assess the validity of inferences from remote sensing data is known as ‘ground-truthing’. The satellite images discriminated well between granite, Palaeozoic metasediments and younger rock types, and highlighted other granite domes in the region (Figure 10.3, p. 212).

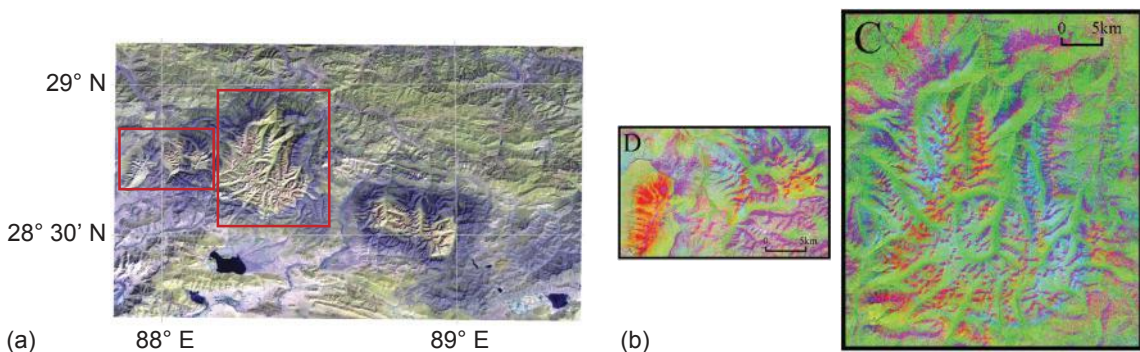


Figure 10.2 (a) Landsat image of part of southern Tibet, using bands 7, 5 and 3 (2.08–2.35 μm , 1.55–2.75 μm , 0.60–0.69 μm wavelength respectively) to make a composite RGB image. Granites and gneisses in domes show up pale pink or beige, while metamorphic schists mantling the domes appear dark purple. Boxes show areas of images in part (b). (b) ASTER satellite images of the two boxed areas shown in (a). Granite appears red; gneisses appear pale blue; Palaeozoic schists appear dark blue to purple. (Landsat data in (a) courtesy of the U.S. Geological Survey/NASA; ASTER images in (b) from Watts *et al.* 2005.)

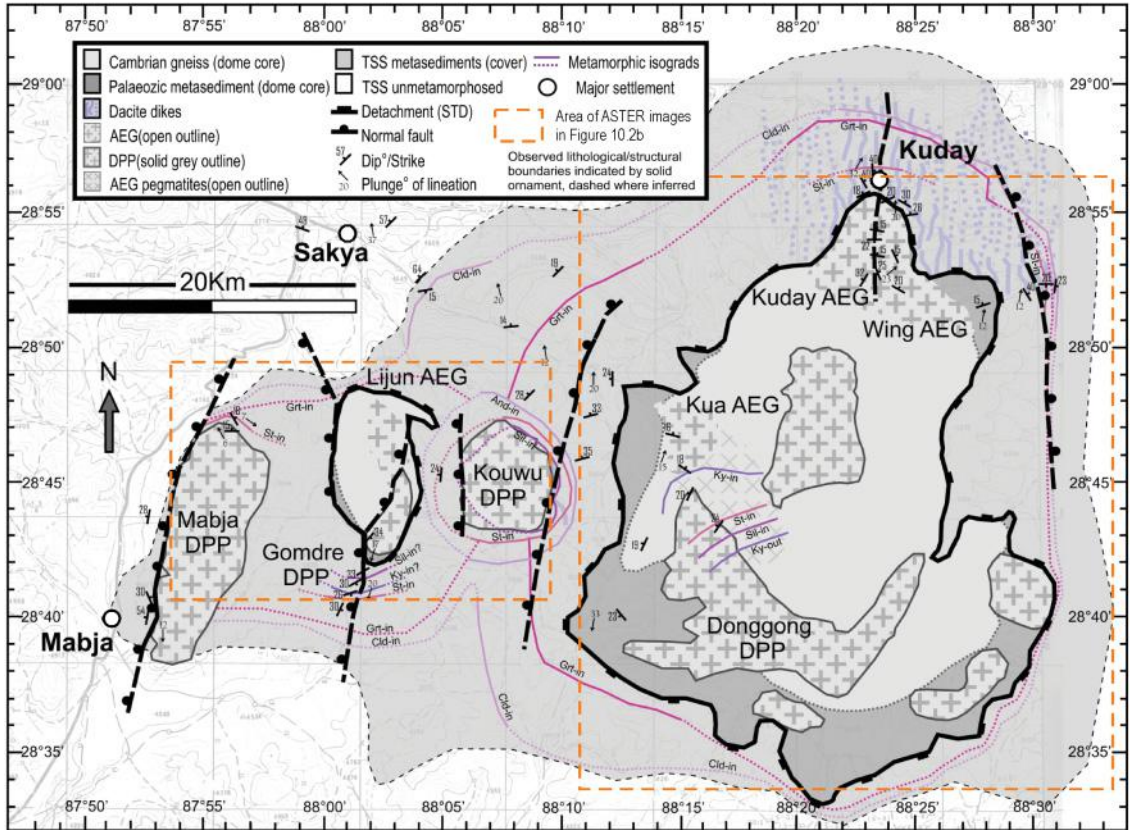


Figure 10.3 Detailed geological map of area shown in Figure 10.2b, drawn after ‘ground-truthing’ of ASTER images confirmed which rock type(s) gave which spectral response. ‘AEG’ and ‘DPP’ are two types of granite distinguished by field relations. (Modified from King 2007.)

Table 10.2 Summary of the equipment required for mapping (see also Tables 2.1–2.3).

Mapping equipment

Ruler

Protractor

Map case

Base maps

Clips/rubber bands

Mapping pens

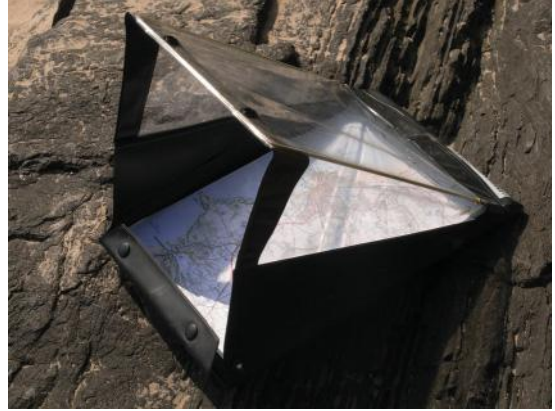
Full selection of coloured pencils

10.2.2 Equipment for mapping

The use of tools for geological fieldwork has been covered in Chapter 2 (Tables 2.1–2.3, pp.4 and 6), and only a few further remarks with regard to equipment needed for geological mapping are made here (Table 10.2). A long surveyor’s type of tape measure (*c.* 30m) is useful for some surveying (e.g. Figure 2.13, item 1, p.26), though you should also practice pacing out distances accurately (Section 3.1.3). A map case (Figure 10.4) is essential to protect field maps from the elements (rain, sun, dust). A good map case has a see-through cover so you can check your position and your data quickly. The case should also allow easy addition of data to the map, with a rigid base on which to write and plot. A supply of strong rubber bands or clips is invaluable for holding field maps and other sheets in place. Some geologists favour the discipline of mapping directly onto a base map; others prefer using a rainproof, plastic overlay



(a)



(b)

Figure 10.4 (a) A home-made map case (c. 30 cm across) incorporating a rigid board for drafting, and a hinged Perspex sheet to protect map sheets without obscuring them. (b) A second map case, which has a clipboard base for A4-sized sheets. The hinge on the plastic cover is sprung so that it holds the position in the photograph unless secured; the side panels help protect the sheets from the elements, while allowing access to the field map.

such as Mylar®, which allows multiple erasures without degrading the sheet. Mylar® overlays for mapping should be taped firmly to the base map (or aerial photograph) at the top, but left untaped at the bottom so that the overlay can be lifted to check features underneath. Always mark one or more cross-hairs on the Mylar® sheet corresponding to a grid intersection on the map, so that it can be replaced accurately if disturbed. Mylar® should be placed shiny side down, so that all working is done on the matte side.

Silva-type compass-clinometers can be used to measure and directly plot azimuths on a map by setting the compass-clinometer dial to the azimuth and then following the instructions in step 3 of Figure 2.12 (p. 24) but a protractor is also a useful addition. If you are using a Brunton-type compass-clinometer a protractor is a necessary addition to your kit. Structural data such as strike lines and lineation arrow should generally be plotted accurately on the map in pencil in the field. At the end of the day they should be checked and inked over. The numbered location of the data must also be marked accurately, and linked via the locality number with systematically recorded data in a notebook (e.g. Figures 4.10 and 4.11, pp. 71 and 73). If you are contact mapping (Section 10.5.2), the boundary should be drawn accurately in the field. Whether you use pens or pencils, map lines and data must be sharp and clear. Mapping pens are more commonly used for inking in at the end of the day's work. A ruler is useful to measure distances on the map, but there are also 'scales' with



Some equipment is easily lost when dropped, or left on the ground by an exposure. Use brightly coloured equipment, bright labels, paint or sticky tape to make your tools more conspicuous.

gradations matched to particular map scales, so no conversion is needed and distances can be read straight off the scale. You may need imperial as well as metric scales if mapping on old base maps.

10.3 Location, location, location

Locating yourself accurately in the field while mapping is of paramount importance. Many of the basic skills involved have been covered in Chapter 2, and these techniques are briefly expanded on here.

10.3.1 Equipment

Handheld GPS units are a valuable aid in mapping, but they may fail in some situations (Section 2.6). If you are working in remote areas, make sure you take spare batteries for the GPS (or alternatively a solar charger for the batteries). It is worth removing the batteries from a GPS unit that will not be used for a while (i.e. weeks or more), as battery drain has been reported for some units (you could keep a set of batteries bundled with the GPS using a rubber band, lest you forget them). Always take a compass (or compass-clinometer) as a back-up (Section 2.3.3, Figures 2.11 and 2.12, pp.22–24), and consider taking an altimeter, particularly if you are mapping heavily vegetated slopes where bearings are difficult to take, or in an area with few landmarks and/or poor base maps.

10.3.2 Using base maps

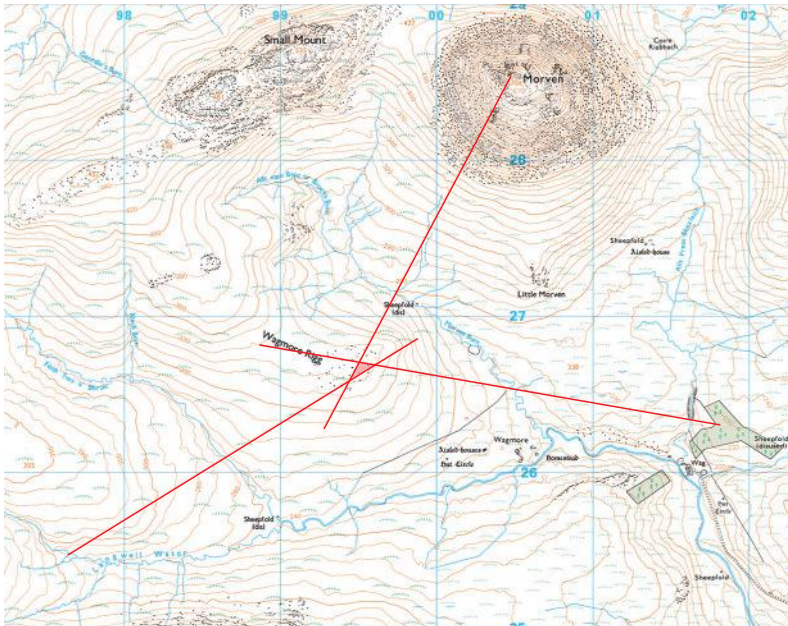
Good base maps may allow you to locate yourself relative to features simply by inspection. Pacing out distances along a linear map feature (i.e. road, stream, wall; see Figure 10.1) is one way to locate yourself during mapping. You should establish your average pace length, and pace steadily; remember that stride lengths will be shorter on slopes than on the flat. In many cases, however, compass bearings can come to the rescue (e.g. for triangulation as in Worked Example 10.2). If you are already on a linear map feature (e.g. path, fence), you can take a bearing on a landmark and find your position from the intersection of that bearing with the linear feature (Section 2.3.3). Choose a landmark on a bearing at a high angle to the trend of the linear feature to improve accuracy, and remember that landmarks closer to you (say, 100m away) will result in more precise bearings than distant features. Repeating the process with a second landmark, if possible at about 90° to the first landmark, should verify your location. Remember that compasses give the *magnetic* bearing to the feature, which needs to be converted to grid north for comparison with the base map (Section 2.3).

BEWARE! When using old base maps, buildings and roads may alter, and even landscape features (e.g. stream courses, woodland) may be different to when they were mapped.

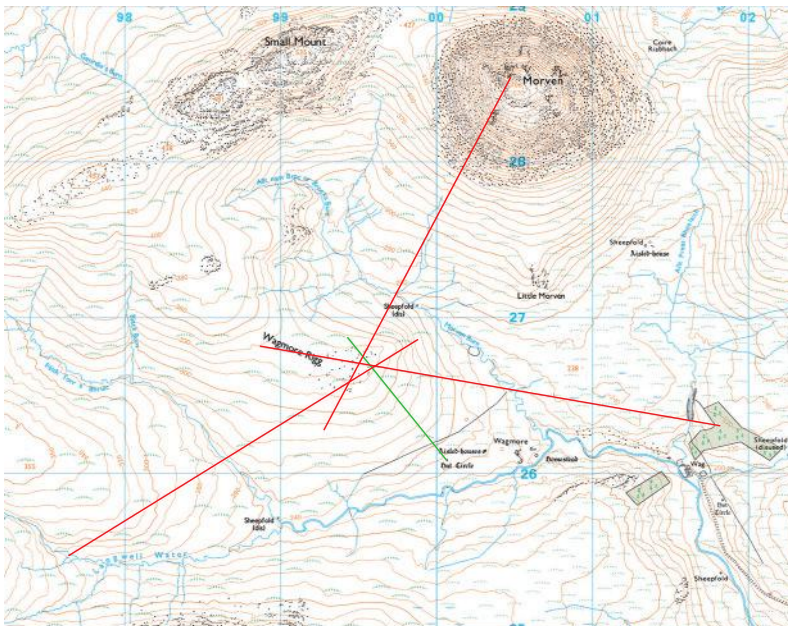
Worked Example 10.2 Trying triangulation

Figure 10.5 shows a topographical map of a remote area with few landmarks where GPS failure occurred. Locations had to be determined by triangulation, using the few landmarks that

were visible and marked on the map. An initial attempt at triangulation was made, yielding three bearings to the three rather distant landmarks listed in Table 10.3 (p.216).



(a)



(b)

Figure 10.5 (a) Initial attempt at triangulating a location in a remote area with few suitable landmarks. The three plotted bearing lines meet in a triangle of error (shaded red), so the location is not determined very precisely. (b) Revised attempt at triangulating the location in (a). The fourth plotted bearing line (green) meets two of the previous lines in a smaller triangle of error, so the location is more precisely – and accurately – determined. (Base maps: Ordnance Survey 1:25,000 Scale Colour Raster from 10km grid square NJ(38)30 © Crown Copyright 2009. An Ordnance Survey/EDINA supplied service.)

Table 10.3 List of landmarks and corresponding bearings used for initial triangulation attempt.

Landmark feature	Grid reference	Corrected bearing*
Summit of Morven	NJ 005285	028°
Corner of Wag Wood	NJ 018263	100°
Confluence of streams	NJ 976255	238°

*Corrected for declination.

This initial triangulation is plotted on Figure 10.5a using three red lines. Perhaps because the landmarks were not very close to the mapper's location, there were some errors in the measurements, and this results in the three lines meeting not at a single point, but in a triangle of error known as a 'cocked hat'.

A further bearing on a separate landmark (a hut circle at grid reference NJ 001261) was fortunately possible to resolve the uncertainty in the location. Figure 10.5b shows the result of

this additional measurement, plotted as a green line. This line intersects two of the red lines in a much smaller triangle of error, but cuts the third red line some distance further northwest. The fact that the hut circle is closer to the mapper's location than the other landmarks means that this bearing is likely to be more accurate. The mapper's location was therefore revised to the centre of the smaller triangle of error, formed by the green line and two of the red lines, giving a location that is both more precise and more accurate than that in Figure 10.5a.

10.4 Making a field map

Mapping aims to *record* as much relevant information as possible on the geology of an area using field maps and a notebook, and then *present* an interpretation of those observations in the form of a final fair copy map, which may include interpretative cross-sections. This section summarizes how to record information on the topographic base maps you take into the field.

10.4.1 Information to record on field maps

Field maps are valuable records of observations and data gathered in the field, from which later geological interpretations will be drawn. Your field maps (and notebook) should be comprehensible to any geologist wishing to make later interpretations; they should not simply be personal records. They should record the geology you see, and also evidence for any geology inferred (Section 10.5.4), discriminating clearly between directly observed and inferred features. The level of detail on field maps depends on the time available, and also the scale of mapping. More detail (and data) can be recorded for an area of 1 km² mapped in two days than a 100 km² area mapped in the same time.

Protect your field maps carefully; use single sheets that fit in the map case, as folded sheets wear quickly so that important topographic details or data can be lost. Make sure each field map sheet has the information in Table 10.4 (on the reverse if there is not enough space, as in Figure 10.6). Table 10.5 (p.218) provides a summary of the other types of information that could be included on the field map; some examples are given in Figure 10.7 (p.219). The emphasis will depend on the purpose of the exercise.

Field maps must be neat, drawn with a sharp, thin pencil lead, and should not include so many notes and symbols that the map becomes cluttered. Record more detailed notes, and multiple structural observations, in your notebook, with localities cross referenced to the map. Label localities on the field map with the same numbers as used in the notebook, and ring or box them to distinguish them from other numbers on the field maps (Figure 10.7c, p.219). Label faults and unconformities (e.g. with 'f', 'uc'), as pencil line thicknesses cannot be standardized (you could also use coloured pencils to distinguish different lines). Colour rock exposures lightly as you go (Figure 10.7a), and label them with their corresponding

Table 10.4 Checklist of information to be included on each field map.

Additions to a field map

Scale and N arrow
Explanation of colours used
Stratigraphic column (if appropriate)
List of non-standard symbols used
Cross reference to notebook(s) used
Name and contact details of author
Date of mapping
Reference direction for structural data (e.g. grid N)

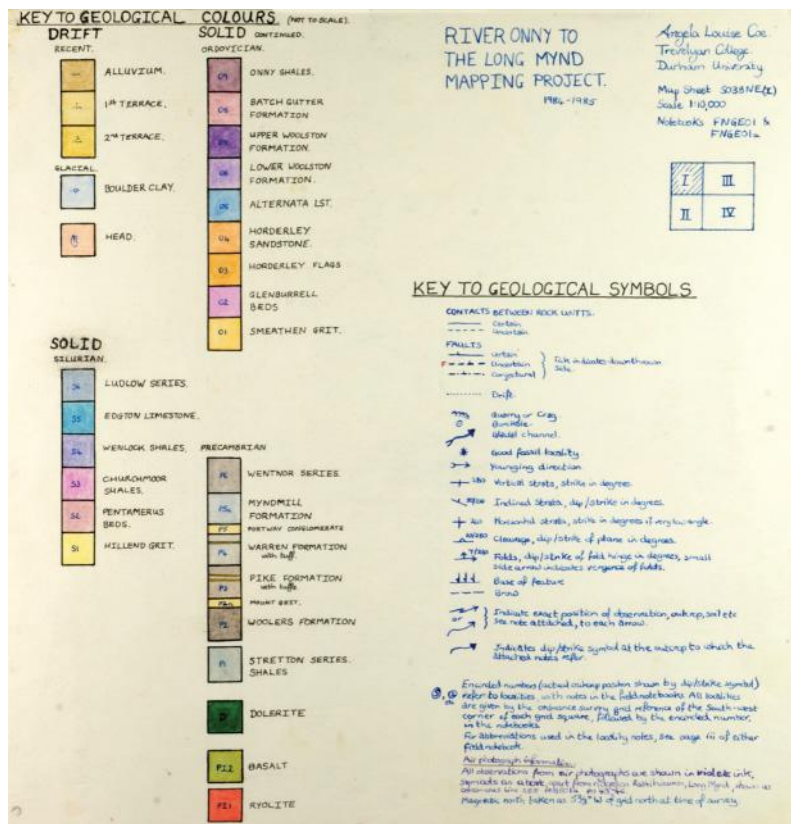


Figure 10.6 A well-structured layout for additional information on a field map that contains most of the elements mentioned in Table 10.4, including a small graphic showing how this field map sheet relates to three adjacent sheets produced for the project. (Reverse side of field map of Angela L. Coe, The Open University, UK.)

Table 10.5 Information to record on a field map. Level of detail is determined by time allocated and scale of mapping. Conventional symbols used for plotting these data are given in Appendix A10 (Figure A10.3).

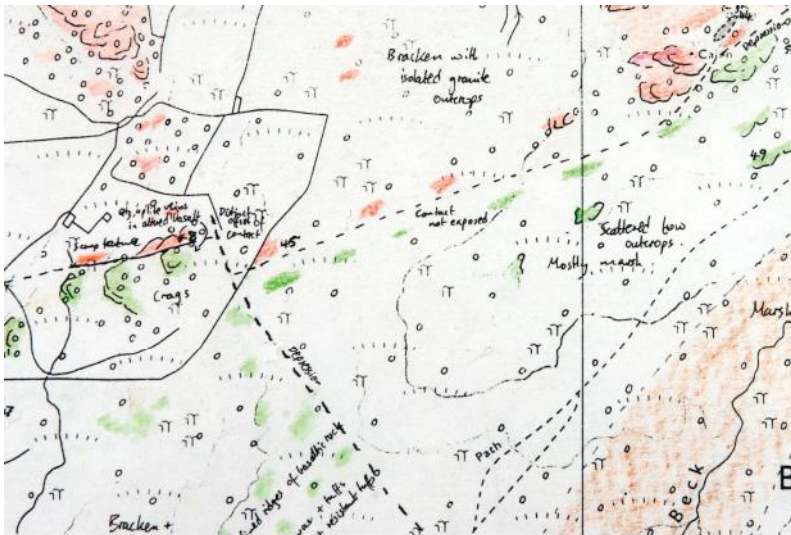
Information	Comments
Rock exposures	Location: extent if appropriate, nature (e.g. man-made). Brief notes of rock types or facies, and other important information (e.g. fossils, index minerals, structures)
Structural data	Symbols <i>and</i> measurements (dip/strike, plunge/trend) for bedding, foliations, lineations, fold axes, joint orientations, etc.
Notebook localities	Clearly label those localities where you have made detailed notes in your book
Specimen localities	Label the locations where samples were taken (rock, fossil, sediment, water, etc.); it is best to link these directly to notebook localities
Photographs, sketches	Label where photographs were taken or field sketches made if not at a notebook locality
Major contacts	Lithological and tectonic: solid where observed, dashed where inferred.
Additional evidence	For example topographic features, drainage, soils, float, vegetation (Figure 10.7a)
Superficial deposits	For example alluvium, glacial/fluvioglacial material, sand, peat, river terraces, etc.
Degree of exposure	Comments on quality and quantity of exposure, weathering, soil cover, etc.
Hazards	Note of hazards not obvious from base map

rock unit letters and/or numbers. Symbols for important structural data (Appendix A10, Figure A10.3) should be plotted accurately in the field, on or as close to their location as possible, and then checked and inked in later (Section 10.6.1). Accurate plotting encourages the mapper to check their orientation frequently, which in turn keeps them alert to even subtle shifts in structural trends. The convention is for the locality to lie at the intersection of strike line and dip tick (planar feature; Figure 10.7b), or the head of the arrow (linear feature). Strike lines and arrows are important as they show, at a glance, changes in the strike of the strata or trends of lineations, and therefore indicate where to look for boundaries and features.

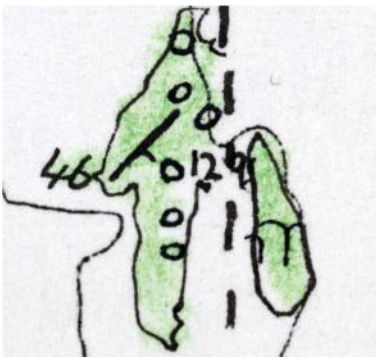
10.4.2 The evolving map

Major lithological divisions

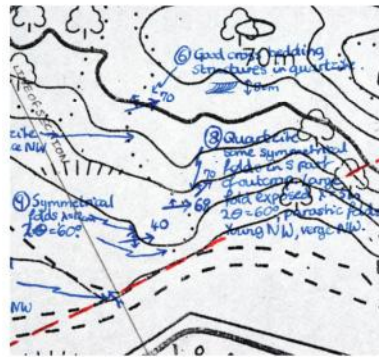
There may be an existing stratigraphic scheme that you can adopt or adapt to define units of the various rock types within the mapped area, in which case the criteria for the unit definitions should be already documented. However, you may need to apply your own unit definitions, either because you are engaged in pioneering fieldwork, or because the existing scheme is inappropriate (e.g. not detailed enough). This is



(a)



(b)



(c)

Figure 10.7 (a) A field map of an area in the English Lake District. Exposures are coloured, but not outlined or labelled with a unit code. Annotation is sparse, but includes some comments on vegetation and landscape features relevant to the underlying geology (depressions, scarps, marshy ground). (b) Magnified portion of an adjacent field map, showing a strike line symbol plotted at locality number 46. The strike line is accurately plotted, with a short tick indicating dip of the stratum to the southeast at 12° , and the exposure has been outlined using a thin black pen line. This map could be improved by using colour to distinguish mapping lines better from the base map, and by ringing the locality number for clarity. (c) A field map from a brief mapping exercise in Scotland. Locality numbers are ringed, and their location given by arrows. Detailed notes compete with structural symbols for space, and the map is rather congested. Such notes could be reserved for the field notebook alone in most mapping situations. (a and b: Extracts from field maps of Tom W. Argles, The Open University, UK. c: Extract from field map of Angela L. Coe, The Open University, UK.)

commonly possible only after you have examined the main rock types in the area, although any scheme can be amended later.

It is perhaps worth remembering that the definition of a geological formation is a unit mappable over a reasonably large area, with characteristics that distinguish it from adjacent units. Mapped units generally have distinct contacts with neighbouring units, though some unit boundaries may be transitional or indistinct; there are no limits to the thickness of a formation. Two or more formations with features in common may be designated as a group. Most igneous and many sedimentary contacts are quite sharp (e.g. dyke margins, bedding planes). However, some unit boundaries are less obvious (e.g. metamorphic zone boundaries, boundaries between sedimentary units that obey Walther's Law). The following criteria may be useful in defining a range of lithological units:

- major rock type (igneous, sedimentary, metamorphic);
- compositional change (indicated by changes in colour, mineralogy, weathering, etc.);
- grain-size changes (e.g. siliciclastic sedimentary deposits, volcaniclastic rocks, intrusive igneous facies);
- textural or structural change (generally indicating a change in *process*);
- change in fossil assemblage (biostratigraphy);
- change in mineral assemblage (metamorphic zones, igneous petrography).

Lithological subdivisions and marker layers

The type and scale of mapping control how detailed a scheme has to be to classify lithological units. A large area may have a wide range of rock types that are easy to categorize. Mapping smaller areas, or those with little variation in rock type, demands discrimination on subtler criteria. For example, volcanic units might be defined by the abundance of different phenocrysts, or sedimentary units by the relative proportions of sand and silt. Such subdivisions may require detailed logs of certain sections to define them.

The basic mappable unit is the formation. Formations may contain one or more subdivisions known as members, which are units with characteristics that distinguish them from the adjacent parts of the formation. In monotonous sections of strata, the widespread occurrence of a distinctive single member or even layer can be critical to interpreting the geology of the area. Examples of such a marker layer could include a

volcanic ash layer, a porphyritic sill, a calc-silicate layer or a sedimentary bed with characteristic ironstone concretions. Recognizing and recording these marker layers is invaluable for understanding the stratigraphy and structure of any region. It is also important to take into account localized variation and to group or split units appropriately.

10.4.3 Sketch cross-sections

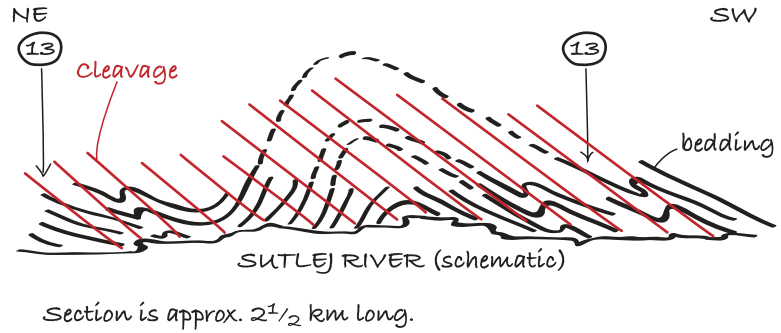
For a geologist, tracing strata such as marker layers across the land surface leads naturally on to questioning the subsurface structure. It is often useful to sketch out rough cross-sections based on the data you collect while mapping, especially in areas where there are distinct topographic features (Figure 4.3d, p. 60) or folding or faulting has affected the rocks (Figure 4.8, p. 69). Fieldwork is frequently conducted along more-or-less linear traverses (Section 10.5.1), and if these cut across the strike of the strata at a high angle, cross-sections can readily be sketched from the data collected.

