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2.1 Introduction

A successful basin analysis requires the collection and integration of several, perhaps many, different kinds of data. Direct observation of the rocks may or may not be fundamental to the study. In the case of a surface geological project, they will be preeminent, though perhaps supplemented by geochemical and geophysical information, plus laboratory analysis of collected samples. For subsurface petroleum studies, actual rock material available for examination may be very limited, consisting of well cuttings from rotary drilling, plus a few short cores. Petrophysical well logs and regional seismic lines may provide at least as important a part of the total data base. Investigations for stratabound ores and minerals typically employ networks of diamond drill holes from which a continuous core normally is available. This provides a wealth of material for analysis, although certain types of observation, such as analysis of sedimentary structures, may be difficult or impossible in such small-diameter cores.

In this chapter we discuss the collection and description of stratigraphic and sedimentologic data from outcrops and drill holes.

2.2 Describing Surface Stratigraphic Sections

Vertical stratigraphic sections, whether measured at the surface or derived from subsurface records, constitute the single most important data set that the basin analyst should assemble. Lithostratigraphic or sequence-stratigraphic classification and correlation, and many sedimentological interpretations, depend on the documentation of vertical relationships within and between lithological units.

2.2.1 Methods of Measuring and Recording the Data

2.2.1.1 Vertical Stratigraphic Sections

The simplest way to record the details of a surface outcrop is by measuring and describing a vertical stratigraphic section. Ideally, the location of the section should be chosen to include important stratigraphic features, such as formation contacts, but, in practice, the location is commonly determined by accessibility, e.g., the presence of bars or beaches allowing us to walk along a river cut, or a negotiable gully cutting through a cliff section. Only those geologists who use their profession as an excuse to practice their favorite sport of mountaineering will be able to apply sound geological principles to the choice of section. The rest of us take what we can reach.

In reconnaissance work, rapid measurement and description techniques are acceptable. For example, a hand-held altimeter (aneroid barometer) may be used in conjunction with dip measurements to reconstruct stratigraphic thicknesses using simple trigonometry. Another method that is commonly described in field handbooks is the pace-and-compass technique, suitable for estimating thicknesses across relatively level ground, given accurate stratigraphic dip. The same distances may be measured from maps or air photographs. Long experience with these methods has shown that they are not very reliable; errors of up to 50 % can be expected.

By far the simplest and most accurate method for measuring a section is the use of a Jacob's staff or "pogo stick." The stick is constructed of a 1.5 m wooden rod, with a clinometer and sighting bar (Fig. 2.1). The clinometer is preset at the measured structural dip and can then be used to measure stratigraphic thickness as fast as the geologist can write down descriptive notes. The best technique is to use two persons. The senior geologist observes the rocks and makes notes, while the junior (who can be an inexperienced student) "pogo's" his or her way up the section recording increments of 1.5 m on a tally counter and collecting samples. The length 1.5 m is convenient for all but the tallest or

shortest persons, although it can be awkward to manipulate on steep slopes. The only skill required by the pogo operator is the ability to visualize the dip of the strata in three dimensions across whatever terrain the geologist may wish to traverse. This is important so that the pogo can at all times be positioned perpendicular to bedding with the line of sight extending from the sighting bar parallel to bedding.

It is far preferable to measure up a stratigraphic section rather than down, even though this often means an arduous climb up steep slopes. Many geologists working by helicopter in rugged terrain have made their traverses physically easier by working downhill wherever possible. But not only is it difficult to manipulate a pogo stick downward in a section, it makes it more difficult for the geologist to comprehend the order of events he or she is observing in the outcrops. It is often convenient to measure a section in separate increments, making use of the most accessible talus slopes or gullies, and traversing laterally along a prominent stratigraphic surface to an adjacent accessible area wherever necessary (Fig. 2.2).

The geologist should search for the cleanest face on which to make observations. Normally, this should be weathered and free of vegetation, talus, or rain wash. Most sedimentary features show up best where they have been etched out by wind or water erosion, or where a face is kept continuously clean and polished by running water, as in a river bed or an intertidal outcrop. Such features rarely show up better on fresh fracture surfaces, so a hammer should only be used for taking samples. Carbonates may benefit from etching with dilute acid. The geologist should methodically examine both vertical cuts and the topside and underside of bedding planes; all may have something to reveal, as described later in this chapter. It is also useful, on larger outcrops, to walk back and examine them from a distance, even from a low-flying helicopter or from a boat offshore, as this may reveal large-scale channels, facies changes, and many other features of interest. A different technique may be used to document such large outcrops, which may conveniently be termed lateral profiling to distinguish it from vertical profiling. We discuss this in the next section.

In the interests of maximum efficiency, the geologist obviously should ensure that all the necessary measurements, observations, and sample collections are made during the first visit to a section. It may be useful to carry along a checklist, for reference each time a lithologic change in the section requires a new bed description. Many geologists have attempted to carry this process one step further by designing the checklist in the form of a computer processible data card, or they record the data in the form of a computer code (e.g., Alexander-Marrack et al. 1970; Friend et al. 1976). There may be two problems with this:

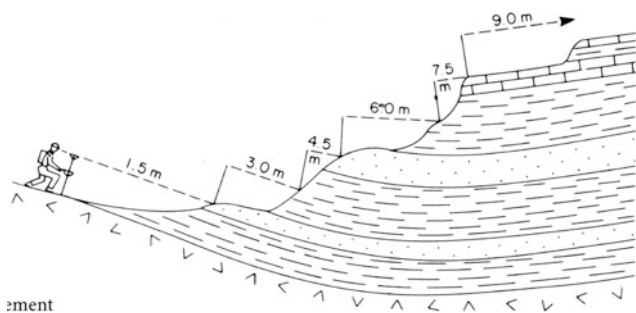
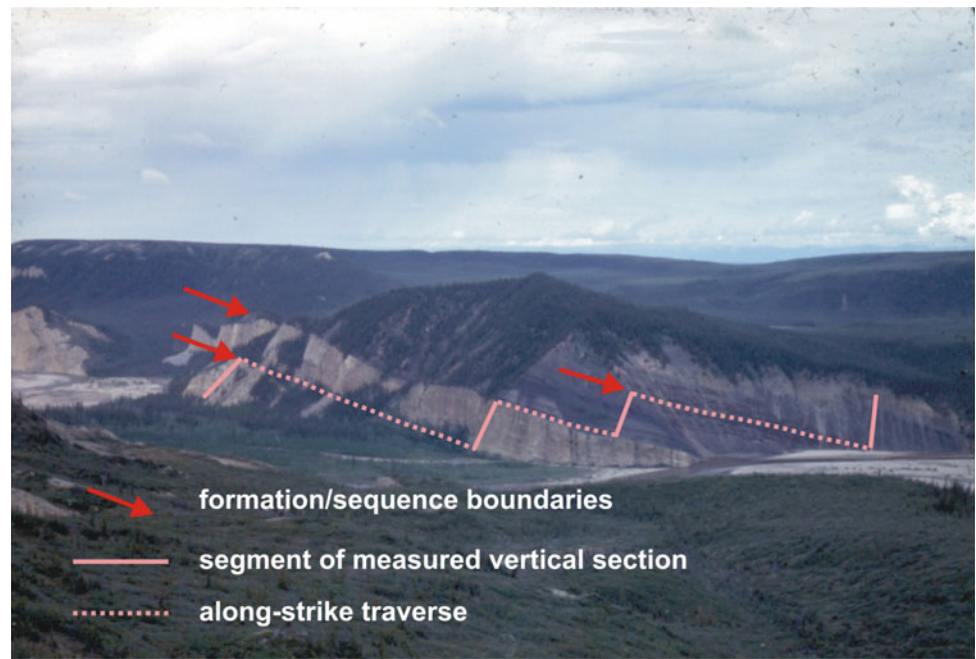


Fig. 2.1 Use of pogo stick in section measurement

Fig. 2.2 Measuring a vertical stratigraphic section in rugged terrain. The section may be offset along a selected stratigraphic surface in order to facilitate ease of access



1. If attempts are made to record every piece of field information on the computer file, the resulting file is likely to be very large and cumbersome. Storage and retrieval programming may consume far more time than the original field work, unless the geologist can draw on some preexisting program package. This leads to the second problem.
2. If data are to be coded in the field or if a preexisting program system is to be used, it means that decisions will already have been made about what data are to be recorded and how they are to be recorded before the geologist goes into the field. If the geologist knows in advance what is likely to be found, as a result of some previous descriptions or reconnaissance work, this may be satisfactory, but in the case of isolated field areas such foreknowledge may not be available. In this case, there is a certain risk involved in having the observation system designed in advance.

Individual geologists vary in their interests and in the observations they make and, of course, the rocks are highly variable, so that it is not possible to design a single, all-purpose, section-measuring software package. Specialized systems have to be designed for specific projects, and although this leads to expense in programming and debugging, it means that the program can be designed for the specific type of output required. It should not be forgotten, though, that programming, as such, is a technical, not a scientific, skill. Students and other workers who write programs for their research get few points for producing a

workable program, only for the interesting scientific ideas their programming allows them to test.

2.2.1.2 The Construction of Lateral Profiles

Some stratigraphic units are essentially tabular at the scale of the outcrop, and can be quickly and accurately documented using vertical profiles, in the way outlined in the previous section. However, some types of sedimentary assemblage contain complex facies changes, which may be at a small enough scale to observe in individual outcrops, especially in large outcrops. For example, a reef core, with its reef-front talus slope and back-reef lagoonal deposits, or a large fluvial or submarine-fan channel, with its fill of complex bar deposits, may be spectacularly displayed in a road cut or mountainside. The measurement of a few vertical sections across such an outcrop is a quite inadequate way to document the wealth of facies detail that may be available. Petroleum companies have developed a considerable interest in such large outcrops because of their use as potential analogs of subsurface reservoir units. Internal heterogeneities of these reservoir analogs can be studied and their porosity and permeability characteristics studied, for example by the use of minipermeameters (e.g., Miall and Tyler 1991; Doyle and Sweet 1995).

In order to document the details in a large outcrop it may be necessary to construct a lateral profile, a long section that encompasses the full vertical stratigraphic height of the outcrop, and also extends along strike as far as possible, to illustrate the facies changes. This may be constructed by careful surveying, but a much quicker method is to make use of photographic mosaics of the outcrop. The geologist

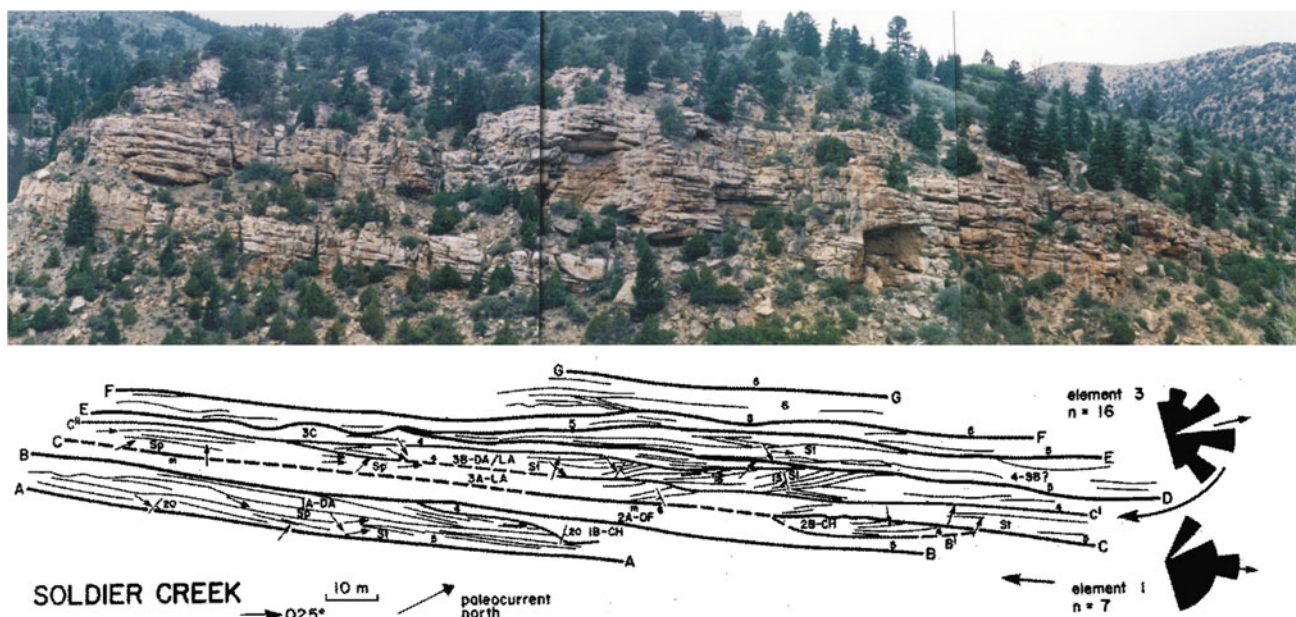


Fig. 2.3 An example of a large outcrop (Upper Cretaceous fluvial Castlegate Sandstone, Utah), with annotation, below. Shown are major bedding surfaces, paleocurrent measurements, and letter codes for major bedding units and bounding surfaces

moves well back from the exposed face, perhaps as much as several hundred meters in the case of a very large outcrop, and carries out a traverse parallel to the face, taking a series of overlapping frames until he or she has covered the entire outcrop. By taking care to remain at the same distance from the face, each frame will be at approximately the same scale. The same end can be achieved by taking photographs from a boat, or even from an aircraft flying low over the outcrop. Unmanned drones are ideal platforms for cameras to take carefully positioned and oriented images.

The images are carefully overlapped in order to construct a mosaic, which can then be used in the field as a kind of topographic map base on which to enter stratigraphic and sedimentologic detail (Fig. 2.3). Some scale distortions inevitably arise. Outcrops are rarely flat, and projections and gullies will not fit together precisely in the mosaic because of the differing perspectives of adjacent frames. Such distortions may be trivial relative to the immense amount of detail that can be shown on such profiles, and if accurate measurements of individual features are required, they should, in any case, be made in the field and not from the photograph.

Modern digital methods, such as the use of Light Detection and Ranging (LIDAR) may make the preparation of the outcrop image for interpretation easier (Hodgetts 2013). This method makes use of laser surveying to record the image, and because the range of each sample point is also recorded, the image can be processed to reduce or eliminate parallax problems, and may then also be rotated to position the image, for example, to remove a structural tilt or to simulate a view parallel to stratigraphic dip.

Techniques for documenting and interpreting lateral profiles are discussed further in Sect. 3.3.4.

2.2.2 Types of Field Observation

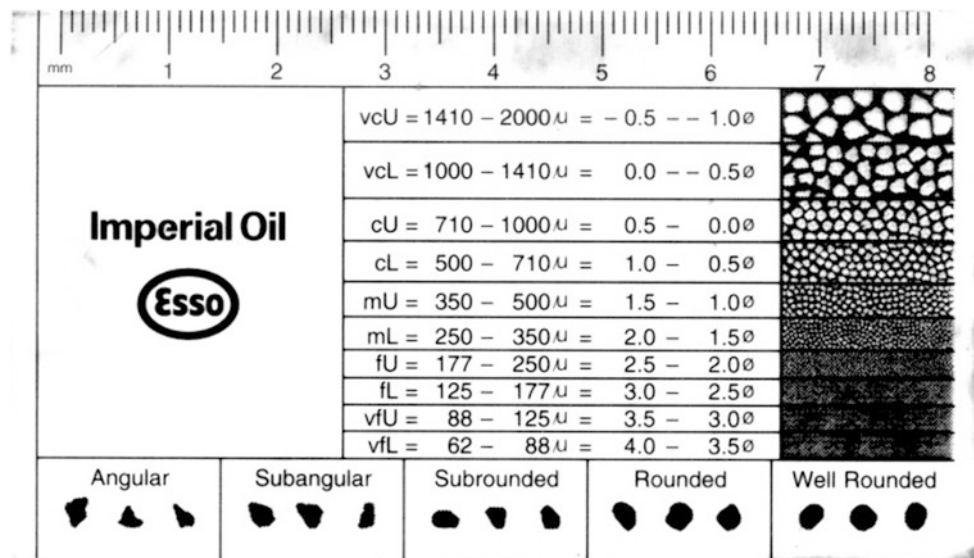
2.2.2.1 Subdivision of the Section into Descriptive Units

This is a subjective operation based on the rock types present, the quality and accessibility of the exposure, and the amount of detail required in the description. Very detailed descriptions may require subdivision into units containing (for example) a single mudstone lens or crossbed set, and will therefore be on the order of a few centimeters or tens of centimeters thick. Thicker units can be defined by grouping similar rock types, but sedimentologically useful detail may be lost thereby. For each unit, the kinds of observations listed in the succeeding paragraphs are made where appropriate.

In the case of lateral profiles (e.g., Fig. 2.3), among the most valuable kinds of observation that can be made is the documentation and classification of the various kinds of bounding surface that separate stratigraphic units. These range from the simple bedding-plane surfaces that separate individual crossbed sets through the surfaces that bound channels and bars to the major (usually horizontal) surfaces that delimit mappable stratigraphic units (formations, members, stratigraphic sequences, etc.). A discussion and classification of bounding surfaces is presented in Sect. 3.5.11.

Fig. 2.4 Grain-size classification of clastic and carbonate rocks

PARTICLE DIAMETER				CLASTICS			CARBONATES	
m	mm	Φ					allochems	matrix
10 ⁰	2048	-11		v. large				
	1024	-10		large	boulders			
	512	-9		medium			v. coarse calcirudite	extremely coarsely crystalline
	256	-8		small				
10 ⁻¹	128	-7		large	cobbles			
	64	-6		small			coarse calcirudite	
	32	-5		v. coarse				
	16	-4		coarse			m. calcirudite	
10 ⁻²	8	-3		medium	pebbles			
	4	-2		fine			f. calcirudite	v.c. crystalline
	2	-1		v. fine				
	1	0		v. coarse			c. calcarenite	c. crystalline
10 ⁻³	0.5	+1		coarse			m. calcarenite	m. crystalline
	0.25	+2		medium			f. calcarenite	
	0.125	+3		fine			v. f. calcarenite	
	0.0625	+4		v. fine				
10 ⁻⁴	0.0312	+5		v. coarse			c. calcilutite	f. crystalline
	0.0156	+6		coarse			m. calcilutite	v. f. crystalline
	0.0078	+7		medium			f. calcilutite	
	0.00390	+8		fine			v. f. calcilutite	
10 ⁻⁵	0.00195	+9		v. fine				aphano-crystalline
					clay/mud			

Fig. 2.5 A chart for estimating grain size in the field

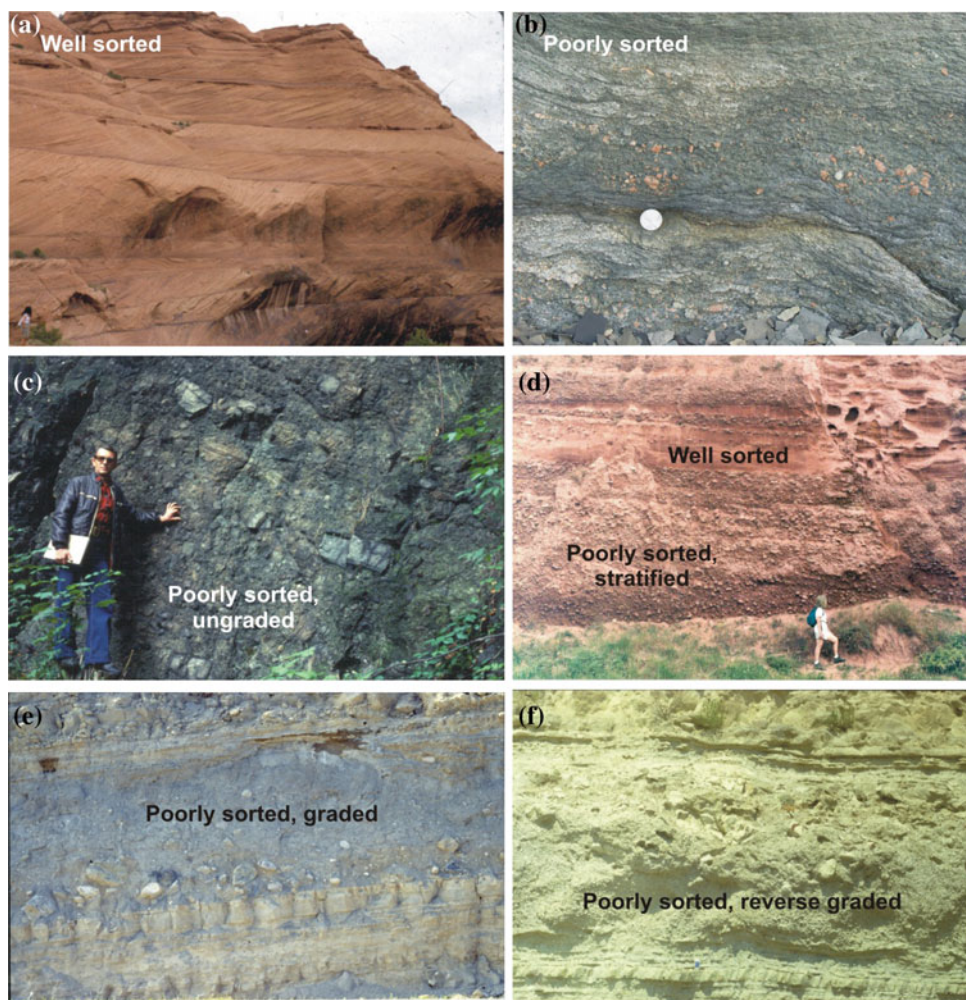
2.2.2.2 Lithology and Grain Size

Lithologic classification of clastic rocks can usually be done satisfactorily by visual observation in the field, without the necessity of follow-up laboratory work. Classification is based on grain size (Fig. 2.4), which is easily measured on the outcrop. For sand grade rocks, it is useful to take into the field a grain size chart (Fig. 2.5) or a set of sand samples each representing one phi class interval through the sand size ranges. These are used for comparison purposes and permit recognition of the main sand grade subdivisions: very fine,

fine, medium, coarse, and very coarse. Many tests by the author and others have shown that such observations provide adequate, accurate information on the modal size range of the sandstones.

Sorting is also an important descriptive criterion. The description should be modified by appropriate adjectives if sorting characteristics require it; for example, pebbly coarse-grained sandstone, silty mudstone, etc. For the purpose of regional facies analysis, this is usually the only kind of grain size information required. Some examples of the use of sorting

Fig. 2.6 Sorting and grading in sandstones and conglomerates



adjectives are shown in Fig. 2.6. The distinction between **well-sorted** and **poorly-sorted** refers to the distribution of grain sizes within an individual bed. For example, eolian dune sands (Fig. 2.6a) and many beach sands exhibit a limited range of grain sizes because of current winnowing, whereas many fluvial deposits are rapidly deposited and may consist of mixtures of a range of grain sizes (Fig. 2.6b, d) although this is not invariably the case, as shown by the well-sorted sandstone in Fig. 2.6d. Likewise, debris-flow conglomerates are typically very poorly sorted (Fig. 2.6c, e, f).

Siltstone and mudstone can be distinguished in a hand specimen by the presence or absence of a gritty texture, as felt by the fingers or the tongue. This is, of course, a crude method, and should be checked by making thin sections of selected samples. However, field identifications of this type commonly are adequate for the purpose of facies analysis.

Fine-grained rocks, including those consisting of a mixture of sandstone, siltstone, and mudstone, are difficult to classify and describe. Dean et al. (1985) discussed the methods used in the Deep Sea Drilling Project based on smear slides of soft sediments made on board ship.

For conglomerates, maximum clast size is often a useful parameter to measure. Typically, this is estimated by taking the average of the 10 largest clasts visible within a specified region of an outcrop, such as a given area of a certain bedding plane. In thick conglomerate units, it may be useful to repeat such measurements over regular vertical intervals of the section. It is also important to note the degree of sorting, clast shape and roundness, matrix content, and fabric of conglomerate beds. For example, does the conglomerate consist predominantly of very well-rounded clasts of approximately the same size, or is it composed of angular fragments of varying size and shape (breccia)? Do the clasts “float” in abundant matrix, a rock type termed **matrix-supported conglomerate**, or do the clasts rest on each other with minor amounts of matrix filling the interstices—**clast-supported conglomerate**? These features are discussed at length in Chap. 4.

Carbonate rocks commonly cannot be described adequately or accurately in outcrops, and require description from thin sections or polished sections observed under a low-power microscope. Among the reasons for this are the

ready susceptibility of carbonate rocks to fine-scale diagenetic change, and the fact that weathering behavior in many cases obscures rather than amplifies such changes, as seen in outcrops. Another important reason for not relying on outcrop observation is that some of the types of information required for carbonate facies analysis are simply too small to be seen properly with the naked eye. These include mud content, certain sedimentary textures, and biogenic features.

Field geologists traditionally take a dropper bottle of 10 % hydrochloric acid with them to test for carbonate content and to aid in distinguishing limestone from dolomite (on the basis of “fizziness”). However, for research purposes, the test is quite unsatisfactory, and the geologist is advised to abandon the acid bottle (and stop worrying about leakage corroding your field bag). Dolomite commonly can be distinguished from limestone by its yellowish weathering color in the field, but a better field test is to use alizarin red-S in weak acid solution. This reagent stains calcite bright pink but leaves dolomite unstained. In both hand specimens and thin sections use of this reagent can reveal patterns of dolomitization on a microscopic scale.

Because of the problem with carbonate rocks discussed previously the geologist is advised not to rely on field notes for facies analysis of these rocks, but to carry out a rigorous sampling program and supplement (and correct) the field notes using observations made on polished slabs or thin sections. Sampling plans are discussed later in this section. Laboratory techniques for studying carbonates are described by Wilson (1975, Chap. 3).

Evaporites are difficult to study in surface outcrops. They are soft and recessive and commonly poorly exposed, except in arid environments. Like carbonates, they are highly susceptible to diagenetic change, so that field observations must be supplemented by careful laboratory analysis.

Mixed carbonate-clastic sediments are common and are typically dealt with as if they were carbonate or clastic, which may not be the most effective way to emphasize subtle lithologic characteristics. Mount (1985) discussed the problems of classifying these rocks and suggested some methodological approaches.

2.2.2.3 Porosity

Porosity and permeability are of particular interest if the rocks are being studied for their petroleum potential. Observations in surface outcrops may be of questionable value because of the effects of surface weathering on texture and composition, but the geologist should always break off a fresh piece of the rock and examine the fracture surface because such observations commonly constitute the only ones made. The geologist should distinguish the various types of porosity, such as intergranular (in detrital rocks), intercrystalline (in chemical rocks), and larger pores, such as vugs, birdseye texture, moulds of allochems, such as oolites

or pellets, fossil moulds, fracture porosity, etc. Porosity types should be reported in terms of the estimated percentage they occupy in the bulk volume of the sample.

More accurate observations may be made from thin sections, and samples may be submitted to a commercial laboratory for flow tests if required. Measurements of relative permeability are now routinely made on outcrop profiles of reservoir analogs using minipermeametry equipment.

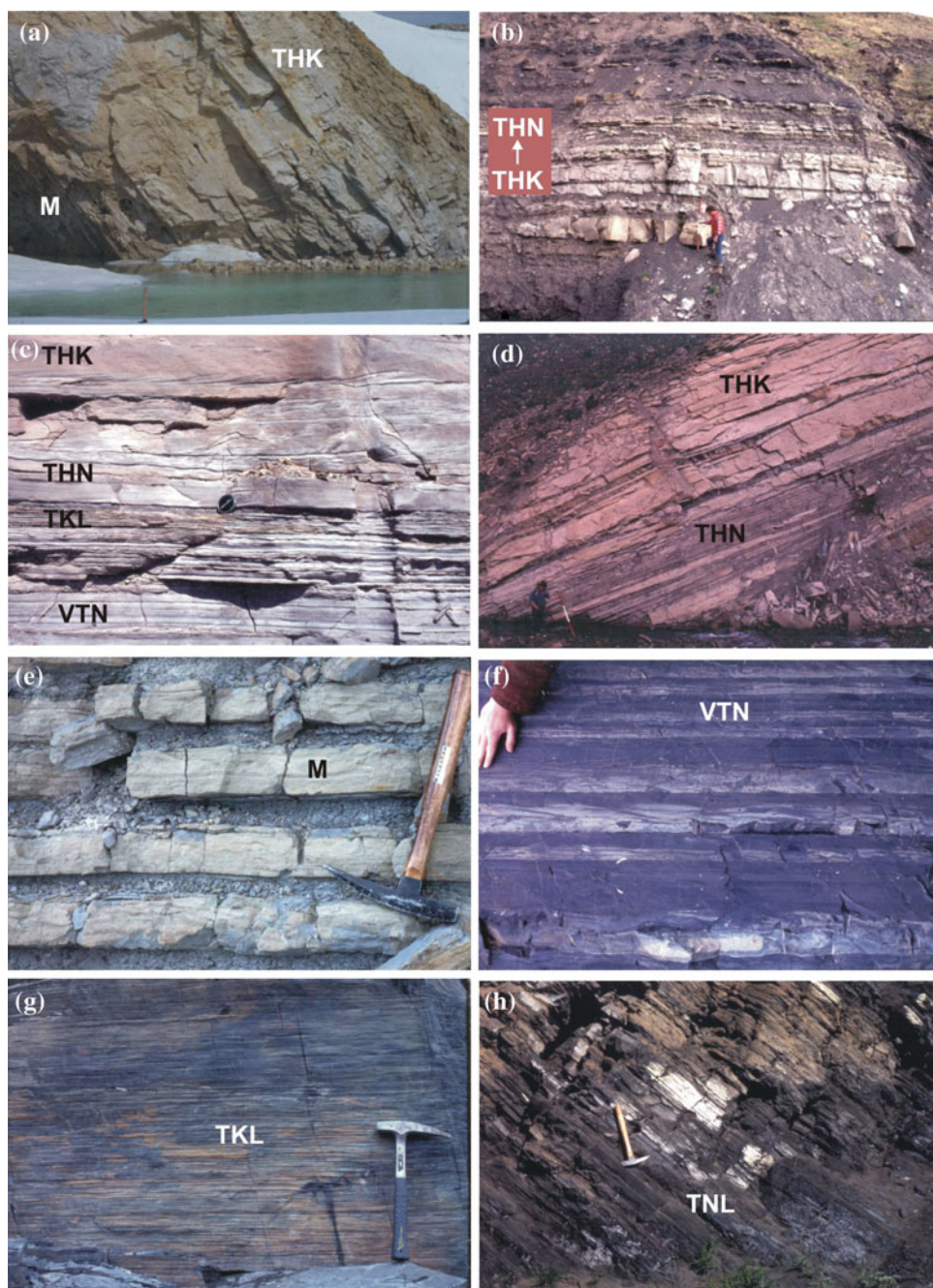
2.2.2.4 Color

Color may or may not be an important parameter in basin analysis. Individual lithologic units may display a very distinctive color, which aids in recognition and mapping. Sometimes it even permits a formation to be mapped almost entirely using helicopter observations from the air, with a minimum of ground checking. However, the sedimentological meaning and interpretation of color may be difficult to resolve.

Some colors are easily interpreted—sandstones and conglomerates commonly take on the combined color of their detrital components, pale grays and white for quartzose sediments, pinks for feldspathic sandstones, and darker colors for lithic rocks. As noted, limestones and dolomites may also be distinguished using color variations. However, color is strongly affected by depositional conditions and diagenesis, particularly the oxidation-reduction balance. Reduced sediments may contain organically derived carbon and Fe^{2+} compounds, such as sulfides, imparting green or drab gray colors. Oxidized sediments may be stained various shades of red, yellow, or brown by the presence of Fe^{3+} compounds such as hematite and limonite. However, local reducing environments, such as those created around decaying organisms, may create localized areas or spots of reduction color. Color can change shortly after deposition, as shown for example by Walker (1967a, b) and Folk (1976). Moberly and Klein (1976) found that oxidation and bacterial action cause permanent color changes when fresh sediments, such as deep sea cores, are exposed to the air. Leaching by groundwaters can also drastically change formation colors.

Thus, the problem is to decide how much time to devote to recording color in the field. Ideally, each descriptive unit in the stratigraphic section should be studied for color using a fresh rock-fracture surface and comparisons to some standard color scheme, such as the U.S. National Research Council Rock-Color Chart (Goddard et al. 1948). In practice, for the purpose of facies and basin analysis, such precision is not required. Simple verbal descriptions, such as pale gray, dark red-brown, etc., are adequate. More precise descriptions may be useful if detailed studies of diagenetic changes are to be undertaken, but research has shown that such studies may give misleading results if carried out exclusively on surface exposures because of the effects of recent weathering (Taylor 1978).

Fig. 2.7 Bedding and lamination. See Table 2.1 for key to abbreviations



2.2.2.5 Bedding

An important type of observation, particularly in clastic rocks, is the thickness of bedding units. Thickness relates to rate of environmental change and to depositional energy. In some cases, bed thickness and maximum grain size are correlated, indicating that both are controlled by the capacity and competency of single depositional events. Bed-thickness changes may be an important indicator of cyclic changes in the environment, and sedimentologists frequently refer to **thinning-upward** and **fining-upward** or **coarsening-and-thickening-upward** cycles. It is important to distinguish

bedding from weathering characteristics. For example, a unit may split into large blocks or slabs upon weathering, but close examination may reveal faint internal bedding or lamination not emphasized by weathering. Bedding can be measured and recorded numerically, or it can be described in field notes semi-quantitatively (Fig. 2.7) using the descriptive classification given in Table 2.1.

2.2.2.6 Inorganic Sedimentary Structures

Sedimentary structures include a wide variety of primary and post-depositional features (Table 2.2). All individually yield

Table 2.1 Table of stratification thicknesses

Descriptor	Range	Figure 2.7
Very thickly bedded	>1 m	
Thickly bedded	30–100 cm	THK
Medium bedded	10–30 cm	M
Thinly bedded	3–10 cm	THN
Very thinly bedded	1–3 cm	VTN
Thickly laminated	0.3–1 cm	TKL
Thinly laminated	<0.3 cm	TNL

useful information regarding depositional or diagenetic events in the rocks, and all should be meticulously recorded and described in the context of the lithology and grain size of the bed in which they occur. The assemblage of structures and, in some cases their orientation, can yield vital paleogeographic information.

Inorganic sedimentary structures can be divided into three main genetic classes, as shown in Table 2.2. These are described briefly in order to aid their recognition in the field, but a discussion of their origin and interpretation is deferred to later chapters. Useful texts on this subject include Potter and Pettijohn (1977), Allen (1982), Harms et al. (1982), and Collinson and Thompson (1982). Ashley (1990) carried out an important overview of bedform types and their names, and proposed a unification of concepts and terminology (referred to briefly below) that has received universal acceptance.

Sediment carried in turbulent suspension by mass gravity-transport processes, such as debris flows and turbidity currents, is subjected to internal sorting processes. When the flow slows and ceases, the sorting may be preserved as a distinct texture termed **graded bedding**. Grading commonly consists of an upward decrease in grain size, as illustrated in Fig. 2.6; this is termed **normal grading**. However, certain sedimentary processes result in an upward increase in grain size, termed **inverse grading**.

Clastic grains can be divided into two classes on the basis of their interactive behavior. Cohesive grains are those that are small enough that they tend to be bound by electrostatic forces and thus resist erosion once deposited on a bed. This includes the clay minerals and fine silt particles. A range of erosional sedimentary structures is present in such rocks (Table 2.2), as discussed later. Larger clastic grains, including siliciclastic, evaporite and carbonate fragments, of silt to cobble size, are **noncohesive**. They are moved by flowing water or wind as a traction carpet along the bed, or by intermittent suspension. The dynamics of movement causes the grains to be moulded into a variety of **bedforms**, which are preserved as **crossbedding** within the rock (Figs. 2.8, 2.9).

Table 2.2 Classification of inorganic sedimentary structures

I. Hydrodynamic structures
A. By mass gravity transport
Graded bedding
a. Normal
b. Reversed
B. By noncohesive flow
1. Lamination
2. Cross-lamination (amplitude <5 cm)
3. Crossbedding (amplitude >5 cm)
4. Clast imbrication
5. Primary current lineation
6. Fossil orientation
II. Hydrodynamic erosion of the bed
A. Macroscopic
1. Scours
2. Channels
3. Low-relief erosion surfaces
B. Mesoscopic
1. Intraformational breccias
2. Hardgrounds
3. Lag concentrates
4. Flutes
5. Tool markings
6. Rain prints
III. Liquefaction, load, and fluid loss structures
A. Load cast
B. Flame structures
C. Ball, pillow, or pseudonodule structures
D. Convolute bedding
E. Syndepositional faults and slumps
F. Growth faults
G. Deformed crossbedding
H. Dish and pillar structures
I. Sand volcanoes
J. Injection features
1. Dikes
2. Mud lumps
3. Diapirs
K. Synaeresis features
L. Desiccation cracks
M. Ice and evaporite crystal casts
N. Gas bubble escape marks
O. Teepee structures
P. Ptygmatic/enterolithic/chicken wire gypsum/anhydrite

Fig. 2.8 Examples of cross-stratification in outcrop and drill core. **a** Wave ripples in shallow-water dolomite; **b** ripples and climbing ripples in glaciofluvial outwash; **c** planar crossbedding in drill core; **d** trough crossbedding; flow direction towards the *right*; **e** low-angle crossbedding; flow direction towards the *left*

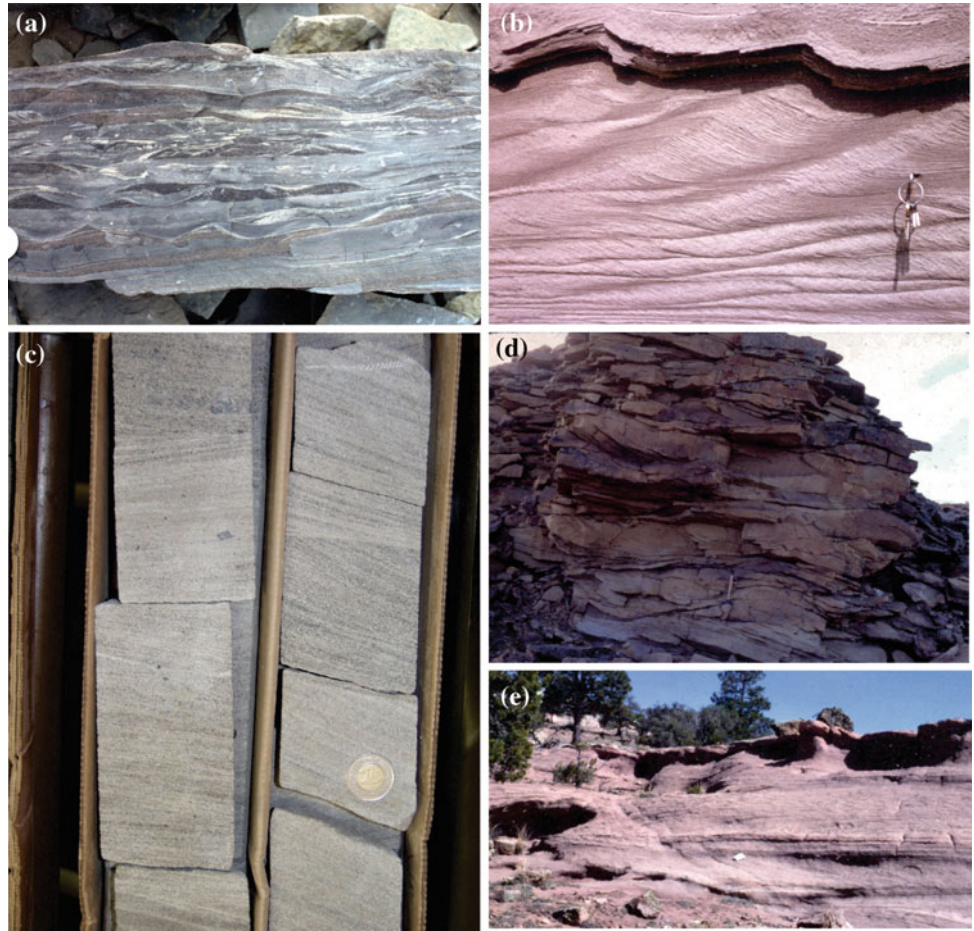
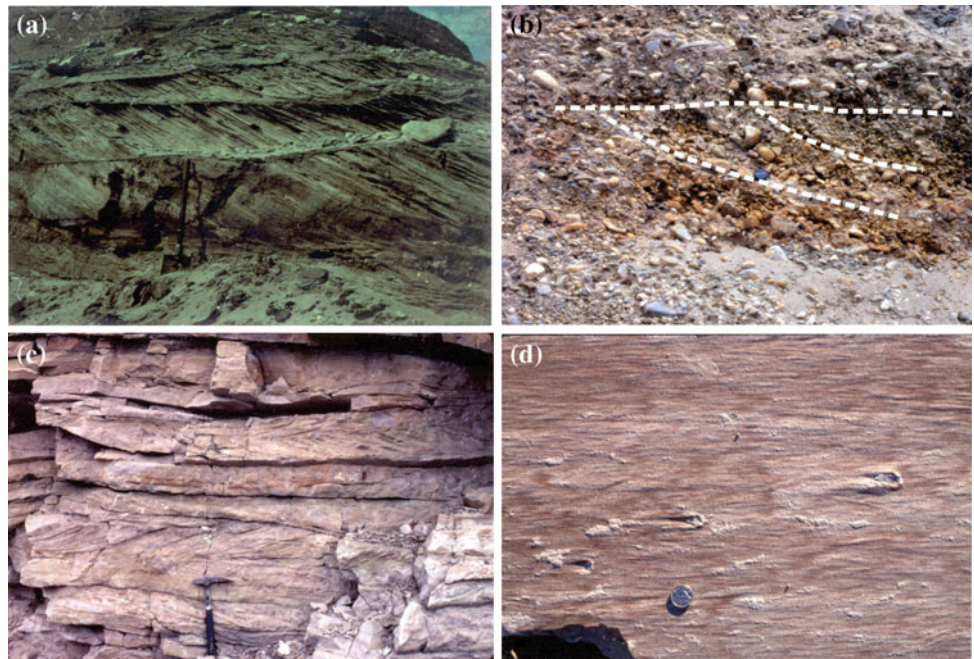


Fig. 2.9 Examples of types of crossbedding. **a** Planar crossbedding in sandstone; **b** planar crossbedding in modern river gravel; **c** herringbone crossbedding (crossbed dip direction reverses 180° from set to set); **d** view of the underside of a bed showing parting lineation with scour hollows around small pebbles. Flow direction was from *right* to *left*



There are three main classes of bedforms and crossbedding found in ancient rocks:

1. Those formed from unidirectional water currents such as are found in rivers and deltas, and oceanic circulation currents in marine shelves and the deep sea.
2. Those formed by oscillatory water-currents, including both wave- and tide-generated features. Although the time scale of current-reversal is, of course, quite different, there are comparable features between the structures generated in these different ways.
3. Those formed by air currents. Such currents may be highly variable, and the structure of the resulting deposits will be correspondingly complex. However, examination of ancient wind-formed (eolian) rocks indicates some consistent and surprisingly simple patterns (Chaps. 4 and 5).