Section 10.6.2 details how to construct an accurate cross-section, but a sketch section can be as rough as you like – it serves simply to help you develop possible interpretations of the geological structure or test different hypotheses. A sketch section could be simply a quick drawing of how one stratum might be folded across an area, or it may involve rather more, as in the following description. First, pick a notional line on the map that cuts at right angles across the dominant strike of the strata as the line of section. In your notebook, or on a separate piece of paper, draw a rough representation of the topography along this notional line. Then quickly mark on the locations of the main boundaries between geological units as short lines dipping below the topographic surface, taking the dip angles from the nearest measurements to the line of section.

Start extending the strata boundaries below the topographic surface. This will give you a first impression of the relative thicknesses of the different units. To continue sketching the section, you may need to consider:

- matching the surface dip measurements to the structures at depth;
- erecting hypotheses to explain repetitions of strata (i.e. folding, faulting);
- potential changes in the thicknesses of strata;
- any alternative structural configurations that might fit the recorded data.

Figure 10.8 An example of a sketch section, redrawn from a notebook, based on observations of cleavage and bedding attitudes and minor fold structures on a road traverse in the northwest Himalaya. Numbers refer to localities. The kilometre-scale antiformal fold inferred here is a subordinate structure on the SW-dipping limb of a 20-km-scale syncline. (Tom W. Argles, The Open University, UK.)



Sketch sections such as the example in Figure 10.8 are not intended to be accurate, but to focus attention on structural problems and try out ideas of the regional geology. They may even direct mapping, for instance by identifying the best location(s) to visit in order to test a hypothesis. This may be an iterative process in areas of poor exposure, and a certain amount of trial and error may be required to deduce the thicknesses of lithological units that produce a geologically reasonable cross-section.

10.5 Mapping techniques

You should always aim to record as much relevant detail as practical in your notebook to help construction of the final geological map. Some features (e.g. uniformly dipping strata) can be adequately recorded with a few measurements. Others, such as complex brittle fault zones, may require numerous measurements and observations to constrain their orientation and kinematics satisfactorily. Mapping may be focused on different aspects of the geology (e.g. bedrock, superficial deposits, artificial deposits, mineral deposits, glacial geomorphology, soils), which will impose different constraints on the mapping techniques used. In addition, other constraints such as time, terrain, vegetation, weather, etc., mean that you must develop an appropriate mapping strategy for the conditions. Three common mapping methods are described in the following sections, although in some areas a combination of these different techniques may be appropriate.

Whichever mapping technique is employed, it is good practice to constantly develop hypotheses that predict what you will find at the next exposure. Then on arrival, the prediction (e.g. the dip will have changed, it will be the same rock type) is tested immediately. If correct, the hypothesis is supported; if wrong, you may need to develop a new hypothesis – for instance, a fold axis or fault has been crossed between the two exposures.

10.5.1 Traverse mapping

This method is often adopted for reconnaissance mapping of a large region, at relatively small scales (1:250,000 to 1:50,000). It may also be the only approach possible where rock exposures are restricted to stream sections or roads, or where access is limited to streams, roads, ridge crests, etc. (Figure 10.9). River sections in mountainous regions are commonly subparallel and quite evenly spaced, presenting the opportunity for multiple traverses. The geology can be interpolated between them if the structure is broadly simple, especially if aerial photographs or satellite images can be used to help trace units or boundaries across sparsely vegetated areas.

Traverse mapping involves simply recording the geology as you walk along a predetermined route. This may be a straight line, or series of straight 'legs', between two definite points on the map. Typically, however, traverses follow linear features such as roads, tracks, streams, wadis or ridge crests, because these provide good exposure and/or easy access (or perhaps the only feasible access!). Such routes may be recorded automatically on GPS units. In open country, binoculars may be handy for examining the traverse route; in addition, high-resolution satellite imagery can be examined (and printouts taken) prior to the mapping season (via online services such as Google Earth™) to plan potential routes.

Linear traverse

Ideally, a traverse runs perpendicular to the strike of stratigraphy or structure, yielding the most information on the regional geology. If the traverse is along a well-defined linear feature (e.g. road or stream), plot the geology as you go. Mark the units you encounter on the map using the appropriate colour or lithology code, and indicate whether they are well- or poorly-exposed (e.g. by marking the traverse line as solid or dashed, respectively). Structural data, faults, fold axes and other geological information can all be recorded on the traverse; an example is shown in Figure 10.10a.

Closed compass traverse

Another way to create a traverse is by pacing out a polygon on a set of compass bearings; some correction for minor bearing errors may be required when you finally reach the end point (Figure 10.10b, p. 224). In this case, it is advisable to record the geology in a notebook with the paced distances, and make the required correction for each traverse point before plotting the geology on the field map.

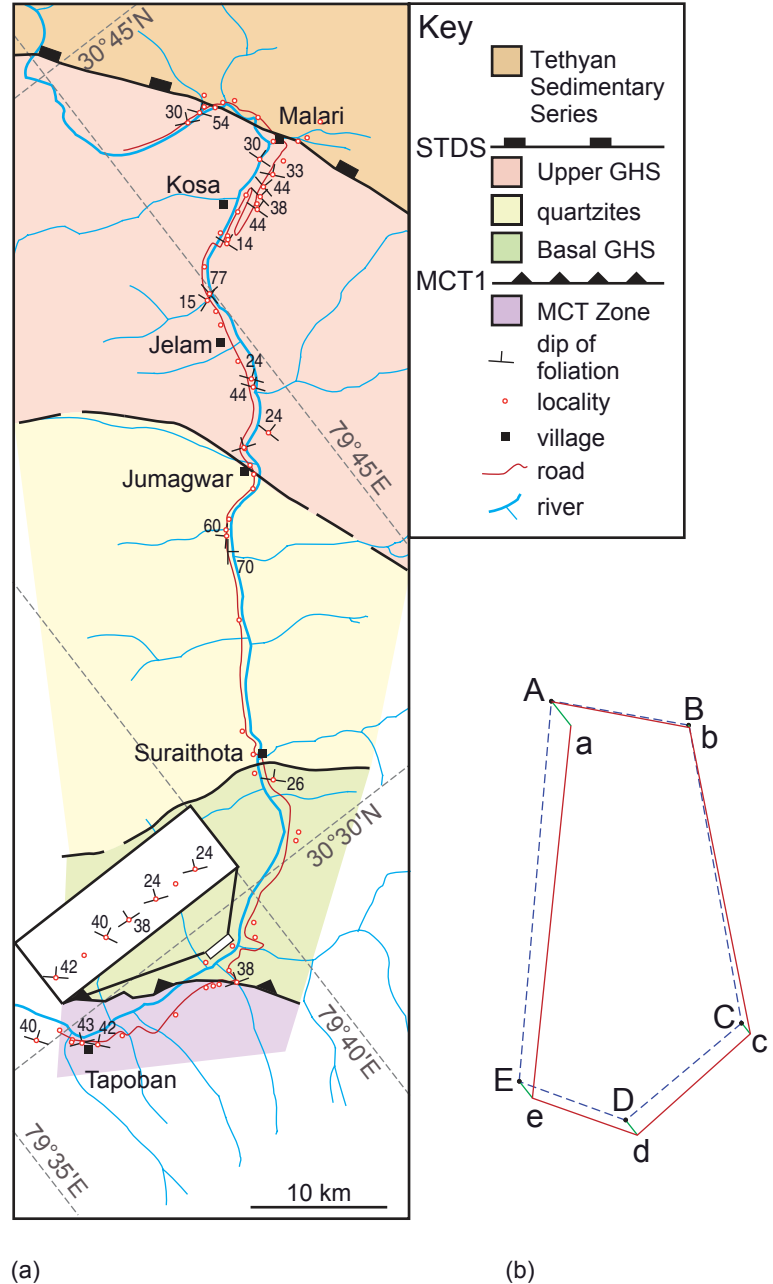
Traverses perpendicular to the regional strike form a good basis for sketching a cross-section in the field (Section 10.4.3) or in



Figure 10.9 River gorge at Wangtu, northwest India, illustrating the point that in very mountainous regions, the only practical mapping approach may be traverses along river sections or roads. In this view, the road is cut into the cliff on the left-hand side of the photograph, about half way up the image. (Tom W. Argles, The Open University, UK.)

sedimentary facies creating a graphic log (Section 6.3). This may highlight anomalies in the regional structure, for instance a concealed fault, which can be investigated without delay. In more accessible regions, traverse mapping can quickly identify important geological contacts that can be exploited, as described in the next section.

Figure 10.10 (a) A linear traverse mapped in the Alaknanda valley, northwest India. In this complex orogenic zone, the focus of this project was on gathering structural data and collecting samples for metamorphic and geochemical analysis. (b) Correcting a closed compass traverse for minor bearing errors. When the traverse was plotted using the bearings and distances in the notebook (red lines), the last leg (e to a) did not join up exactly to the origin (Point A), by a closure error of 43 m. The traverse was corrected by adjusting each plotted point (a to e) parallel to the closure error (green lines) by an amount proportional to the cumulative distance travelled to reach that point. So, for point d, correction = $43 \times (780/1435) = 23.4$ m. The result is the corrected closed traverse ABCDE (dashed blue lines).



10.5.2 Contact mapping

One important objective of geological mapping is to trace out the contacts between different geological units. In many cases, careful examination of aerial photographs or satellite images (including online sources) prior to (or during) mapping may pay rich dividends, since these may pick up subtler differences in soil type and vegetation than can be seen while on the ground. Contacts may be rapidly traceable across rugged terrain, and even under superficial deposits, in this way. Because contacts typically juxtapose rock units that have different properties (hardness, permeability, composition), there are often landscape clues to their presence (Section 10.5.4).

All that is required thereafter is to ‘ground-truth’ (Worked Example 10.1) your interpretation by visiting selected exposures at intervals along (or as close as possible to) the contact identified from the aerial photograph or satellite image. For a well-exposed contact you may simply be able to follow it, marking it on the map as you go. Exposures either side of the contact may contain clues to its proximity (e.g. minor faulting, sedimentological variations, contact metamorphic effects; abundant xenoliths). The field map in Figure 10.7a (p. 219) shows a contact mapped in this way between granite (red) and volcanic rocks (green), its position constrained by exposures marked on either side.

This technique is generally suited to mapping at scales of between 1:50,000 and 1:15,000, but it can also be used for very detailed mapping of small areas. In areas of good exposure, this method can build up a geological map quickly, especially if the structure is reasonably simple. The technique can be compromised by difficult terrain, poor exposure or complex geology. However, in poorly exposed terrain, contacts may still be traced by combining information from the few exposures with other information (Section 10.5.4): landscape features, drainage and mapping of the drift deposits that obscure the contact. Obvious contacts may be traced further using binoculars, especially in rugged landscapes with extensive exposure (Figure 10.11, p. 226).

To map a contact, mark it as a solid line on the field map where it is exposed, and as a dashed line where inferred (e.g. under vegetation, superficial deposits, ice, water, etc.; see Figure 10.7a). Confirm which rock units lie adjacent to the contact (these may change along a major fault), and use colour to show their outcrop. Shade actual *exposures* of rock more heavily than areas where rock units obscured by superficial deposits or vegetation are inferred (i.e. their outcrop).

Figure 10.11 Contacts like this one in southern Tibet may be conspicuous enough to be traced across difficult terrain using binoculars. (Tom W. Argles, The Open University, UK.)



10.5.3 Exposure mapping

This technique is typically more detailed than either contact or traverse mapping, and is used to produce maps at a scale of between 1:15,000 and 1:1000. Many landscapes are composed of more-or-less scattered exposures of rock separated by areas where the rock is obscured, by superficial deposits, vegetation, ice, water and so on. In this environment, the geologist aims to examine as many exposures as possible, outlining the extent of exposed rock in pencil and filling in each outlined exposure with the colour assigned to each rock unit that occurs there (Figure 10.12). The pencil outlines should be traced over in ink at the end of the day, because pencil will smudge or fade over a long field season. It is also a good opportunity to review the day's work. However, exposure mapping is not simply a 'colour by numbers' exercise! Do not be tempted to leave important contacts or boundaries to be drawn between different units later. You should investigate and confirm the suspected presence of a boundary in the field where possible, and dash boundaries where inferred. This constant re-evaluation of the structure will help you pick up offsets and anomalies more quickly.

Exposures too small to outline can be marked with a coloured dot and annotated with the rock type if there is space on the map. Areas of no exposure should be labelled as such, along with any additional information that may give clues to the underlying rock type (e.g. 'boggy ground'; 'grass with sinkholes'; 'thin soil with abundant flint cobbles'; see Section 10.5.4). Once all the exposures in an area have been mapped, the intervening blank areas on the map can be lightly coloured in if the underlying rock unit can be inferred from the adjacent exposures and/or other clues such as changes in topography,

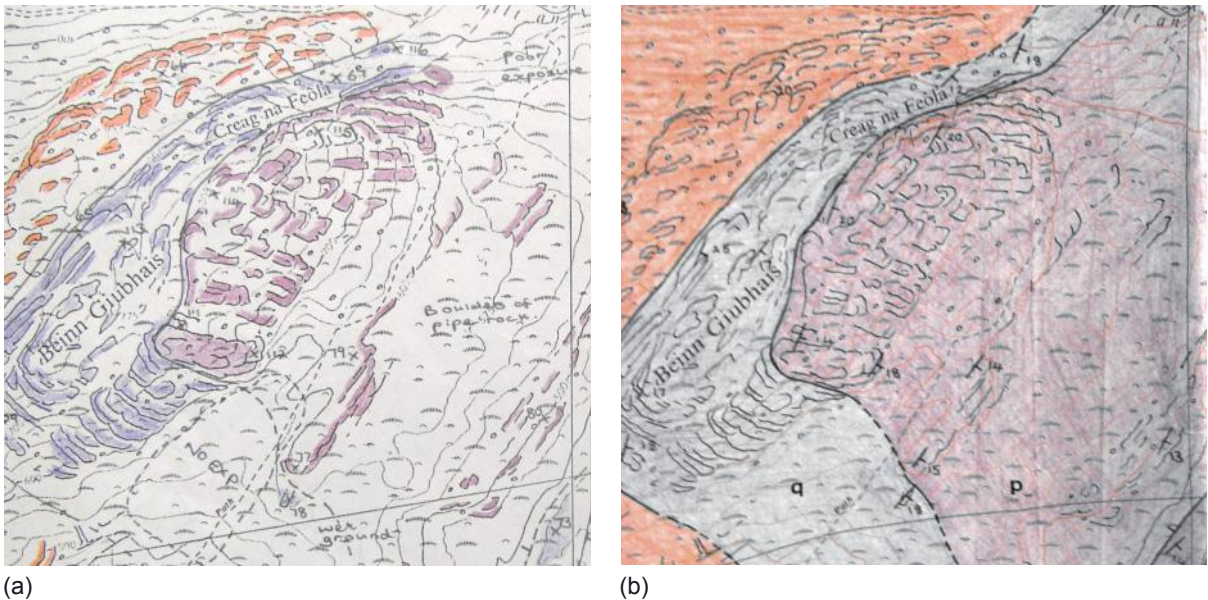


Figure 10.12 (a) An example of a field map produced by exposure mapping, with exposures outlined in pen; note that unit boundaries are also shown as dashed or solid lines. (b) A portion of the final fair copy map from the field map in (a), showing how the inferred outcrops of the mapped units are shown as solid blocks of colour. (Field map and final fair copy map of Susie Clarke, Oxford, UK.)

soil type and vegetation (Section 10.5.4). Strata, contacts and/or faults could be traced across a blank area along their strike, provided exposures either side of the blank area match. If a linear feature on the map (contact, dyke, lithological boundary) is offset across the blank area, a fault may be the cause. The broken rock along fault lines is susceptible to weathering and erosion, so faults are commonly concealed in ravines, watercourses, or depressions that accumulate superficial deposits. In some cases, clues in the landscape (Section 10.5.4) may allow a feature to be traced across an area of no exposure; for instance, the presence of an unconformity between permeable limestone and impermeable mudstone may be betrayed by an abrupt contrast in surface drainage (dry ground above limestone, wet ground above mudstone).

Exposure mapping can be challenging in areas at either extreme, i.e. where exposure is poor, or almost 100%. If almost all rocks are exposed, the challenge may be to separate rock types that grade into each other (e.g. phyllites, schists, gneisses), and divide them into mappable units. It can be difficult to achieve this before all the units in the area have been examined, although judicious study of river pebbles can help, or a suitable transect through the area. Once the units have been established, contact mapping may then be the best way to proceed.

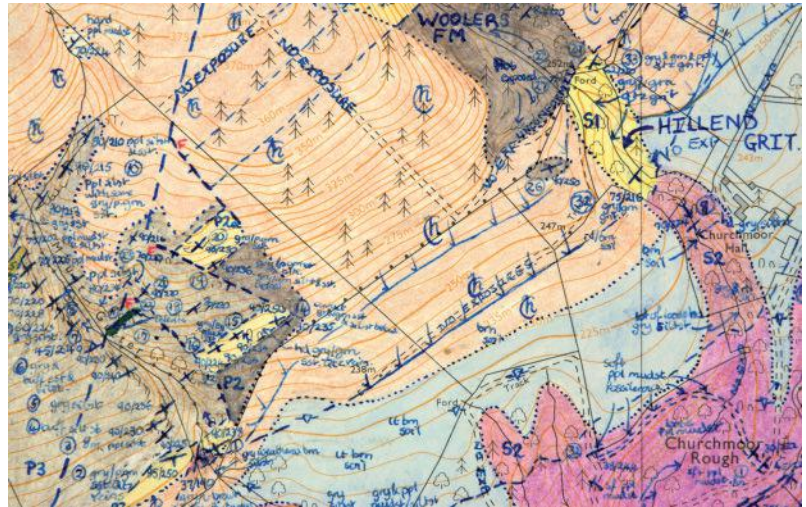
For a snapshot of the rock types exposed in a particular area, spend a short time picking over pebbles in large alluvial fans or bars of rivers that drain the mapping area. This will give an overview of the rock types present (although biased in favour of harder rocks).

In areas of few exposures two strategies are useful: (1) observe the area from a high viewpoint, and mark the locations of exposures on your field maps – you can then plot a route to visit all of them efficiently; (2) check all the other small exposures and clues (Table 3.2, p. 45).

10.5.4 Using other evidence

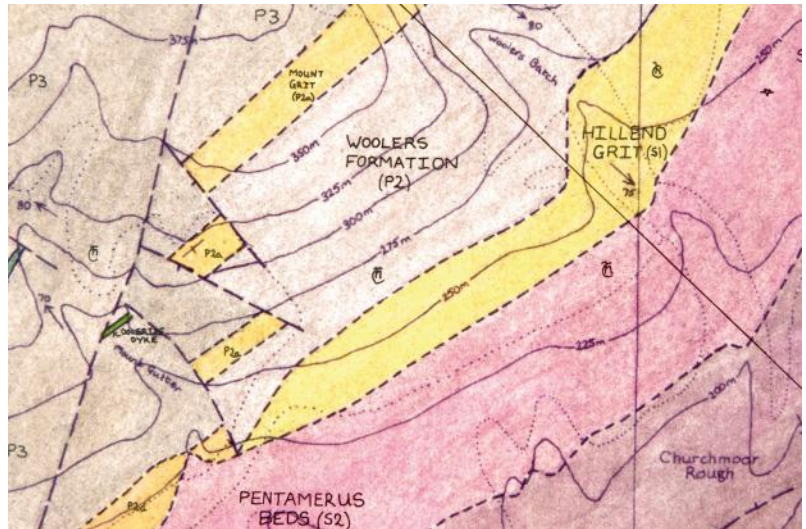
Topographic features: Feature mapping

In any area of poor exposure, gathering clues to the underlying geology from the landscape is a useful skill. The topography itself is heavily influenced by the bedrock underneath, so that, for example, many breaks in slope mark the location of a



(a)

Figure 10.13 (a) Part of a field map of the Long Mynd area, Shropshire, UK, incorporating landscape features (e.g. breaks in slope) as evidence of stratigraphic boundaries. Each break in slope is marked as a line with a series of arrows pointing at it; two occur in the centre of this extract, with another at top right. Superficial deposits that obscure the bedrock geology are also mapped. (b) The corresponding portion of the final fair copy map from the field map in (a), showing how the inferred outcrop of the bedrock units is depicted; the two central breaks in slope mark the boundaries of the Hillend Grit. (Field map and final fair copy map of Angela L. Coe, Open University, UK.)



(b)

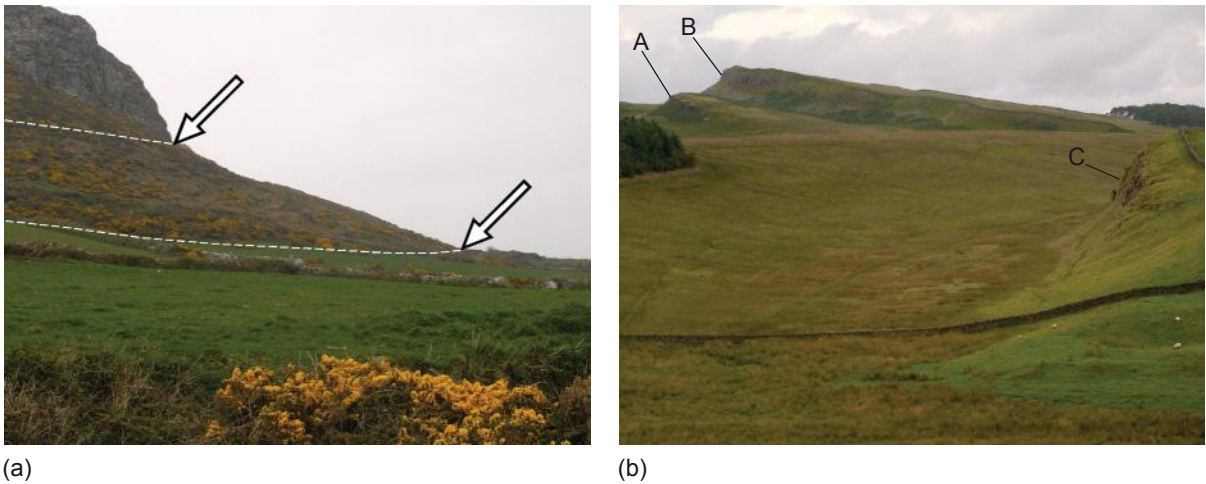


Figure 10.14 Some landscape clues to bedrock geology. (a) Two breaks in slope (arrowed) mark the boundaries between massive gabbro (crag on left) and cleaved mudstones (underlying fields on right) at Carn Llidi, southwest Wales, UK. The intermediate slopes are underlain by contact metamorphosed mudstones and gabbro debris. (b) Steep scarp slopes mark resistant strata, near Haltwhistle, UK: a sandstone at A and the Whin Sill (dolerite sill) at B and C. The horizon dipping to the right (south) follows the dip of the sill. Depressions between the scarps are underlain by softer siltstones and limestones. (a and b: Tom W. Argles, The Open University, UK.)

Table 10.6 Topographic clues to bedrock geology.

Topographic feature	Possible cause(s)
Break in slope	Stratigraphic boundary, fault, unconformity, limit of metamorphic aureole
Depression, ravine	Fault, shear zone, layer of softer material, synformal fold
Ridge	Dipping resistant rock layer, dyke, mineralized fault zone, antiformal fold
Escarpment	Edge of gently dipping strata, fault

lithological boundary (Figure 10.13a). Gently dipping strata can be mapped out by the succession of scarp and dip slopes (Figure 10.14b), even where rock is not exposed. Systematic offsets of scarp features may indicate faults, especially where the offsets coincide with linear depressions. Curved ridges may indicate folding that can be traced out, either on the ground or by reference to aerial photographs. Where scarps or ridges die out gradually, you might suspect that the resistant bed forming the feature has pinched out. Table 10.6 lists how some common topographic features might reflect the bedrock geology, with some examples shown in Figure 10.14 (see also Figure 8.2, p. 167). Conventional symbols for these features on a field map are included in Appendix A10, Figure A10.3.

Drainage

Many conspicuous drainage features owe their existence to the underlying bedrock or superficial geology (e.g. Figure 10.15). Table 10.7 summarizes some common examples. Care is needed in interpretation, as both bedrock and superficial deposits may influence drainage. For example, waterlogged ground could be due to a thin layer of impermeable glacial till that is itself underlain by permeable sandstone. Some drainage patterns may be antecedent: i.e. they pre-date the formation of a later landscape (e.g. a young mountain range) and hence bear little or no relation to the underlying geology; this is true of



(a)



(b)

Figure 10.15 Examples of drainage and vegetation contrasts.

(a) Marshy ground with rushes (foreground) marks the outcrop of impermeable Silurian mudstones, while most of the sheep are grazing on the well-drained pasture underlain by permeable Carboniferous Limestone (exposed in the crags behind). The contact between the two rock types is marked by a distinct break in slope, conspicuous against the woodland near the left-hand side of the photograph. Witherslack, Cumbria, UK.

(b) The green verdant vegetation and flatter foreground is underlain by interbedded limestones and mudstones. The steeper slopes with vegetation typical of acidic soils (heather, bracken) are underlain by sandstone. The contact is marked by the vegetation change, running from just left of the group of trees on the horizon obliquely left behind the plantation on the left-hand side. This locality is near Alnwick, Northumberland, UK. (a: Tom W. Argles, The Open University, UK; b: Angela L. Coe, The Open University, UK.)

Table 10.7 Drainage characteristics of the underlying geology.

Drainage feature	Possible cause(s)
Wet, boggy ground, marsh	Impermeable substrate (e.g. mudstone, granite, gneiss, glacial till)
Dry, well-drained ground	Permeable substrate (e.g. limestone, chalk, some sandstones, gravel, blown sand)
Ephemeral streams	Permeable bedrock (e.g. limestone, chalk), or low rainfall (arid areas)
Spring lines, seeps	Boundary between permeable (up-slope) and impermeable (down-slope) substrates (e.g. fault, unconformity, or stratigraphic boundary)
Sinkholes	Boundary between impermeable (up-slope) and permeable (down-slope) substrates (e.g. fault, unconformity, igneous or stratigraphic boundary); typical of limestone areas
Potholes, caves, karst features	Typical of limestone areas, rare in regions underlain by other rocks
Dendritic drainage	Area underlain by similar substrates (or even a single rock type)
Rectangular drainage	Exploiting regular lines of weakness in bedrock, such as joints in granite
Radial drainage	Water drains outward from a raised feature (e.g. structural dome, granite intrusion, volcanic centre)
Linear drainage	Lines of relative weakness in bedrock (e.g. faults, fold axes, soft strata, dykes)

several major Himalayan rivers that cut deep gorges through the range. However, some watercourses may be deflected by strike-slip faults, preserving offsets that betray the presence and kinematic sense of the fault (Figure 8.1d, p. 166).

Soils and vegetation

Other clues may be drawn from soils and vegetation. Fragments of the underlying rock (float) may be found in the soil (Figure 10.16a, p. 232), although these may be misleading in formerly glaciated areas with extensive till or river gravel deposits that contain pebbles from several (perhaps distant) sources.

Otherwise, the mineral content may give some hint of the bedrock: sandy soils could reflect sandstone or granite; red, iron-rich soils occur commonly on mafic rocks (e.g. basalt). An efficient way of investigating the soil type down to a few decimetres is by using a hand auger to take a sample of the soil and particularly the subsoil (Figure 10.16b). As well as information on the soil type, the auger may yield fragments of weathered bedrock (regolith) that is not exposed nearby, and it is a common reconnaissance tool. The vegetation is strongly influenced by both soil type and drainage, so certain rock types support distinctive plant associations (e.g. calcareous grasslands on chalk; acidic soils hosting gorse bushes and heather on sandstones (Figure 10.15b) and peat bogs on granite).



(a)



(b)

Figure 10.16 (a) White fragments of chalk in this soil are a conspicuous clue to the bedrock beneath. It is always worth checking soil excavated by burrowing organisms (in this case prairie dogs at Whipsnade Zoo, Bedfordshire, UK). Burrow is about 12 cm across. (b) A hand auger, useful for obtaining samples of the shallow subsurface, including soil. The auger is lying alongside a loose 'core' of soil obtained from this locality. (a: Tom W. Argles, The Open University, UK; b: Mark Brandon, The Open University, UK.)