Recognition in an outcrop or in a core of the diagnostic features of these crossbedding classes is an invaluable aid to environmental interpretation (as discussed at length in Chap. 4), and therefore crossbedding structures must be examined and described with great care wherever they are found.

Attributes of crossbedding and examples are illustrated in Figs. 2.8, 2.9, 2.10 and 2.11. A **foreset** represents an avalanche face, down which grains roll or slump or are swept down by air or water currents. Continuous deposition produces repeated foreset bedding or lamination as the bedform accretes laterally, resulting in a crossbed **set** (Fig. 2.10; McKee and Weir 1953). A **coset** is defined as a sedimentary unit made up of two or more sets of strata or crossbedding separated from other cosets by surfaces of erosion, nondeposition, or abrupt change in character (McKee and Weir

1953). Note that a coset can contain more than one type of bedding.

When describing crossbedding, attention must be paid to seven attributes (Fig. 2.11). All but the last of these were first described in detail in an important paper on crossbedding classification by Allen (1963a). In the field, crossbeds are classified first according to whether they are solitary or grouped. Solitary sets are bounded by other types of bedding or crossbedding, grouped sets are cosets consisting entirely of one crossbed type. Scale is the next important attribute. In water-laid strata, it is found that a bedform amplitude of about 5 cm is of hydrodynamic significance (Allen 1982; Ashley 1990) and, accordingly, this amplitude is used to subdivide crossbeds into small- and large-scale forms. An assumption is made that little or none of the top of a bedform is lost to erosion prior to burial; generally, the amount lost seems to increase in approximate proportion to the scale of the bedform or the thickness of the crossbed structure. Forms thinner than 5 cm are termed **ripples**, whereas forms larger than 5 cm have been given a variety of names, reflecting in part a diversity of hydrodynamic causes and in part a considerable terminological confusion. Ashley (1990) proposed several recommendations for a simplification of the terminology that have become widely adopted. Most forms larger than ripples are now termed **dunes**. This will be discussed further in Chap. 4.

Most crossbed sets contain foresets that terminate at the base of the set, in which case the foresets are said to be discordant. In rare cases where the crossbeds are parallel to the lower bounding surface, as occurs in some sets with curved lower surfaces, the crossbeds are described as concordant.

Fig. 2.10 Terminology for stratified and cross-stratified (crossbedded) units (McKee and Weir 1953)

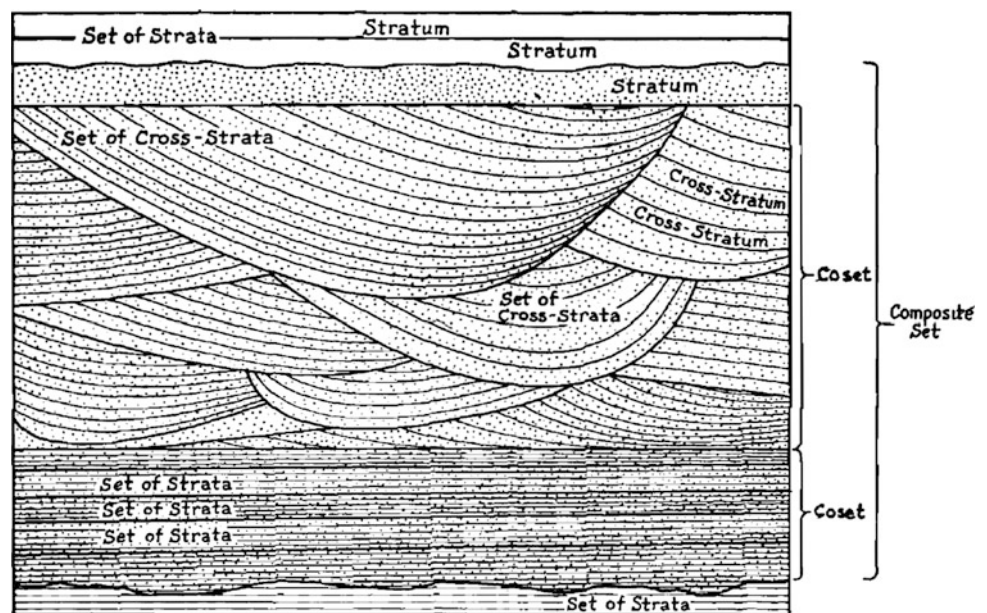
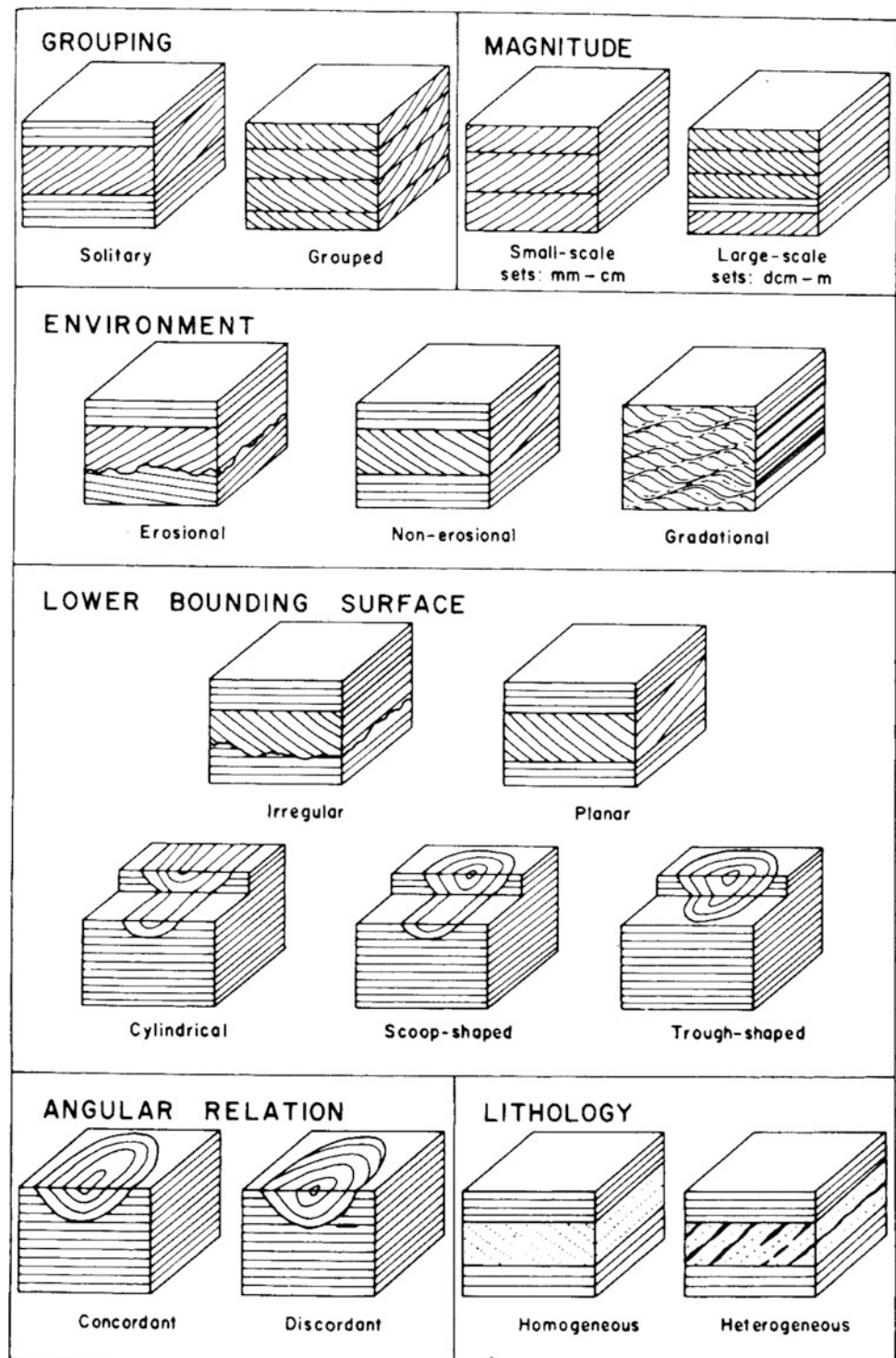


Fig. 2.11 Criteria used in the description and definition of crossbedding types (Allen 1963a)



The crossbeds may show either homogeneous or heterogeneous lithology. Homogeneous crossbeds are those composed of foresets whose mean grain size varies by less than two phi classes. Heterogeneous (or heterolithic) crossbeds may contain laminae of widely varying grain size, including

interbedded sand and mud or sand and gravel, possibly even including carbonaceous lenses.

The minor internal structures within crossbeds are highly diagnostic of their origin. The dip angle of the foreset relative to the bounding surface is of considerable dynamic

significance. Are the foresets curved, linear, or irregular in sections parallel to the dip? Is the direction of dip constant, or are there wide variations or reversals of dip within a set or between sets? Do the sets contain smaller scale hydrodynamic sedimentary structures on the foresets, and if so, what is the dip orientation of their foresets relative to that of the larger structure? What is the small-scale internal geometry of the foresets—are they tabular, lens, or wedge shaped? Do they display other kinds of sedimentary structures, such as trace fossils, synsedimentary faults, or slumps? Are **reaction surfaces** present? These represent minor erosion surfaces on bedforms that were abandoned by a decrease in flow strength and then reactivated at some later time.

These attributes can be used to classify crossbed sets in the field. It is time-consuming to observe every attribute of every set, but it is usually possible to define a limited range of crossbed types that occur repeatedly within a given stratigraphic unit. These can then be assigned some kind of local unique descriptor, enabling repeated observations to be recorded rapidly in the field notebook. Modern methods of facies classification that encompass variations in crossbed type are discussed in Sect. 3.3.

A vital component of basin analysis is an investigation of sedimentological trends, such as determining the shape and orientation of porous rock units. **Paleocurrent analysis** is one of several techniques for investigating sedimentary trends based, among other attributes, on studying the size, orientation, and relative arrangement of crossbedding structures. Therefore, when describing outcrop sections, it is essential to record the orientation of crossbed sets. The procedures for doing this and the methods of interpretation are described in Sect. 6.7.

Crossbedding represents a macroscopic orientation feature, but each clastic grain is individually affected by a flow system and may take up a specific orientation within a deposit in response to flow dynamics. The longest dimension of elongated particles tends to assume a preferred position parallel or perpendicular to the direction of movement and is commonly inclined upflow, producing an imbricated or shingled fabric. This fabric may be present in sand-sized grains and can be measured optically, in thin section (Martini 1971) or using bulk properties such as dielectric or acoustic anisotropy (Sippel 1971). In recent years, paleomagnetic data have also been recognized to contain much useful information relating to primary sedimentary fabrics. Eyles et al. (1987) discussed magnetic orientation and anisotropy data with reference to the depositional processes of till and till-like diamict deposits. Oriented specimens must be collected in the field for such an analysis (see Sect. 2.2.3.2). In conglomerates, an **imbrication** fabric commonly is visible in an outcrop and can be readily measured by a visual approximation of average orientation or by laborious individual measurements of clasts. Figure 2.12

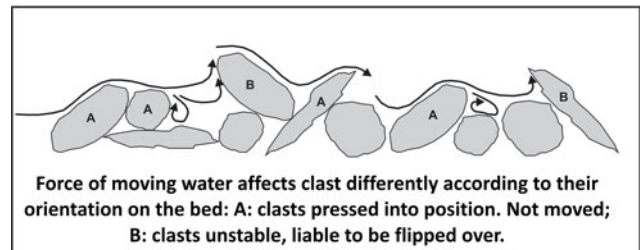
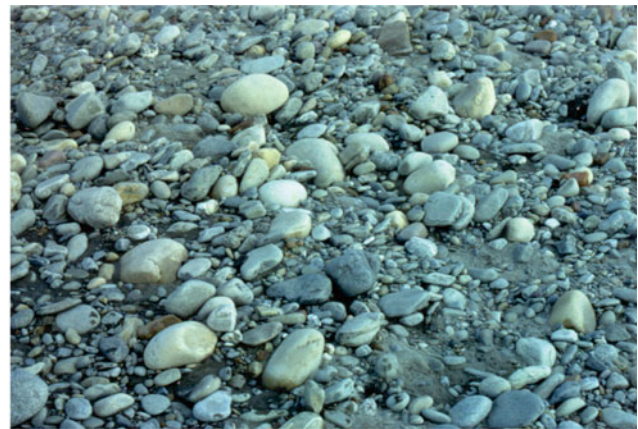


Fig. 2.12 Class imbrication. *Top* imbrication fabric in a modern river. Currents flowed from *left to right*. *Bottom* how turbulent currents generate the imbricated fabric

illustrates imbrication in a modern river bed. As discussed in Sect. 6.7.2, it has been found that in nonmarine deposits, in which imbrication is most common, the structure is one of the most accurate of paleocurrent indicators (Rust 1975).

Grain sorting is responsible for generating another type of fabric in sand grade material, which is also an excellent paleocurrent indicator. This is **primary current lineation**, also termed **parting lineation** because it occurs on bedding-plane surfaces of sandstones that are flat bedded and usually readily split along bedding planes. An example is illustrated in Fig. 2.9d. Primary current lineation is the product of a specific style of water turbulence above a bed of cohesionless grains, as are the various bedforms that give rise to crossbedding (Sect. 3.5.4). It therefore has a specific hydrodynamic meaning and is useful in facies analysis as well as paleocurrent analysis.

Rather than the bed itself, objects such as plant fragments, bones, or shells may be oriented on a bedding plane. This should be observed if possible, but interpretation commonly is not easy, as discussed in Sect. 6.7.

2.2.2.7 Sedimentary Structures Produced by Hydrodynamic Erosion of the Bed

A wide variety of erosional features is produced by water erosion of newly deposited sediment. These result from changes in water level or water energy in response to floods,

storms, tides, or wind-driven waves and currents. They can also result from evolutionary change in a system under steady equilibrium conditions. These processes result in the development of various types of **bounding surfaces** in the rocks (Fig. 2.13). Recognition and plotting of these features in outcrop sections are important components of facies analysis, and with adequate exposure, orientation studies may contribute significantly to the analysis of depositional trends.

These features range in size up to major **river** and **tidal channels**, **submarine canyons**, and **distributary channels** several kilometers across and tens or hundreds of meters deep, but large features such as these can rarely be detected

in the average small outcrop. They may be visible in large outcrop sections, where they can be documented using lateral profiles (Sect. 3.5.11) and on seismic sections (Chap. 6), and it may be possible to reconstruct them by careful lithostratigraphic correlation and facies analysis of scattered outcrops, but this is beyond the scope of our immediate discussion. At the outcrop scale, there are two types of small-scale erosional features to discuss, those that truncate one or more bedding units and those that scour or pit the bedding plane without significantly disrupting it.