Superficial deposits

Landforms commonly reflect superficial deposits, which should be noted on field maps, especially where they mask the bedrock. The extent to which you map the distribution of different superficial deposits depends on the focus of the mapping project; in some cases, mapping is specifically targeted at Quaternary superficial deposits. Sand dunes, peat, alluvium, laterite and beach deposits all represent a chapter in the geological history of the area, and different projects may focus on one or more of these deposits. Glacial and fluvio-glacial deposits can form dramatic landscape features (e.g. drumlins, eskers, terminal moraines, terraces), so you should distinguish these from bedrock landforms where possible. A few superficial deposits (e.g. landslides) can be positively misleading. Large landslides may not be obvious at first (Figure 10.17), and the jumbled structure could prove a puzzle. Clues to landslides include: a prominent scar (commonly curved); hummocky ground with a rather low average slope and small-scale drainage, small ponds, etc.; a vegetation contrast between the landslide debris and the surrounding undisturbed land.

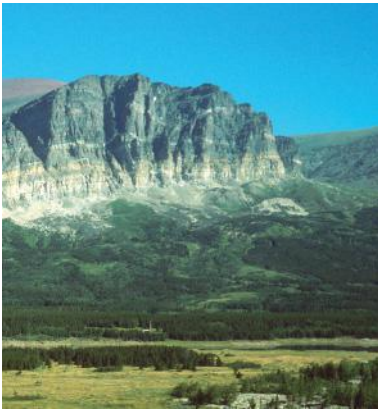


Figure 10.17 Typical landslide topography in Glacier National Park, Montana. The landslide material forms the hummocky ground with patchy vegetation sloping from the scree fans at the base of the cliffs towards the level plain in the foreground. (Courtesy of the U.S. Geological Survey; photographer P. Carrara.)

Wherever exposure is poor, take the opportunity to annotate your field map with any relevant information on topography, superficial deposits, drainage, soils or vegetation. Figure 10.18 shows an example of a field map drawn largely from the results of numerous auger holes, combined with landscape features. These observations will help corroborate your interpretation of the underlying geology when drawing the final map.

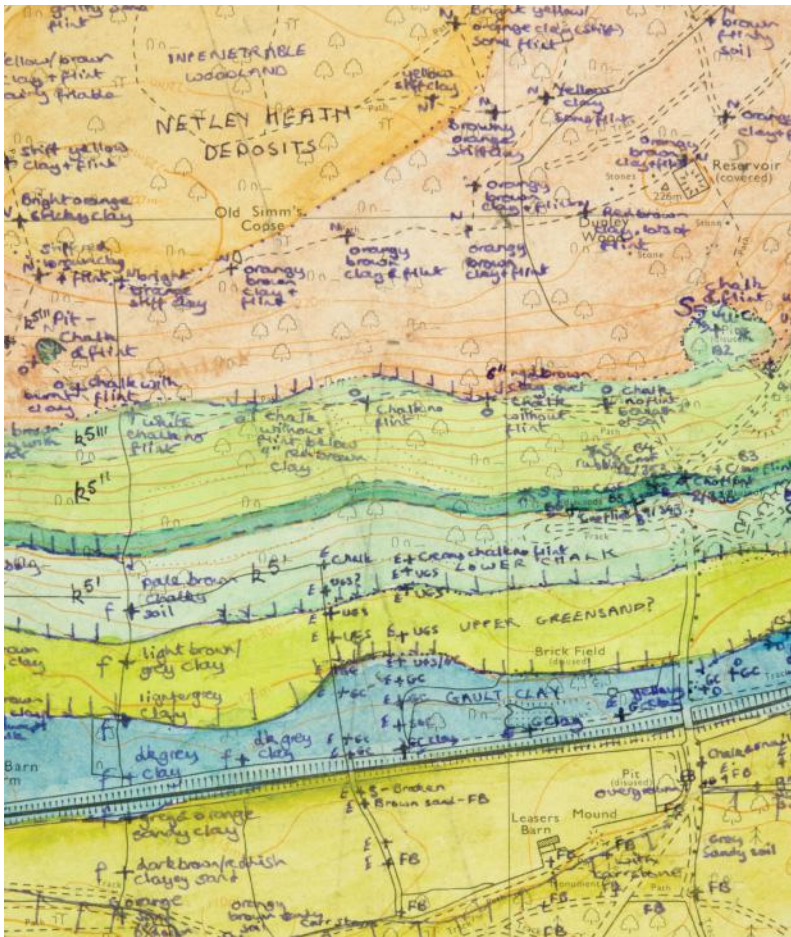


Figure 10.18 Field map in an area of poor exposure, with annotations on auger borings of the shallow subsurface augmented by notes on breaks in slope. Most boundaries are dashed or dotted (inferred). Auger holes are marked with a plus symbol (+); actual exposures are marked with a star (*); letters refer to notebook entries. (Map of Kate J. Andrew, Herefordshire Heritage Service, UK.)

10.6 The geological map

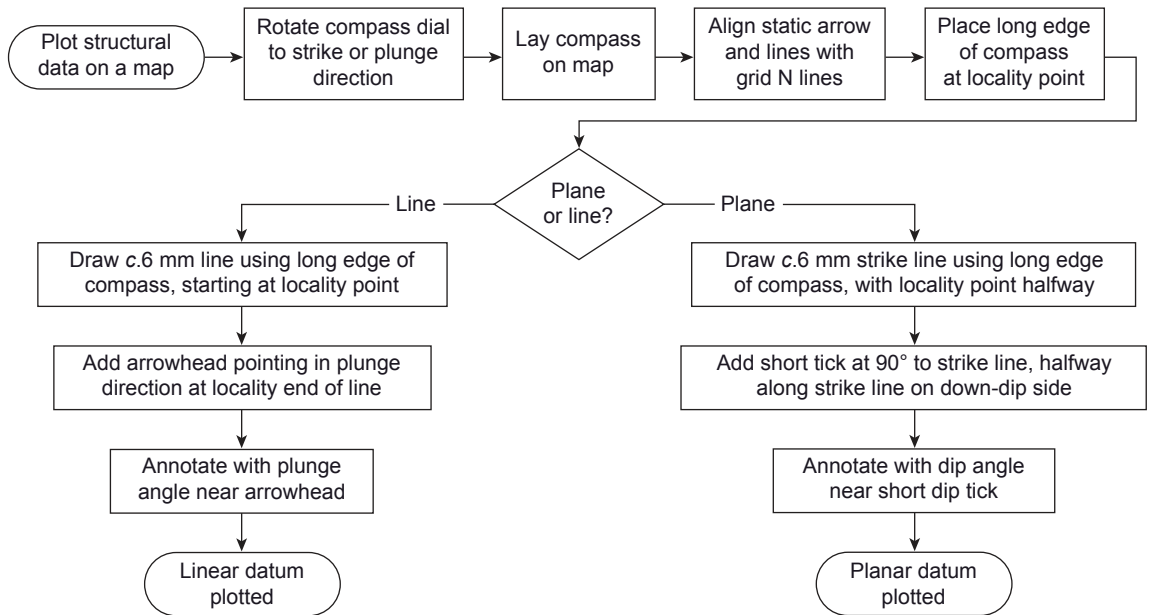
This section will discuss how to proceed from field maps and notebook information through to producing the final fair copy map, along with additional interpretative material such as cross-sections.

10.6.1 Inking in the field map

It is advisable to 'ink-in' field maps as soon as possible after mapping (e.g. in the evening). The aim is not to create a neat 'final map', but to review your observations and evidence while they are fresh in your mind, resolve any discrepancies, and then

preserve and emphasize information for further interpretation. Inking in will involve the following as appropriate to the area.

1. Structural symbols should be checked and redrawn using permanent mapping pens with waterproof ink, at different thicknesses (or in different colours) for faults and unconformities. Ensure the symbols are consistently marked relative to their locations: convention is for the locality to lie at the intersection of strike line and dip tick (planar feature), or the head of the arrow (linear feature). Make strike lines and plunge arrows long enough (*c.* 6 mm) so that they can be traced, or their azimuth determined, if necessary (for instance if the data are lost). Make sure bearings of all data are retrievable in case of imperfect plotting (e.g. in a notebook, unambiguously keyed to the locality on the map). Omit symbols only to avoid congestion, and then omit data that are less crucial to your study (e.g. joints, vein orientations). This important recording process is summarized in the flowchart below.



2. Other annotations such as locality numbers and brief notes can be rewritten in ink, and may be repositioned for clarity at the same time.
3. Lines marking certain geological boundaries can be inked in and those marking uncertain geological boundaries can be left in pencil, but may need renewing.
4. Exposures can be outlined in ink and coloured strongly, but areas where rock units are inferred should only be coloured very lightly. Figure 10.12 (p. 227) compares a field map with the corresponding 'inked-in' map.

10.6.2 Cross-sections

Constructing or sketching cross-sections while mapping an area is an important step in understanding the geology, and may provide critical insights into the developing map. Sections are generally drawn along a line perpendicular to the dominant strike of strata and structures (e.g. faults, fold axes), so that they show the subsurface structure most clearly. Accurate sections typically have a horizontal scale equal to that of the map on which they are based, but the vertical scale may be exaggerated to emphasize the structures (in which case, strata dip more on the section than in reality). The process of drawing a cross-section is illustrated by Figure 10.19 (pp.236–237), and broken down into stages in the following section.

10.6.3 Fair copy maps

Geologists make a final fair copy of their field maps to present their interpretation of the geology, commonly as part of a report. The map itself is generally only one element of a complete map sheet, which includes scale, explanatory material and commonly cross-sections too; a typical layout is shown in Figure 10.20 (p.238). Geological maps are increasingly drafted electronically, but there are several ways to transfer geological information gathered in the field to a fair copy map. A brief review of the main steps in that process is provided here.

- Aim either to draw your fair copy map onto a fresh copy of the base map (in paper or digital format) or start with a blank page and redraw sufficient topographical elements to find the geological features (e.g. Figure 10.20, p. 238). Make sure that at least some elements of the topography are represented on the final map; for instance, if contours are dense, trace a few at selected intervals. If no contours are available, try and include at least drainages (rivers, streams) and major peaks. Electronic base maps can be rendered in greyscale so as to distinguish them from the coloured geological data.
- Transfer geological boundaries and faults onto the fair copy base map. This can be done in a variety of ways (Table 10.8). Lines should be solid, except where boundaries were inferred; in this case dashed lines are used. Draw faults as thicker lines than stratigraphic boundaries, and apply ornaments (e.g. downthrow ticks for normal faults, triangular teeth for thrusts).
- Distortion of field sheets by initial photocopying and later weathering typically means that they do not exactly match the fair copy base map, which may need to be shifted repeatedly by small amounts to maintain as good a fit as possible between the two.

Table 10.8 Methods for transferring lines to a fair copy map.

Line transfer methods

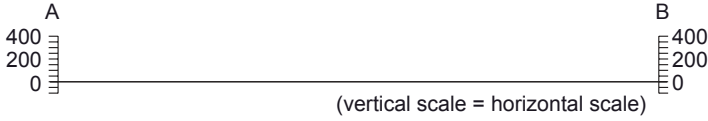
Digitize (trace over) electronically scanned field maps on a computer

Copy by inspection onto a fresh paper or digital base map (if detailed enough)

Copy onto a fresh base map, using the same grid on both maps for reference

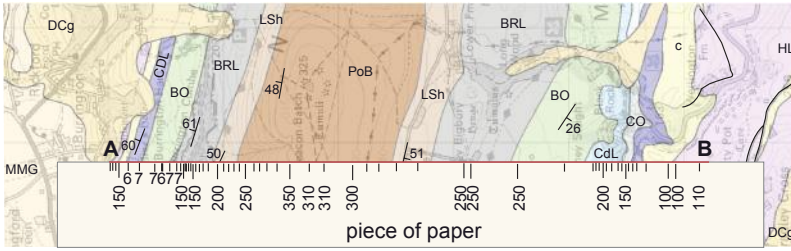
Overlay the field map with the fair copy map on a light table and trace by hand

Draw the map digitally using GIS or graphics software while in the field



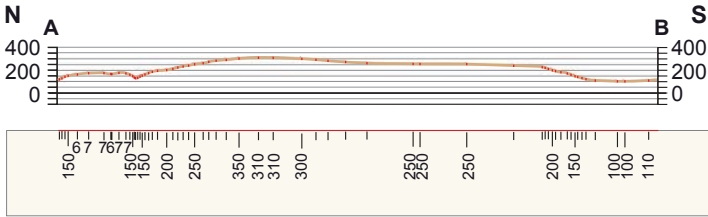
(a) Decide on an appropriate vertical scale for the cross-section. Mark the line of section on the map with a faint line, or mark the end points. On a separate sheet of graph paper of

the same length, to represent mean sea level (the usual reference datum). Add vertical axes at each end, labelling them with an appropriate scale for the height relative to sea level.



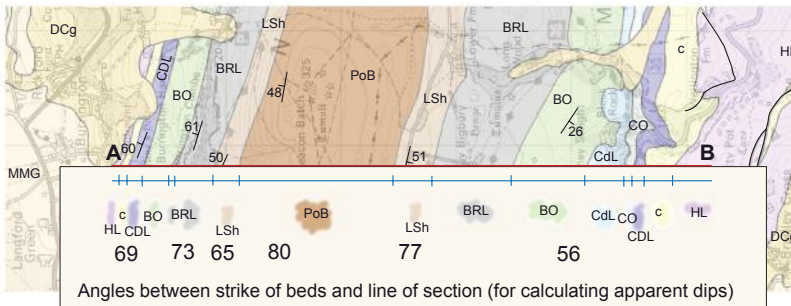
(b) Lay the straight edge of a second sheet of paper along the section line on the map. Mark the end points of the section line on the edge of the paper, and wherever

topographic contours cross the section line mark ticks, labelled with the contour height, on the second sheet of paper. (It may help to mark rivers and ridge crests too.)



(c) Transfer the contour heights to the graph paper by laying the edge of the paper along the horizontal axis, and marking dots projected up to the correct height all along the cross-section. Join these dots with a smooth

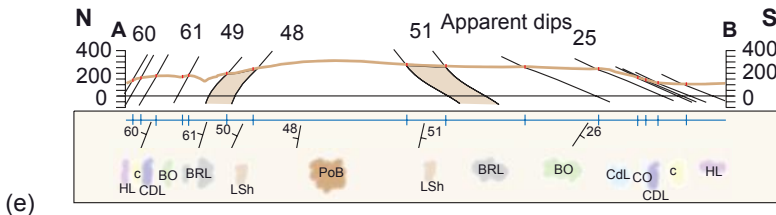
curve interpolated between them to produce a topographic profile as a base for your cross-section. Label the end points with a grid or GPS reference, or a compass bearing.



(d) Using a third sheet of paper, transfer geological information such as stratigraphic boundaries, faults and igneous contacts along the line of section from the

map to the cross-section in the same way as you did for the contour heights (stage (b)).

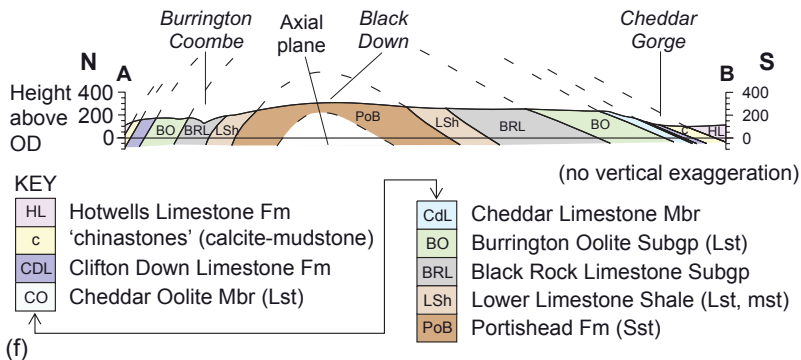
Figure 10.19



(e)

Transfer the position of these features directly onto the topographic profile on the graph paper. Dip measurements can also be transferred onto the section. If there are none on the line of section, data lying short distances away from the section line can be projected at right angles onto the line. However, only where strata strike at exactly 90° to the section line can their dip angles be drawn directly onto the cross-section. Dips of strata striking at more oblique angles to the

line of section must be corrected to lower values, because in effect the cross-section cuts these strata obliquely, and their dips will hence be apparent dips on the cross-section. The more oblique the strike to the section line, the lower the apparent dip will be. (Appendix 10, Figure A10.1 shows a graph you can use to determine apparent dips.) Draw short lines for the dip data at the correct angle just above the profile initially, as a guide.



(f)

Choose an important marker horizon or stratigraphic boundary, and draw this across the section, matching its dip to the dip measurements where possible, and interpolating between the different points on intersection with the topography. With this guide to the overall structure, add other unit boundaries in the same way; unless you have evidence for varying strata thickness,

draw these parallel to the first horizon. In some cases, you may know or be able to determine the throw on faults, and their attitude; you may also be able to define fold structures. Generally, you will be able to extend your section further below the surface in folded areas; indicate uncertainty with question marks. Finally, add a key to unit colours and other symbols.

Figure 10.19 Stages in drawing a geological cross-section. (Map for b and d: Ordnance Survey 1:25,000 Scale Raster © Crown Copyright 2009. An Ordnance Survey/EDINA supplied service. Geological Map Data © NERC 2009.)

- Colour the outcrops of geological units as continuous blocks, even where inferred. Use colours thoughtfully: for example, choose pale colours for widespread units and stronger colours for those with limited outcrop (e.g. dykes, thin strata). Colour on a computer has the advantage of being standardized (e.g. using CMYK values). For hardcopy maps, various media can be employed (e.g. watercolours, coloured pencils).
- Every unit should be identified by a code, in many cases an abbreviation of the unit name (e.g. MMG for Mercia

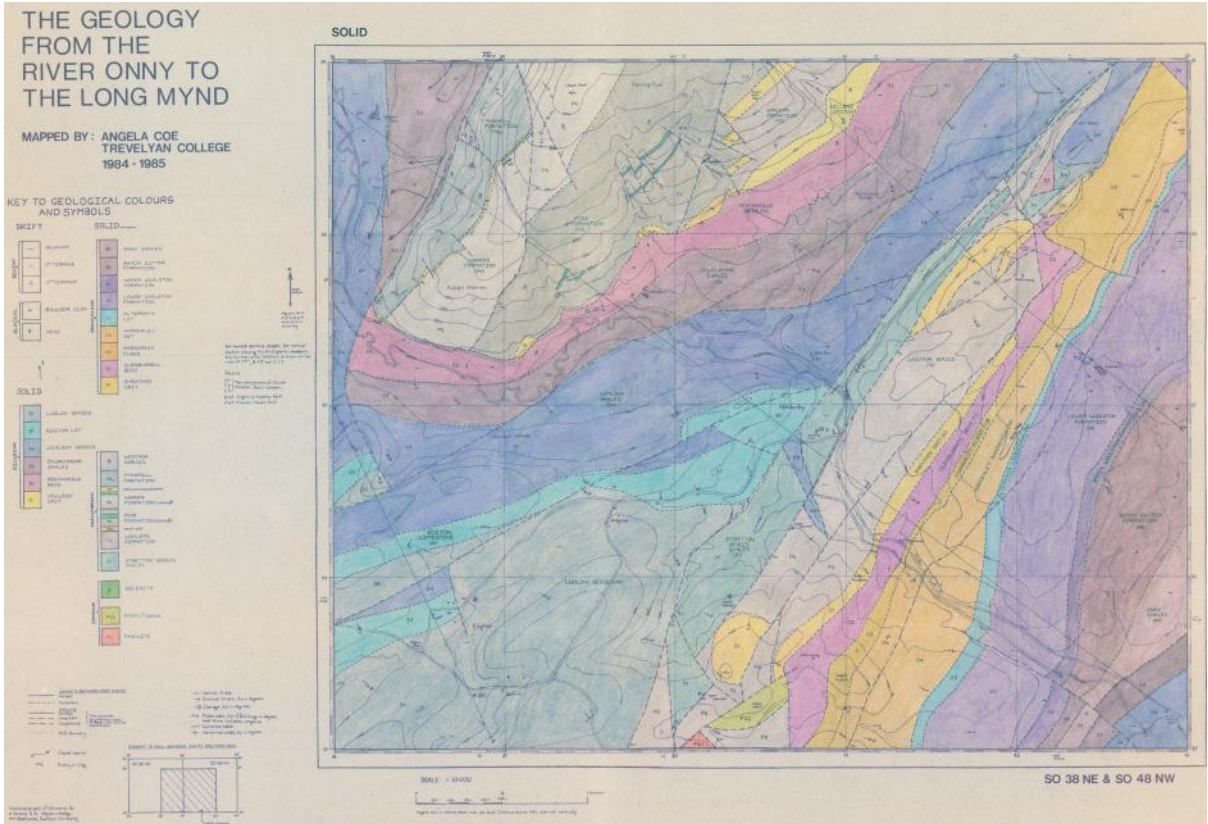


Figure 10.20 An example layout for a fair copy map. (Map of Angela L. Coe, The Open University, UK.)

Mudstone Group), or a code of letters and numbers based on the age of the unit (e.g. K6 is a code for the Cretaceous White Chalk Subgroup in the UK; Obe stands for the Ordovician Bald Eagle Formation in Pennsylvania, USA). These may conform to formal lithostratigraphic schemes, or you may need to devise your own. Place several labels within a large outcrop; link labels to small outcrops with a leader line. Lettering can be done using transfers (costly) or stencils, printed neatly by hand or typed directly onto digital maps.

- Add sufficient structural symbols (bedding, foliation, lineation and folds) to allow the stratigraphy and structure to be determined. Mark only the dip or plunge angle by the symbol, not the strike bearing (because the line itself defines the strike azimuth). Make sure that symbol types and sizes are consistent (Appendix A10, Figure A10.3), both across the map and in the explanatory key.
- Clarity is essential, so make sure that symbols are neat and not congested. Omit locality and sample numbers, and

Table 10.9 Additional elements of a final fair copy map.

Element	Comments
Title	Include the name of the area mapped, and indicate any special theme (e.g. ore mineralization)
Scale	As a ratio (e.g. 1:10,000) and in graphical form (e.g. a graduated bar)
N arrow	Indicate true north, and also show relative deviations of grid and magnetic north
Author, date	Include both the date of mapping and of map publication
Sources	Cite the sources of topographic base maps and any additional data used (e.g. previous maps)
Explanation	A detailed legend showing colours, ornaments and letters for units, all symbols, lines, etc., similar to that in Figure 10.6
Stratigraphic column	A vertical section, showing the stratigraphic order and relative thickness of strata
Cross-section(s)	Include one or more horizontal cross-sections, generally along the base, to illustrate the structure of the area

information not bearing directly on the geology (e.g. soil annotations – just use these for interpretation of the geology); fossil and ore mineral locations may be retained if appropriate.

Alongside the actual map, several other elements are either essential or highly desirable, generally as marginal additions. Table 10.9 summarizes these components.

Make sure that the symbols and ornaments in the explanation of a fair copy geological map are all at the same scale as on the main map.

10.6.4 Digital maps and GIS

Many final geological maps are drafted electronically, using Geographic Information System (GIS) technology to plot the geological data in a geospatial framework. However, in some cases the actual mapping is also conducted using portable computers (laptops or ‘tablet’ PCs), which allow data to be directly entered into databases, and maps to be drafted on-screen on an electronic base map. Professional surveys and other companies increasingly use this technology, but it has limitations as well as advantages (Section 2.9). Such methods are beyond the scope of this introduction, as each system is likely to require specific training in the software and mapping styles adopted by the organization. However, the general principles of mapping outlined in this chapter should still be followed while mapping in this way; it is only the tools that have changed.

10.7 Further reading

- Barnes, J. W. and Lisle, R. J. 2003. *Basic Geological Mapping* (4th edition), Blackwell Science, 196 pp. [Good introductory text, covering many basic techniques succinctly, along with chapters on equipment, cross-sections and report writing.]
- Bennison, G. and Moseley, K. 2003. *An Introduction to Geological Structures and Maps*, Hodder Education, 176 pp. [A concise book covering both basic and more advanced techniques in geological mapping. The text is illustrated with line drawings and photographs, and contains solutions to all exercises in the appendices.]
- Bolton, T. 1989. *Geological Maps: Their Solution and Interpretation*, Cambridge University Press, 156 pp. [A useful practical text on the interpretation of geological maps, with numerous exercises involving maps based on real examples.]
- Drury, S. A. 2001. *Image Interpretation in Geology*, Routledge, 304 pp. [An excellent introduction to the interpretation and manipulation of images in geology, focusing mainly on remote sensing and satellite imagery.]
- Maltman, A. 1998. *Geological Maps: An Introduction*, Blackwell Publishing, 272 pp. [A readable introductory text, incorporating historical aspects of geological mapping as well as reference to example maps.]
- McClay, K. R. 1991. *The Mapping of Geological Structures*, John Wiley & Sons, 168 pp. [A small-format book focusing on how to map, record and analyse geological structures.]
- Spencer, E. W. 1999. *Geologic Maps: A Practical Guide to the Interpretations and Preparation of Geologic Maps*, Prentice Hall, 184 pp. [A step-by-step approach to interpreting and preparing geological maps, including the use of aerial photographs.]

11 Recording numerical data and use of instruments in the field

Angela L. Coe

A wide range of geophysical instruments can be used to: detect and characterize rock bodies that are not exposed; quantify relative changes in rock composition; and measure ground movements related to earthquakes and active volcanoes. Instruments to collect data on subsurface geology include magnetometers, gravity meters and geophones for seismic surveys. Common instruments used to quantify the changing composition of a rock include the portable gamma-ray spectrometer and magnetic susceptibility meter. These instruments are particularly useful on mudstone successions and can be used as a proxy for changes in clay mineralogy (gamma-ray spectrometer) and relative changes in the amount of clay to carbonate (magnetic susceptibility meter).

All of these geophysical methods have the advantage that they are non-destructive. The use of specific geophysical instruments and more specialist techniques is beyond the scope of this book and instead the manufacturers' handbooks or more specialist text books should be consulted. Here we provide a brief overview of some of the instruments available and their possible applications (Table 11.1) along with some general notes on data collection.

11.1 Data collection

The built-in memory of many geophysical instruments makes data collection fast and easy. However, given that weather conditions and field access can be challenging, the demands put on any instrument are large. Therefore if the data will be hard or too expensive to re-collect should it be lost, it is essential either to back-up regularly to a separate device or to make a hard copy in the field. A separate record of the data will also prevent it all being lost if the instrument is stolen, or confiscated by Customs! In addition, if there is no way of entering extra data into the device it will also be necessary to

Table 11.1 Commonly used equipment, main use and examples.

Instrument	Main uses	Examples
Gravity meter	Large-scale surveys of subsurface bodies of different density or of bodies that are changing mass or volume	Boundaries of sedimentary basins, detecting granite plutons and, in conjunction with elevation surveys (such as differential GPS), studies of the inflation and deflation of volcanic regions
Magnetometer	Medium- to small-scale surveys of bodies with a magnetic character that is distinctly different from that of the surrounding rock	Dykes, sills, ore bodies and other buried geological contacts
Seismic surveys	Survey of features with an acoustic impedance contrast (related to density) on a wide range of scales from tens of metres to thousands of kilometres	Extensively used method for surveying stratigraphy within sedimentary basins. Can also be used to examine deep crustal structure or to locate magma chambers
Portable XRF	Small-scale variation (decimetres to metres) in the major and minor element concentrations of rocks exposed at the surface	Provenance of derived rocks through chemical characterization. General characterization to determine position of high-resolution surveys. Generation of data for time-series analysis to determine if there are regular cycles relating to the time of deposition recorded in the rocks
Gamma-ray spectrometer	Small-scale spatial variation in the Th, K and U concentration in rocks exposed at the surface. 30cm to tens of metres	Variation in clay mineralogy and/or organic carbon content (U can be used as a proxy for organic carbon). Characterization of the U, Th and K composition of granites
Magnetic susceptibility meter	Very small-scale spatial variation in the response of rocks to an imposed magnetic field; this relates not only to the composition of rocks containing magnetic minerals but also paramagnetic minerals such as clay minerals	Variation in the clay, carbonate and silica content of mudstone successions. Detection of variation in interbedded salt and mudstone/carbonate deposits. Generation of data for time-series analysis to determine if there are regular cycles in the rocks

make a separate record of where each datum point was collected and any other constraints or observations. If the measurements are taken over a large- to medium-scale lateral grid, GPS or differential GPS can be used, but notes will be necessary for vertical grids and those of small spatial scale. The most easily accessible way to display a large amount of data and ensure that you do not miss anything is to construct a table with cells for each of the datum entries that you need (Figure 11.1).