The first type includes **channels**, **scours**, low-relief **erosion surfaces** and **rill markings**, in decreasing order of scale. These may be classified as macroscopic erosion

Fig. 2.13 Examples of bounding surfaces exposed in outcrop

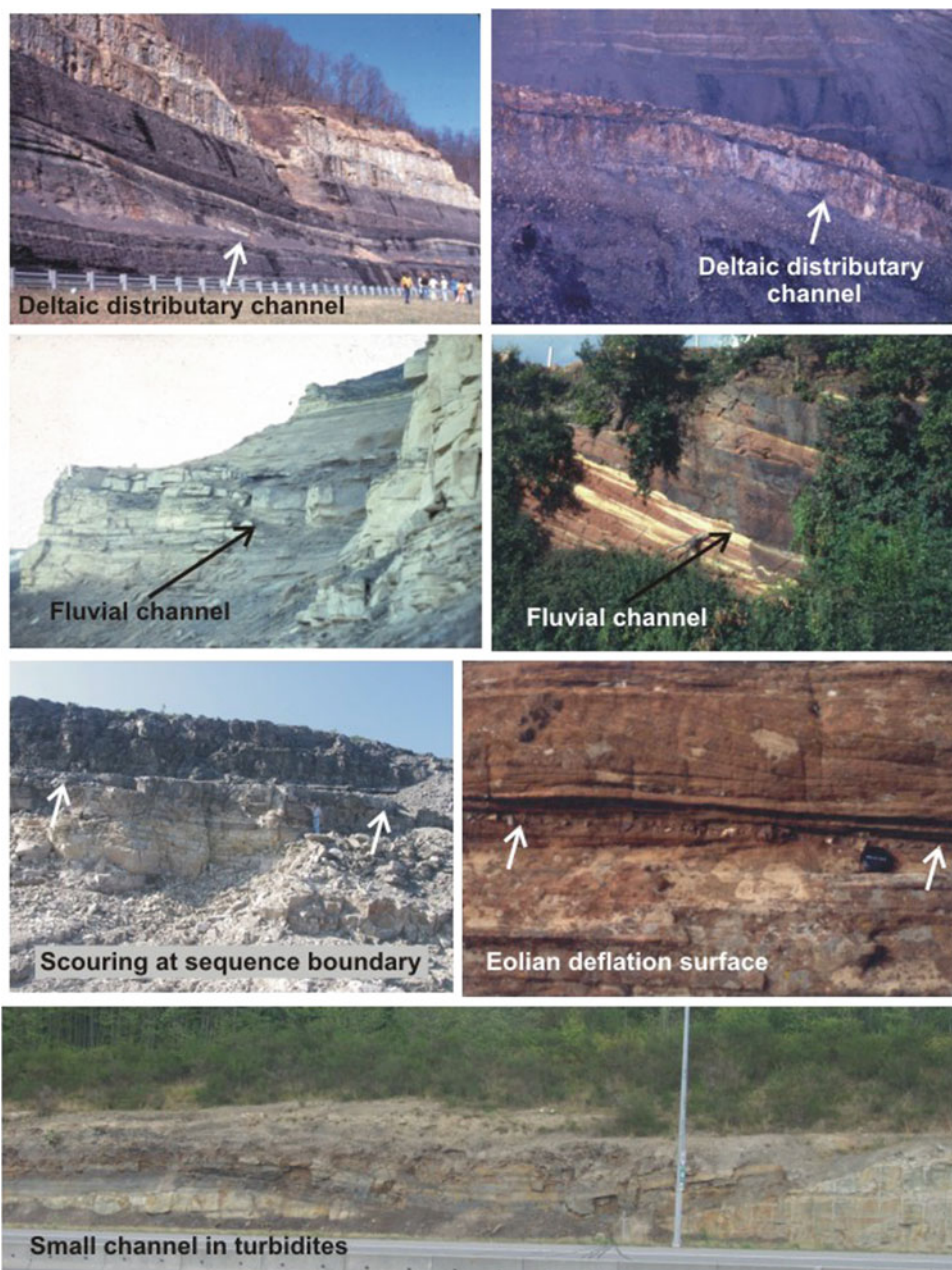
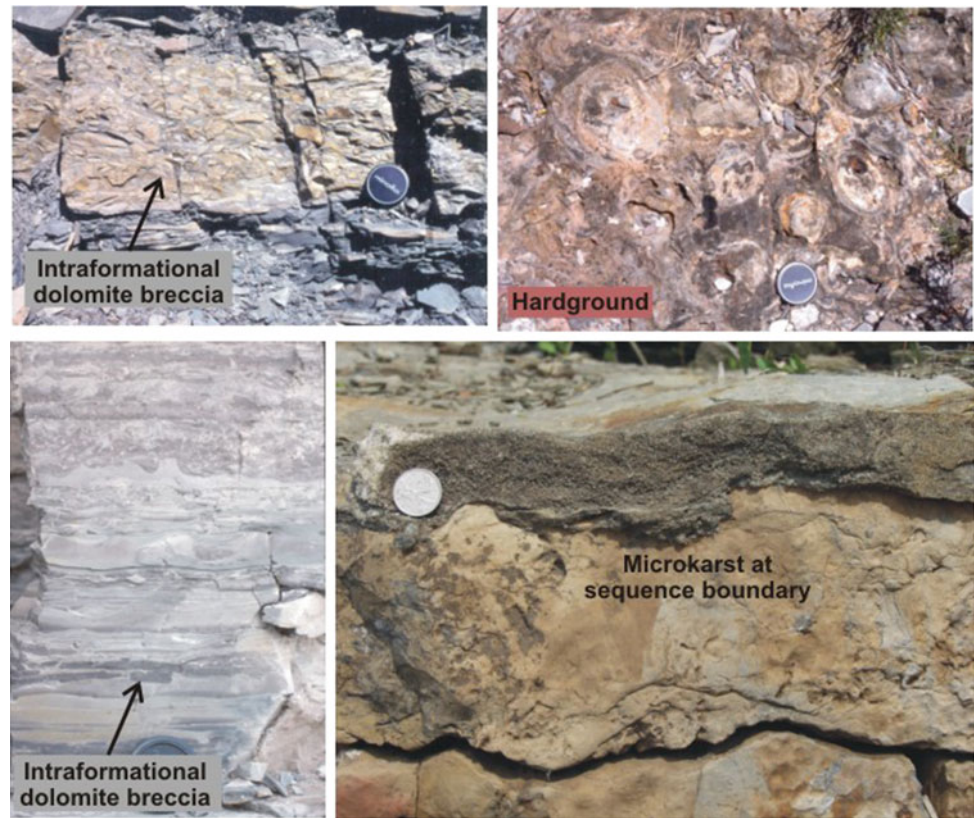


Fig. 2.14 Structures formed during periods of intraformational non-deposition or erosion



features (Table 2.2). Channels and scours are usually filled by sediment that is distinctly different in grain size and bedding characteristics from that into which the channel is cut. Almost invariably the channel fill is coarser than the eroded strata indicating, as might be expected, that the generation of the channel was caused by a local increase in energy level. Exceptions are where a channel was abandoned and subsequently filled by fine sediment and coal under low-energy conditions.

It is a common error to confuse trough crossbedding with channels. Troughs are formed by the migration of trains of dunes or sinuous-crested megaripples (Sect. 3.5.4). They rest on curved scour surfaces, but these are not channels. The scours are formed by vortex erosion in front of the advancing dunes and are filled with sediment almost immediately. Channels, on the other hand, may not be filled with sediment for periods ranging from hours to thousands of years after the erosion surface is cut, and so the cutting and filling of the channel are quite separate events.

Erosion surfaces may exhibit little erosional relief, which may belie their importance. In the nonmarine environment, sheet erosion, wind deflation, and pedimentation can generate virtually planar erosion surfaces. In subaqueous environments, oceanic currents in sediment-starved areas, particularly in abyssal depths, can have the same result. Exposed carbonate terrains may develop **karst** surfaces, with the

formation of extensive cave systems. At the outcrop scale, careful examination of erosion surfaces may reveal a small-scale relief and the presence of features such as infilled **desiccation cracks**, basal intraformational or extrabasinal **lag gravels**, fissures filled with sediment from the overlying bed, zones of bioclastic debris, etc. In some subaerial environments, soil or weathering profiles may have developed, including the development of **caliche** or **calcrete**, and the presence of surfaces of nondeposition. In carbonate environments surfaces of nondeposition commonly develop subaqueously. **Hardgrounds** are organically bored surfaces that may be encrusted with fossils in growth positions (Fig. 2.14). Alternatively, they may be discolored by oxidation, giving a red stain, or blackened by decayed algal matter. Long-continued winnowing of a surface of nondeposition may leave **lag concentrates** or **condensed sections** consisting of larger particles, blackened by algal decay, and possibly including abundant phosphatized fossil material (Wilson 1975, pp. 80–81). Condensed sections may be generated by rapid transgression, which forces coastal sediment sources to undergo retreat (Chap. 5). In continental-slope deposits, giant slumps and slides are common and are particularly well exposed as **intraformational truncation surfaces** in deep water carbonate sediments.

It may be difficult to assess the length of time missing at erosion surfaces. Some may even represent major time



Fig. 2.15 Sole marks on the underside of a sandstone bed. These are groove casts formed at the base of a turbidity current

breaks detectable by biostratigraphic zonation. In any case, a careful search for and description of such features in the field is an important part of section description. The recognition and mapping of erosion surfaces is a critical element in the study of sequence stratigraphy, as discussed at greater length in Chap. 6. As further discussed in Chap. 7, modern chronostratigraphic documentation of sedimentation rates is indicating that a significant proportion of the elapsed time during which a stratigraphic succession accumulated may be represented by hiatuses and surfaces of non-deposition.

Mesoscopic erosional features fall mainly into a class of structure termed **sole markings**. These are features seen on the underside of bedding planes, usually in sandstones, and they represent the natural casts of erosional features cut into the bed below, which is typically siltstone or mudstone. They attest to the erosive power of the depositional event that formed the sandstone bed, but beyond this, most have little facies or environmental significance. However, they can be invaluable paleocurrent indicators. **Tool markings** are a class of sole structure formed by erosional impact of large objects entrained in the flow, including pebbles, plant fragments, bone, or shell material. The many varieties that have been observed have been assigned names that indicate the interpreted mode of origin. They include **groove, drag, bounce, prod, skip, brush** and **roll markings**. A few examples are illustrated in Fig. 2.15, which show the strongly linear pattern on the bed, providing excellent paleocurrent indicators.

Flute markings are formed by vortex erosion, typically at the base of turbidity currents, although they have also been observed at the base of fluvial channels (Fig. 2.16). Erosion is deepest at the up-current end of the scour and decreases down current, so that in a flute cast the high-relief nose of the cast points up current. In rare examples vortex flow lines may be perceived in the walls of the flute. Flutes generally are in the order of a few centimeters deep.

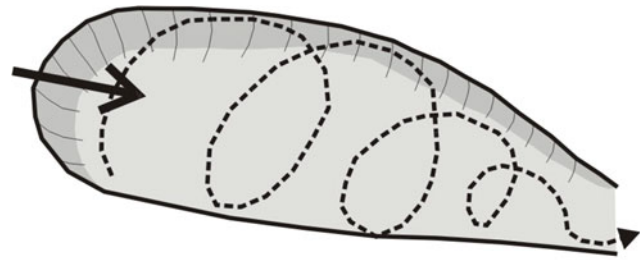


Fig. 2.16 Flute marks. Diagram at *top* illustrates the formation of flutes by vortex erosion at the base of a high-energy turbid flow. *Middle* view of underside of bed showing flutes and scour around a pebble. *Bottom* flutes at the base of a fluvial channel sandstone

2.2.2.8 Liquefaction, Load, and Fluid Loss Structures

Clay deposits saturated with water are characterized by a property termed **thixotropy**: when subjected to a sudden vibration, such as that generated by an earthquake, they tend to liquify and loose all internal strength. This behavior is responsible for generating a variety of structures in clastic rocks. Clay beds commonly are interbedded with sand or silt and, when liquefied, the coarser beds have a higher density than the clay and tend to founder under gravity. This may or may not result in the disruption of the sand units. Where complete disruption does not take place, the sand forms bulbous shapes projecting into the underlying clay, termed **load structures** (Fig. 2.17). These may be well seen in

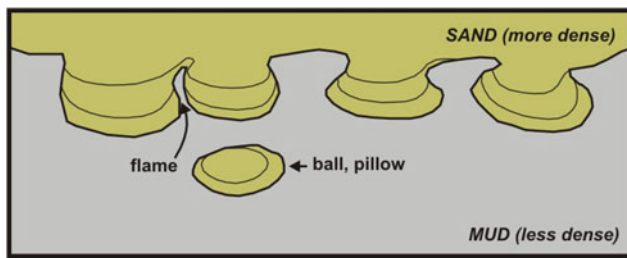


Fig. 2.17 Load structures, in the form of balls, pillows, and flame structures of mud trapped between them. Note the deformed lamination. The example (*below*) is from a turbidite succession

ancient rocks by examining the underside of a sandstone bed. They are therefore a class of sole structure, though one produced without current movement. Clay wisps squeezed up between the load masses form pointed shapes termed **flame structures** because of a resemblance to the shape of flames. These are best seen in cross section. Occasionally, loading may take place under a moving current, such as a turbidity flow, and load structures may then be stretched, possibly by shear effects, into linear shapes paralleling the direction of movement.

Commonly, load masses become completely disrupted. The sand bed may break up into a series of ovate or spherical masses that sink into the underlying bed and become surrounded by mud. Lamination in the sand is usually preserved in the form of concave-up folds truncated at the sides or tops of each sand mass, attesting to the fragmentation and sinking of the original layer. Various names have been given to these features, including **ball, pillow, or pseudonodule structures** (Fig. 2.17). These structures rarely have a preferred shape or orientation and are not to be confused with slump structures, which are produced primarily by lateral rather than vertical movement.

In many environments, sediment is deposited on a sloping rather than a flat surface (large-scale examples of this are visible on seismic reflection surveys and are called **clinoforms**—see Chaps. 5 and 6), for example, the subaqueous front of a delta, which is something like a very large-scale

foreset built into a standing body of water. The difference is that once deposited such material usually does not move again as individual grains because the angle of the slope is too low. Typically, large-scale submarine fans and deltas exhibit slopes of less than 2° . However, the sediment in such environments is water saturated and has little cohesive strength. Slopes may therefore become oversteepened, and masses of material may be induced to slump and slide downslope by shock-induced failure. Undoubtedly, the thixotropic effects described previously facilitate this process. The result is the production of internal shear or glide surfaces and deformed masses of sediment, termed **slump structures**. Failure surfaces may be preserved as **syndepositional faults**. Some examples of **convolute bedding** may be produced this way, although others are the result of water escape, as discussed below.

Structures produced by failure and lateral movement commonly retain an internal orientation with a simple geometric relationship to the orientation of the depositional slope. This could include the elongation of slump masses and the orientation (strike) of slide surfaces, both parallel to depositional strike, or the asymmetry, even overturning, of folds in convolute beds. Recognition of these geometric properties in an outcrop is important because it helps distinguish the structures from those of different origin, and orientation characteristics obviously have potential as paleoslope indicators.

Very large-scale slumps and syndepositional faults are developed on major deltas. The latter are termed **growth faults**. **Olistostromes** are giant slumps developed on tectonically active continental slopes.

Deformed or overturned crossbedding (Fig. 2.18) is developed in saturated sand beds by the shearing action of water or turbid flow across the top of the bedform. The upper few centimeters of the crossbedded unit move down current by a process of intragranular shear, and foreset lamination is overturned as a result, producing an up-current dip. Obviously, to produce this structure the shearing current must have a similar orientation to that of the current that generated the crossbedding. Deformed crossbedding is common in fluvial and deltaic environments. As additional sediment is laid on top of saturated deposits, grains within the substrate begin to settle and pack more tightly. Pore waters are expelled in this process and move upward or laterally to regions of lower hydrostatic pressure. Eventually, they may escape to the surface. This process may take place slowly if sediment is being deposited grain by grain and the fluid movement leaves little or no impression on the sediments.

If loading is rapid, a much more energetic process of fluid loss takes place, and the sediment itself will be moved around in the process. The result, in sand-grade deposits, is a group of features called **dish and pillar structures** (Fig. 2.19c, d, e). Dishes are produced by escaping water

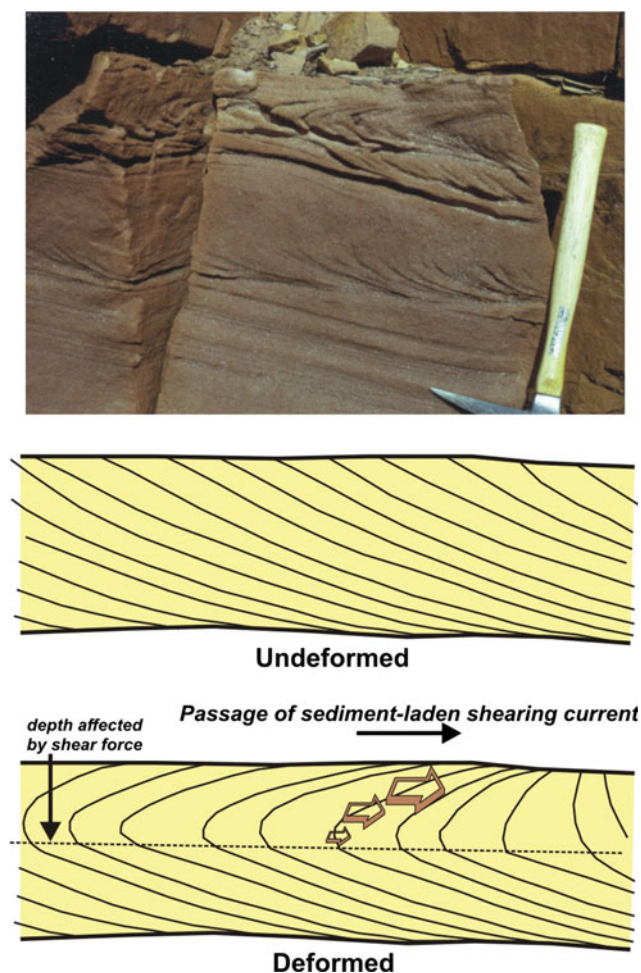


Fig. 2.18 The development of deformed or overturned crossbedding

breaking upward through a lamination and turning up the edges; pillars record the vertical path of water flow moving to the surface. Dishes may be up to 50 cm in diameter. These structures are particularly common in the deposits of sediment gravity flows, such as fluidized flows, in which sediment emplacement is rapid. They are produced by water escape as a flow ceases movement, the loss of the lubricating effect of water itself being one of the main reasons why the flow stops. However, dish and pillar structures have also been observed in fluvial and other deposits and are therefore not environmentally diagnostic. Obviously, they can only be seen in deposits containing lamination and will not be present if the sand is uniform in texture.

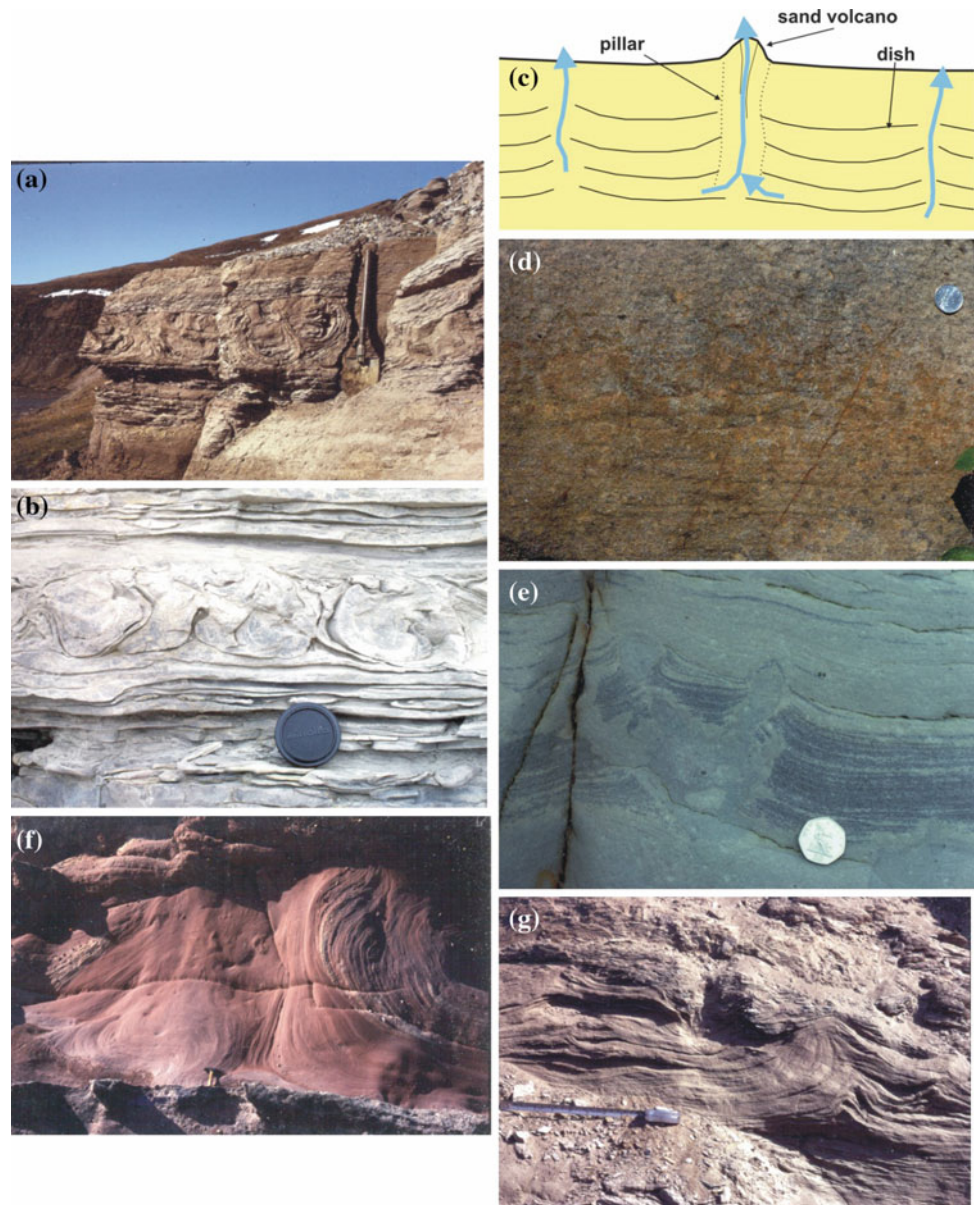
Fluid movement within a bed is an additional cause of convolute lamination. In this case, the laminations are folded by internal shear and may occasionally be broken through by pipes (Fig. 2.19f). At the sediment-water interface, escaping water may bubble out as a small spring, building up a miniature **sand volcano** (Fig. 2.19g).

The emplacement of relatively more dense material over a lower density layer was discussed previously as the cause of load casts. In addition to the downward movement of the denser material, this situation can be the cause of upward movement of lighter sediment, which is injected, together with contained pore fluids, into the overlying rocks. This can occur on a large scale, producing **diapirs** of evaporite or mud, both of which flow readily under the overburden weight of a few hundred meters of sediment. These diapirs may be several kilometers across and may extend up for several kilometers through overlying deposits. Evaporite diapirs commonly develop on continental margins. Mud diapirs are a characteristic feature of deltas, where coarser deltaic sediment is dumped rapidly on marine mud deposits. Pore fluids may be sealed in the sand beds by this process, with the resulting high overburden pressures leading to overpressuring. Exploration drilling into such deposits must include the use of blow-out preventers to guard against the explosive release of pore fluids and gases when an overpressured bed is penetrated by the drill.