6/10/96 2nd Bay from Chapman's Pool

Bed grp/bed	Stn No	Total	K	U	Th	Tc/Pos/live time
51/8	3	29.9	3.1	6.1	14.6	629959
		3521	825	179	126	27
		12396	2761	620	427	194
51/8	6	29.4	3.4	6.8	15.5	623334
		3701	907	197	135	28
		12977	3028	678	455	194
52/1	9	30.4	3.4	6.7	16.0	646215
		3824	904	197	138	29
		13361	3015	677	466	194
52/1	12	30.2	3.1	8.3	13.8	63114
		3804	870	218	122	30
		13307	2906	748	414	194
52/2	15	28.9	3.1	6.8	12.7	617335
		3638	834	186	111	31
		12772	2791	643	378	194

(a)

100 Stn b/g readings

AK 8.75	049.061/060.	
AK 8.5	051.070/069.	
AK 8.25	050.071/071.	
AK 8	051.063/064.	
AK 7.75	054.070/070.	close to very thin bentonite.
AK 7.5	057.071/072.	
AK 7.25	059.075/074.	
AK 7	059.084/082.	- percentack. but si starting to fade down - not quite at base of si rich yet.
AK 6.75	062.083/083.	
AK 6.5	065.080/080.	
AK 6.25	067.086/086.	
AK 6	071.090/089.	← 1cm below ie 5.9 = base of Si band

2125 = 2.1m
0 = 70
09

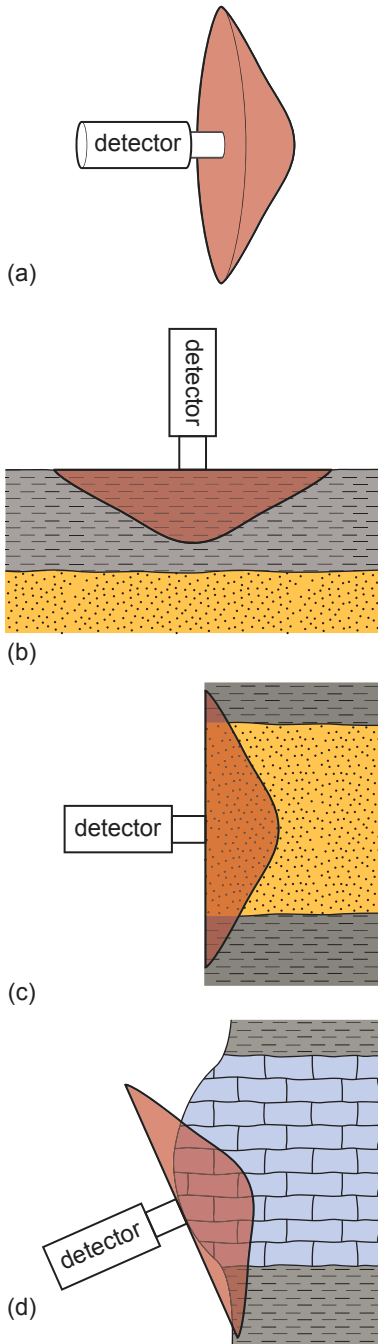
(b)

Figure 11.1 Some examples of the recording of numerical data in a field notebook. (a) Gamma-ray spectrometer data from five sample points (stations), showing stratigraphic position, raw and processed data and electronic file reference (pos). In this case gamma-ray spectrometer readings were taken every 30 cm (i.e. every third station, in order to match with the resolution of the instrument; other readings were taken every 10 cm). (b) Magnetic susceptibility data every 2.5 cm (whole-number stations are every 10 cm), background readings in air and two readings on the rock. This instrument measures continuously and integrates the data to provide a reading every 10 seconds. The small black circles represent readings given by the instrument as it is moved from rock to air. The recording of this as a point ensures that there is no mistake made between these meaningless measurements and the data required. (Notebooks of Angela L. Coe, The Open University, UK.)

When collecting numerical data using an instrument consider:

- devising a systematic method so that you do not miss anything;
- whether the resolution of the data is appropriate for the aim of the fieldwork but also the limitations of the instrument;
- the most appropriate way to use the instrument depending on where the instrument obtains most of its signal from.

The third point may sound obvious but an example would be the gamma-ray spectrometer which measures the gamma rays from a volume that is a flattened bell shape adjacent to the end



of the detector (Figure 11.2a). For a reading that characterizes a particular bed it is best to place the detector perpendicular to the bedding plane (Figure 11.2b). However, to obtain a reading that is more comparable to a borehole record and which averages the stratigraphic variation, it is better to place the instrument perpendicular to the bedding (Figure 11.2c). Figure 11.2d shows the proportion of signal lost by placing the detector on an uneven surface. This would result in a very inaccurate measurement.

11.1.1 Instrument calibration and base stations

Instruments need to be checked and calibrated regularly before going out into the field. A further good practice is to set up a base station at a convenient location where a few readings can be taken each day on the same spot to check for, and to monitor, instrument drift. Not all 'drift' is an artefact of the instrument, for example the strength of the Earth's magnetic field fluctuates continuously (mainly diurnally but there are shorter-term changes too), and apparent gravity at any point varies because of tidal effects. These gravity variations can be calculated, but magnetic changes have to be measured. In practice there is no need to untangle either of these from the instrumental drift; repeat readings at the base station show the sum of both effects, which is all you need to know in order to derive a correction for the time of your survey. These base-station readings are also likely to reveal any problems with the instrument.

11.1.2 Survey grids

A crucial part of any geophysical survey is setting up an appropriate grid over which to take the measurements. The grid needs to consider the resolution of the instrument, the size and shape of the geological feature under investigation and/or the overall objective, type of terrain and time available. The resolution of the instrument is very important. It is not worth surveying every 10cm if the resolution of the instrument is only 1m. Likewise if the resolution of the instrument is only a few centimetres then the survey needs to be designed so that crucial data are not lost between measurement stations, unless of course the purpose is a regional study.

Figure 11.2 (a) Three-dimensional representation of the bell-shaped volume (shown in red) over which the gamma-ray spectrometer measures. Two-dimensional representation of the area that the instrument will detect if used (b) parallel to the bedding plane, (c) perpendicular to bedding or (d) at an angle.

If the area is unknown it might be useful to run a pilot study with a low-resolution grid first, followed by a higher resolution study over the area of interest. Care also needs to be taken to ensure that sufficient data are collected to delineate the edge of the geological feature under investigation.

In all but exceptional circumstances the data should be collected at regularly spaced intervals so the mathematical processing that will need to be done later is easier. Maps, satellite images, GPS and/or surveying equipment should be used to set up large-scale grids. Small-scale grids and stratigraphic transects can be established using tapes, rules, a Jacob staff and compass (Section 2.5). Care should be taken to measure not only the distance between measurement stations but also the total distance between a number of measurement stations to check for cumulative error. For instance, if the measurements are taken every 10 cm check that the 1 m stations are correctly positioned relative to each other.

11.2 Transport and protection of the instruments

Some forethought needs to be applied to transporting electronic equipment in the field. Larger backpacks/rucksacks and/or one of the specially designed carrying cases may be necessary. However, some compromise between bulk and padding will need to be struck. All electronic equipment needs to be protected against rain and particularly saltwater. A large umbrella or mountain shelter tent can be useful under wet conditions. Carry spares of smaller items such as cables that are susceptible to damage. If you are carrying instruments to another country ensure you have documentation to indicate what the instrument is, what it will be used for and to whom it belongs. Custom regulations may need checking in advance and you may be required to demonstrate how the instrument works. Advance planning, and possibly permission, will be necessary for any instrument that under X-ray looks like a gun (as some detectors do) or contains radioactive material (e.g. gamma-ray spectrometer and portable XRF).

11.3 Correlation with other data sets

The geophysical data will often need to be correlated with geological and, in some cases, topographical data. This is best done when the measurement grid is set up. If appropriate to the size and type of survey, consider incorporating each data set into a Geographic Information System (GIS) that will allow appropriate display of each set of data and will let you look for

correlations. The higher the resolution of the geophysical data set, the more difficult this can be, especially if the geological data set is neither accurate nor precise. In some cases it may be necessary to refine or even re-collect the geological data. In new areas where there is little information a team of people can work together to produce an integrated data set. For high-resolution studies also see Section 13.1.7.

11.4 Further reading

- Keary, P., Brooks, M. and Hill, I. 2002. *An Introduction to Geophysical Exploration*, Blackwell Science, 272 pp. [Good basic text on geophysical techniques.]
- Judd, P. and Brown, S. 2006. *Getting to Grips with GPS, Navigation and Digital Mapping*, Cordee, 176 pp.
- Milsom, J. 2002. *Field Geophysics*, Blackwell Science, 244 pp.
- Parasnis, D. S. 1996. *Principles of Applied Geophysics*, Springer-Verlag, 456 pp.
- Sherieff, R. E. and Geldart, L. P. 1995. *Exploration Seismology*, Cambridge University Press, 628 pp.
- Telford, W. M., Geldart, L. P. and Sheriff, R. E. 1990. *Applied Geophysics*, Cambridge University Press, 792 pp.
- Weedon, G. P. 2003. *Time-Series Analysis and Cyclostratigraphy: Examining Stratigraphic Records of Environmental Cycles*, Cambridge University Press, 276 pp.

12 Photography

Angela L. Coe

Photographs are a key part of most geological fieldwork. They can serve as an *aide memoire*, be used for image analysis (Sections 5.4 and 5.5), to document changes in an exposure over time and are also essential to illustrate key geological features in a report, talk or publication. As outlined in Section 4.3 it is very important in the field not only to take a photograph but also to make field notes and sketches, because a photograph is *not* a replacement for a field sketch. A field sketch records how you have divided up the succession, provides a key to further notes and shows some geological interpretation. The photographs taken should be recorded in your field notebook and electronic information on the geological features and location added either through the camera or image processing software (Figure 12.1).

The detailed advantages and disadvantages of the wide range of cameras available on the market are outside of the scope of this book, so here we provide some general comments. Digital single-lens reflex (SLR) cameras provide the most amount of flexibility for a range of lighting conditions and types of photograph; they also generally have better lenses. However, many compact cameras give excellent results and have the added advantage that they are small and light. As with Personal Digital Assistants (PDAs), etc. (Section 2.9), check if the screen is visible under strong lighting conditions. This is essential when the camera does not have a view finder. If the camera does have a view finder but is not an SLR, the view finder does not usually give an exact representation of the frame of the photograph so you may need to work out exactly what that is if you wish to frame your subject exactly. Even with digital SLRs the view is not exactly the same. Cameras with good reviews for outdoor and scenic use will probably give the best geological field photographs. A good macro lens setting is advantageous if you are going to take a lot of close up photographs. In addition cameras that are sensitive to a wide range of lighting conditions allow maximum flexibility.

There is almost no limit to the number of photographs you can take with a digital camera, provided that is you have enough



(a)



(b)

Figure 12.1 Two photographs taken under slightly different f-stops to illustrate the effect of varying the camera settings. Images are 40 cm high. (a) f6.3 and (b) f4.5. The associated metadata that it is useful to include in an electronic file are: camera type, shutter speed, f-stop, ISO setting, white balance (see Figure 12.2), focal length, date, time, place, subject, keywords. Some of this is recorded automatically and other parts such as the subject matter need to be added by the user. (a and b: Angela L. Coe, The Open University, UK.)



(a)



(b)

Figure 12.2 Two images of grey mudstones from the Monterey Formation, California, USA showing the large colour difference when using a different white balance setting. Images are 1 m high. (a) Auto setting. (b) After using a white balance card to adjust the balance for the lighting conditions (seek advice from professional photographer/ photographic shop). All other camera light settings are exactly the same. (a and b: Angela L. Coe, The Open University, UK.)

memory and battery capacity for the camera. This means you can take many more photographs than you will eventually use. The following tips may help give you a set of photographs that cover all eventualities.

- Make the first photograph at a locality a general view; this will remind you of where the photographs that follow on were taken.
- Take both general views and close-up views of different features.
- Take note of the lighting conditions. The best view under sunny conditions is often with the sun behind you, so this may mean returning to a locality at a different time of day to get the best lighting. Cloudy conditions provide a more even light, but sunny conditions can show some geological features better.
- If the lighting conditions are poor or variable take several shots with different settings. Note that underexposed digital photographs can be processed later to achieve a good image whereas overexposed photographs do not record all of the information. In Figure 12.1, (b) is better than (a).
- The lighting late in the day and early in the morning (i.e. low-angle lighting) can bring out small- and medium-scale topographical features such as trace fossils and sedimentary structures.
- If you are using the photograph for image analysis ensure that it does not have any edge distortion, for instance that produced by using a wide-angle setting, or taking photos with the lens set to 50 mm or longer focal length. You will also need to take account of white balance under different lighting conditions (see manufacturer's instructions and Figure 12.2).
- Under low lighting conditions a tripod is useful; if you do not have a tripod with you try setting the camera up on a rock and using the self timer or a remote shutter release.
- If you are working where weather conditions are bad consider purchasing a waterproof camera case of the type used by divers for underwater photography.
- If you are taking a lot of photographs, for instance of shell beds or fine-scale detail, take the photographs in stratigraphic order to avoid confusion and consider marking the rocks in some manner, for instance with a marker pen, correction fluid or a tile scribe, so you know how the different photographs relate to each other.

- In most instances it is best if you stand perpendicular to the object being photographed.
- You can use the white pages of a notebook to reflect light into the shadowed portions of exposures, especially under overhangs.
- Include a scale or make a note of the size of the area being photographed. Depending on the subject of the photograph this could be anything from another person to a ruler, camera lens cap, coin or penknife. For small-scale photographs a finger is also useful and one of the advantages of this is that you will not inadvertently leave it behind! Ideally with medium and small objects use a metric scale rather than an object such as a lens cap or coin because these have variable dimensions. In addition the scale should preferably be of a neutral colour (grey) so that it will not unduly affect photographic exposure. Alternatively draw a scale on the cover of your notebook with a bold marker pen.
- When taking a photograph of an area you have sketched consider including the field notebook page in one corner of one of the photographs as a means of cross referencing between the photographs and your field notebook (assuming the field of view is appropriate).
- Use a page of your field notebook to point out or label particular features (e.g. Figure 7.15) on the photograph.
- Assuming you are using a digital camera check, using the camera display screen, the exposure and as far as possible that the focus is OK before you leave the locality so that you can take another photograph if necessary.

Remember to include a scale in every photograph and ensure that it is appropriate. A badly chosen scale or one that is not against the rock face can produce confusing results.

13 Sampling

Angela L. Coe

Sampling can be a crucial part of a field programme because the samples, your field notes and photographs are all that you will have when you return from the field. But all too often sampling is rushed either because it is the last task completed or because of the perceived need to cover a wide area within a short time and extract material that is easily accessible. It is, however, well worth spending some time collecting samples and recording exactly where they are from, especially if you are going to complete many hours of laboratory work on them. Once collected, samples are often used for purposes other than those for which they were originally intended. The key points to consider when taking samples are:

- What are the objectives and therefore how much and what type of sample is required?
- Is the sample representative?
- What does the sampling resolution need to be?
- Is the sample fresh and unweathered? (Unless of course the study is about weathering.)
- Does the sample need to be orientated?
- Do I have the appropriate tools for the job?
- Have I recorded exactly where the sample is from?
- Is there a record of how the samples were collected, for instance the tools used (to eliminate possible contamination) and stratigraphic precision?
- What are the conservation issues? Am I taking only what is necessary, have I got the necessary permission and have I considered the visual impact on the environment?

13.1 Selecting and labelling samples

The size and nature of the sample required depend on the type of analyses that need to be performed. The appropriate

vertical and horizontal sampling interval will depend upon the purpose of the study. Secondary to this consider the following: lithological variations, deposition rate, proximity to suspected boundaries, suspected or known repetition, resources and field constraints. This section outlines the factors to be taken into account depending on the intended purpose of the samples.

Care needs to be taken to avoid cross-contamination when selecting samples for geochemical analysis, mineral analysis, microfossils, molecular fossils and high-resolution studies.

13.1.1 Samples for thin-sections

A sample of about 10 cm thick \times 5 cm \times 5 cm is usually sufficient for producing one or more thin-sections provided the rock is not too coarse-grained. If the rock is coarse-grained then a sample size that is appropriate to the grain size should be taken. The sample needs to be large enough to enable it to be clamped in the rock saw and care needs to be taken with sample position and shape if it needs to be orientated (see below). In deformed rocks it is useful to cut two or even three thin-sections at right angles to each other, so a slightly larger sample may be required.

13.1.2 Orientated samples

Younging direction and approximately orientated samples

For sedimentary rocks the younging direction is often required and is usually recorded on the face perpendicular to bedding with an arrow. If the bedding orientation is not clear this may also need to be recorded so that the section can be cut perpendicular to the bedding. For igneous rocks the younging direction may need to be recorded for cumulates, pyroclastic rocks, and igneous rocks containing flow features and vesicles. For samples from metamorphic rocks it is also often necessary to record the top surface because of the need to obtain thin-sections in a particular orientation relative to the structural fabric(s). A more precise method of orientating samples is provided below.

Precisely orientated samples

Some samples need to be precisely orientated in the field so that this can be taken into account during later processing (Figure 13.1, p. 252). This includes samples for palaeomagnetism studies and some samples for more precise metamorphic and structural analysis. To do this, find a piece of rock on the exposure that is going to be easily extractable, or if the rocks fracture in a manner that is suitable, extract the rock sample and then fit it back into place exactly. Using a compass-



(a)



(b)

Figure 13.1 Orientated sample with combined strike line and direction of dip on the top surface and the sample number (H01) and way up (arrow) on the side. In this case part of the limestone that is fractured but nevertheless still intact and orientated has been chosen. Carboniferous strata, Rumbling Kern, Northumberland, UK. (a and b: Angela L. Coe, The Open University, UK.)

clinometer mark the rock exactly with the line of strike, direction of dip and either the way up (Figure 13.1) or the top. Take note of the dip and strike. Orientated samples can also be obtained with a drill used for palaeomagnetic studies. This is a diamond-tipped tube of about 2 cm diameter. Samples are obtained by drilling the rock to obtain a cylinder of rock that is still attached at the back. This cylinder is then orientated using a modified compass-clinometer and wire to mark the core before it is extracted.

13.1.3 Samples for geochemical analysis

A 200g sample is usually sufficient for a range of major and minor element, trace element and isotopic analyses, except for very coarse-grained or heterogeneous rocks, where about 1 kg may be required. Particular care needs to be taken to ensure that the sample is fresh. This might mean that weathered material needs to be removed first. If possible it is better to remove the weathered material in the field to ensure that what you take back is a fresh sample, and also because it is easier to allow for the extent of the weathering in the field. Colour changes are a good indication of weathering, but also the fracture pattern and hardness of the rock tend to change. In addition some rocks contain minerals that are the product of weathering (e.g. weathered mudstones often develop gypsum crystals). Some caution may also need to be exercised if the sample is being analysed for metal isotopes in order to avoid contamination from metal chisels and hammers.

13.1.4 Samples for mineral extraction

The amount of sample that needs to be collected for mineral analysis depends on the minerals to be extracted and the composition of the rock. For heavy minerals such as zircon that are present only in low abundance, 1–2 kg of rock may be required. For volcanic glass and feldspars for ^{40}Ar – ^{39}Ar and K–Ar dating, generally at least 1 kg of rock is required. For pyroclastic and sedimentary rocks it is particularly important to collect from the base of the bed as the coarser-grained minerals that are more easily picked out will be most abundant there.

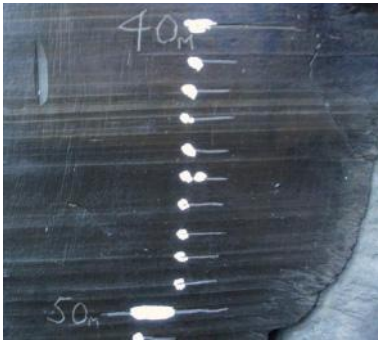
13.1.5 Samples for fossils

Samples for megafossil analysis: Megafossil samples and their supporting rock material tend to be large. They are best wrapped in paper. If they are fragile or the rock needs to dry out slowly, wrap them in cling film/plastic food wrap and then paper. They commonly have commercial value and therefore special permission may be needed to remove and/or ship them out of the locality or country where they were collected. Important specimens should be donated to a museum after analysis and their sample (or museum acquisition) number referred to in any subsequent publication.

Samples for microfossil analysis: The size of samples for microfossil analysis depends on the likely abundance of fossils within the sample. For an average abundance of foraminifers 200g should be sufficient; for nanofossils and



(a)



(b)



(c)

diatoms a small 10g sample is ample. For palynology samples of 0.5–1 kg are required.

Samples for molecular fossils: Very small samples are required for molecular fossils but the sample needs to be large enough (2–5g) to avoid contamination. The samples should be packaged in metal foil or glass or polythene bags of known composition. In addition care needs to be taken not to cross-contaminate samples by carefully cleaning the sampling instruments between each sample.

13.1.6 Sampling for regional studies

Regional and low-resolution studies require samples that are representative of the whole area. In addition samples should be collected from units that need laboratory analysis because their composition is enigmatic. It is difficult to generalize here though, as the sampling strategy will need to be adapted according to the hypothesis being tested. Collecting a sample from each of the main lithostratigraphic units is probably a good place to start. If the region is fairly monolithic (for instance a large igneous province) then take regularly spaced samples that are spatially separated both horizontally and vertically, in addition to other key features such as potential feeder dykes. Other samples that are worth considering are a set to test for compositional variation across an igneous body, representative fossils, tectonic contacts, representative samples from metamorphic zones and representative samples from a set of dykes.

13.1.7 High-resolution sample sets

High-resolution sampling requires great care and patience. A logical means of labelling the samples/sample positions will need to be devised. In any situation where closely spaced samples are required it is best to mark the exposure clearly first with a scale (Figure 13.2) and, if irregularly spaced samples are required, mark where the samples will be taken from. The exposure can then be photographed as a permanent record before extracting the samples. Marking up the section can be done with a tile scribe, a marker pen, paint or paper correction



Figure 13.2 Marked sections ready for sampling. Lower Jurassic, Yorkshire, UK. (a) One stratigraphic metre of rock marked every 1 cm. (b) Detail section showing marks every 1 cm made with a tile scribe and correction fluid. Note in this case the letter 'm' indicates minus as the marks are below the zero reference datum shown in (a). (c) Marking sections on both sides of a corner can be helpful when putting the section back together. (a–c: Christopher Pearce, The Open University, UK.)

fluid according to what is appropriate and shows up clearly on the rock (Section 13.2.1). An alternative method, provided that there are no conservation issues, is to accurately mark up and then to extract a large sample or set of samples and then to subsample it back in the laboratory. Overlapping and/or duplicate samples according to the aims of the project may be required (Figure 5.8). Figure 13.2 shows part of a sedimentary section marked ready for sampling. A corner section has been selected for ease of extraction and a centimetre scale has been marked using both a tile scribe and correction fluid. The tile scribe has been used as this creates a thin but permanent mark that is retained after packaging and transportation, and the correction fluid has been used as it makes the scribe marks easier to identify in photographs and a quick glance.

Contamination is an issue for high-resolution sample sets. Depending on the nature of the exposure it might be best to sample from the bottom up in order to avoid material falling onto the part which is yet to be sampled. In addition the tools used to collect the samples need to be cleaned carefully. An effective means of sampling sedimentary or other softish rocks where rock powders are required for chemical analysis is to mark the rock and then to drill it with a masonry drill bit of between 10 to 15 mm diameter, collecting the powder in a bag held under the drill bit as the rock is drilled. Care needs to be taken to clean the drill bit in between samples to ensure that there is no cross-contamination. This method is not appropriate for samples that will be analysed for metal isotopes because of possible contamination from the close contact of the drill bit. Very soft sedimentary deposits, particularly those with a high water content, can be sampled with a knife by cutting out the required samples. Drills designed for palaeomagnetism studies that extract small cores of about 2 cm diameter can be used to obtain small high-resolution samples of harder rocks.

In some cases samples of the whole bed or set of beds are required. In this case it is best to extract large samples that overlap stratigraphically. A suitable section should be found for extraction and the rocks marked before extraction with either hammer and chisels or a disc rock saw. Do not forget to obtain permission if you are extracting large samples or if there are conservation issues.

13.1.8 Labelling samples and their packaging

It is worth spending some time devising a suitable labelling scheme for your samples. There are a variety of possibilities depending on the purpose of the study. For regional studies the locality number or an abbreviation of the name and then sample number at that locality is often used, e.g. 24/3 or FB/3, but an alternative way is to use the national grid square and

Collecting contiguous orientated samples of friable sedimentary deposits such as coals and mudstones can be difficult as they can easily break during transport. A quick way of keeping them intact is to wrap the samples in stretchable self-adhering plastic material such as 'cling film/ shrink wrap'.

then a sample number. The advantage of this is that the sample number gives an immediate indication of where it is from without the need to look at the field notes. Another possibility is to include the date or part of the date in the sample number to allow you to easily find the associated field notes. For higher resolution studies where hundreds of samples are being collected a different strategy is often required. If the samples are at particular stratigraphic heights it can be useful to incorporate the height into the sample number. This makes handling of the numbers easier in spreadsheets at a later stage. An abbreviation for the age of the sample, e.g. S for Silurian, or for the lithostratigraphic name, e.g. BS for Burgess Shale, are other possibilities to consider including.

On the sample itself, provided it is large enough and there is not going to be a contamination issue, it is useful to record the sample number and, if applicable, the way up and/or orientation. On the sample bag or outside of the packing material itself it is useful to record the following as appropriate:

- sample number;
- cross reference to field notebook page and/or date collected;
- location;
- whether or not the sample is orientated;
- rock type;
- associated samples.

13.2 Practical advice

13.2.1 Packing and marking materials

- *Cling film/shrink wrap*: This is very useful for fragile specimens such as fossils and mudstones. As well as the obvious advantage of helping to hold the specimen together the film also retains the moisture in the sample, allowing it to be dried out under controlled conditions.
- *Paper*: This is useful to help protect delicate specimens and for packing. It should not be used in direct contact with the rocks if the samples are also to be used for geochemical analysis, particularly organic carbon analyses.
- *Polythene sample bags*: It is good practice to put each sample into a new bag to avoid cross-contamination. Most

bags come with write-on labels available from a variety of suppliers. Check for rocks with sharp edges because they tend to split the bag. If the rock has sharp edges either round them by gently tapping them using the square end of your hammer or carefully place the rock in a bag and wrap over this with paper.

- *Aluminium foil:* This is useful for holding together very fragile specimens such as mudstones. Wrap the foil around the specimen immediately after extraction in a systematic manner so that you are able to remove it sequentially in the laboratory. Aluminium foil is best avoided if the samples will be stored for any length of time as salts from the rock tend to corrode the foil.
- *Glue:* A strong glue suitable for metal or wood can be used for sticking samples together. If you need to protect fragile specimens such as shelly material within mudstone or vertebrate teeth before shipping or transporting them back, soak the sample for several hours in a 50:50 mixture of PVA glue and water. Then allow the specimen to dry.
- *Marker pens:* Permanent marker pens provide a distinct label. Note that wet, dusty or fine-grained dark coloured rocks can be difficult to mark. It is worth carrying several markers into the field because they tend to wear out quickly.

Specimens of fine-grained rocks (mudstones and siltstones) are often easier to mark up with a tile scribe and/or paper correction fluid because marker pen ink often tends to be absorbed into the rock.

13.2.2 Extraction of samples

Different rocks break in different ways, but skill and experience enable the geologist to obtain the best samples. It is worth spending some time working out where to extract the best sample. Look for somewhere that is safe and easy to access and where there is a piece jutting out that might easily be removed. You should also consider the impact of extraction on the environment and preferably choose a location that will not be obvious. If you need just a small sample, tapping off the edge of the bed with the flat end of the hammer usually works. If you need a larger sample look for areas where there is already a line of weakness such as a bedding plane or joint. This can often be widened and the rock weakened by hammering a cold chisel into the joint or bedding plane and then using leverage to extract the rock. For most fossils the rocks will need to be split along the bedding plane. Some samples are hard to extract and it may take a lot of forceful blows with the hammer over time to weaken the rock. If you need a specific piece then use a chisel and work carefully around the sample. You should chisel far enough away from the specific area that you need because there will always be some material lost close to where

you chisel. When you have extracted the sample trim off any sharp corners. If you are extracting samples that need a way up it is a good idea to mark the way up first before you hammer it off just in case it is not possible to reorientate the sample after extraction.

14 Concluding remarks

Angela L. Coe

In conclusion, the following list summarizes the different stages for geological fieldwork. It covers the preparation, fieldwork period and some notes on what to do after the fieldwork.

Before going into the field

1. Be clear on the objective(s) of the fieldwork.
2. Consult published and other information available including relevant web material and other researchers who have visited the area to gain a general overview.
3. If required, obtain permission to visit the site and sample.
4. Fill in health and safety forms, get first aid training, etc., as required.
5. Put together the necessary field equipment (Tables 2.1–2.3, pp.4 and 6).

In the field

6. Choose the best exposure(s) for the objective(s) of the fieldwork.
7. Have at least one clear aim every day.
8. Check for, and monitor, hazards.
9. Collect data, samples, etc. and start to formulate interpretations. Use your hard copy or electronic notebook to keep the main record of your data, sample positions, reference to other materials with field data such as maps, thinking and planning (Table 14.1).
10. Collect any samples that are needed responsibly and discreetly.
11. At the end of each day review the work that you have completed and amend the list of further fieldwork tasks and aims as required.
12. If possible allow time to double check any discrepancies.

Table 14.1 Summary of information to consider recording in your field notebook.

Field notebook information

Name and contact details

Table of contents

Useful information

Date, day

Locality

Sketch map of locality

Sketch(es) to show the relationship between the units

Sketch(es) of individual features

Data and observations

Reference to field maps, maps, literature

Preliminary interpretation(s)

Any questions

To do lists

Photographs taken

List of samples

On return from the field

13. Curate and store samples as required (for instance mudstones and some fossils may need to be stored in cold conditions).
14. Check field notes and tidy up any loose ends.
15. Discuss data and interpretation with colleagues and other experts. Seek further help where required, for instance by visiting museums to compare fossils you have found with the type specimens, or by analysing the rocks in comparison with other known specimens.
16. Analyse data and samples.
17. Write up the work, for instance as a report or scientific paper. There are several books available on scientific report writing and these may be of help. Some of these are listed in the further reading.

14.1 Further reading on scientific report writing

- Day, R. A. and Gastel, B. 2006. *How to Write and Publish a Scientific Paper* (6th edition), Cambridge University Press, 320 pp. [Long running popular book on structuring a paper, language style, ethics, choosing a journal as well as writing popular science articles.]
- Tredinnick, M. 2008. *Writing Well: The Essential Guide*, Cambridge University Press, 251 pp. [Guide to effective professional prose as well as creative writing.]

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Appendix A1: General

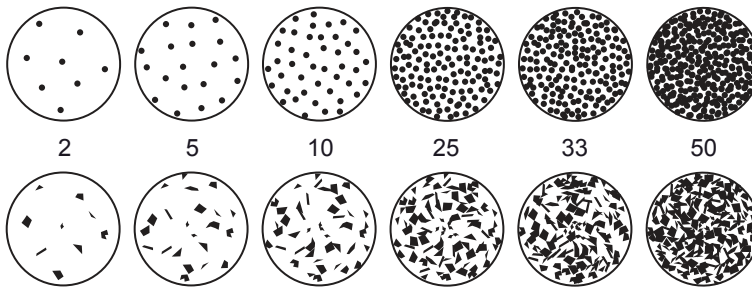


Figure A1.1 Chart to estimate percentage composition from area.

Table A1.1 Mohs' scale of hardness.

Mohs' hardness	Reference mineral	Non-mineral example
1	Talc	
2	Gypsum	
(2.5)	–	Fingernail
3	Calcite	
(3.5)		Copper coin*
4	Fluorite	
5	Apatite	
(5.5)	–	Window glass
6	Feldspar	
(6.5)	–	Hardened steel (e.g. knife blade)
7	Quartz	
8	Topaz	
9	Corundum	
10	Diamond	

*Note that many modern copper coins are actually copper coated steel and are therefore harder.

A metal hand lens provides an excellent surface to test for quartz. Simply scratch the rock across the lens surface: if it leaves a scratch on the steel it is likely to contain quartz. Note: For sedimentary rocks it is diagnostic of quartz, but in crystalline rocks a few other minerals will also scratch the steel.

Table A1.2 Metric to Imperial length conversion chart.

Metric/SI	Imperial/USA
2.054×10^{-2} m	1 inch
0.3048 m	1 foot
0.9144 m	1 yard
1.0609×10^3 m	1 mile

Table A1.3 Natural sines for conversion of horizontal measurements to true thickness (see Section 2.5.1).

Degrees	Natural sine
1	0.017
2	0.035
3	0.052
4	0.07
5	0.087
10	0.174
15	0.259
20	0.342
25	0.422
30	0.5
35	0.574
40	0.643
45	0.707
50	0.766
55	0.82
60	0.866
65	0.906
70	0.94
75	0.966
80	0.985
85	0.996

Geological timescale

An up-to-date geological timescale, information on boundaries, links to International Stratigraphic Subcommission websites and a program to compile your own timescale (Timescale creator) is available from the website of the Subcommission for Stratigraphic Information. A link is provided from the website that accompanies this book (www.wiley.com/go/coe/geology).

Appendix A5: Fossils

Table A5.1 Modes of fossil preservation.

Mode of preservation	Explanation	Examples	
Preservation of the original material (duripartic)	Due either to the chemical composition of the original material, and/or to special characteristics of the depositional environment. Original characteristics are well preserved and can be used for a range of geochemical environmental proxies	Natural mummification (Figure 5.3a); insects in amber	
Chemical alteration of the fossil:	permineralization	Cell walls of the original organism remain more or less unaltered	Ammonites with their original aragonitic shell
	petrification	All the original material is replaced by minerals. Several phases of mineralization may be present	Figure 5.3b
Casts and moulds	Mould refers to the sedimentary deposits that show the internal or external form of the fossil after the soft parts have decayed. Cast refers to fossils where the hard parts (e.g. shell) have been replaced.	Figures A5.2, 5.3c, 5.6	
Impressions	Two-dimensional remains of where a fossil has been in contact with the rock. The term impression is also given to a leaf fossil where the organic remains have been oxidized away leaving only a 'mould' of the original leaf surface.	Figure 5.3d	

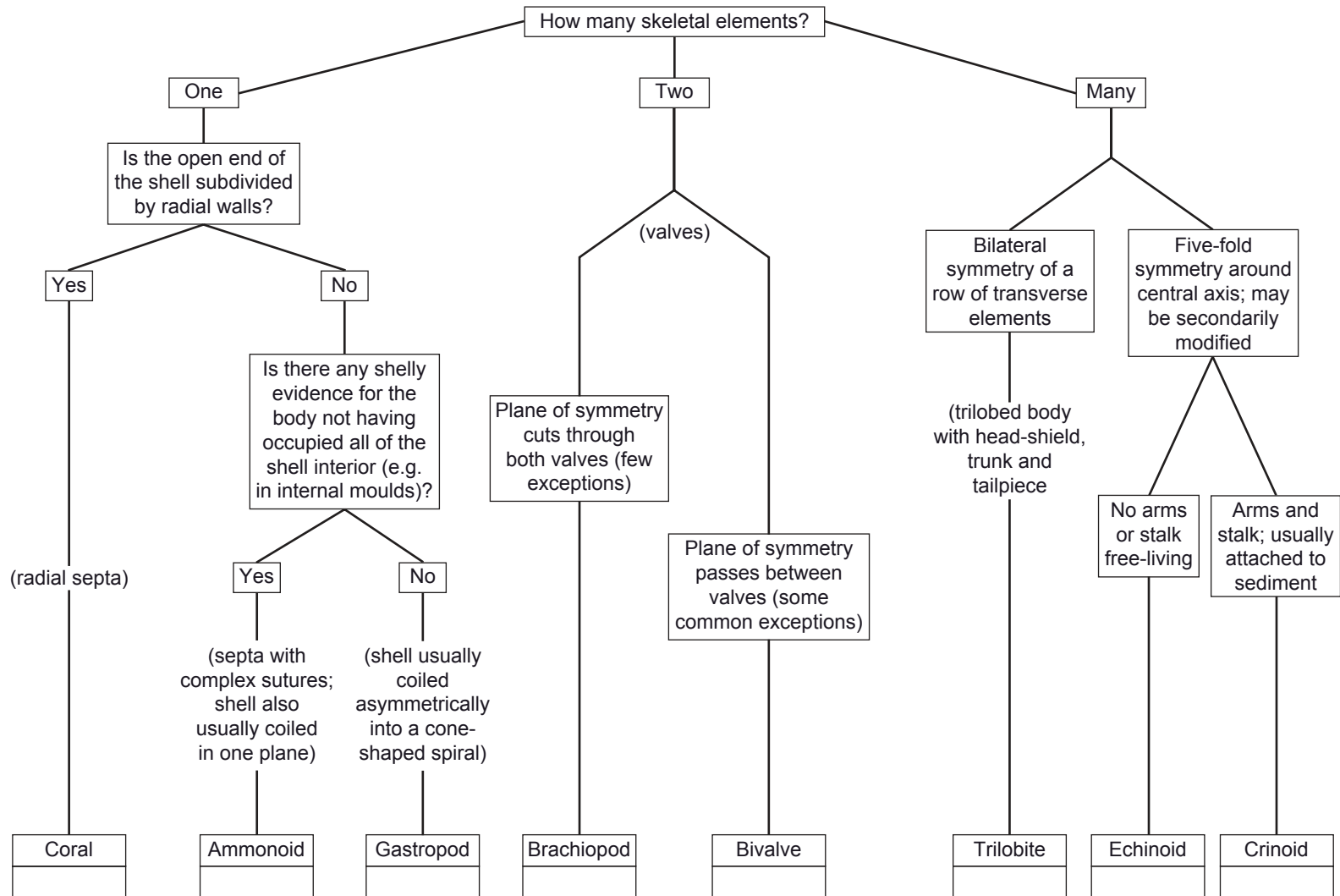


Figure A5.1 A simple scheme for the identification of invertebrate fossils based on symmetry.

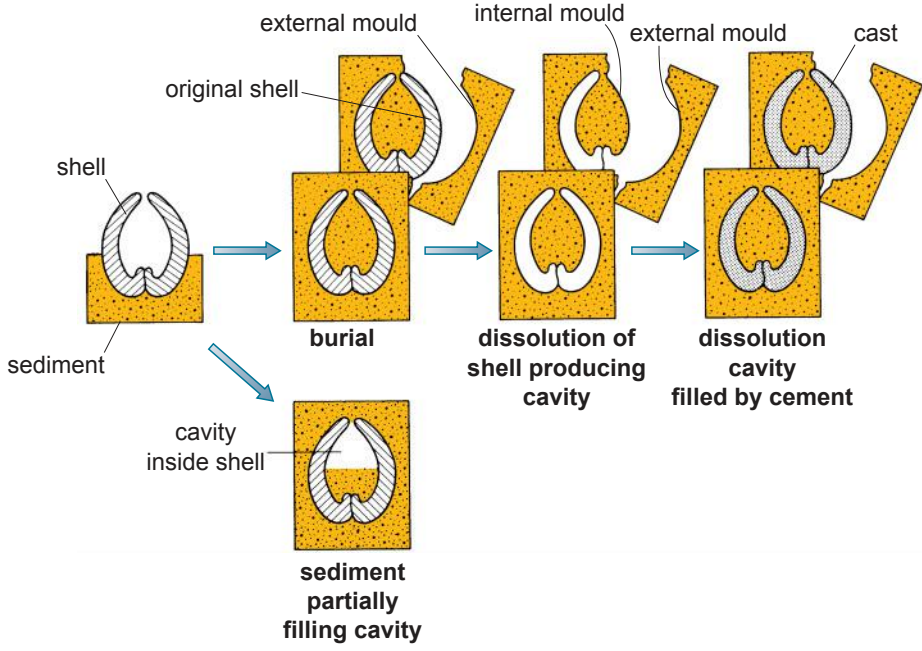
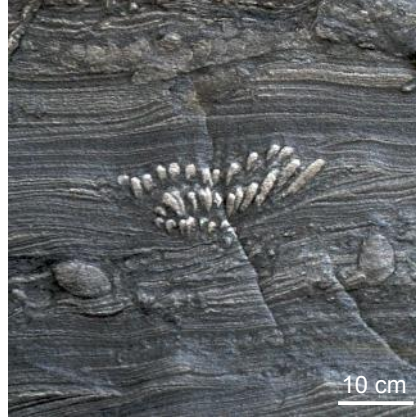


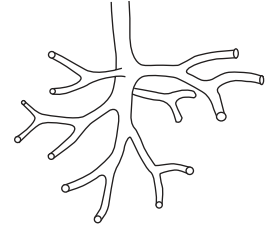
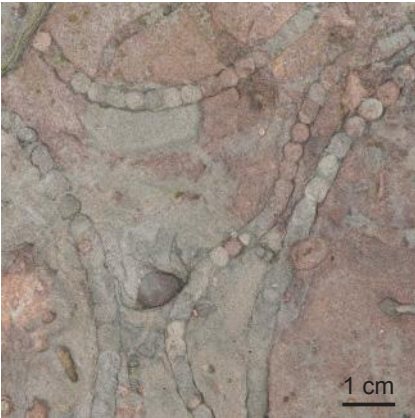
Figure A5.2 Diagram illustrating the formation of moulds and casts using a bivalve as an example.

Thalassinoides

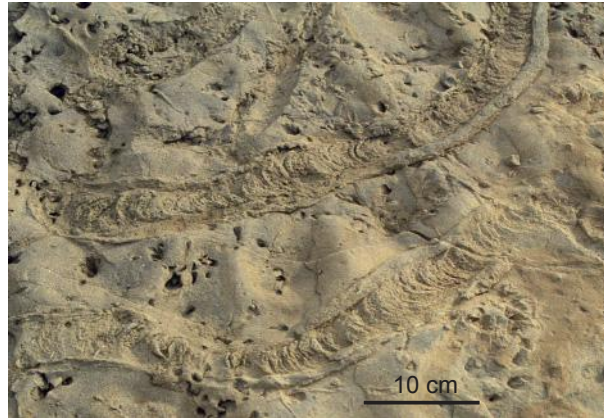
(a) plan view

Chondrites

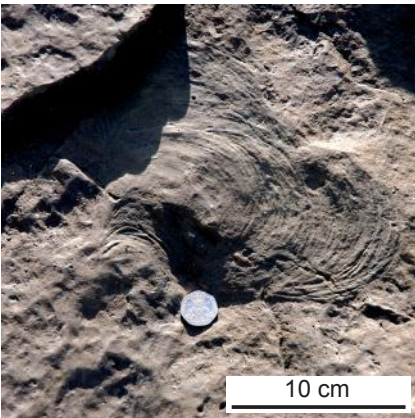
(b) cross-section

***Muensteria***

(c) plan view

Rhizocorallium

(d) plan view

Zoophycos

(e) plan view

Cruziana

(f) plan view



plan view

Figure A5.3 Illustrations of some common trace fossils. ((a)–(j) Angela L. Coe, The Open University, UK. Except (f) plan view; Fiona Hyden, Open University Associate Lecturer, UK.)

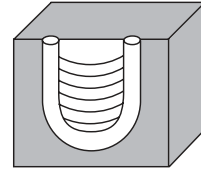
Diplocraterion



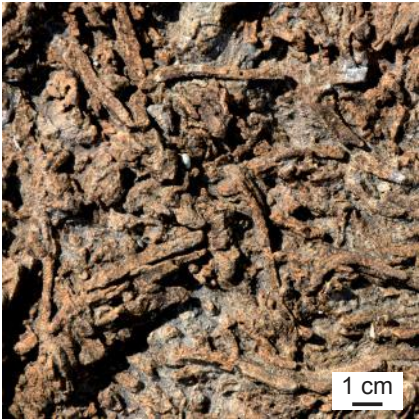
(g) cross-section



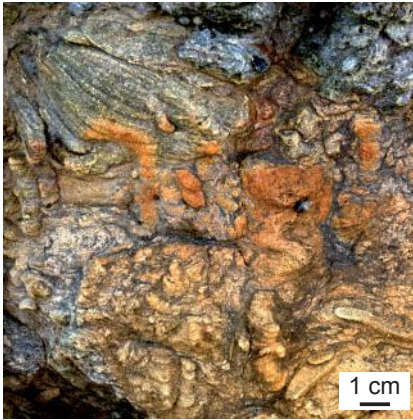
plan view



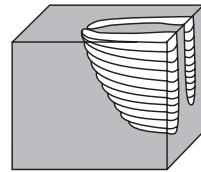
Teichichnus



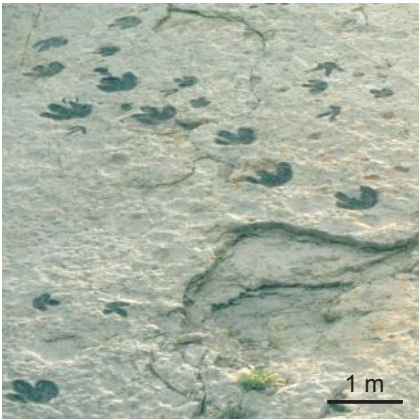
(h) plan view



cross-section



Dinosaur footprints



(i) plan view

Boring made by gastropod



(j) plan view

Figure A5.3 Continued

Table A5.2 There has been a plethora of categories for classifying trace fossils. One such classification is based on the interpretation of what the animal was doing. Note that many of these are not mutually exclusive.

Category	Explanation	Examples
Grazing (<i>Pascichnia</i>)	Traces left as an organism moves over a sediment surface. The substrate may be either soft or hard. Often movement over a surface is associated with feeding as well as locomotion	<i>Nereites</i> , <i>Spirorhaphe</i>
Feeding (<i>Fodinichnia</i>)	These traces are left as organisms move through sediment as they feed. They are usually three dimensional	<i>Chondrites</i> , <i>Muensteria</i> , <i>Teichichnus</i> , <i>Rhizocorallium</i> , <i>Zoophycos</i>
Dwelling (<i>Domichnia</i>)	Structures resulting from an organism's living space	<i>Thalassinoides</i> , <i>Ophiomorpha</i> , <i>Diplocraterion</i> (also <i>Fodinichnia</i>)
Resting (<i>Cubichnia</i>)	Formed by the impression of an organism in soft sediment	<i>Rusophycus</i> , <i>Asteriacites</i>
Moving (<i>Repichnia</i>)	Formed by normal locomotion as distinct from feeding	<i>Cruziana</i>
Predation (<i>Praedichnia</i>)	Predatory traces such as drill holes in shells or bite marks	<i>Entobia</i> , <i>Gastrochaenolites</i> , <i>Trypanites</i>
Gardening (<i>Agrichnia</i>)	Formed as organisms create (usually complex) burrows or structures to capture or cultivate other organisms such as bacteria or fungi for food	<i>Paleodictyon</i>

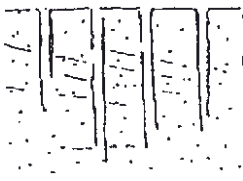
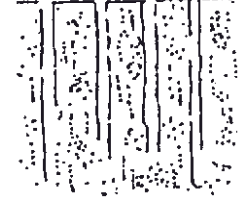
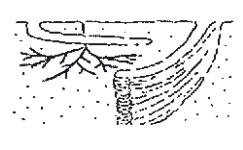
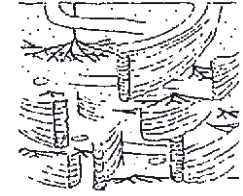


Example	Observations	Implications	Environment
1 	Single colonization with clearly visible primary structures	Initial colonization of, for example, an event bed by a low diversity biota	Most likely an unstable high sedimentation rate environment, e.g. estuarine
2 	Successive colonization without an increase in biotic diversity	Gradual/moderate sedimentation in stressed environments	Possibly longer intervals between events than in examples 1 or 3 but with low diversity biota
3 	Simple tiering by increasingly diverse biota	A wide range of environments associated with event beds	Moderate sedimentation rates, but perhaps longer intervals between events than in example 1
4 	Complex tiering	Gradual aggradation	Stable environment with low sedimentation rates
5 	Gradual overlap	Low sedimentation	Gradual environmental change
6 	Omission and possible truncation of burrows	Sudden facies change, perhaps with the development of a firmground or even hardground	Period of non-deposition and condensation

Figure A5.4 Examples of tiering of burrows and their implications. (Modified after Goldring 1991.)

Appendix A6: Sedimentary

All of the following descriptors and some of the classification charts are applicable to both sediments (i.e. unconsolidated sediments) and sedimentary rocks (consolidated sediments).

Table A6.1 Checklist for the description of sedimentary deposits.

Property	Questions	
Composition	Grains	What is the composition of the most abundant grains?
	Matrix	Is there any fine-grained (clay-sized) fragmentary material infilling the spaces between larger grains? If so, what is it?
	Cement	Is there any crystalline material precipitated around the edges of grains, or in the spaces between grains? If so, what is it?
Texture	Grain size	What is the most abundant grain size present (use a grain-size card and Figure A6.1)?
	Grain sorting	Are the grains all more or less of the same size (i.e. well-sorted) or different sizes (i.e. poorly sorted) or somewhere in between (use the sorting scale; Figure A6.2)?
	Grain morphology:	See Figure A6.3
	shape or form	Are the grains long and thin or equidimensional?
	roundness	Do the grains have rounded or angular corners (use roundness scale)?
	sphericity	Are the grains like spheres (i.e. high sphericity) or are they elongate (low sphericity)?
	Grain surface texture	Are any quartz grains present smooth and glassy, or are they frosted?
Grain fabric (packing)	Are the grains orientated in any preferred direction? Are the grains closely packed together? Are the grains matrix- or grain-supported? (See Figure A6.4)	
Fossils	Can you see the remains of any body fossils or their movements (trace fossils)?	
Sedimentary structures	Are there any obvious layers or other structures in the rocks? (See Figures A6.5–A6.7)	

Table A6.2 Features of common minerals that constitute sedimentary deposits.

Mineral	Chemical formula and name	Colour in hand specimen	Cleavage	Other features in hand specimen	Form and occurrence
Quartz	SiO ₂ (silica)	Translucent	None	Will scratch steel	Common detrital grain, also a cement
Clay minerals	Various hydrous aluminosilicates	Typically grey, green or red	Planar or none	Fine-grained	
Calcite (sparite and micrite)*	CaCO ₃ (calcium carbonate)	Translucent or white; variety of pale colours due to impurities	Rhombic	Scratched by steel; fresh surfaces fizz with acid	Forms grains, matrix and cement in limestones, dolomites and sandstones
Aragonite	CaCO ₃ (calcium carbonate)	White with a pearly iridescence	Rectilinear	Original aragonitic bioclasts are often preserved in marine mudrocks	
Dolomite	CaMg(CO ₃) ₂ (calcium magnesium carbonate)	Buff, cream	Rhombic	Fizzes with warm acid and very weakly with cold acid	
Feldspar	Various including K(Na)AlSi ₃ O ₈ (orthoclase) and Na(Ca) AlSi ₃ O ₈ (albite)	Translucent or pink or white	Present	Scratched by steel; weathers to white, powdery clay minerals	Detrital crystals
Glauconite	KMg(Fe,Al)(SiO ₃) ₆ ·3H ₂ O	Green	Planar	Soft; weathers to the iron oxide limonite	Ooids, mud and peloids; forms exclusively in marine environments
Iron oxide	Various including Fe ₂ O ₃ (haematite) and H ₂ Fe ₂ O ₄ (H ₂ O) _x (limonite)	Red (haematite) or yellow-brown (limonite) or green	None	Often more apparent on weathered surfaces	Crystals, grains, cements and as replacements

*See note on p. 276 about distinguishing between micrite and sparite.

Table A6.3 Types of common coals and their depositional environment.

Coal type	Components	Environment
Dull and bright, brittle, crystalline clarain, vitrain	Woody	Lush, well vegetated, mature plants
Dull, waxy conchoidal, cannel	Wind blown spores, resin, cuticles, algae	Open water, lagoons, pools in forest/mire
Dirty, crumbly, soft, fusain	Charcoal	Burnt vegetation, dry weather conditions, e.g. present-day Borneo in an El Niño year
Dirty, heavy	High ash, clay minerals	Forest, mire, raised bog, dirty windy conditions, high muddy water level, seasonal rainfall changes, tropical/temperate climate
Pyrite	High sulfur	Forest/mire/swamp, coastal estuarine, marginal marine
No pyrite	Low or no sulfur	Inland forest, mire, raised bog

Table A6.4 Ripples are common in the sedimentary record. This table indicates how to distinguish current-formed ripples diagnostic of linear fluid flow from wave-formed ripples diagnostic of the orbital motion of waves produced by wind blowing over standing bodies of water.

	Wave-formed ripples	Current-formed ripples
Profile	Individual ripples are symmetrical	Individual ripples are asymmetrical
	Ridges tend to have a sharp top	Ridges are gently rounded
	Laminations within the ripple dip in opposing directions	Laminations within the ripple dip in the same direction
	Ripple index (wavelength/height) = 6–10	Ripple index (wavelength/height) = 8–20
Plan view	Crests are sinuous and bifurcate	Crests are straight or curved
Possible associated structures that are unique to either wave or current processes	Hummocky cross-stratification, swaley cross-stratification	Herringbone cross-stratification (but care needs to be taken not to confuse this with complex wave-formed structures where the sediment has been deposited on both sides of the bedform)

Distinguishing between micrite and sparite

Micrite and sparite are both forms of calcite, the only physical difference between them being the grain or crystal size. Micrite refers to calcite that is less than $4\mu\text{m}$ (0.004mm) in size and sparite refers to calcite that is greater than $4\mu\text{m}$ (0.004mm) in size. They can be distinguished in hand specimen; sparite is translucent or semi-translucent because the large crystal size transmits the light through it, whereas micrite is opaque because of its small grain size. Micrite is often white or cream but it can also have pink, yellow or even green tinges depending on the other minerals present. You may find it useful to wet the rock specimen before you look at it through a hand lens to distinguish micrite from sparite.

The distinction between micrite and sparite is important because it yields information about the depositional process. Micrite is precipitated and settles out from suspension at the time of deposition as a matrix, and indicates low energy conditions. In contrast, sparite is a cement which is precipitated after deposition. Sparite can be subdivided into several different types; including poikilotopic (large crystals enclosing several grains); drusy (small- to medium-sized crystals which increase in size away from the edge of the grains into the centre of the cavity); isopachous (a thin fringe around the grains); and syntaxial overgrowth (crystal in optical continuity with the grain it has overgrown).

mm	grain term	sediment and sedimentary rock terms implying grain size
256	boulders	
128	cobbles	
64		gravel, rudite,
32		rudaceous sediments,
16	pebbles	conglomerates, breccias
8		
4	granules	
2	very coarse	sand, sandstone, arenites, arenaceous sediments
1	coarse	
0.5	medium	
0.25	fine	
0.125	very fine	
0.062	coarse	silt, siltstone
0.031	medium	
0.016	fine	
0.008	very fine	
0.004	clay	clay, claystone

Figure A6.1 Grain-size descriptors.

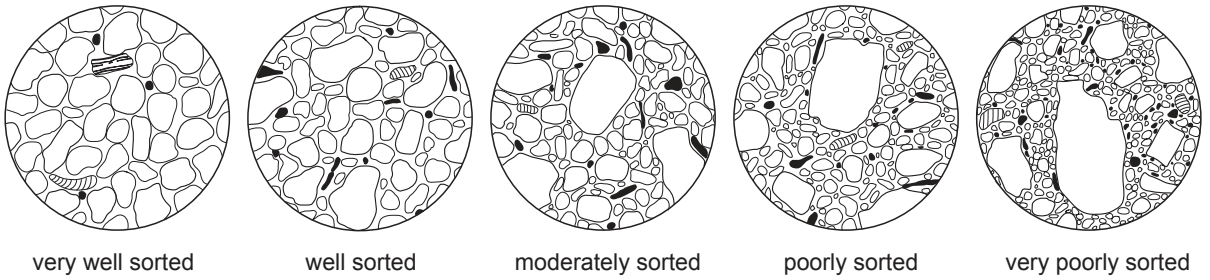
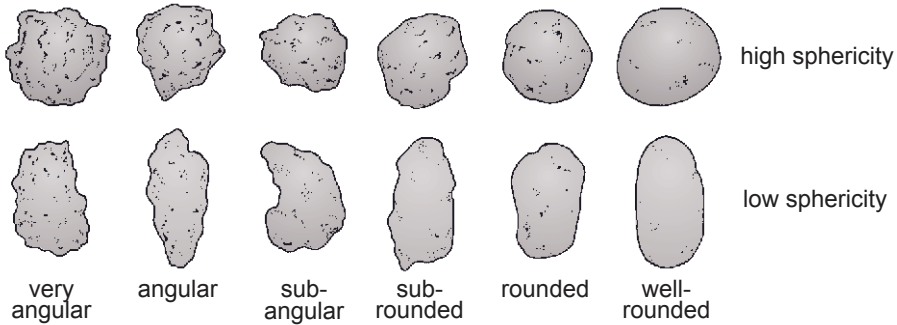
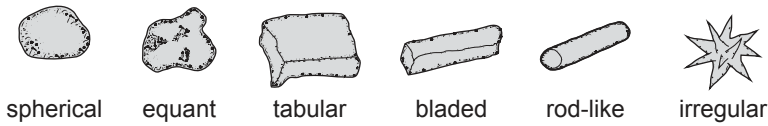


Figure A6.2 Comparison charts for particle sorting.



(a)



(b)

Figure A6.3 Comparison charts for grain morphology. (a) Rounding and sphericity. (b) Shape.

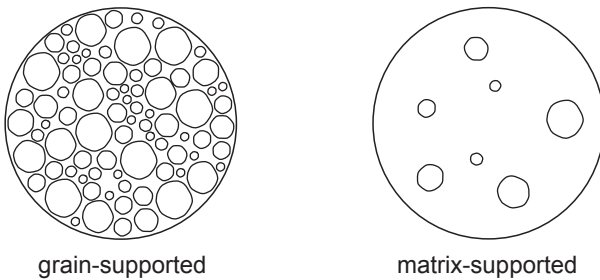


Figure A6.4 Comparison charts for grain fabric. It is also appropriate to note whether the grains are aligned if they are tabular or bladed.