On a smaller scale, the same injection process can generate **clastic dikes**, consisting of sheets of sandstone or conglomerate (siliciclastic or carbonate) cutting through overlying or underlying beds (Fig. 2.20). The host rocks usually are sharply truncated and not internally deformed, indicating that they were at least partially lithified prior to intrusion. Some dikes intrude along fault planes. Some are intensely folded, suggesting deformation by compaction and further dewatering after injection.

Desiccation cracks are readily recognized by even the untrained eye (Fig. 2.21). They are one of the best and most common indicators of subaerial exposure in the rock record (note the spelling of “desiccation”, a word that is almost invariably misspelled by students). They may penetrate as deep as a few meters into the underlying rocks (although a few centimeters is more typical) and are normally filled by sediment from the overlying bed. **Teepee structures** are a variety of large desiccation cracks caused by limestone or evaporite expansion on tidal flats. Desiccated beds on tidal flats may peel or curl as they dry, and disrupted fragments commonly are redeposited nearby as an **intraclast breccia** (Fig. 2.14). A subtly different kind of shrinkage feature, termed a **synaeresis structure** may be distinguished from desiccation cracks by two principal differences: unlike desiccation cracks they do not normally form continuous polygonal networks across bedding planes, but may appear as a loose assemblage of small worm-like relief markings on a bedding surface; second, they do not show deep penetration into the substrate, but appear to rest on the bedding plane in which they are found. Synaeresis structures are common in such environments as lakes, lagoons, and tidal pools, where salinity

Fig. 2.19 a, b Convolute bedding generated by syndepositional collapse or gravity sliding; c mechanism of formation of dish-and-pillar structures; d, e examples of dish-and-pillar structures; f water escape structure formed by sediment loading; g sand volcano formed by water escape at the depositional surface



changes may be frequent. As noted in Sect. 3.5.7, these features were thought to be subaqueous shrinkage cracks, but have now been reinterpreted as gypsum pseudomorphs.

Evaporation and freezing may cause the development of crystals of evaporite salts and water, respectively, on the depositional surface, particularly on alluvial floodplains, supratidal flats, and lake margins. Evaporite crystals and nodules may be preserved in the rock record and, of course, major evaporite deposits are common; but individual crystals commonly are replaced by pseudomorphs, or are dissolved and the cavity filled with silt or sand, forming a **crystal cast**. Such structures are a useful indicator of subaerial exposure and desiccation, but do not necessarily imply long-term aridity. Gypsum and halite are the two commonest minerals

to leave such traces. Gypsum forms blade-shaped casts and halite characteristic cubic or “hopper-shaped” structures. Ice casts may be formed in soft sediments during periods of freezing, but have a low preservation potential.

Particularly distinctive evaporite structures on supratidal (sabkha) flats are termed **ptygmatic**, **enterolithic**, and **chicken-wire structures**. These are caused by in-place crystal growth, expansion, and consequent lateral compression of evaporite nodules, possibly aided by slight overburden pressures. Enterolithic structure is so named for a resemblance to intestines; chicken-wire structure is caused by squeezing of carbonate films between the nodules; ptygmatic folds may be caused largely by overburden pressures (Maiklem et al. 1969).

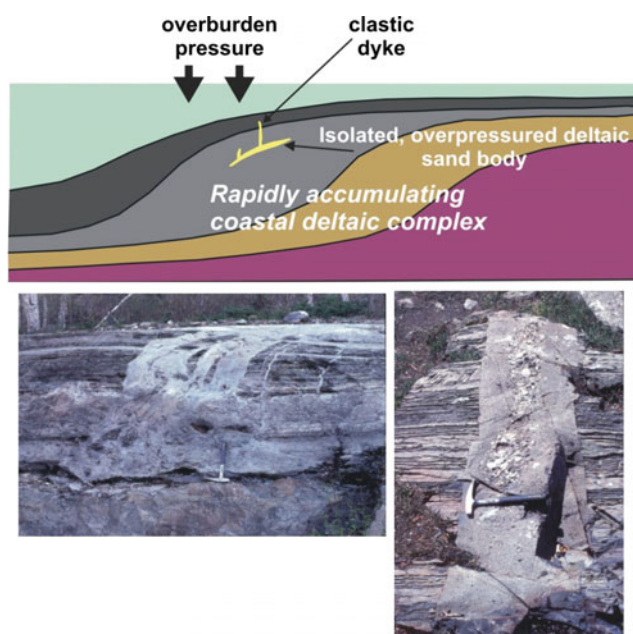


Fig. 2.20 Clastic dykes

Last, **gas bubble escape structures** should be mentioned. These are produced by carbon dioxide, hydrogen sulfide, or methane escaping from buried, decaying organic matter. Gas passes up through wet, unconsolidated sediment and forms bubbles at the sediment-water interface, leaving small pits on the bedding surface. These structures have been confused with **rain-drop imprints**, but form subaqueously, as may be apparent from associated features preserved in the rocks. True rain-drop imprints probably are very rare.

Mills (1983) provided a discussion and review of this class of structures.

2.2.2.9 Fossils

Body fossils are obviously among the most powerful environmental indicators to be found in sedimentary rocks and should be observed and identified with care. Paleontology and paleoecology are specialized subjects, a detailed discussion of which is beyond the scope of this book. However, those engaged in describing outcrop sections for

basin-analysis purposes should be able to make use of such information as they can gather. A complete and thorough paleontological-paleoecological examination of an outcrop section may take several hours, days, or even weeks of work, involving the systematic examination of loose talus and breaking open fresh material or sieving unconsolidated sediment in the search for a complete suite of fossil types. Extensive suites of palynomorphs or microfossils may be extracted by laboratory processing of field samples. Many apparently unfossiliferous or sparsely fossiliferous stratigraphic intervals have been found to contain a rich and varied fauna or flora by work of this kind, but it is the kind of research for which few basin analysts have the time or inclination.

We are concerned in this book with reconstructing depositional environments and paleogeography. Fossils can be preserved in three different ways that yield useful environmental information.

1. In-place life assemblages include invertebrate forms attached to the sea bottom, such as corals, archaeocyathids, rudists, some brachiopods and pelecypods in growth positions, some bryozoa, stromatoporoids (Fig. 2.22a), stromatolites, and trees. In-place preservation usually is easy to recognize by the upright position of the fossil and presence of roots, if originally part of the organism. This type of preservation is the easiest to interpret because it permits the drawing of close analogies with similar modern forms, in the knowledge that the fauna or flora almost certainly is an accurate indicator of the environment in which the rocks now enclosing it were formed.
2. Environmental indicators almost as good as in-place life assemblages are examples of soft-bodied or delicately articulated body fossils preserved intact. These indicate very little transport or agitation after death, and preservation in quiet waters, such as shallow lakes, lagoons, abandoned river channels, or deep oceans. The Cambrian Burgess Shale in the Rocky Mountains near Field, British Columbia, contains one of the most famous examples of such a fossil assemblage, including impressions of soft,

Fig. 2.21 Desiccation cracks, in bedding plane view (left) and cross-section view (right)

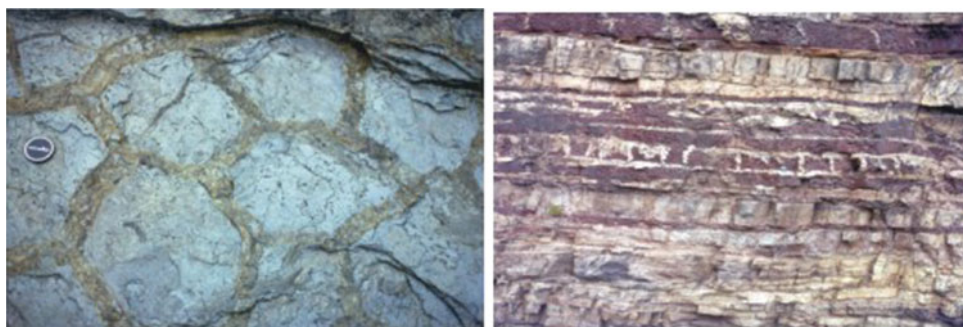


Fig. 2.22 Examples of fossils in outcrop. **a** Stromatoporoid “reef”, Devonian, Alberta; **b** soft-bodied preservation of arthropod jaws, Burgess Shale, British Columbia; **c** marine reptile bones, Cretaceous, Northeastern British Columbia; **d** trilobites, Burgess Shale, British Columbia; **e** modern shell beach, Florida; **f** pelecypod shell bed, Cretaceous, Arctic Canada



nonskeletal parts of many organisms, such as sponges, that are not found anywhere else (Fig. 2.22b). The Jurassic Solnhofen Limestone of Germany is another good example. These are both examples of what are termed **lagerstätte**, sedimentary units with exceptional, in situ preservation.

The bones of vertebrate animals tend to disarticulate after death, because of the decay of muscle and cartilage and the destructive effects of predators (Fig. 2.22c). Nevertheless, entire skeletons of bony fish, reptiles, and mammals are commonly found in certain rock units, indicating rapid burial under quiet conditions. The Solnhofen Limestone is a well-known example, containing, among other fossils, the entire skeleton and feather impressions of a primitive bird. Such fossil assemblages must, nevertheless, be interpreted with care because a limited amount of transportation is possible from the life environment to the site of eventual burial. Presumably the bird of the Solnhofen Limestone lived in the air, not at the sediment-water interface where it was deposited!

3. Much more common than either of the foregoing are death assemblages of fossils that may have been transported a significant distance, perhaps many kilometers from their life environment. These commonly occur as lag concentrates of shelly debris such as gastropod, pelecypod, brachiopod, or trilobite fragments, and fish bones or scales (Fig. 2.22e). Such concentrations may be abundant enough to be locally rock forming, for example, the famous Silurian Ludlow Bone Bed of the Welsh borderlands. They normally indicate a channel-floor lag concentration or the product of wave winnowing, and can usually be readily recognized by the fact that fragment grain size tends to be relatively uniform.

Transported body fossils may not occur as concentrations but as scattered, individual occurrences, in which case each find must be interpreted with care. Did it live where it is now found or was it transported a significant distance following death? The environmental deduction resulting from such an analysis may be quite different depending on which

interpretation is chosen. Evidence of transportation may be obvious and should be sought; for example, broken or abraded fossils may have traveled significant distances. Overturned corals, rolled stromatolites (including oncolites), and uprooted tree trunks, are all obviously transported.

These problems are particularly acute in the case of microfossils and palynomorphs that, on account of their size, are particularly susceptible to being transported long distances from their life environment. For example, modern foraminiferal tests are blown tens of kilometers across the supratidal desert flats of India and Arabia, and shallow water marine forms are commonly carried into the deep sea by sediment gravity flows, such as turbidity currents. Detritus eroded from earlier stratigraphic units may also include derived fossil material. Environmental interpretations based on such fossil types may therefore be very difficult, though it may still be possible if the analysis is carried out in conjunction with the examination of other sedimentary features. In fact, it was the occurrence of sandstones containing shallow-water foraminifera interbedded with mudstones containing deep-water forms in the Cenozoic of the Ventura

Basin, California, that was one of the principal clues leading to the development of the turbidity current theory for the origin of deep water sandstones.

Because of the great variety of life forms preserved as fossils, the subject of paleoecology is a large and complex one. Detailed studies are for the specialist and a complete treatment is beyond the scope of this book. The reader is referred to such texts as Hallam (1973), McKerrow (1978), and Dodd and Stanton (1981). A few examples are discussed in Chap. 4.

2.2.2.10 Biogenic Sedimentary Structures

Footprints, burrows, resting, crawling or grazing trails, and escape burrows are examples of what are termed **trace fossils**. They are abundant in some rock units, particularly shallow-marine deposits; all may yield useful environmental information, including water depth, rate of sedimentation, and degree of agitation (Figs. 2.23 and 2.24). The study of trace fossils is termed **ichnology**. Distinctive assemblages of trace fossils Even the nondescript structure **bioturbation**, which is ubiquitous in many shallow marine rocks, can be

Fig. 2.23 Trace fossils. **a**, **b**. *Skolithus* (Jurassic) in bedding-plane (**a**) and vertical (**b**) exposure; **c** feeding and crawling trails on a shallow-marine bedding-plane surface (Ordovician); **d**, **e**, **f** shallow-marine burrows, all Cretaceous, including *Diplocraterion* (**d**), *Thalassinoides* (**e**) and *Arenicolites* (**f**)

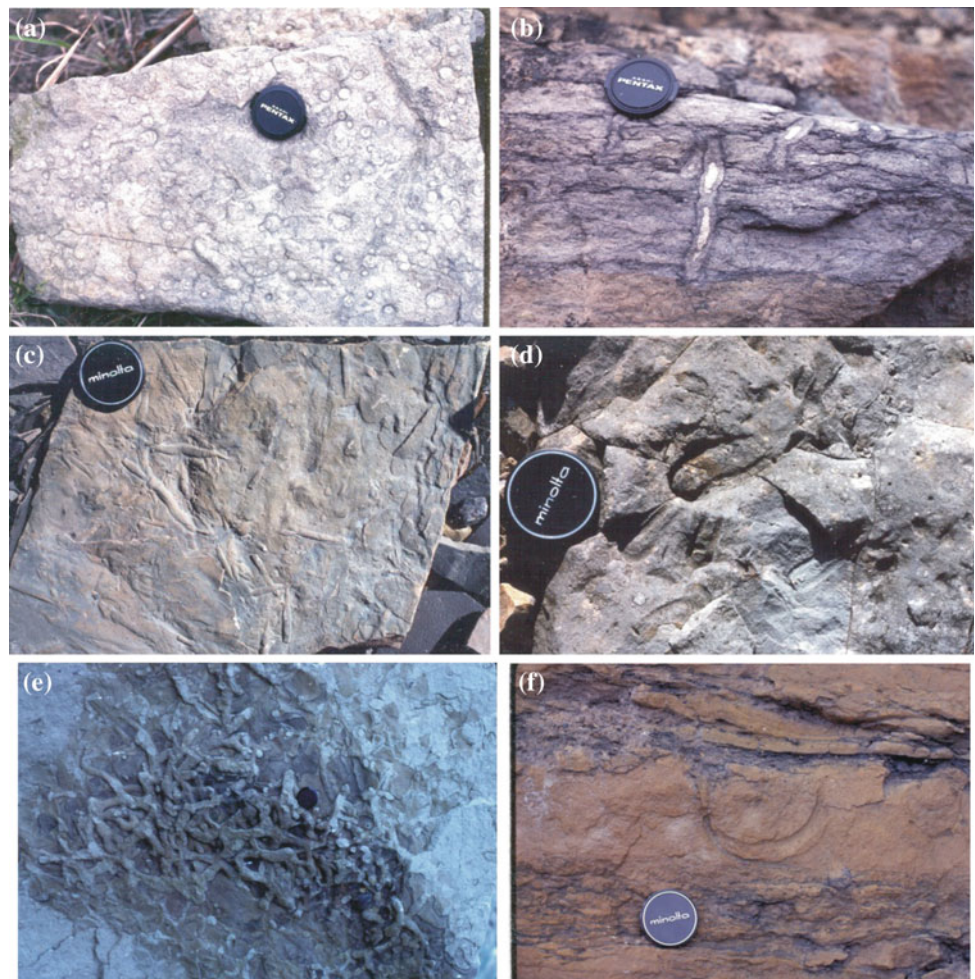




Fig. 2.24 Example of trace fossils in a drill core, showing how well these features can be seen. They include *Skolithus* (top) and *Rosella* (bottom)

interpreted usefully by the sedimentologist. Footprints are, of course, best seen on bedding-plane surfaces, as are many types of feeding trails and crawling traces (Fig. 2.25). Burrows are better examined in vertical cross section and are most visible either in very clean, fresh, wetted rock surfaces or in wind- or water-etched weathered outcrops (Fig. 2.23).

Stromatolites are a distinctive component of many carbonate successions, particularly those of Precambrian age, and have been the subject of much detailed study.

Studies of trace-fossils in modern settings and in ancient rocks have led to the recognition of distinctive assemblages, or **ichnofacies**, that are environmentally dependent, reflecting such conditions as the water depths, energy levels and nutrient availability preferred by the organisms that leave the traces. An ecological zonation is shown in Fig. 2.26. Here, for example, can be seen the *Skolithus* assemblage of traces, one which is characteristic of high-energy shoreline environments. Here, a burrowing mode of life permits organisms to live in protected environments while benefiting from the oxygenated and nutrient-rich waters of wave-influenced coastal settings. The *Nereites* assemblage is one composed of organisms that systematically mine the nutrient-poor sediments of deep-water settings. *Glossifungites* organisms like semi-consolidated substrates, and are commonly to be found at major stratigraphic bounding surfaces. And so on.

Figure 2.26 is from McEachern et al. (2010), which is by far the best modern text dealing with the description, classification and interpretation of trace fossils.

2.2.3 Sampling Plan

The amount of sampling to be carried out in outcrop section depends on the nature of the problem in hand, as discussed in Sect. 1.4. We are not concerned here with sampling of ore, hydrocarbon source beds, or coal to be analyzed for economic purposes, but the sampling required to perform a satisfactory basin analysis. Sampling is carried out for three basic purposes: (1) to provide a suite of typical lithologic samples illustrating textures, structures, or distinctive fossils on a hand-specimen scale; (2) to provide a set for laboratory analysis of petrography and maturation using polished slabs, the optical microscope, and possibly other tools, such as x-ray diffraction analysis and the scanning electron microscope; and (3) to gather macrofossil and lithologic samples for microfossil or palynological examination to be used for studying biostratigraphy.

2.2.3.1 Illustrative Samples

The choice of such samples is usually simple and can be based on a trade-off between how much it would be useful to take and how much the geologist can physically carry. Large samples showing sedimentary structures or suites of fossils



Fig. 2.25 Examples of vertebrate footprints. *Left* view of underside of bed, showing a projecting dinosaur footprint; *right* bird footprints

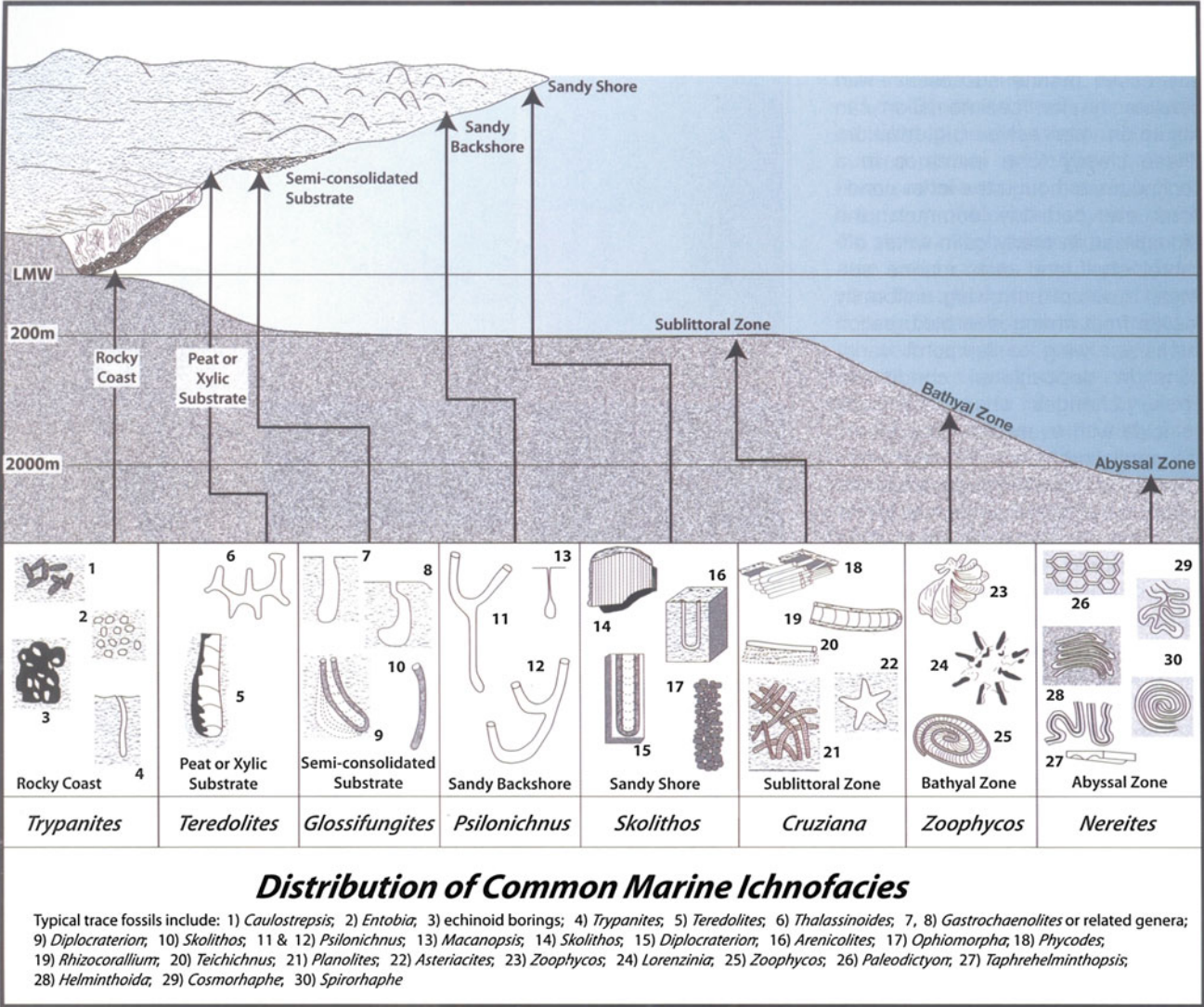


Fig. 2.26 Ecological zonation of trace-fossil assemblages (McEachern et al. 2010)

may be an invaluable aid in illustrating the geology of the project area to the geologist's supervisor or for practical demonstration at a seminar or a poster display at a

conference. Unless field work is done close to a road or is being continuously supported by helicopter, it is rarely possible to collect as much as one would like.