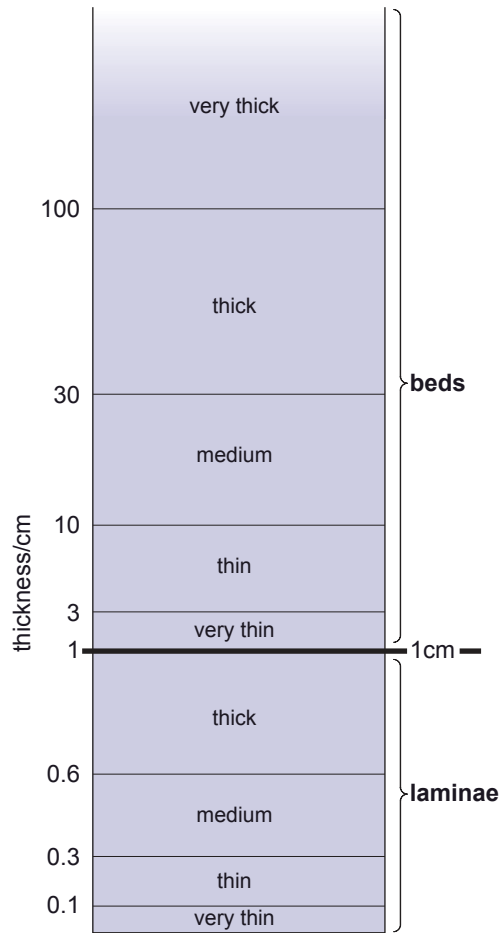


Figure A6.5 Terms for the description of lamination/bed thickness, etc.

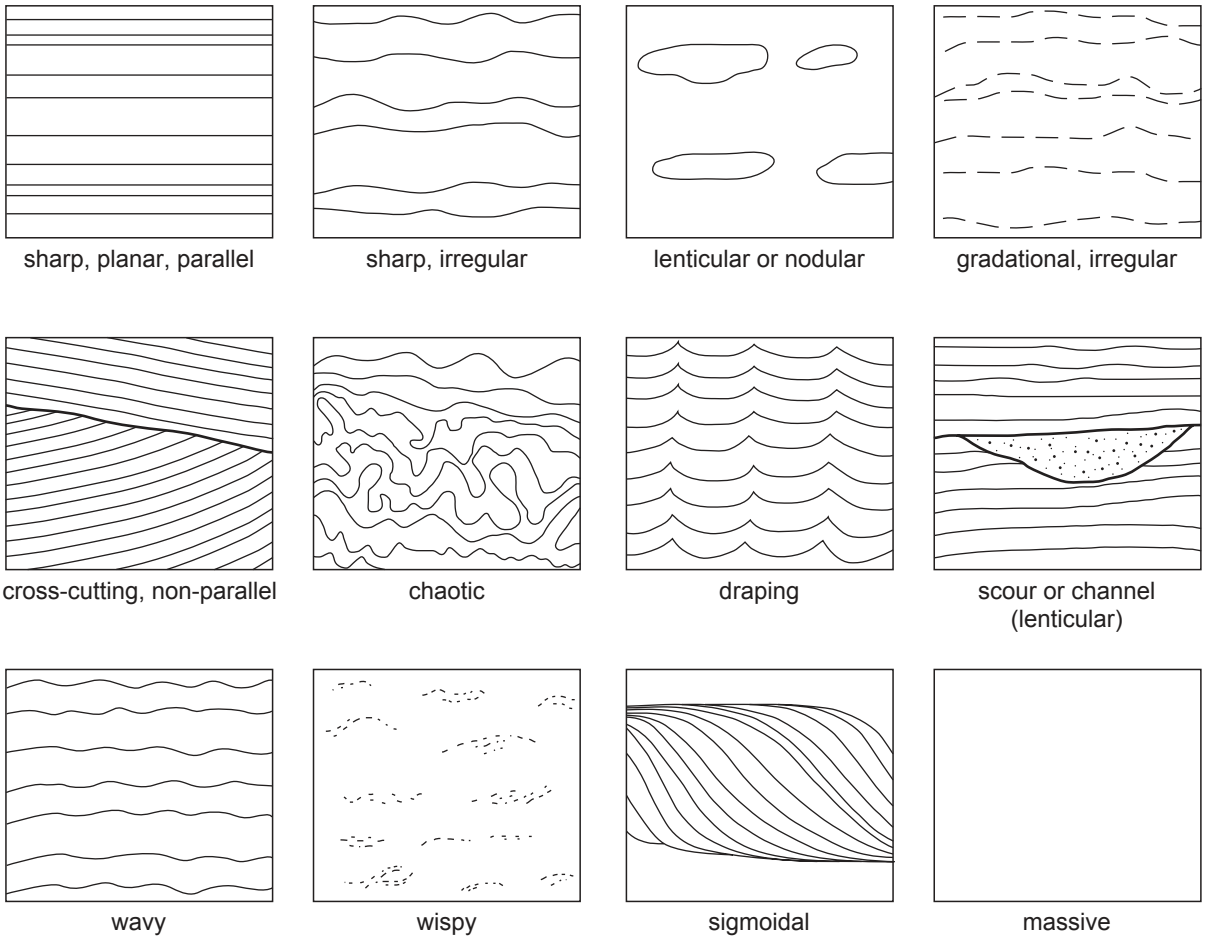


Figure A6.6 Terms for the description of bed character.

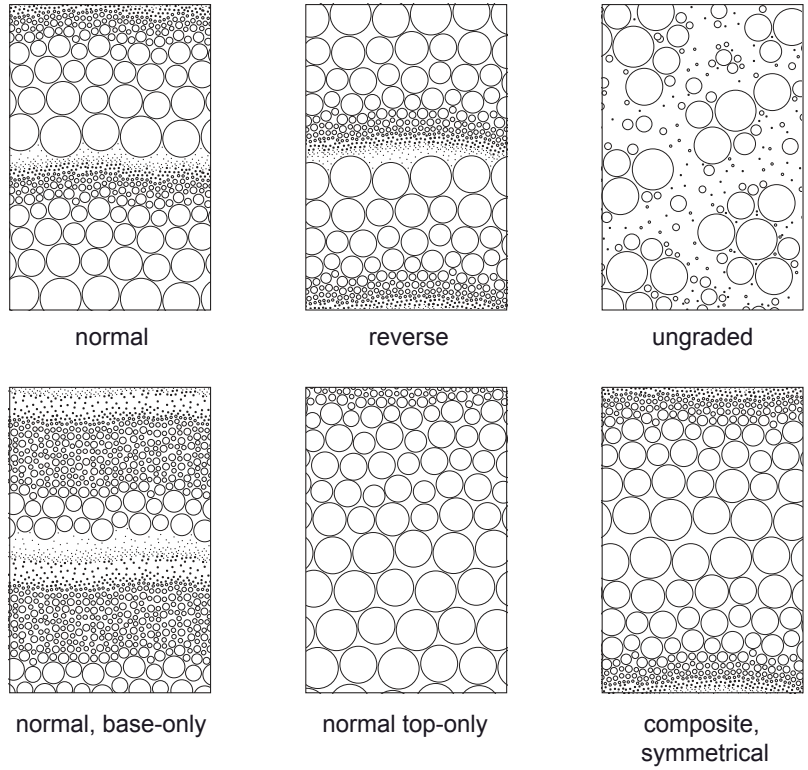


Figure A6.7 Different types of sedimentary grading.

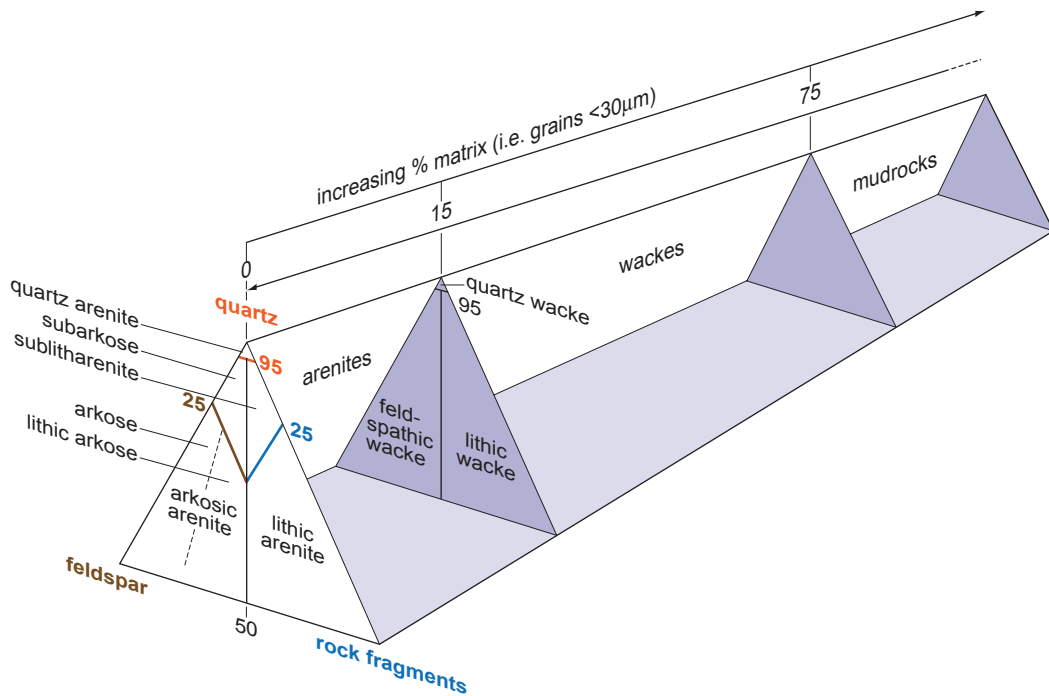


Figure A6.8 Classification of sandstones. (Modified after Pettijohn *et al.* 1973.)

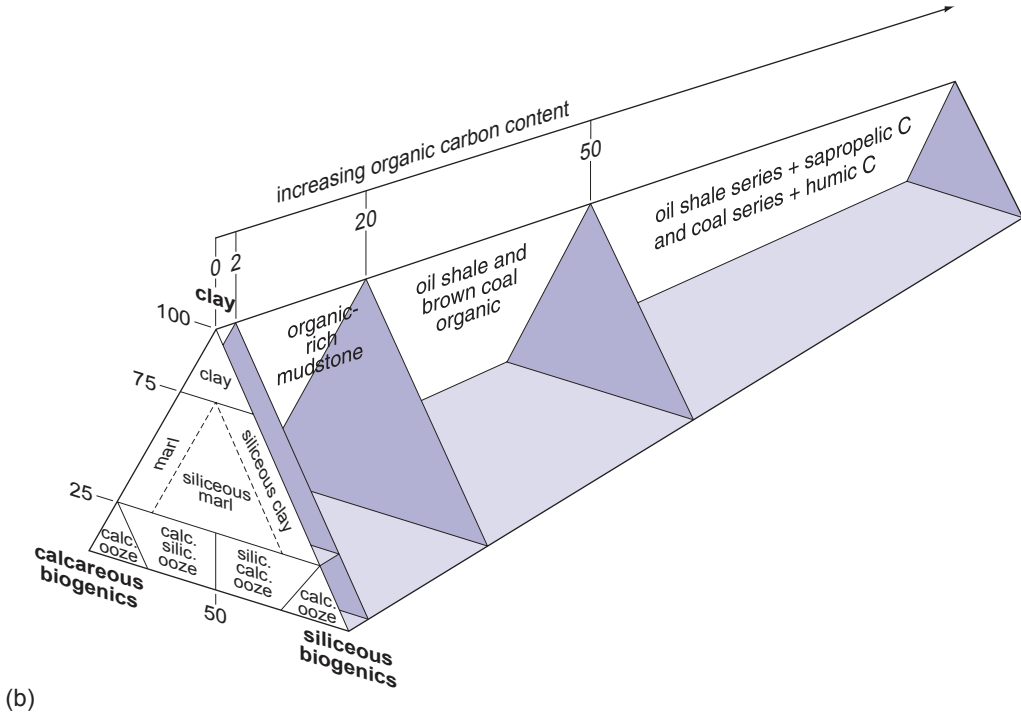
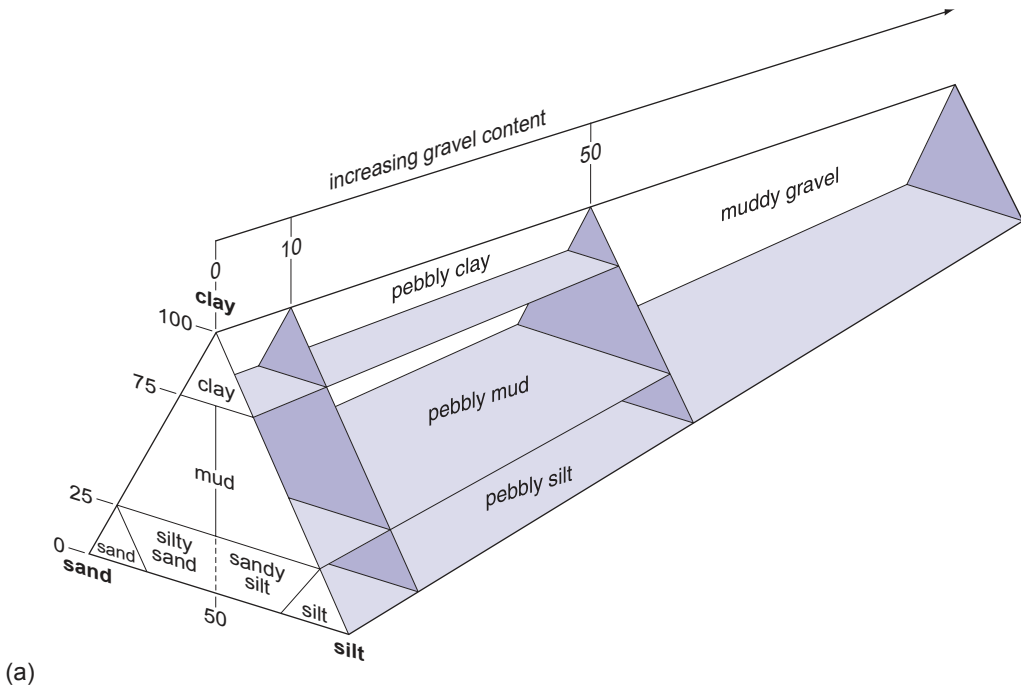
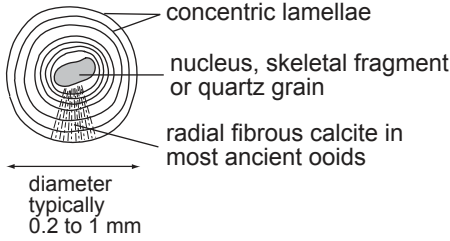


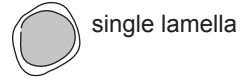
Figure A6.9 Classification of mudstones. (Modified after Stow 2005.)

OOID



Ooids typically form in agitated water of no greater depth than 15 m; more typically the depth is 5 m; Most oolitic rocks are marine.

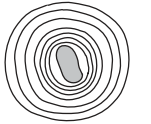
SUPERFICIAL OOID



COMPOSITE OOID

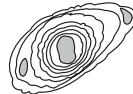


PISOID (PISOLITH)



diameter > 2 mm

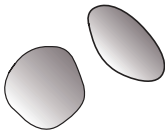
ONCOID (ONCOLITH)



diameter > 2 mm

Oncoids are pisoids of algal origin. The algal layers are wavy in cross-section and often incorporate other bioclasts and grains.

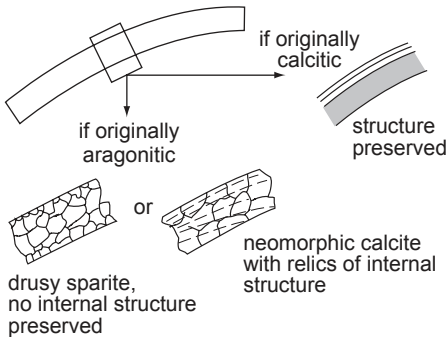
PELOID



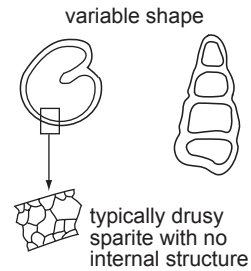
Peloids are pellets or amorphous grains composed of micrite, typically 0.1–0.5 mm diameter; most are micritized skeletal grains or faecal pellets.

BIOCLASTS

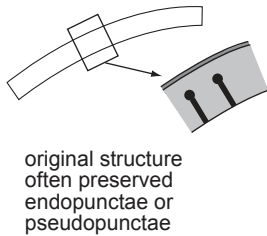
BIVALVE



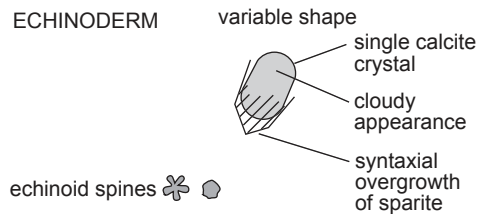
GASTROPOD



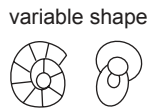
BRACHIOPOD



ECHINODERM



FORAMINIFERA



BRYOZOA

variable shape

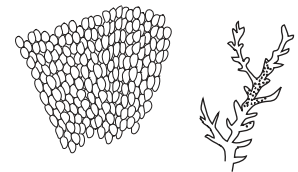


Figure A6.10 Main limestone-forming grains.

principal grain type	limestone type	
	cemented by sparite	micritic matrix
bioclasts	biosparite	biomicrite
ooids	oosparite	oomicrite
peloids	pelsparite	pelmicrite
intraclasts	intrasparite	intramicrite

limestone formed *in situ* (e.g. reef or stromatolite)= biolithite
 fenestral limestone (micrite with cavities) = dismicrite

Figure A6.11 Folk scheme for the classification of limestones. (Modified after Folk 1962.)

original components not organically bound together during deposition						Boundstones: original components organically bound during deposition		
contains lime mud		grain-supported with muddy matrix	lacks mud and is grain-supported	>10% grains >2 mm		organisms act as baffles	organisms encrust and bind	organisms build a rigid 3-D framework
mud-supported				matrix-supported	supported by >2 mm component			
<10% grains	>10% grains							
mudstone	wackestone	packstone	grainstone	floatstone	rudstone	baffle-stone	bindstones	frame-stone

Figure A6.12 Dunham scheme for the classification of limestones. (Modified after Dunham 1962 with additions from Embry and Klovan 1971.)

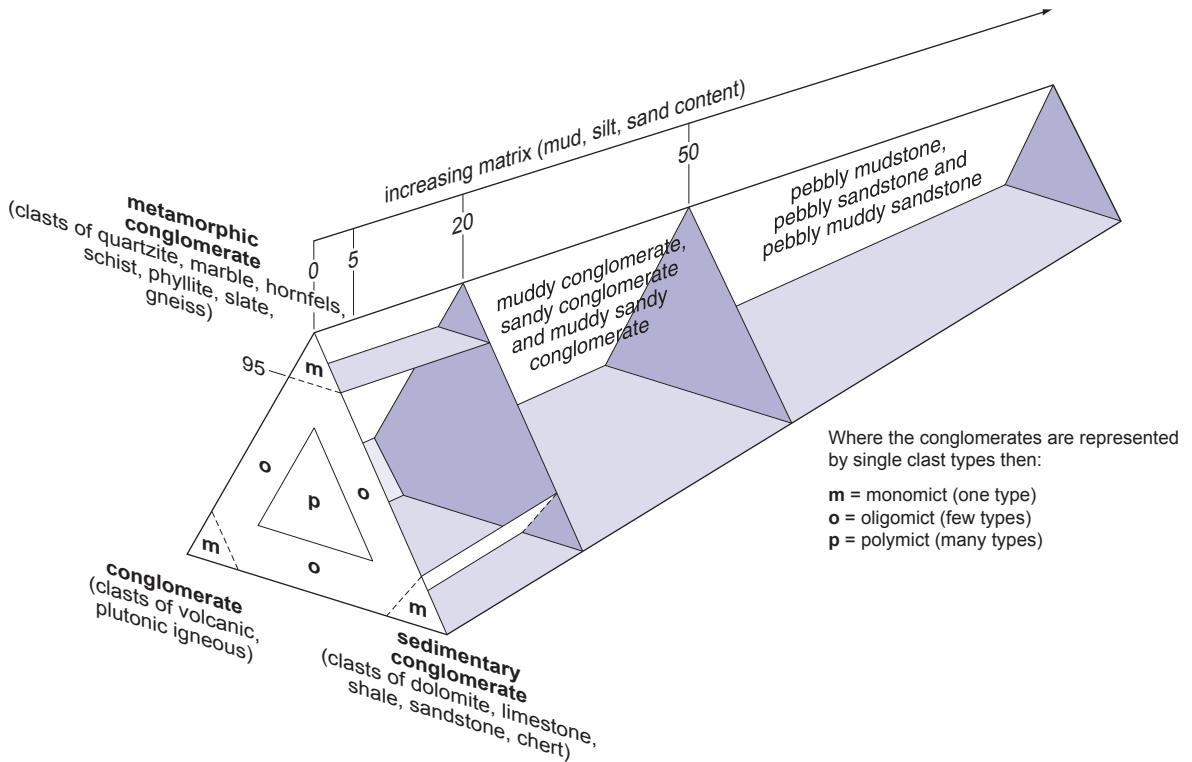


Figure A6.13 Classification of coarse-grained sedimentary rocks (conglomerates, breccias, etc.). Modified after Boggs 1992, Nichols 1999 and Stow 2005. In addition the following terms can be applied: intraformational conglomerate and breccia, composed of clasts of the same material as the matrix; extraformational conglomerate, composed of a mixture of rock types; clast-supported (or orthoconglomerate); matrix-supported (or paraconglomerate or diamictite).

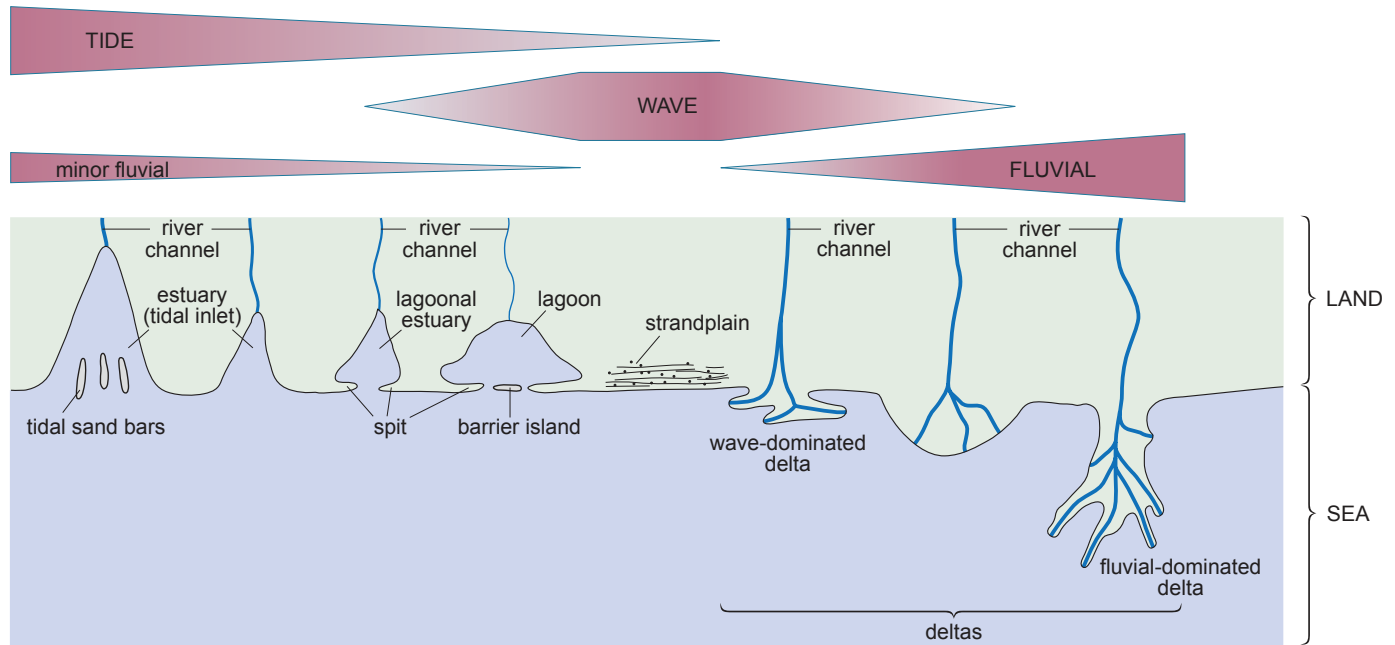


Figure A6.14 Sketch illustrating the spectrum of coastal morphological features and the processes dominant in each case. The importance of waves, tides and fluvial input is shown schematically by the boxes at the top of each figure; tapering of the box indicates less influence of that process.

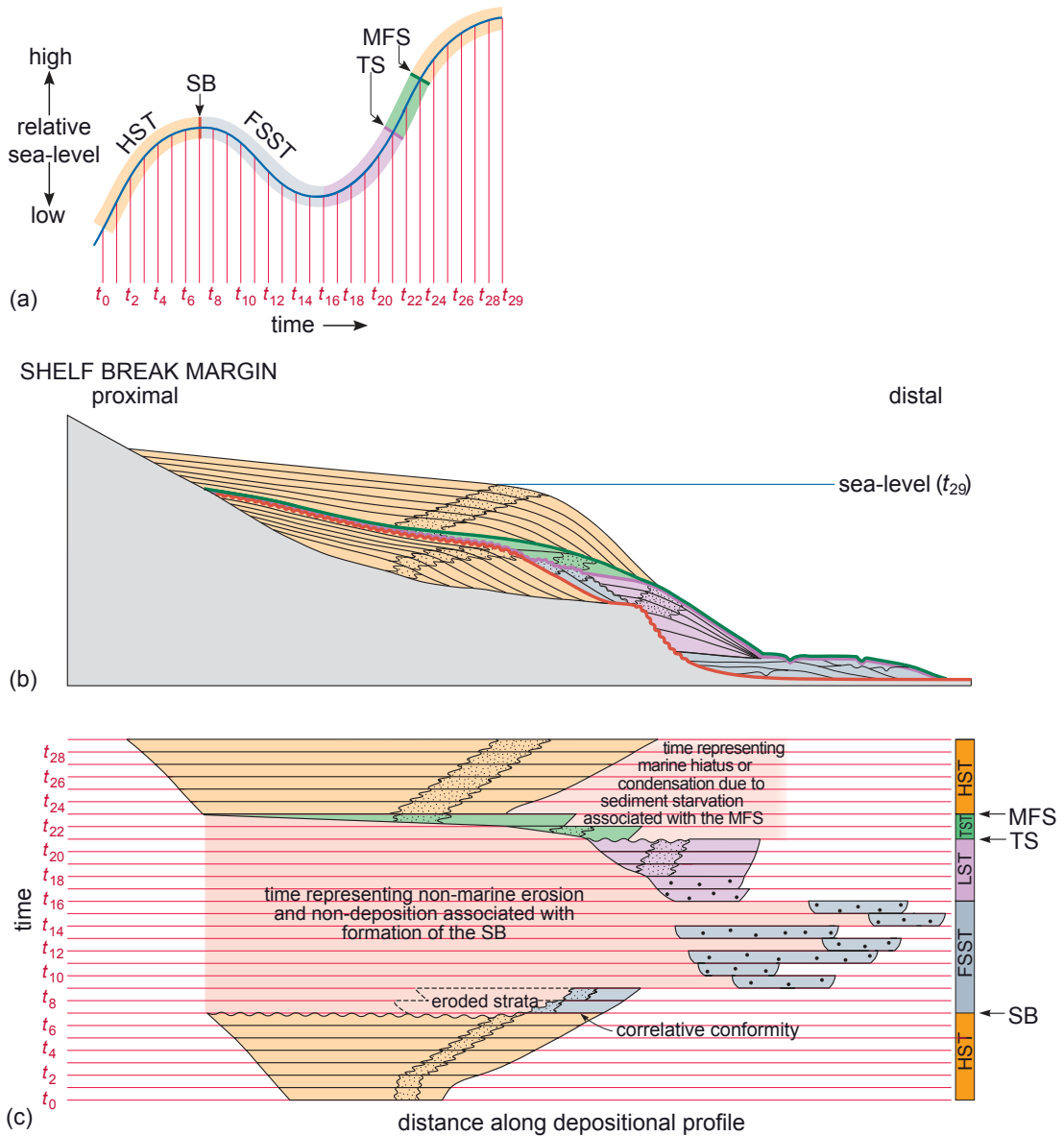


Figure A6.15 Sequence stratigraphy summary figures. (a) Idealized illustrations of key features of the sequence stratigraphy model on the relative sea-level curve for (b) to (e), showing the position of the systems tracts and key surfaces. In this example, parasequences are assumed to have equal duration as indicated by the equal time units t_0 , t_2 , etc. (b and d) Cross-sections through a HST and the overlying depositional sequence (FSST, LST, TST and HST) for a continental margin with a shelf break (b) and ramp type continental margin (d). (c and e) Chronostratigraphical representation of (b) and (d) respectively. Hemipelagic and pelagic sediments are not shown. (From Coe 2003.)

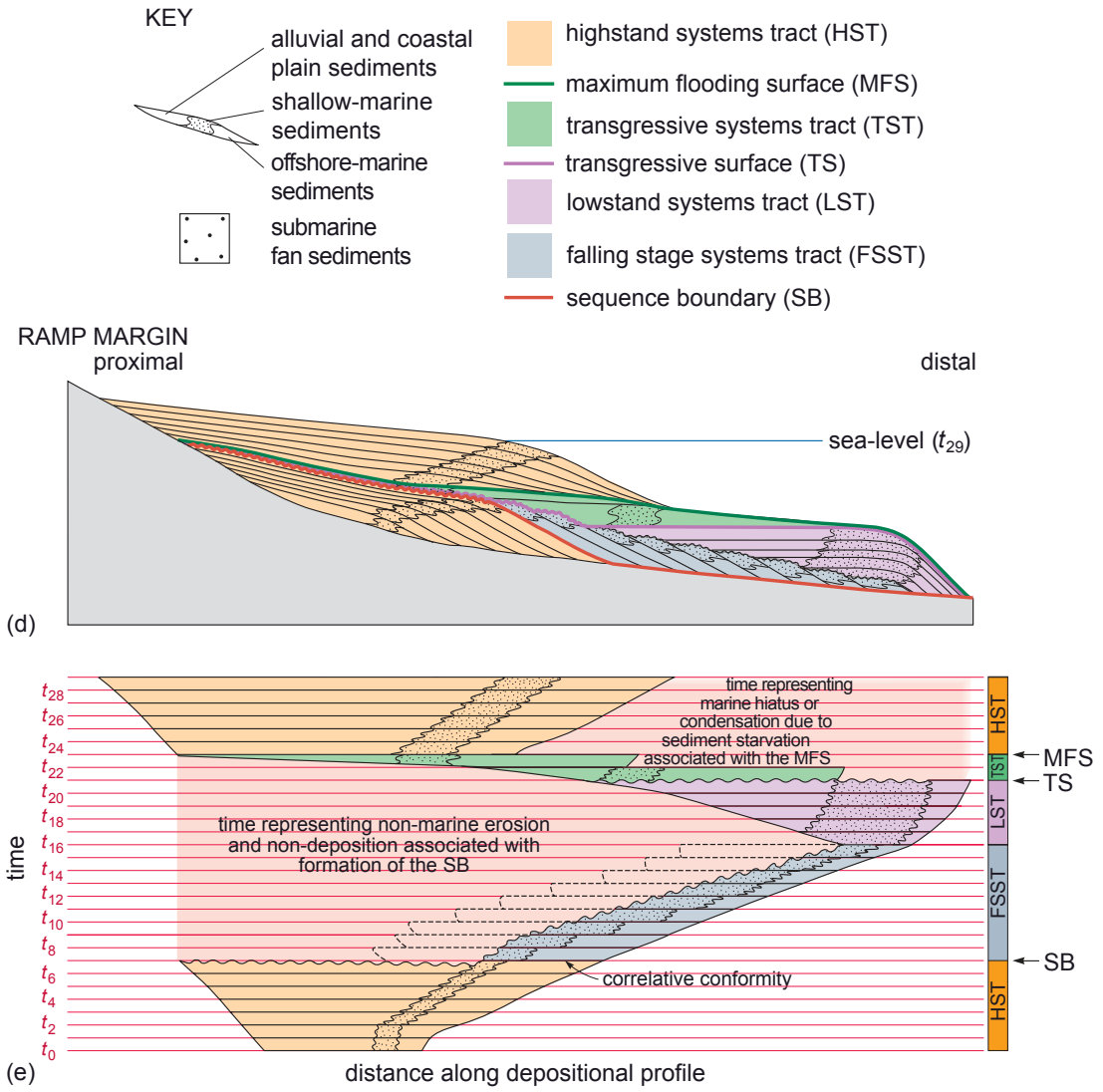


Figure A6.15 Continued

Lithology

	sandstone
	granules & pebbles
	siltstone
	mudstone / claystone
	laminated mudstone / claystone
	marl
	limestone
	dolomite
	siderite
	evaporite
	coal
	ooids
	peloids
	oncoids
	intraclasts
	bioclasts
	pyrite framboids
Nodules	
	calcium carbonate
	siderite
	chert/flint
	pyrite

Body fossils

	ammonite
	bivalve
	belemnite
	brachiopod
	bryozoan
	coral
	crinoid
	echinoid
	fish
	gastropod
	graptolite
	serpulid
	starfish
	sponges
	stromatolites
	trilobite
	vertebrate bone / tooth
	leaf or stem or flower or seed pod
	wood / charcoal
	roots

Trace fossils

	bioturbation		<i>Ophiomorpha</i>
	vertebrate footprints		<i>Gyrochorte</i>
	<i>Arenicolites</i>		<i>Planolites</i>
	<i>Chondrites</i>		<i>Rhizocorallium</i>
	<i>Cruziana</i>		<i>Skolithos</i>
	<i>Diplocraterion</i>		<i>Teichichnus</i>
	<i>Muenesteria</i>		<i>Thalassinoides</i>
	<i>Nereites</i>		<i>Zoophycos</i>

Physical sedimentary structures

	cross-stratification (denote type/geometry and scale by accurate drawing and/or abbreviations, e.g. HCS = hummocky cross-stratification, TCS = trough cross-stratification)
	desiccation cracks
	planar stratification
	ripples (climbing)
	ripples (current-formed)
	ripples (wave-formed)
	scours

Symbol modifiers

	line through the fossil symbol indicates fossils are fragmented (e.g. gastropod fragments)
	encircled symbol indicates high abundance (e.g. abundant gastropods)

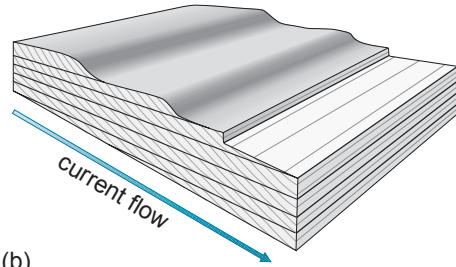
Figure A6.16 Some of the commonly used symbols for graphic logs and some ideas for other more specific features.

Planar cross-stratification



(a) plan view

Note: Structure needs to be examined in faces at right angles to confirm identification. Tabular beds and the horizontal lamination between the inclined beds as shown in (a) are consistent with planar cross-stratification.



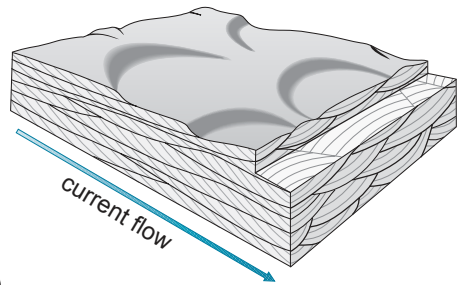
(b)

Trough cross-stratification



(c) cross-section

Note: Structure needs to be examined in faces at right angles to confirm identification. Lensoid shaped beds as shown in (c) are consistent with trough cross-stratification.



(d)

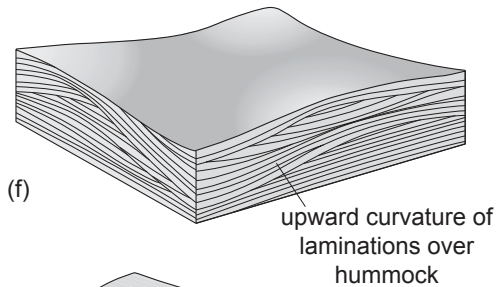
Hummocky and swaley cross-stratification

Hummocky cross-stratification (HCS)



(e) cross-section

Note: Hummocky and swaley cross-stratification are part of a continuum. HCS has a 1:1 ratio of hummocks : swales whereas SCS is mainly swales as the hummocks have been eroded. For any location the wave length of the structure increases from HCS to SCS.

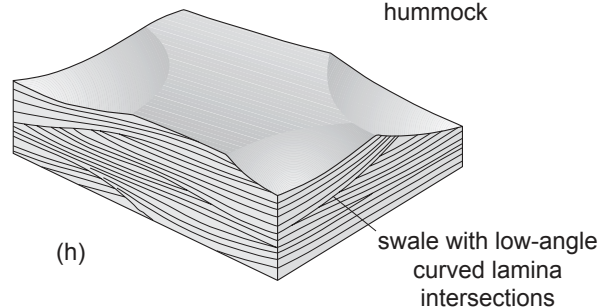


(f)

Swaley cross-stratification (SCS)



(g) cross-section

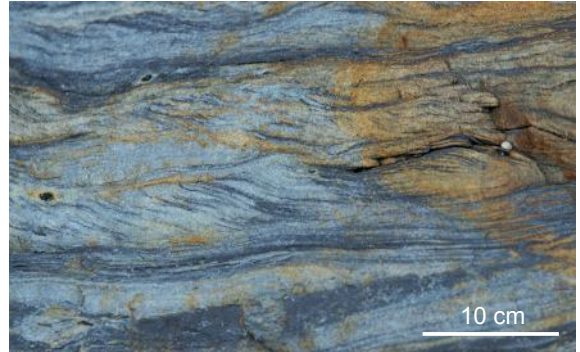


(h)

Figure A6.17 Common sedimentary structures. See also Tables 6.2–6.4. Red penknife is 9 cm long. (All Angela L. Coe, The Open University, UK, except (x) and (cc), R. Chris L. Wilson.)

Current-formed ripples

(i) plan view



(j) cross-section

Note: Asymmetric profile and relatively simple internal geometry of the inclined surfaces that build up as the ripple migrates.

Wave-formed ripples

(k) plan view

Note: Asymmetric profile, bifurcating crests, complex internal geometry



(l) cross-section



(m) Cross-section of climbing wave-formed ripples

Wave-formed ripples with current

(n) cross-section

Complex wave-formed ripples formed within wave-base where there was also a dominant current. Note also the clay drapes.

Lenticular [l] and flaser [f] bedding

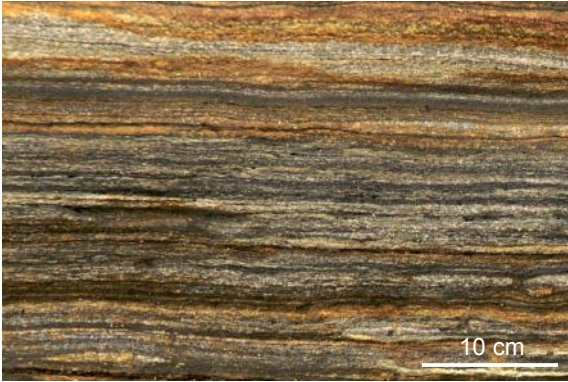
(o) cross-section

Tidal bundles

(p) cross-section

Note: Laminae are in multiples of seven and either widely spaced (spring tides) or closely spaced (neap tides).

Planar lamination



(q) cross-section

Current lineation



(r) plan view

Note: Looks like low amplitude ridges, best seen in low-angle lighting conditions

Grading



(s) cross-section

Coarsening-upward cycles with plant roots



(t) cross-section

Crudely fining-upward cycles

Evidence of desiccation

Desiccation cracks



(u) plan view

Pseudomorphs after halite



(v) plan view

Evidence for erosion

Scour



(w) cross-section

Groove casts



(x) underside

Flute casts



(y) underside

Figure A6.17 *Continued*

Nodules



(z) cross-section

Depositional evaporite nodules



(aa) cross-section

Early post-depositional siderite nodules (note ovoid shape)



(bb) cross-section

Late post-depositional calcium carbonate nodules (note spherical shape)

Evidence of dewatering

Load casts



(cc) plan view underside

Dish structures



(ee) cross-section

Flame structures



(gg) cross-section

Note: Distinct flame shapes are flame structures. Otherwise this can be termed convolute bedding.

Ball and pillow structures

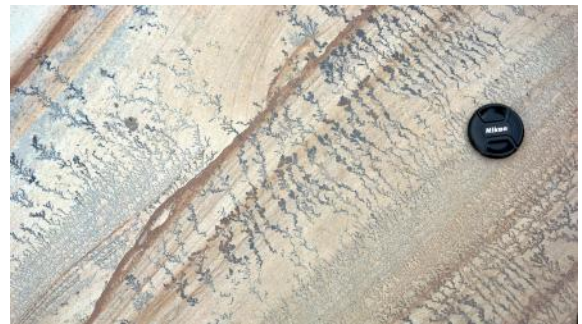


(dd) cross-section



(ff) cross-section

Leisgang rings and dendrites



(hh) plan view

Note: Both of these form during late diagenesis due to the precipitation of iron oxide (Leisgang rings) or manganese oxide (dendrites) in the rock.

Appendix A7: Igneous

Table A7.1 Names for igneous intrusions, based on shape and relationship with country rocks.

Name	Description
Batholith	Grouping of more-or-less contiguous plutons
Central complex	Assemblage of largely intrusive rocks, with screens and other masses of extrusive and country rocks, arranged around one or more focal points. Considered to represent the interior or shallow roots of a volcano
Cone-sheet	Cone-shaped curtain (sheet) intrusion dipping inwards towards a central focal point. Essentially a dyke, with roughly circular outcrop pattern, dipping inwards
Cupola	Dome-shaped upward protuberance from the top of an intrusion
Diapir	Dome-shaped body of igneous rock, inferred to have deformed and ruptured the country rock during ascent
Diatreme	Breccia-filled volcanic pipe
Dyke (US spelling is dike)	Discordant curtain of igneous rock, originally intruded into a steep or vertical fracture. Typically tens of centimetres to several metres in width
Dyke swarm	A number of spatially associated dykes, typically radial, parallel or en échelon
Laccolith	Intrusion that is roughly circular in plan, generally concordant with the country rock and having a planar floor but a domed roof
Lopolith	Large, generally concordant intrusion that is broadly saucer-shaped
Minor intrusion	General informal term for any intrusion too small to be classed as a pluton
Neck	Feeder pipe of a former volcano, occupied either by collapsed material from the vent or by a cylindrical intrusion of magma also referred to as a 'plug'
Pluton	Discordant intrusive body a kilometre or greater in scale. Of cylindrical, lenticular or tabular shape, resulting in a roughly circular or elliptical outcrop pattern. May be <i>simple</i> (one intrusion) or <i>composite</i> (supplied by more than one recognizable pulse of magma)
Ring complex	Association of ring-intrusions, ring-dykes and cone-sheets
Ring-dyke	Dyke with annular outcrop pattern. Either vertical or dipping steeply outwards (whereas a <i>cone-sheet</i> dips inwards)
Ring-intrusion	Intrusion emplaced within, or bounded by, a cylindrical ring-fracture
Sheet	Intrusion with broadly parallel margins and one dimension much shorter than the other two (such as a sill or a dyke). More aptly referred to as a curtain if steeply dipping. 'Inclined sheet' is sometimes used for a dipping sheet that cannot be called a sill but is not steep enough to be called a dyke
Sill	Roughly horizontal sheet of intrusive rock with top and bottom generally concordant with stratified country rock. Local discordancies may occur where a sill steps from one horizon to another. Typically metres to tens of metres thick
Vein	Sheet of igneous rock narrower and more irregular than would be classified as a sill, dyke or sheet. (Beware: veins occupied by minerals precipitated from hydrothermal fluids are not igneous)

Table A7.2 Typical properties, visible in hand specimen, of common minerals that may be found in igneous rocks.

Mineral category	Mineral	Features (note – other colours may be possible)
Felsic	Quartz	Colourless or white (but may be tinted by impurities), no cleavages, hardness 7. May look milky in veins
	Feldspar: orthoclase microcline plagioclase	Two poorly developed cleavages, at roughly 90° Pink, simple twinning sometimes visible, hardness 6–8 White, hardness 6–7 White (but transparent grey if unaltered), twinning rarely visible, hardness 7
	Nepheline	White to pale grey, two poor cleavages, hardness 5.5–6
	Muscovite	Silvery-grey to white, one excellent cleavage so that it occurs as tabular (flakey) crystals, shiny cleavage surfaces, hardness 2–3
Mafic	Amphibole	Dark green to black, 60° cleavages (hard to see), crystals sometimes elongated, hardness 5–6
	Pyroxene	Dark green to black, 90° cleavages (hard to see), hardness 5–6
	Olivine	Grass green or darker, equidimensional crystals, no cleavage, hardness 6–7
	Chlorite	Pale green, hardness 2–3
	Biotite	Dark brown to black, one excellent cleavage so that it occurs as tabular (flakey) crystals, shiny cleavage surfaces, hardness 2–3
	Tourmaline	Usually black, but may be blue, red or green. Long thin crystals, sometimes with longitudinal striations. Hardness 7
Accessory	Garnet	Red or green, equidimensional crystals
	Apatite	Pale green-yellowish. Very poor cleavage. May look hexagonal, sometimes fibrous. Hardness 5
	Sphene (titanite)	Colourless to yellow, green or brown. One good cleavage. Often as euhedral rhombic crystals. Hardness 5
	Leucite	White or grey, no cleavage. Often euhedral trapezohedral crystals in alkaline lavas. Hardness 5.5–6
	Opaque minerals (mostly metal oxides or sulfides)	Metallic lustre (some oxides are shiny black). Various colours
	Volcanic glass (not a mineral!)	Brown to black, amorphous, often breaks with conchoidal fractures. May devitrify to develop fine, feathery internal structure

Table A7.2 *Continued*

Mineral category	Mineral	Features (note – other colours may be possible)
Secondary	Calcite	White or colourless, three cleavages often seen (not at 90°), hardness 3, fizzes with dilute HCl
	Epidote	(In hydrothermally altered rocks) Apple green, variable but often elongated crystals. Hardness 6–7
	Chlorite	Mid-green to dark greenish-yellow. Often in thin flakes due to good cleavage. Hardness 2–3
	Zeolites	Usually whitish, fine fibrous growths on joint faces or within vesicles (amygdales). Hardness 5–6

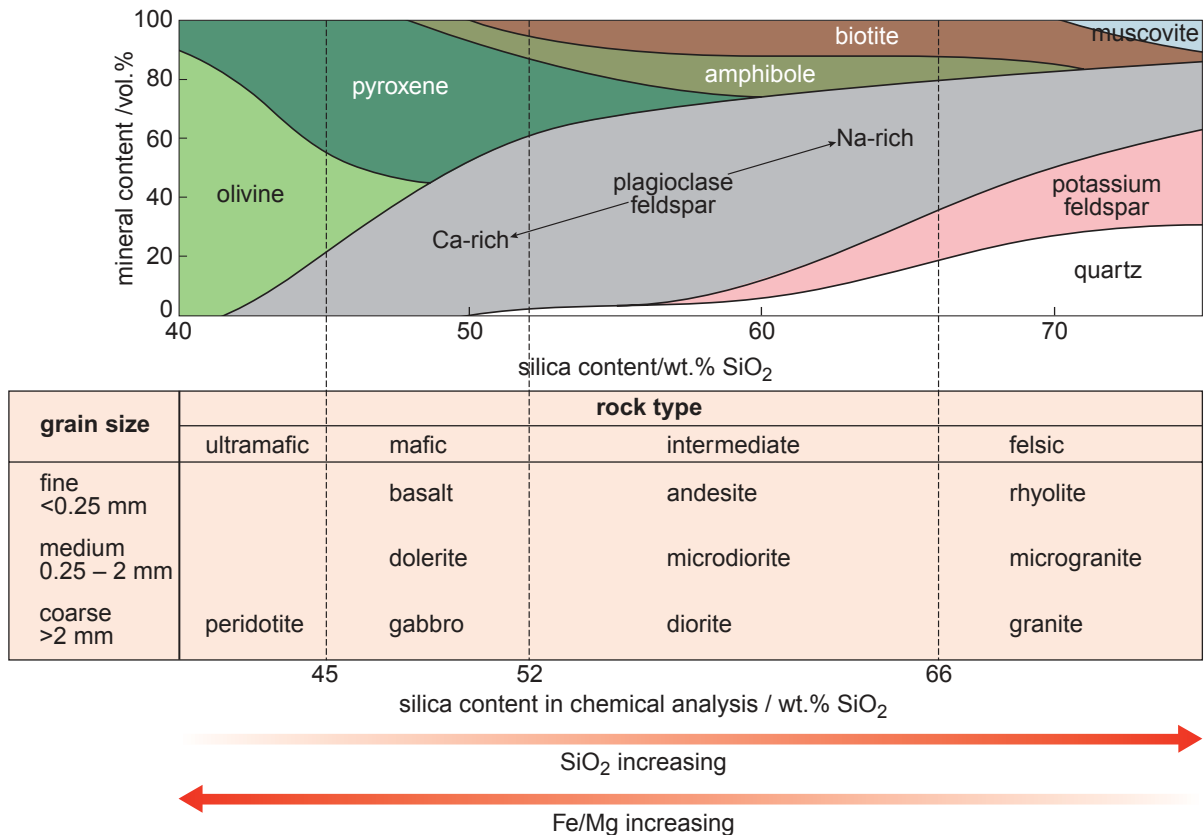


Figure A7.1 Classification scheme for igneous rock types, by grain size and mineralogy. Fine-grained felsic rocks are paler than fine-grained mafic rocks, and may be reddened by alteration. However, *glassy* rhyolite (obsidian) can be black.

Appendix A8: Structural

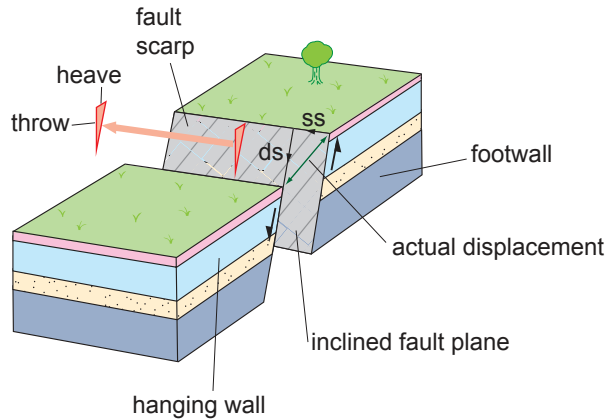


Figure A8.1 Diagram of an oblique-slip fault, annotated with terms for its main components. The actual displacement (green arrows) can be divided into two components: dip-slip component (ds) and strike-slip component (ss).

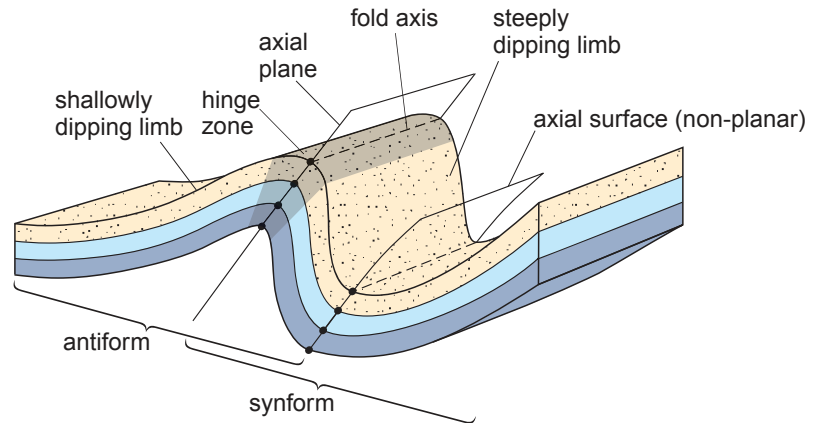


Figure A8.2 Diagram of a typical fold pair, labelled with terms for the main parts of fold structures. The terms antiform and synform describe the form of the folds. If the sequence is right-way up (i.e. the stippled layer is younger than the pale blue layer), then the antiform is an anticline, and the synform is a syncline.

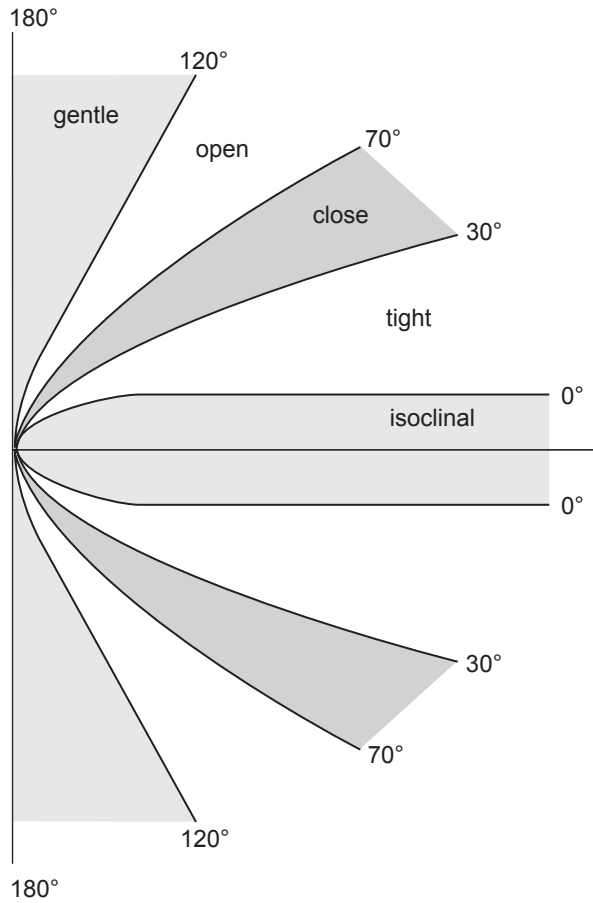


Figure A8.3 Schematic illustration of different types of fold tightness, defined according to the angle between the two fold limbs (the interlimb angle). (Based on Fleuty 1964.)

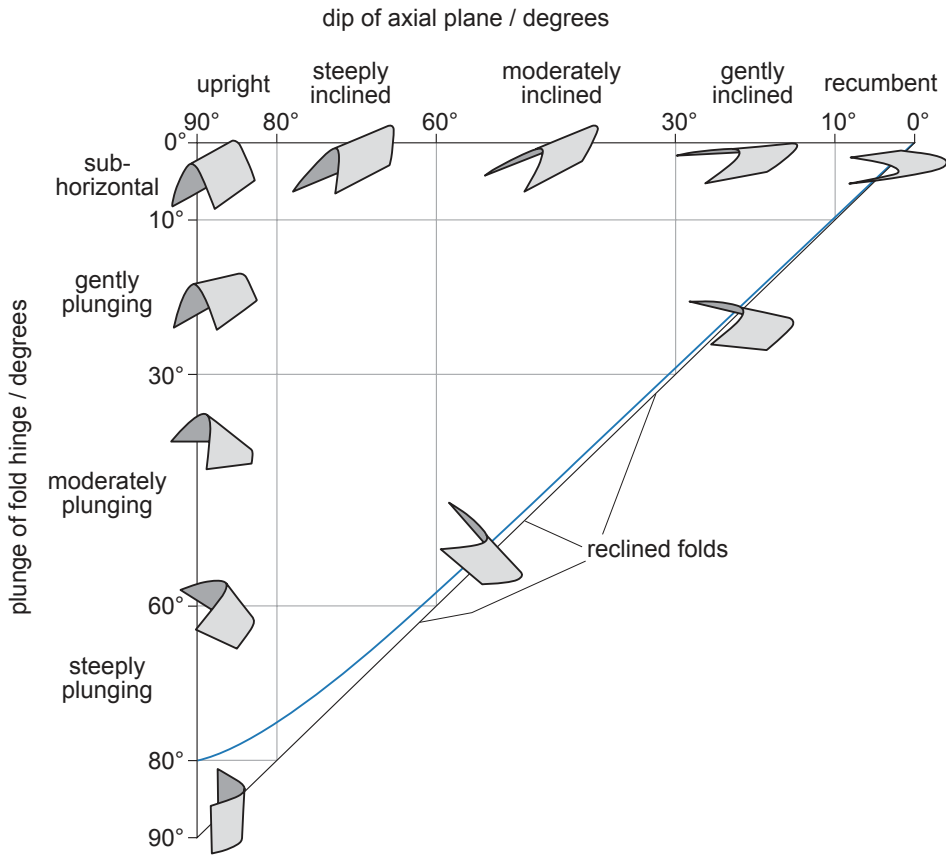


Figure A8.4 Classification of fold types using a combination of the dip of the axial plane and the plunge of hinge line.