2.2.3.2 Petrographic Samples

Before carrying out a detailed sampling program for petrographic work, the geologist should think very carefully about what the samples are intended to demonstrate. Here are some typical research objectives:

1. grain-size analysis of siliciclastic and carbonate clastic rocks, as a descriptive parameter and as an aid to interpreting the depositional environment;
2. petrography of detrital grains, including heavy minerals, as an aid to determining sediment sources;
3. petrography of carbonate grains as an aid to determining the depositional environment;
4. studies of grain interactions, matrix, and cement of both carbonate and clastic grains in order to investigate diagenetic history;
5. studies of detrital grain fabric in order to determine paleocurrent patterns or, in certain cases, as an aid to interpreting the depositional environment;
6. studies of thermal basin-maturity using clay-mineral characteristics, vitrinite reflectance, microfossil color or fluid inclusions; and
7. samples for paleomagnetic study, for use in developing a reversal stratigraphy, a paleopole, or for studying diagenesis.

The geologist must define the scope of the problem before collecting any samples, otherwise it may later be discovered that the collection is unsatisfactory. Work in remote regions is excellent training in such planning exercises, because only rarely is there a chance to return to an outcrop a second time. For the purpose of most regional studies, it is useful to examine petrographic variations vertically through a sequence and areally within a single stratigraphic unit. For example, the composition of detrital grains in a sequence may show progressive vertical changes, recording erosional unroofing of a source area or the switching of source areas. Sampling should be adequate to document this statistically. Samples taken every 10–50 m through a sequence will normally suffice. For diagenetic and fabric studies and for paleomagnetic work, more detailed sampling may be required. Paleomagnetic research normally requires several samples from a single locality in order to permit checks for accuracy.

The most detailed sampling program is required for carbonate sequences, particularly those of shallow marine origin, which show the most facies variation. Laboratory work on polished slabs or thin sections is required for a reliable facies description of most carbonate rocks, and this may call for sampling every meter, or less, through a section.

For certain purposes, it is necessary that the sample be oriented; that is, it should be marked in the field so that its

position in space can be reconstructed in the laboratory. For paleomagnetic and fabric studies, this need is obvious, but it may also be useful for petrographic purposes, for example, where it is necessary to examine cavity-filling detrital matrix to determine the time of filling relative to tectonic deformation, as an aid to determining structural top, or for studying microscopic grain-size changes related to bedding (e.g., graded bedding). To collect an oriented sample, the geologist selects a projecting piece of the outcrop that is still in place, not having been moved by frost heave, exfoliation, or other processes, and yet is still removable by hammer and chisel. A flat face on this piece is measured for orientation and marked by felt pen before removal. A more detailed discussion of the methods and purpose of sample orientation is given by Prior et al. (1987).

How much should be collected at each sample station? A few hundred grams is adequate for most purposes. Thin sections can be made from blocks with sides less than 2 cm. Grain mounts of unconsolidated sediment can be made from less than 20 g. Where a particular component is sought, such as disseminated carbonaceous fragments for vitrinite-reflectance measurements, it may be necessary to take a larger sample to ensure that enough fragments are included for a statistical study at each sample station. Samples for paleomagnetic study are collected in a variety of ways, including the use of portable drills, which collect cores about 2 cm in diameter. Alternatively, the geologist may wish to take oriented blocks about $4 \times 8 \times 15$ cm, from which several cores can be drilled in the laboratory. Oriented specimens of unconsolidated sediment are collected by means of small plastic core boxes or tubes pushed into an unweathered face by hand. Textures may be preserved by on-site infiltration with resin (see also Prior et al. 1987).

How do we ensure that samples are truly representative? There is a conflict here between statistically valid experimental design and what is practically possible. Statistical theory requires that we take samples according to some specific plan, such as once every 10 or 30 m (for example) through a vertical section, or by dividing a map area into a square grid and taking one sample from somewhere within each cell of the grid. By these methods we can satisfy the assumptions of statistical theory that our samples are truly representative of the total population of all possible samples. In practice, we can never fully satisfy such assumptions. Parts of any given rock body are eroded or too deeply buried for sampling. Exposures may not be available where sampling design might require them, or a particular interval might be covered by talus. An additional consideration is that the very existence of exposures of a geological unit might be governed by weathering factors related to the parameter the geologist hopes to measure. For example, imagine a sandstone bed formed at the confluence of two river systems,

one draining a quartz-rich terrain and one a quartz-poor terrain. The quartzose sandstone intervals may be quartz cemented, much more resistant to erosion, and therefore much more likely to crop out at the surface. Sampling of such a unit might give very biased petrographic results.

In carrying out a basin analysis, we often deal with large areas and considerable thicknesses of strata. Petrographic, textural, and maturity trends are usually strong enough to show through any imperfections in our sampling program. We collect what we can, taking care that our measurements are controlled by the appropriate geological variables, for example, that counts of detrital components are all made on the same grain-size range.

2.2.3.3 Biostratigraphic Samples

The study of any fossil group for biostratigraphic purposes is a subject for the appropriate specialists who, ideally, should collect their own material. However, this may not be possible, and the geologist often is required to do the collecting.

Unless a unit is particularly fossiliferous, the collecting of macrofossils can rarely be performed in a fully satisfactory way by the geologist, who is also measuring and describing the section. The search for fossils may take a considerable amount of time, far more than is necessary for the other aspects of the work. In practice, what the geologist usually ends up with are scattered bits and pieces and spot samples of more obviously fossiliferous units, in which it may be fortuitous whether or not any species of biostratigraphic value are present. Given adequate time, for example the two or three field seasons required for dissertation research, the geologist may be able to spend more time on collecting and to familiarize him or herself with the fauna and/or flora, but in reconnaissance mapping exercises, this is usually impracticable.

The increased sophistication of subsurface stratigraphic analysis by the petroleum industry has led to a greatly expanded interest in fossil microorganisms. Groups such as conodonts, acritarchs, foraminifera, palynomorphs, diatoms, and radiolaria have been found to be sensitive stratigraphic indicators and commonly have the inestimable advantage of occurring in large numbers, so that biostratigraphic zonation can be based on statistical studies of taxon distribution. Microfossils are extracted by deflocculation or acid dissolution of suitable host rocks. Most useful fossil forms are pelagic, or are distributed by wind (palynomorphs), so that potentially they may be found in a wide variety of rock types. However, their occurrence is affected by questions of hydrodynamics in the depositional setting and postdepositional preservation. Palynomorphs may be rare in sandstones because they cannot settle out in the turbulent environments in which sand is deposited, but they are abundant in associated silts, mudrocks, and coal. Radiolarians and other siliceous organisms may be entirely absent in mudstones but abundantly preserved in silts, cherts, and volcanic tuffs, because

they are dissolved in the waters of relatively high pH commonly associated with the formation of mud rocks. Conodonts are most commonly preserved in limestones and calcareous mudstones and may be sparse in dolomites, because dolomitization commonly occurs penecontemporaneously in environments inimical to conodonts, such as sabkha flats.

Armed with advice of this kind from the appropriate specialist, the geologist can rapidly collect excellent suites of samples for later biostratigraphic analysis and can cut down on the amount of barren material carried home at great effort and expense, only to be discarded. Advice should be sought on how much material to collect. Normally, a few hundred grams of the appropriate rock type will yield a satisfactory fossil suite, but more may be required for more sparse fossiliferous intervals, for example, several kilograms for conodonts to be extracted from unpromising carbonate units.

Samples should be collected at regular vertical intervals through a section, preferably every 10–50 m. This will vary with rock type, in order to permit more detailed sampling from condensed units or particularly favorable lithologies. Such sample suites permit the biostratigrapher to plot range charts of each taxon and may allow detailed zonation. Scattered or spot samples have to be examined out of context and may not permit very satisfactory age assignments.

2.2.4 Plotting the Section

A stratigraphic section can be published in the form of a written description, but this is not a very effective use of the information. It is required for the formal description of type and reference sections of named stratigraphic units, but it is doubtful if much is to be gained by reading such a description. The same information can be conveyed in a much more compact and digestible form as a graphic log, with a central column for lithology and adjacent columns for other features of importance. Such logs have the added advantage that they can be laid side by side, permitting comparisons and correlations between sections from several locations.

It is possible to devise logging techniques with columns and symbols to convey every scrap of lithologic and petrographic information, plus details of fossils, sedimentary structures, paleocurrent measurements, even chemical composition. Many companies and government organizations print blank logging forms of this type for use by their geologists to facilitate the logging process and to standardize the results of different workers. Johnson (1992) developed a comprehensive, all-purpose logging form that he offered as a standard for field workers.

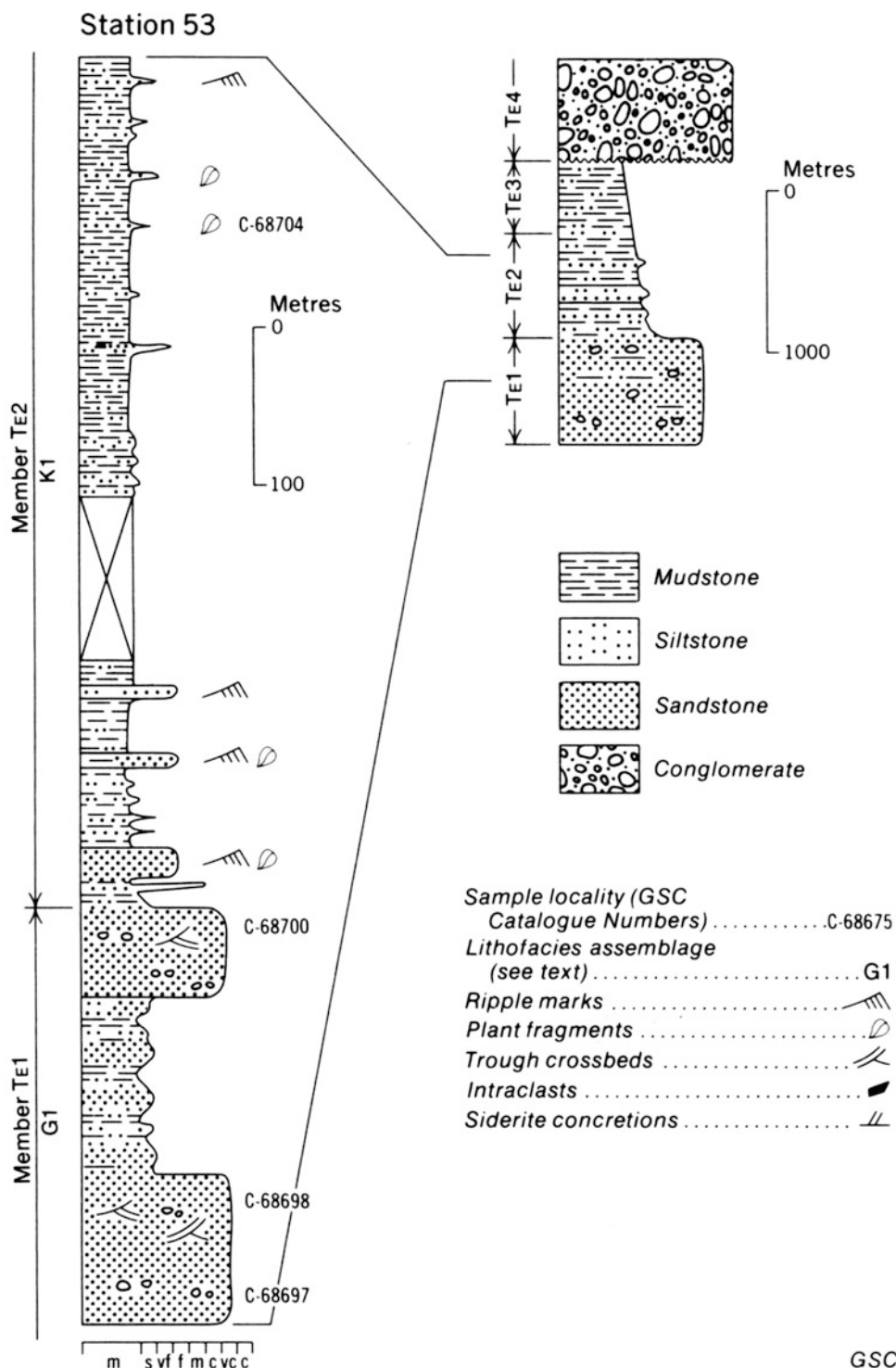
However, such logs have the disadvantage that significant information may be lost in a welter of detail. If a main purpose of a log is to permit visual comparisons between different sections, it is advisable to simplify the logs so that

the critical features stand out from the page. For the purpose of basin analysis, the most important data are those that carry paleogeographic information, such as lithology, grain size, sedimentary structures, and fossil content. Paleocurrent data can be added to these, but commonly are treated separately (Chap. 6). As we shall see in Chap. 4, the vertical succession of facies is often of crucial importance in interpreting the

depositional environment, and so it is helpful to emphasize this in the logs.

For clastic rocks, one of the most useful techniques is to vary the width of the central lithology column according to grain-size, the wider the column, the coarser the rocks. Examples are illustrated in Fig. 2.27. Many other examples are given by Reading (1986) and James and Dalrymple

Fig. 2.27 Typical representation of surface stratigraphic sections. Grain-size scale at base of column: *m* mud, *s* silt, *vf* to *vc* very fine to very coarse sand, *c* conglomerate



(2010). This method imitates the weathering profile of most clastic rocks, as muddy units tend to be less resistant and to form recessive intervals, in contrast to the projecting buttresses and cliffs of coarser sandstones and conglomerates. Drawing the column in this way enables rapid visual comparisons between sections and also permits instant recognition of gradual trends, such as upward fining, and sharp breaks in lithology, as at an erosion surface. Subtleties, such as changes in sorting or a bimodal grain size distribution, cannot be displayed in this way, but are rarely as important from a facies perspective and may, in any case, be accompanied by other kinds of facies change, such as in a sedimentary structure assemblage, which can be readily displayed in visual logs.

The variable column-width technique has not been widely used for carbonate rocks, but there is no reason why it should not be. However, grain size is subject to changes by diagenesis, and this may make interpretation more difficult.

Within the column, various patterns can be used to indicate lithology, including symbols for sedimentary structures and fossils. For siliciclastic sequences consisting of interbedded mudstone, siltstone, sandstone, and conglomerate, the column width conveys most of the necessary lithologic information, and the body of the column can be used primarily for structures and fossils. Some loggers split the column in two, one side for lithology and one for structures, but this is rarely as visually successful. Very little need be placed outside the column, which preserves an uncluttered appearance and increases the graphic impact of the log.

Symbols, abbreviations and other plotting conventions are discussed in Sect. 2.3.4.

At what scale should the logs be drawn? This depends on what it is they are intended to demonstrate. Detailed, local sedimentological logs may require a scale of between 1 cm:1 m and 1 cm:10 m. Regional stratigraphic studies can be illustrated in large foldout diagrams or wall charts at scales in the order of 1 cm:10 m to 1 cm:50 m, whereas page-sized logs of major stratigraphic sequences can be drawn (grossly simplified) at scales as small as 1 cm:1000 m. In the petroleum industry, the scale 1 in.:100 ft has long been a convenient standard for subsurface stratigraphic work. This translates to a convenient approximate metric equivalent of 1 cm:10 m, although it is actually closer to 1 cm:12 m. Metric units should always be used, preferably in multiples of 10.

2.3 Describing Subsurface Stratigraphic Sections

2.3.1 Methods of Measuring and Recording the Data

Subsurface sections are logged and described using three types of data, well cuttings, core and petrophysical logs (see

Sects. 1.4.3 and 1.4.4). All three are typically available for the large-diameter holes drilled by petroleum exploration companies. Diamond-drill holes (DDH) provide a continuous core but nothing else. The logging techniques and the results obtainable are therefore different.

To reduce costs, corporate practice may make use of outside consultant services to provide wireline-log and core descriptions, or they may limit staff to using photographs of core instead of encouraging them to view the actual core. Key observational detail could be lost as a result, particularly where the investigator is developing an hypothesis that depends on recording critical depositional or diagenetic features.

2.3.1.1 Examination of Well Cuttings

Samples stored in company and government laboratories are of two types, washed and unwashed. Unwashed cuttings consist of samples of all the material that settles out of the mud stream into a settling pit at the drill site. Unconsolidated mudrocks may disperse completely into the mud stream during drilling, in which case little of them will be preserved except as coatings on larger fragments or occasional soft chips. Washed cuttings are those from which all mud has been removed (Fig. 1.4). The washing process makes the cutting examination process easier, but it further biases the distribution of rock types present if the drill penetrated any unconsolidated muddy units. Stratigraphic well logging is normally carried out on the washed cuttings, whereas palynological and micropaleontological sampling is done on the unwashed material. Stratigraphic logging techniques are described later in this chapter. A detailed guide and manual was published by Low (1951) and is well worth reading. Many companies also provide their own manuals. McNeal (1959) has some useful comments, and the American Association of Petroleum Geologists has also issued a logging guide (Swanson 1981).

As described in Sect. 1.4.3, samples are collected at the well site and bagged every 10 ft (3 m). The bag is labeled according to the depth of recovery by the well-site geologist, who makes allowances for the time taken for the mud and cuttings to rise to the surface. Measurements are normally given as “depth below K.B.”; K.B. stands for kelly bushing, a convenient measurement location on the drilling platform a few meters above ground level. The altitude above sea level of this point is determined by surveying, so that these drilling depths can be converted to “depths subsea.” On offshore rigs K.B. is 25–30 m above sea level.