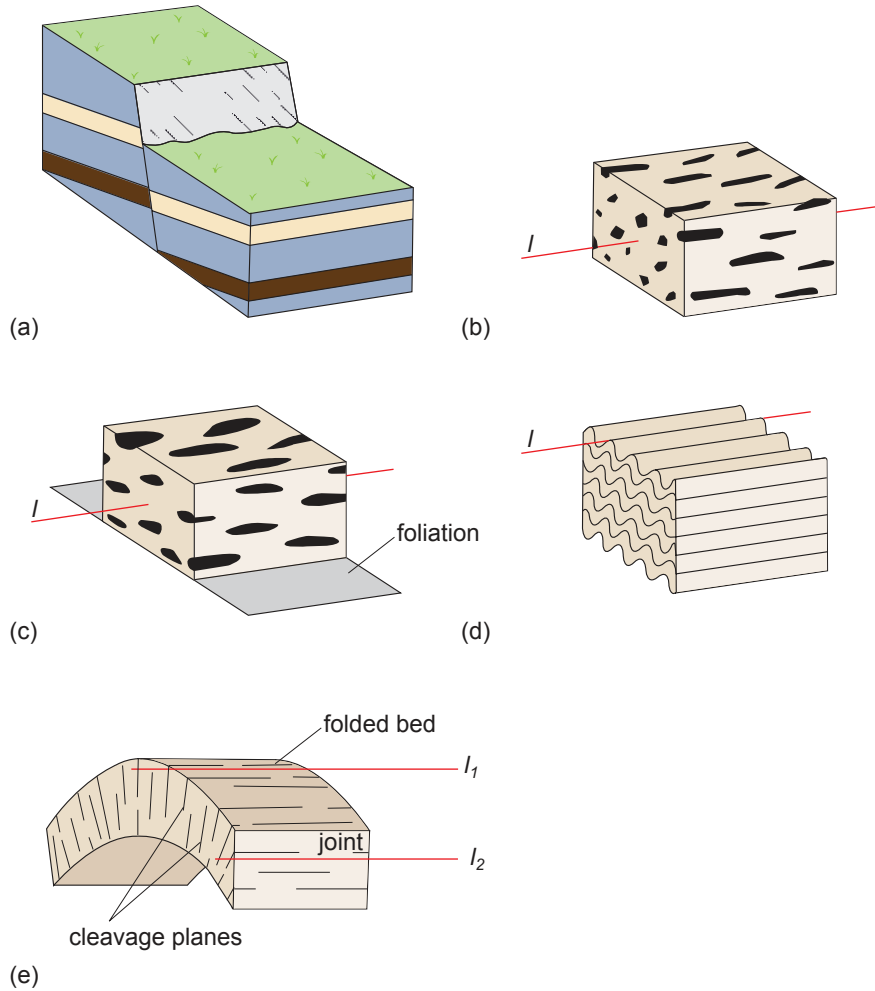


Figure A8.5 Block diagrams illustrating several different types of lineations. (a) Striations (slickenlines) on a fault plane. (b) Stretching lineation defined by deformed (elongated) mineral grains. (c) A rock with both foliation (flattening) and lineation (stretching). (d) Crenulation lineation defined by the hinge lines of microfolds. (e) Intersection lineations in a fold. Two different lineations are shown: the intersection of cleavage on a folded bedding plane, and the intersection of cleavage on a joint plane. (Modified from Park 1989.)

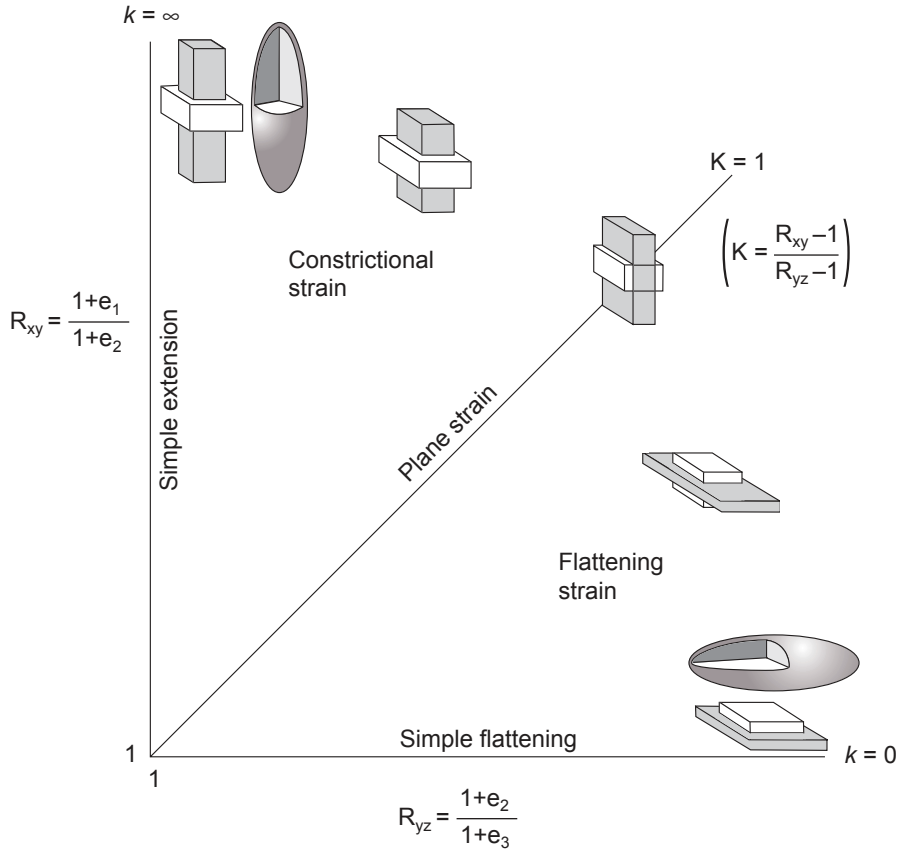


Figure A8.6 The Flinn diagram uses measurements of the principal strain axes in deformed rocks to distinguish constrictional from flattening strains. The equiline ($k = 1$) bisecting the plot represents plane strain. R_{xy} and R_{yz} are the principal plane strain ratios, calculated from the principal longitudinal strains e_1 , e_2 and e_3 . (Modified from Ramsay and Huber 1984.)

Table A8.1 Textural classification of fault rocks based on Sibson 1977.

Matrix nature		Random fabric	Foliated	Percentage matrix
Incohesive		Fault breccia (visible fragments >30% of rock mass)	?	
		Fault gouge (visible fragments <30% of rock mass)	?	
Cohesive	Glass/devitrified glass	Pseudotachylite	?	
	Tectonic reduction in grain size dominates grain growth by recrystallization	Crush breccia (fragments >0.5 cm)		
		Fine crush breccia (0.1 cm < fragments < 0.5 cm)		
		Crush microbreccia (fragments < 0.1 cm)		0–10
		Cataclasite series protocataclasite cataclasite ultracataclasite	Mylonite series protomylonite mylonite ultramylonite	10–15 50–90 90–100
Grain growth pronounced	?	Blastomylonite		

? indicates no known natural rock types in these categories.

A note on stereographic projections

Three-dimensional structural data are typically projected into a two-dimensional form (as in Figure 8.12) using a lower hemisphere stereographic projection technique. Traditionally, this method used a graphical ‘net’: in the case of structural data, the Schmidt net. This net allows analysis of angular relationships and statistical evaluation of orientation data. Projection, analysis and presentation of data are now routinely handled by software applications on personal computers, but were formerly accomplished by hand, using tracing paper and a Schmidt net.

The projection results in planes plotting as great circle lines (the curves in Figure 8.12), whereas linear structures plot as points. To simplify plots with numerous planes, the pole (a line orthogonal) to each plane may be plotted as a point, instead of the great circle representing the plane.

A detailed treatment of the stereographic projection and its uses can be found in Ragan (2009).

Appendix A9: Metamorphic

Table A9.1 Properties useful for field identification of some common metamorphic minerals. Mohs' scale of hardness (H) is given in Appendix A1, Table A1.1.

Mineral (abbreviation) formula	Colour; lustre	Typical habit	Cleavage; twinning	Hardness (H)
Quartz (Qtz) SiO_2	Grey, greasy or glassy; white in veins	Interstitial, irregular grains	None	7
K-feldspar (Kfs) $\text{KA1Si}_3\text{O}_8$	Pink, white or grey; glassy, but chalky when weathered	Stumpy, tabular crystals	2 cleavages; simple twins common	6
Plagioclase (Pl) $\text{NaAlSi}_3\text{O}_8\text{--CaAl}_2\text{Si}_2\text{O}_8$	White or grey; glassy or pearly	Tabular crystals or ovoid grains	2 cleavages; multiple or simple twins	6–6.5
Chlorite (Chl) $(\text{MgFe})_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_8$	Dark 'bottle' green; pearly	Flexible flakes; fine groundmass	1 perfect cleavage	2–3
Biotite (Bt) $\text{K}(\text{Mg,Fe})_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$	Dark brown to black; pearly	Elastic flakes; forms foliations	1 perfect cleavage	2.5–3
Muscovite (Ms) $\text{KA1}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$	Silvery-white to pale golden; pearly	Elastic flakes; forms foliations	1 perfect cleavage	2–2.5
Andalusite (And) Al_2SiO_5	White, grey, dull red; glassy	Euhedral prisms; square cross-sections	2 cleavages	6.5–7
Kyanite (Ky) Al_2SiO_5	Pale blue to white, grey; pearly to glassy	Bladed crystals; porphyroblasts	2 cleavages	4.5–7
Sillimanite (Sil) Al_2SiO_5	White, grey; glassy, or pearly when fibrous	Slender prisms, or fibrous; forms foliations	1 cleavage	7
Garnet (Grt) $(\text{Mg,Fe,Ca,Mn})_3\text{Al}_2\text{Si}_3\text{O}_{12}$	Red to orange, pink, violet, brown, black, green; glassy	Equant crystals, dodecahedral, robust	None	6.5–7.5
Staurolite (St) $(\text{Mg,Fe})_4\text{Al}_{18}\text{Si}_{7.5}\text{O}_{44}(\text{OH})_4$	Brown, orange, yellow, black; glassy, resinous or dull	Stumpy, tabular crystals; porphyroblasts	1 cleavage; twinning common	7–7.5

Table A9.1 *Continued*

Mineral (abbreviation) formula	Colour; lustre	Typical habit	Cleavage; twinning	Hardness (H)
Cordierite (Crd) $(\text{Mg,Fe})_2\text{Al}_4\text{Si}_5\text{O}_{18}$	Colourless, grey, green, blue if fresh; greasy to glassy	Indistinct ovoid blobs or interstitial grains	Poor cleavage	7
Chloritoid (Cld) $(\text{Fe,Mg})\text{Al}_2\text{SiO}_5 (\text{OH})_2$	Green to grey; pearly	Elongate or stumpy prisms	Poor cleavage; multiple twins	6.5
Epidote (Ep) $\text{Ca}_2(\text{Al,Fe})_3(\text{SiO}_4)_3 (\text{OH})$	Pistachio-green; glassy	Stumpy prisms or groundmass	1 cleavage	6–7
Glaucophanes (Gln) $\text{Na}_2(\text{Mg,Fe})_3\text{Al}_2\text{Si}_8\text{O}_{22}$ $(\text{OH})_2$	Dark blue to black; glassy to pearly	Elongate prisms	2 cleavages intersect at 124° and 56°	6–6.5
Pyroxene (Px) $(\text{Ca,Na})(\text{Mg,Fe})(\text{Si,Al})_8\text{O}_6$	Green, brown, black, bright green (omphacite); glassy	Stocky prisms; porphyroblasts	2 cleavages intersect at 92° and 88°	6
Hornblende (Hbl) $\text{Ca}_2(\text{Mg,Fe,Al})_5(\text{Al,Si})_8\text{O}_{22}$ $(\text{OH})_2$	Green, black, brown; more glassy than most pyroxenes	Stumpy or elongate prisms; porphyroblasts	2 cleavages intersect at 124° and 56°	5–6
Actinolite (Act) $\text{Ca}_2(\text{Mg,Fe})_5\text{Si}_8\text{O}_{22} (\text{OH})_2$	Dark green; more glassy than pyroxenes	Slender prisms	2 cleavages intersect at 124° and 56°	5.5
Talc (Tlc) $\text{Mg}_3\text{Si}_4\text{O}_{10} (\text{OH})_2$	White, pale green; pearly	Soft flakes; forms scaly foliations	1 perfect cleavage	1
Calcite (Cal) CaCO_3	Colourless, white, pink, yellow; glassy	Irregular, interstitial grains	3 perfect cleavages, forming rhombs	3
Serpentine (Srp) $(\text{Mg,Fe})_3\text{Si}_2\text{O}_5 (\text{OH})_4$	Green; silky	Fibrous masses	Usually not visible (fibrous crystals)	2.5
Tourmaline (Tur) $\text{NaFe}_3\text{Al}_6\text{Si}_6\text{O}_{18} (\text{BO}_3)(\text{OH})_4$	Black, brown, grey-blue; glassy	Slender prisms with triangular cross-sections	Poor cleavage	7.5

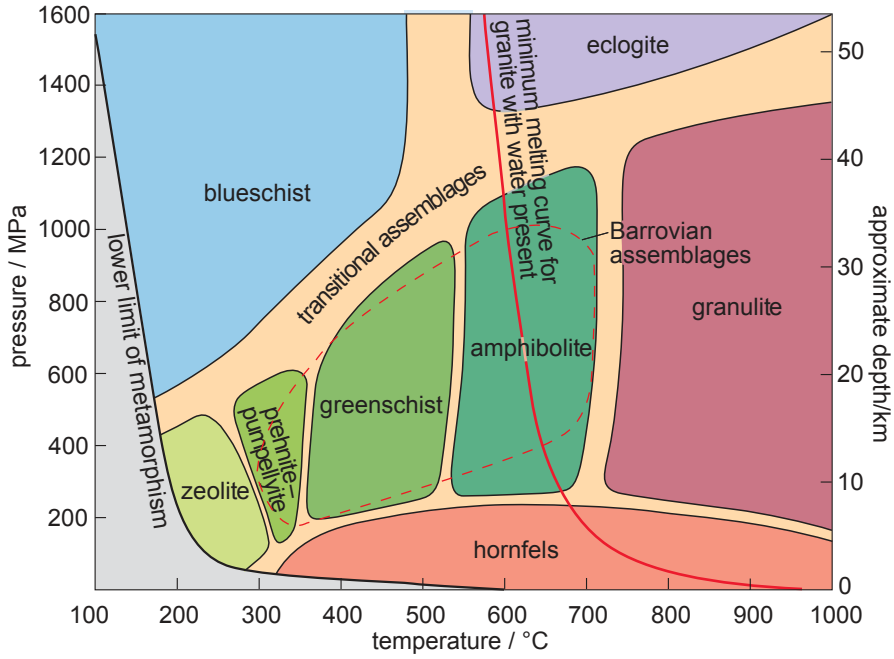


Figure A9.1 The metamorphic facies diagram, dividing P - T space into different fields characterized by particular mineral assemblages in mafic rocks. The wet melting curve for granite is also shown, and the approximate region of Barrovian metamorphic assemblages is outlined (dashed line).

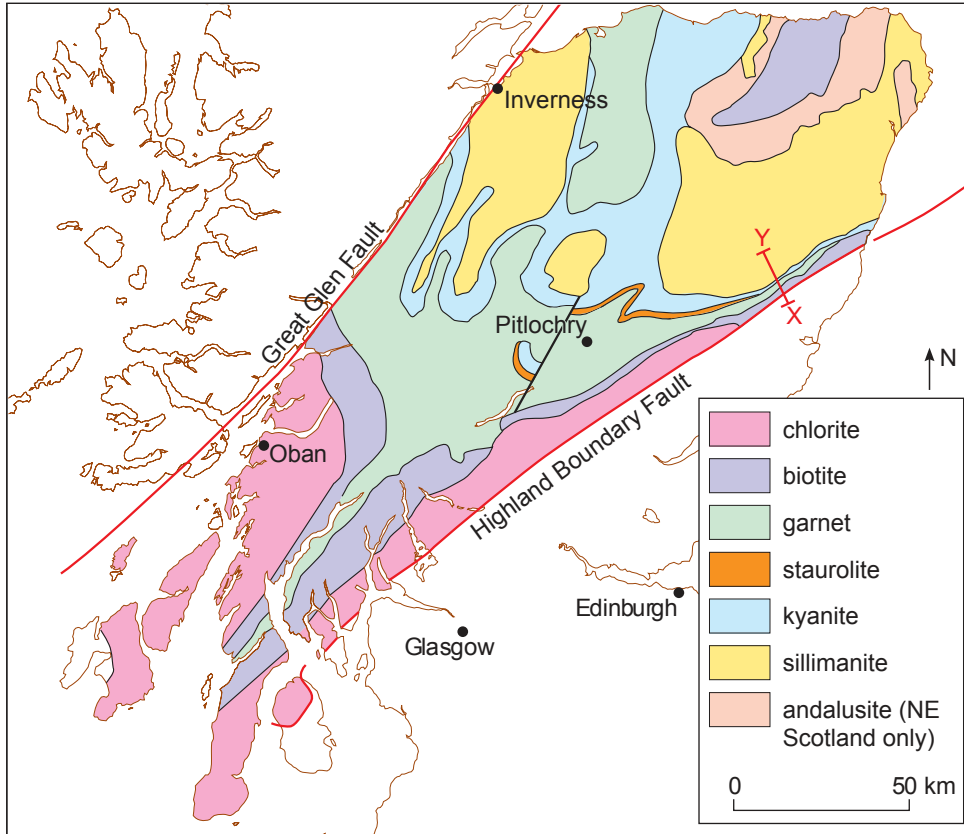


Figure A9.2 A map of the Scottish Highlands, showing the distribution of Barrow metamorphic zones (and the low-pressure Buchan andalusite zone in the northeast). One of the classic transects where the metamorphic zones were first mapped by George Barrow, Glen Esk, is marked by the line XY.

Appendix A10: Mapping

Determination of true and apparent dip

When projecting structural data onto a cross-section, the true dip of strata can be drawn on the section only for data with strikes at 90° to the line of section. If the strikes of data are at a lower angle, an apparent dip less than the true dip must be determined. The trigonometric solution to this problem is often very convenient (for values of $\beta < 60^\circ$):

$$\tan \alpha = \tan \delta \sin \beta$$

where α is the apparent dip (in the line of section), δ is the true dip and β is the angle between the line of strike and the line of interest (section).

The formula to calculate α in Microsoft Excel has the form:

```
=DEGREES(ATAN(TAN(RADIANS(B2))*SIN(RADIANS(B3))))
```

where B2 = δ and B3 = β .

Alternatively, you can use a nomogram (Figure A10.1), a graphical approach to determining one of the three angles above (α , δ , β) given the other two.

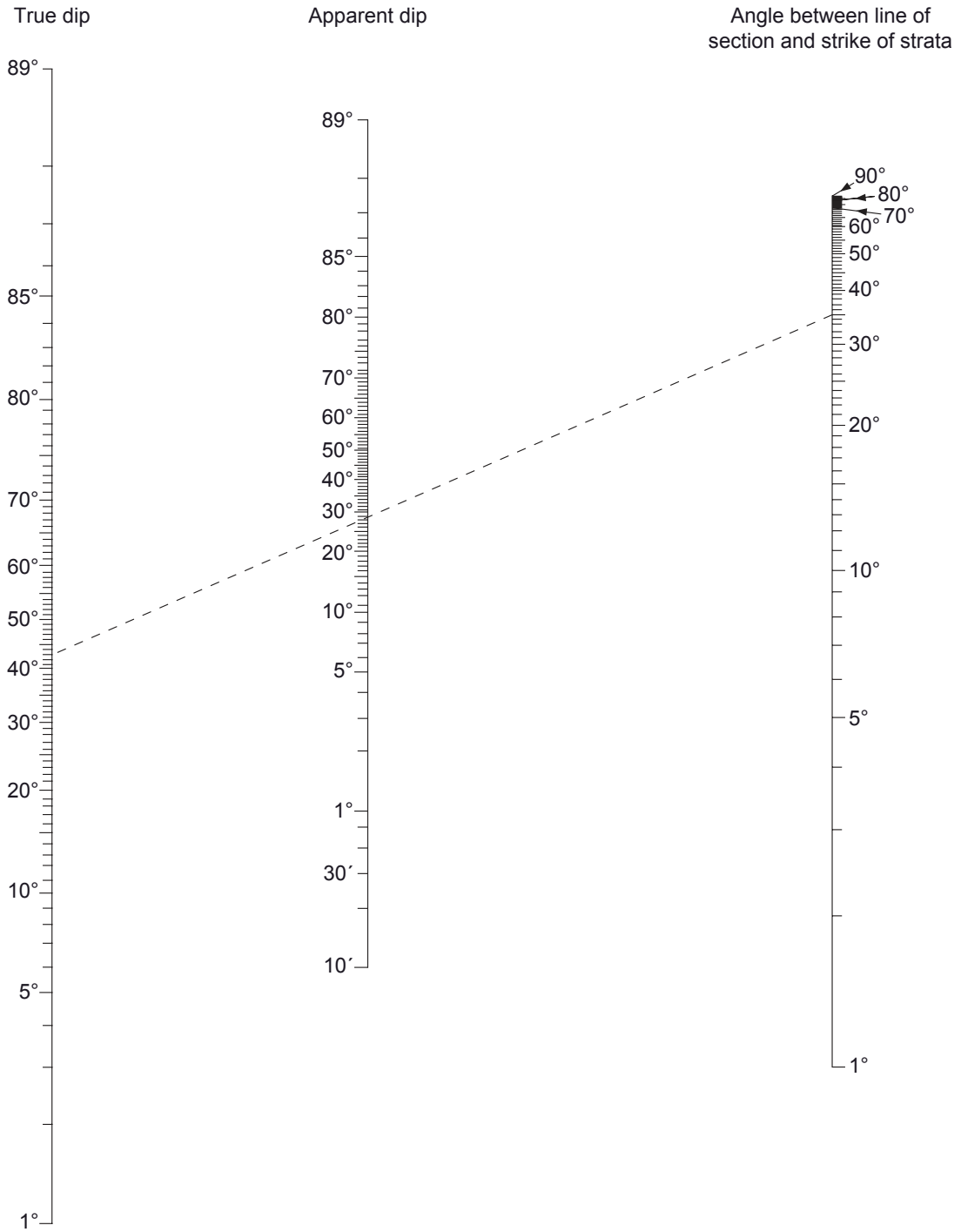


Figure A10.1 Nomogram to determine the apparent dip given the true dip and the angle between the strike and the line of section. The dashed line illustrates an example: for a true dip of 43° on a cross-section oriented at 35° to the strike of the bedding, the apparent dip on the cross-section would be 28° . (Based on Billings 1972.)

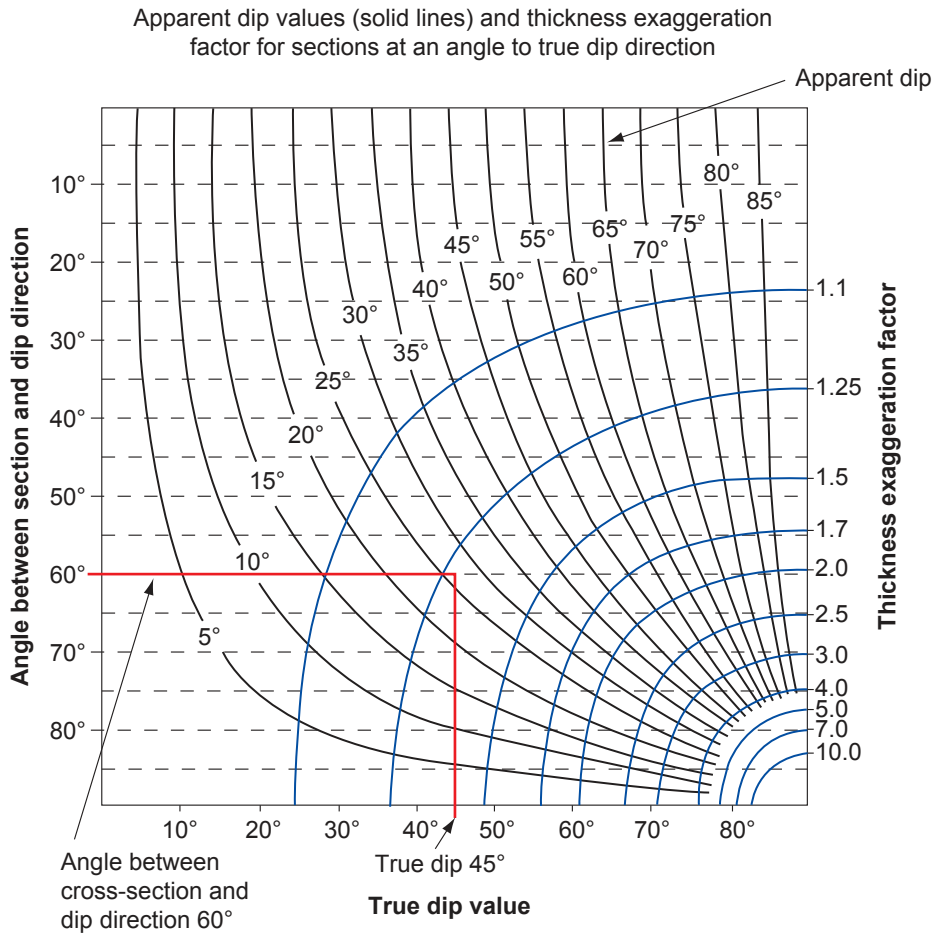


Figure A10.2 A graph to determine the apparent dip angles (solid, curved lines) and the thickness exaggeration (curved blue lines) for bedding in cross-sections that are not parallel to the true dip direction (i.e. where the strike of bedding is not perpendicular to the line of section). An example is given on the diagram (red lines) for bedding with a true dip of 45° on a cross-section orientated at 60° to the dip direction. In this case, the apparent dip of 27° can be read off the graph, and the thickness of bedding will be 1.275 times the actual thickness. (Modified from McClay 1991.)

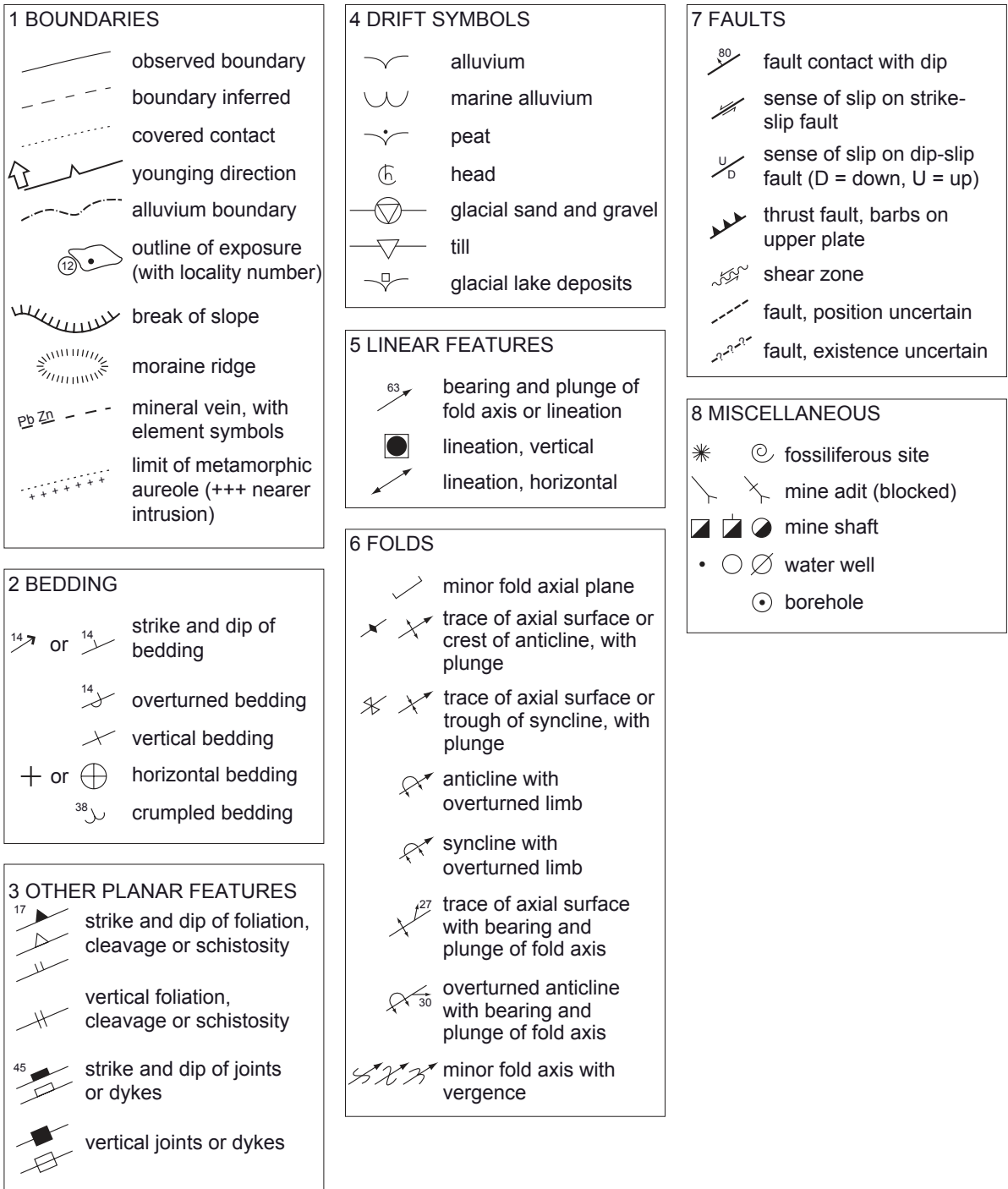


Figure A10.3 A selection of symbols for use in preparing geological maps. Alternatives are given for some of the symbols.

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