For various reasons, not all the cuttings in any given bag may be derived from the depth shown. The problems of caving and variable chip density have been referred to in Sect. 1.4.3 (see Fig. 2.28). These problems are particularly acute in soft or unconsolidated rocks, and samples from such a sequence may consist of a heterogeneous mixture bearing

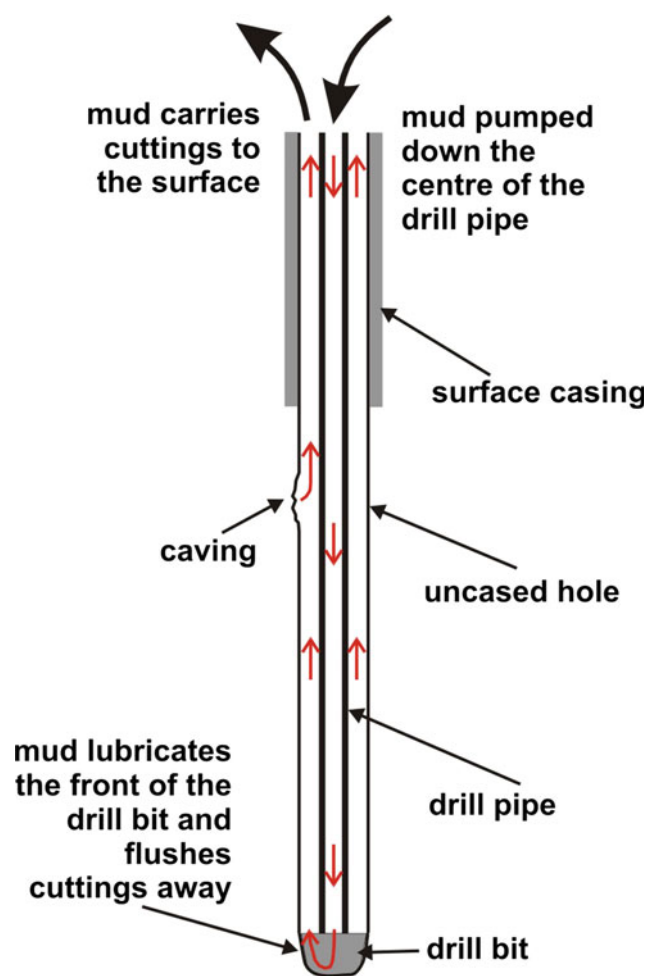


Fig. 2.28 How cavings enter the mud stream in a drill hole

little relation to such stratigraphic detail as thinly interbedded units of contrasting lithology. The loss of the muds from the cutting suite compounds the problem. There are several ways in which these problems can be at least partially resolved. Caved material may be obvious by the large size of the fragments or by its exotic lithology or fossil content. For example, in one well in the Canadian Arctic, I logged Jurassic pelecypods and foraminifera 270 m below the unconformable contact of the Jurassic with the Devonian. The geologist will gradually become familiar with the formations under study, and will then readily recognize such obvious contamination.

A more powerful tool is available to the logger and that is to study the cuttings in conjunction with the suite of petrophysical (wireline) logs from the hole. These logs record various physical properties as a measuring tool is slowly run the length of the hole. Modern petrophysical logging methods are capable of resolving lithologic variations over vertical intervals of a few decimeters or less and can therefore be used, with practice, to interpret lithologies in

conjunction with the well cuttings. A description of the common petrophysical methods and their uses is given later in this chapter. Once the geologist is familiar with the petrophysical response of the various lithologies in the hole under examination, it is possible to use the logs to adjust or correct the sample description. A lithologic log may therefore be drawn up that bears only a loose relationship to the material actually present in the sample bags. Such a log is an interpretive log, and should be clearly labeled as such. It is likely to be more useful in basin interpretation than a log which simply records the cuttings dogmatically, particularly in the case of poorly consolidated beds or those with rapid vertical lithologic variations. Soft muds will be entirely unrecorded in a straight sample log, which may give the geologist a very inaccurate picture of the subsurface stratigraphy. All this can be allowed for in an interpretive log, but interpretations can be wrong, and the geologist must be aware of it when using this type of record.

Cuttings are observed under a low-power, reflected-light binocular microscope. Immersing the samples in water may aid observation, particularly as dust adhering to the chips can be washed off. The most useful magnification range for such a microscope is from about X5 to X50. The critical petrophysical logs should be unfolded to the appropriate depth interval and placed at one side of the microscope. It is advisable to scan rapidly the samples from several tens of meters of section before beginning the detailed description. Like standing back from an outcrop section, this gives the geologist the opportunity to perceive major lithologic variations. These may be correlated with changes in the petrophysical log response, permitting precise depth control.

As the samples are described, the information may be recorded directly on a preprinted logging form, or written out in note form. If the log is to be an interpretive one, several tens of meters of section should be examined before plotting the graphic log, so as to give the geologist time to digest what is being observed. It may be necessary for publication or other purposes to produce a written sample description, but, as discussed under surface sections, these are difficult for a reader to absorb and are likely to be seldom used. The *Geological Survey of Canada* now publishes them in microfiche form to save paper and space.

Many petroleum and mining exploration companies and service companies (such as the *American Stratigraphic Company*, *Canadian Stratigraphic Service Ltd.*, and *International Geosystems Corporation*) now use computer processible logging forms. The data are then stored in digital form in data banks. Retrieval programs may be available that can use these data for automated log plotting, and the same data bank can be exploited for automated plotting of maps and sections, as discussed in Chap. 5.

2.3.1.2 Examination of Core

The large-diameter core produced by petroleum drilling (Fig. 1.5) is stored either in a company laboratory or an official government repository. North American practice is to divide the core into 2.5 ft (0.8 m) lengths, which are stored side by side, two to a box. Top and bottom should be marked on the box. The core usually consists of a series of short pieces, broken from each other by torque during the drilling process. The well-site geologist should number or label each piece with respect to its position in the box and its orientation because, unless this is done, once a piece is moved it may be very difficult to restore it to its correct position, and serious errors may be introduced in reconstructing the vertical lithologic succession. Diamond-drill-hole (DDH) cores are normally stored in 5 ft (1.6 m) lengths, five to a box. The same remarks apply with regard to the position and orientation of core pieces. DDH cores are rarely brought from the field back into the office, except for crucial holes. They are examined and logged in the field, and then are commonly abandoned. They may even be tipped out of the box to prevent competitors from taking a look. This is a great waste of research material, but the practice seems unlikely to change.

Cores are most conveniently examined in a laboratory specifically designed for this purpose (Fig. 2.29). Core boxes are laid on roller tables, so that they can be readily loaded and unloaded using a fork-lift vehicle. A movable platform is positioned above the core boxes, on which are placed the microscope, petrophysical logs, note book, etc.

The grinding action of the core barrel during drilling may smear the core surface and obscure lithologic features; sometimes this can be rectified by washing the core with water or even dilute hydrochloric acid. An even more useful technique is to have the core cut longitudinally with a rock

saw, creating a flat section. This should always be wetted with water or etched lightly with dilute acid before examination. The etching technique is particularly useful when examining carbonate rocks, as it tends to generate a fine relief between grains and cement or different carbonate minerals.

Where petrophysical logs are available, it is important to correlate core lithology with log response. This exercise may reveal that parts of the core are missing, perhaps as a result of fragmentation of soft lithologies. Such information is of importance in attempts to reconstruct a detailed vertical lithologic profile.

For a discussion of description and plotting routines, refer to the previous section on well cuttings. Essentially the same methods are used, except that many more features are visible in core, such as bedding features, sedimentary structures and macroscopic trace and body fossils. Orientation of core for geological purposes was discussed by Davison and Haszeldine (1984) and Nelson et al. (1987).

2.3.2 Types of Cutting and Core Observation

Large-scale features, including most sedimentary structures and the subtleties of bedding, cannot be identified in well cuttings. They are partly visible in cores, but cores usually provide only frustratingly small snapshots of major features, and core research is rather like trying to describe elephant anatomy by examining a piece of skin with a microscope. The following notes are given in the same format as for surface sections, so that the contrasts with the latter can be emphasized. The description of field observation techniques should be referred to where appropriate.

2.3.2.1 Subdivision of the Section into Descriptive Units

This is best carried out by core and sample examination in conjunction with petrophysical logs, in the case of petroleum exploration wells. The combination is a powerful one and yields good generalized stratigraphic subdivisions with precise depth control. For DDH cores the absence of petrophysical logs is compensated by the availability of a continuous core, and stratigraphic subdivision is simple. Because so many features, such as sedimentary structures, cannot be observed in cuttings, descriptive units in the subsurface tend to be thicker and more generalized than those observed in the outcrop. However, for core, the focus on what are really very small samples and the attempt to maximize the use of limited amounts of information tends to lead to very detailed descriptions. Examination of surface sections, sections based on cuttings and those on core, particularly short petroleum cores, require very different



Fig. 2.29 A core laboratory. Energy Resources Conservation Board, Calgary, Alberta

concepts of scale. These should be borne in mind when a basin-analysis exercise calls for the correlation of all three types of data.

2.3.2.2 Lithology and Grain Size

These can be observed satisfactorily in cuttings for all rock types except conglomerates, using the same techniques as described under surface sections. Conglomerates cannot be adequately studied in cuttings where clast size is larger than cutting size. It may not be possible to ascertain which cuttings represent clast fragments and which matrix, and no observations of clast grain size can be made. Remember, also, that unconsolidated silts, muds, and evaporites may not be represented in well cuttings. These may require identification using petrophysical logs.

Well cuttings commonly contain contaminants that the logger should discard or ignore. Many are easy to recognize, such as metal pipe shavings or bit fragments. Oily substances, such as pipe dope or grease, may coat some fragments, but can usually be distinguished from natural oil stains by the fact that they coat the cuttings and do not penetrate them. Drilling mud may also coat the cuttings, particularly poorly washed samples. Casing cement may appear as a flood of cuttings at certain levels, where the hole was reentered following the setting of the casing. Cement can be easily mistaken for sandy, silty, or chalky carbonate. Finally, foreign materials, such as feathers, sacking, seeds, cellophane, perlite, or coarse mica flakes, may be present. These are used in the drilling mud to clog large pores and prevent loss of mud circulation.

Usually there are few restrictions on lithology and grain size determinations in core, except where particularly coarse conglomerates are present.

2.3.2.3 Porosity

See the discussion in Sect. 2.2.3. Observations and measurements from subsurface rocks are more reliable than are those from outcrops because of the complications of surface weathering.

2.3.2.4 Color

See the discussion under the heading of surface sections (Sect. 2.2.3).

2.3.2.5 Bedding

For core, see the discussion under the heading of surface sections (Sect. 2.2.3). Bedding cannot be seen in well cuttings except for fine lamination, whereas core provides good information on bedding variation. Caution should be exercised in attempts to extract any quantitative information about bed thickness from cores, because of the possibility of core loss, as discussed earlier.

2.3.2.6 Sedimentary Structures

Very few, if any structures can be observed in well cuttings. However, a wide range of structures is visible in core (e.g., Fig. 2.8c). Large structures, such as major erosion features and giant crossbedding, may be difficult to discern because the small sample of the structure visible in the core may easily be confused with something else. For example, thick crossbed sets could be mistaken for structural dip if the upper or lower termination of the set against a horizontal bedding plane cannot be determined. Dipmeter interpretations and formation microscanner observations may help here, as discussed in Sect. 6.7. Erosion surfaces are practically impossible to interpret in small outcrops or cores. The break may indicate anything from a storm-induced scour surface to an unconformity representing several hundred million years of nondeposition. The presence of soils or regoliths below the erosion surface is about the only reliable indicator of a major sedimentary break (except, of course, where there is structural discordance).

Ripple marks, and crossbed sets up to a few decimeters thick, are more readily recognizable in core, and the reader should turn to the discussion of these in the section on surface exposures for methods of study. The large-scale geometry of crossbed sets is difficult to interpret in core. For example, the difference between the flat shape of a foreset in planar crossbedding and the curved surface of a trough crossbed is practically impossible to detect in core, even the large-diameter petroleum core. Curvature of a typical trough crossbed across such a core amounts to about 2°. Sensitive dipmeter logs have considerable potential for interpreting crossbedding in the subsurface, but the methodology of interpretation has yet to be fully worked out. Dipmeter or formation microscanner logs will eventually permit paleocurrent measurements to be made in the subsurface (Sect. 6.7), something which cannot now be done without an oriented core, and the availability of the latter is practically zero.

Small-scale erosion features such as flutes, tool markings, and rain prints, and other bedding features such as desiccation cracks, and syneresis markings, are difficult to find in core because bedding plane sections are rare and the geologist is discouraged from creating additional sections by breaking up the core.

Liquefaction, load, and fluid-loss structures are commonly visible in core and, except for the larger features, should be readily interpretable.

2.3.2.7 Fossils

Fossil fragments are commonly visible in well cuttings, but are difficult to recognize and interpret. The best solution is to examine them in thin section, when distinctive features of internal structure may be apparent. A program of routine

thin-section examination of fossiliferous sequences may be desirable and, particularly if the rocks are carbonates, this can be combined with the lithologic analysis. An excellent textbook by Horowitz and Potter (1971) discusses the petrography of fossils in detail.

Macrofossils can rarely be satisfactorily studied in core, except in the case of highly fossiliferous sections, such as reefs and bioherms. The reason is that the chance sections afforded by core surfaces and longitudinal cuts do not necessarily provide exposures of a representative suite of the forms present, and unlike sparsely fossiliferous surface outcrops, there is no opportunity to break up more rock in a search for additional specimens. Fragments may be studied in thin section, as described previously, but the limitations on the quantity of material still apply.

Both cores and cuttings may be used by biostratigraphic specialists, who extract palynomorphs and microfossils from them by processes of deflocculation or acid dissolution. Much useful ecological information may be obtainable from these suites of fossils. For example, Mesozoic and Cenozoic foraminifera were sensitive to water depth (as are modern forms), and documentation of foram assemblages through a succession can permit a detailed reconstruction of the varying depths of marine depositional environments (Sect. 3.5.8).

2.3.2.8 Biogenic Sedimentary Structures

As in the case of most other mesoscopic features, very little can be seen in cuttings, whereas cores commonly contain particularly well-displayed biogenic sedimentary structures. Those confined to bedding planes may not be particularly easy to find, whereas burrows usually are easy to study and can provide invaluable environmental interpretation (Fig. 2.24). Refer to the notes and references in Sect. 2.2.2.10.

2.3.3 Sampling Plan

As in the case of surface sections, we are concerned here with sampling for basin analysis purposes in three main categories: illustrative lithologic samples; samples for laboratory petrographic analysis using thin and polished sections, X-ray diffraction, etc.; and samples for biostratigraphic purposes.

Very limited quantities of material are available for any kind of sampling in subsurface sections. The cuttings and core stored in the laboratory are all that will ever be available and once used cannot be replaced. Thus, they should be used with care, and permission should always be sought from the appropriate company or government agency before removing any material for research purposes.

A core may provide excellent illustrative material for demonstrating lithology, sedimentary structures, and facies sequences. The *Canadian Society of Petroleum Geologists* has established a tradition of holding a “core conference” every year in one of the government core laboratories in Calgary (other societies, such as the *Society for Sedimentary Geology* now hold their own workshops). Each contributor to the conference provides a display of a selected core from a producing unit, and uses this as a basis for presenting an interpretation of its geology, with emphasis on depositional environments, diagenesis, and petroleum migration history. The educational value of these conferences is inestimable, and they are always well attended. Some have resulted in the publication of well-illustrated proceedings volumes, for example, Shawa (1974), Lerand (1976), and McIlreath and Harrison (1977). As of Spring 2014 the *Society for Sedimentary Geology (SEPM)* had published 22 “Core Workshop” notes.

The use of well cuttings as illustrative material of this type is clearly limited. However, cuttings may be sampled routinely for petrographic studies, using etching and staining techniques on the raw, unwashed cuttings or preparing polished or thin sections. Fortunately, very small samples are adequate for this kind of work.

Sampling for biostratigraphic purposes should always be carried out on the unwashed rather than the washed cuttings. Depth control is, of course, better for core, but in petroleum wells, there is rarely adequate core for routine biostratigraphic sampling. Very rarely a petroleum exploration well may be drilled by continuous coring for stratigraphic research purposes, and these provide ample sample material free of the problems of sample caving and depth lag. The same is true, of course, for DDH cores. The quantity of material required for biostratigraphic purposes depends on the fossil type under investigation. A few hundred grams is usually adequate for palynological purposes, whereas to extract a representative conodont suite from sparsely fossiliferous carbonate sediments may require several kilograms of material. In the latter case, samples from several depth intervals may have to be combined.

2.3.4 Plotting the Section

Well logging is a routine procedure, and most organizations provide standard forms for plotting graphic logs, with a set of standard symbols and abbreviations. That used by the American Stratigraphic Company and Canadian Stratigraphic Services is typical. An example is illustrated in Fig. 2.30. Lithology is shown by color in a column near the center of the log, and accessories, cements, fossil types, and certain structures are shown by symbols. To the left of this column are columns for formation tops, porosity type and

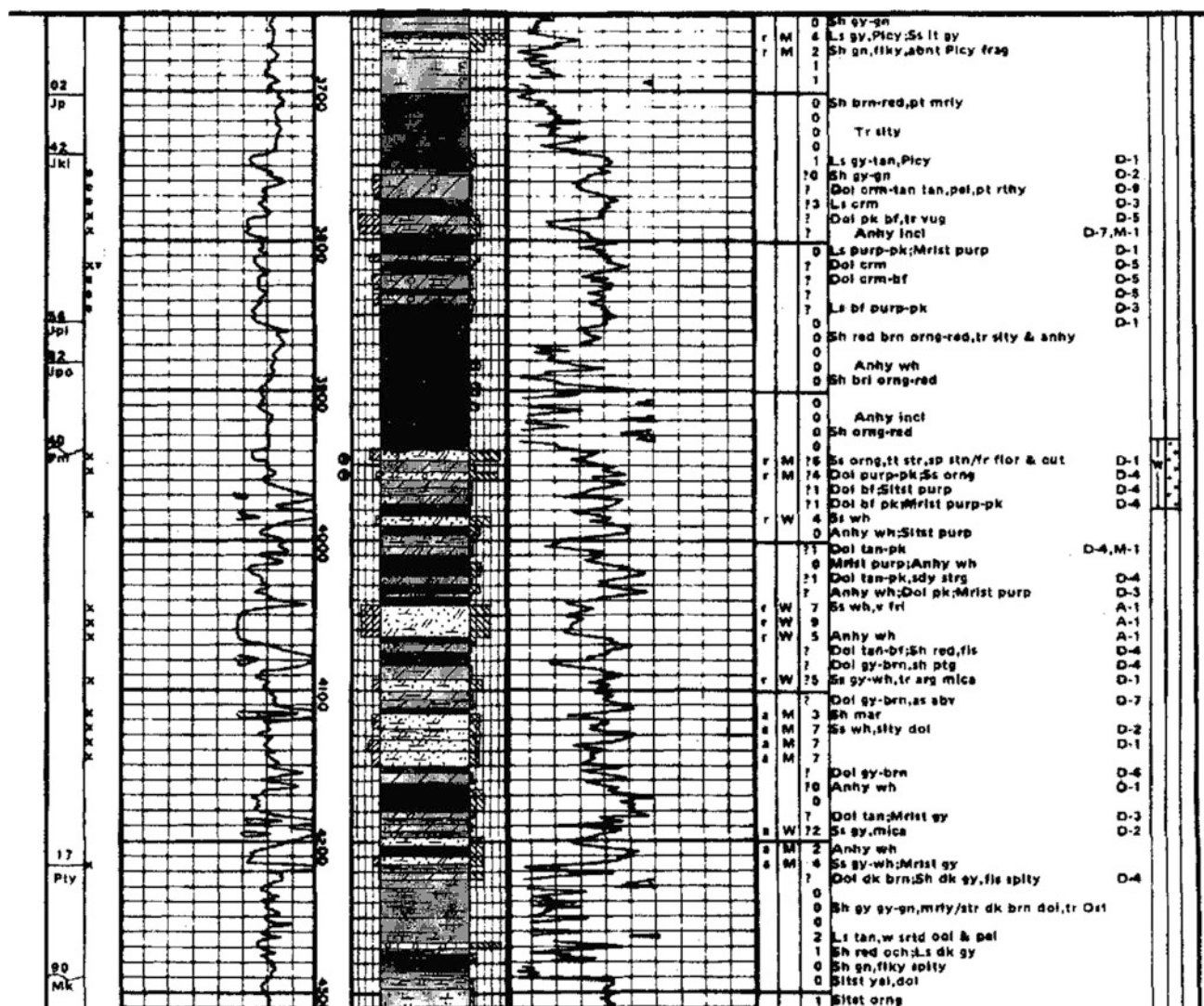


Fig. 2.30 Example of part of a log produced by the American/Canadian Stratigraphic Company

porosity grade (amount). Formation tops are shown by a formation code. They are interpreted and may be subject to revision. Porosity type, is given in a standard code or symbol and porosity grade by a crude graph based on visual estimates. The depth column may be used for symbols to indicate hydrocarbon shows or stains. To the right of the lithology column is a column for crystal or detrital grain size, based on visual estimates or measurements against a grain-size comparison set (Fig. 2.5). Both to the left and right of the lithology column are spaces for selected petrophysical logs. On the right-hand side of the log there, is a space for typing in an abbreviated description of each lithologic interval. The American/Canadian Stratigraphic Company system uses a list of more than 450 abbreviations, covering almost every conceivable descriptive parameter. Remaining columns are used for grain rounding and sorting and for engineering data.

Much of this detail is not necessary for basin analysis purposes. Figure 2.31 illustrates the more limited range of symbols and codes used by Tassonyi (1969) in a study of the subsurface stratigraphy of the Mackenzie Basin in northern Canada. Figure 2.32 illustrates one of his graphic logs. This style emphasizes lithology and other important stratigraphic variables.

2.4 Petrophysical Logs

A wide range of physical parameters can be measured using tools lowered down a petroleum exploration hole. Because of the method of data acquisition these are commonly called by the alternative name **wireline logs**. These tools provide information on lithology, porosity, and oil and water saturation (Table 2.3). In many cases, the measurements are not

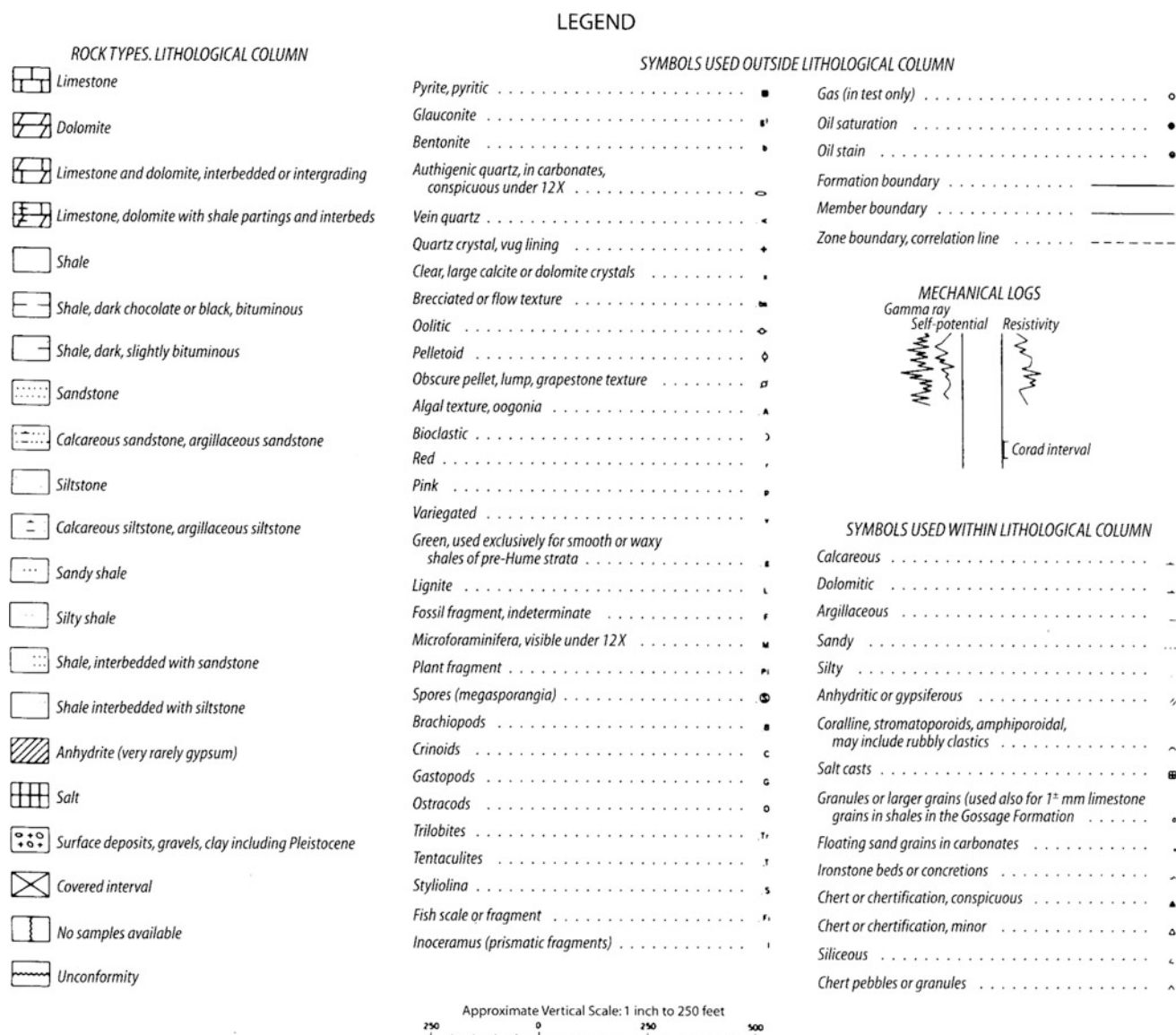


Fig. 2.31 Codes and symbols used in a regional subsurface study of Paleozoic and Mesozoic stratigraphy in the Mackenzie Valley region, Northwest Territories (Tassonyi 1969)

direct, but require interpretation by analogy or by correlating values between two or more logs run in the same hole. The subject of petrophysics is a highly advanced one and is beyond the scope of this book. Some approaches are described by Pirson (1977); others are given in the various interpretation manuals issued by the logging companies. Some excellent texts that discuss geological interpretations are those by Cant (1992) and Doveton (1994). Whittaker (1998) provided a more recent review of petrophysical logging methods.

In this section, some of the principal log types are described briefly, and some demonstrations of their utility are given. Petrophysical logs are used routinely by stratigraphers and basin analysts to provide information on lithology and to aid facies analysis, as discussed in Sects. 1.

4.3 and 3.5.10. The use of the gamma ray and other log types in stratigraphic correlation is discussed in Sect. 6.2.

2.4.1 Gamma Ray Log (GR)

This log measures the natural radioactivity of the formation, and therefore finds economic application in the evaluation of radioactive minerals, such as potash or uranium deposits. In sedimentary rocks, radioactive elements (potassium, thorium) tend to concentrate in clay minerals, and therefore the log provides a measurement of the muddiness of a unit. Texturally and mineralogically mature clastic lithologies, such as quartz arenites and clean carbonate sediments, give a

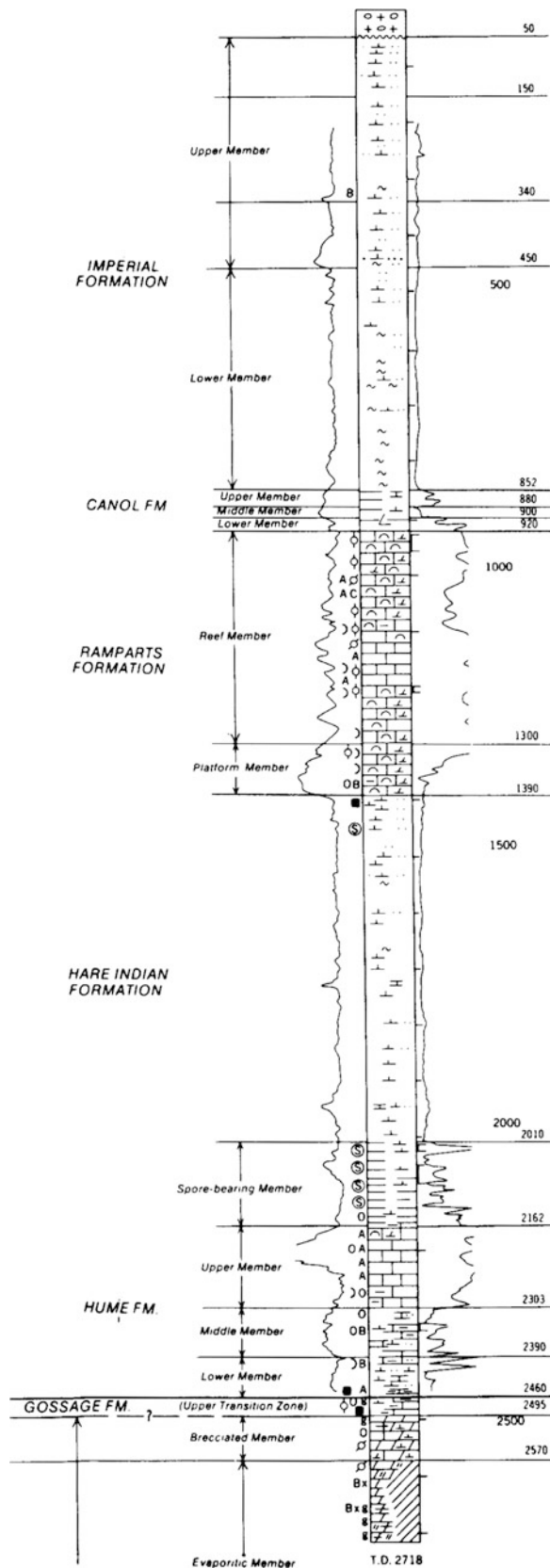


Fig. 2.32 A subsurface log drawn to emphasize stratigraphically important details, using the codes and symbols given in Fig. 2.31. Devonian, Mackenzie Valley, Northwest Territories. SP and resistivity logs have been redrawn beside the lithologic column (Tassonyi 1969)

low log response, whereas mudstones and certain special sediment types, such as volcanic ash and granite wash (which has a high feldspar content), give a high log response. Absolute values and quantitative calculations of radioactivity are not necessary for the stratigrapher. The shape of the log trace is a sensitive lithostratigraphic indicator, and the gamma ray log is commonly used in correlation and facies studies. The log has the advantage that gamma radiation penetrates steel, and so the log can be run in cased holes. Low GR readings (deflection to the left) correspond to cleaner, sandy parts of the succession. For clastic rocks, the variable-width column defined by the two log traces for each well provides a graphical portrayal of grain-size variations analogous to the variable-width log-plotting methods recommended for drawing surface sections (Sect. 2.2.4). The gamma ray log is therefore widely used for plotting interpretive sample logs of subsurface clastic sections, and for log-shape studies. An example is illustrated in Fig. 2.33, showing how “upward-fining” and “upward-coarsening” cycles commonly yield a distinctive signature on gamma ray logs (see also Fig. 3.61).

2.4.2 Spontaneous Potential Log (SP)

The curve is a recording of the potential difference between a movable electrode in the borehole and the fixed potential of a surface electrode. SP readings mainly record currents of electrochemical origin, in millivolts, and are either positive or negative. There are two separate electrochemical effects, as illustrated in Fig. 2.34. When the movable electrode is opposite a muddy unit, a positive current is recorded as a result of the membrane potential of the mudstone. The latter is permeable to most cations, particularly the Na^+ of saline formation waters, as a result of ion exchange processes, but is impermeable to anions. A flow of cations therefore proceeds toward the least saturated fluid, which in most cases is the drilling mud in the hole (log deflection to the right).

Opposite permeable units such as porous limestones and sandstones there is a liquid junction potential that generates a negative potential in the movable electrode. Both anions and cations are free to diffuse into the drilling mud from the more concentrated saline formation waters, but Cl^- ions have the greater mobility, and the net effect is a negative charge (deflection to the left).

The SP log trace, particularly in clastic sequences, is very similar in shape to that of the GR log (examples are given in Figs. 2.34, 2.36, 3.63 and 3.64), and the two may be used alternatively for correlation purposes, as illustrated in Fig. 6.3. The SP curve is normally smoother, and this log type does not offer the same facility for identifying thin beds. SP deflections are small where the saltiness and resistivities of the formation fluids and the drilling mud are similar.

Table 2.3 The major petrophysical log types and their uses

Log	Property measured	Unit	Geological uses
Spontaneous potential	Natural electric potential (compared to drilling mud)	Millivolts	Lithology (in some cases), correlation, curve shape analysis, identification of porous zones
Resistivity	Resistance to electric current flow	Ohm-metres	Identification of coals, bentonites, fluid evaluation
Gamma-ray	Natural radioactivity-related to K, Th, U	API units	Lithology (shaliness), correlation, curve shape analysis
Sonic	Velocity of compressional sound wave	Microseconds/metre	Identification of porous zones, coal, tightly cemented zones.
Caliper	Size of hole	Centimetres	Evaluate hole conditions and reliability of other logs
Neutron	Concentrations of hydrogen (water and hydrocarbons) in pores	Percent porosity	Identification of porous zones, cross-plots with sonic, density logs for empirical separation of lithologies
Density	Bulk density (electron density) includes pore fluid in measurement	Kilograms per cubic metre (gm/cm ³)	Identification of some lithologies such as anhydrite, halite, non-porous carbonates
Dipmeter	Orientation of dipping surfaces by resistivity changes	Degrees (and direction)	Structural analysis, stratigraphic analysis

2.4.3 Resistivity Logs

Most rock types, in a dry state, do not transmit electric currents and are therefore highly resistive. The main exception consists of those rocks with abundant clay minerals. These transmit electricity by ion exchange of the cations in the clay lattice. In the natural state, rocks in the subsurface are saturated with water or hydrocarbons in pore spaces. Formation waters are normally saline and thus act as electrolytes. The resistivity therefore depends on the salinity and the continuity of the formation waters. The latter depends, in turn, on porosity and permeability, so that resistivity is lowest in units such as clean sandstone and vuggy dolomite and highest in impermeable rocks, for example, poorly sorted, dirty, silty sandstones and tight carbonates. Evaporites and coal are also highly resistive. Metallic ores have very low resistivity. Oil is highly resistive and so, under certain conditions, resistivity tools may be used to detect oil-saturated intervals.

A wide variety of resistivity measurement tools has been devised, as listed below. Published logs are commonly identified by the appropriate abbreviation, such as shown in Fig. 6.3.

Electrical survey (ES)
 Laterolog¹ (LL)
 Induction-electrical survey (IES)
 Dual induction laterolog (DIL)
 Microlog
 Microlaterolog

¹These are registered trade names for tools developed by Schlumberger Limited.

The conventional electrical survey was, together with the SP log, the only logging tool available for many years, during the early days of petrophysical logging before the war. An electrical current is passed into the formation via an electrode, and this sets up spherical equipotential surfaces centered on the electrode-rock contact. Three additional electrodes are positioned on the tool to intersect these surfaces at set distances from the first electrode. The standard spacing is

short-normal electrode: 40.6 cm (16 in.)
 medium-normal electrode: 1.63 m (64 in.)
 lateral electrode: 5.69 m (18 ft 8 in.)

The wider the spacing the deeper the penetration of the current into the formation. This permits comparisons between zones close to the hole, permeated by drilling mud, and uninvaded zones further out (Fig. 2.35). The wide spacing of the electrodes also means that the ES tool is not sensitive to thin beds, and so it is not a very satisfactory device for stratigraphic studies.

The laterolog uses an arrangement of several electrodes designed to force an electrical current to flow horizontally out from the borehole as a thin sheet. A monitoring electrode measures a variable current that is automatically adjusted to maintain this pattern as the tool passes through lithologies of variable resistivity. This device is much more responsive to thin beds. Examples, run together with a SP survey and plotted on a logarithmic scale, are shown in Fig. 2.36.

Induction logs were developed for use with oil-based drilling muds which, because they are nonconductive, make the use of electrodes unsatisfactory. A high-frequency alternating current is passed through a transmitting coil, creating a magnetic field that induces a secondary current to flow in the surrounding rocks. This, in turn, creates a

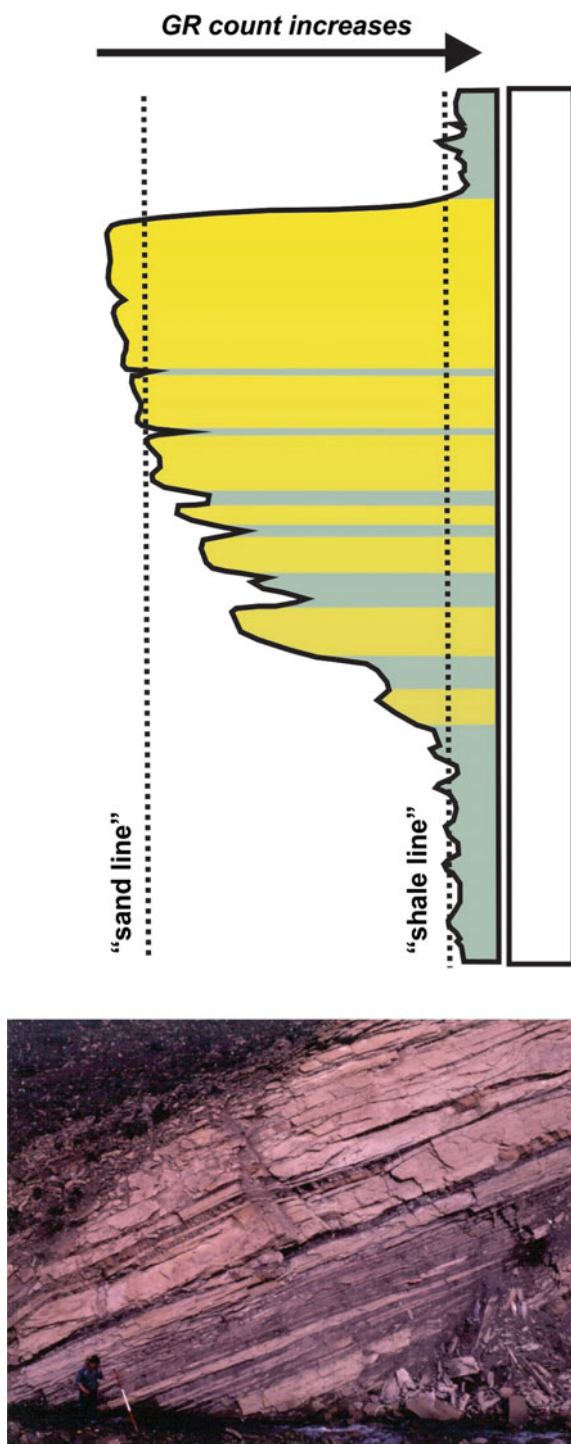


Fig. 2.33 The gamma ray log. Radioactive traces of uranium, radium, thorium and potassium are concentrated in clay minerals. Gamma-ray readings are therefore a measure of the “clayeyiness” of the sediments. The gamma ray log is therefore an excellent recorder of sand-shale variations, as in this “upward-coarsening” or “funnel-shaped” profile, characteristic of a deltaic succession. The outcrop example is a deltaic profile in the Tertiary Eureka Sound Group of the Canadian Arctic Islands

magnetic field that induces a current in a receiver coil. The strength of the induced current is proportional to formation conductivity.

The DIL survey is a combination of two induction devices and a laterolog device, with different formation penetration characteristics. It is normally run with a SP tool. An example is illustrated in Fig. 2.36. Separation between the three resistivity curves occurs opposite permeable units, where the low resistivity of the saline formation waters contrasts with the higher resistivity of the zone close to the borehole, which has been invaded by low-salinity drilling mud (Fig. 2.35). The deep-penetration induction log (ILD) therefore gives the lowest resistivity reading and the shallow penetration laterolog (LL8) the highest. The presence of these permeable zones is confirmed by the SP curve, which has a pattern very similar to that of the induction logs in the example shown.

The Microlog is the most sensitive device for studying lithologic variations in thin bedded sequences. Its primary petrophysical purpose is to measure the resistivity of the invaded zone. The principle is as follows: during the drilling process mud enters permeable beds and hardens on the surface as a mud cake up to about 1 cm thick. No mud cake is formed opposite impermeable units. The microlog tool consists of two closely spaced electrodes. Opposite the mud cake, they record the low resistivity of the mud itself, whereas opposite impermeable units, they record the generally higher resistivities of uninvaded rocks. The presence of mud cake is confirmed by a caliper log, which is sensitive to the slight reduction in hole diameter when a mud cake is present. Muddy units commonly cave and give a very erratic caliper log. The microlog readings are also likely to be erratic because of the poor electrode contact. All these responses are illustrated in Fig. 2.37. The Microlaterolog is a more sensitive version of the Laterolog. Use of both the microresistivity devices permits accurate determinations of permeable sandstone and carbonate thickness, of considerable use in regional subsurface facies studies (Chaps. 5 and 6).

2.4.4 Sonic Log

The sonic tool consists of a set of transmitters for emitting sound pulses and a set of receivers. The fastest path for sound waves to travel between transmitters and receivers is along the surface of the hole, in the rock itself rather than through the mud or the actual tool. The time of first arrival of the sound pulses is therefore a measure of formation density, which depends on lithology and porosity. The sonic log is normally run with a GR tool.

The sonic tool has two main uses, the estimation of porosity where lithology is known, and the calibration of regional seismic data (Sect. 6.3.1). For the latter purpose,

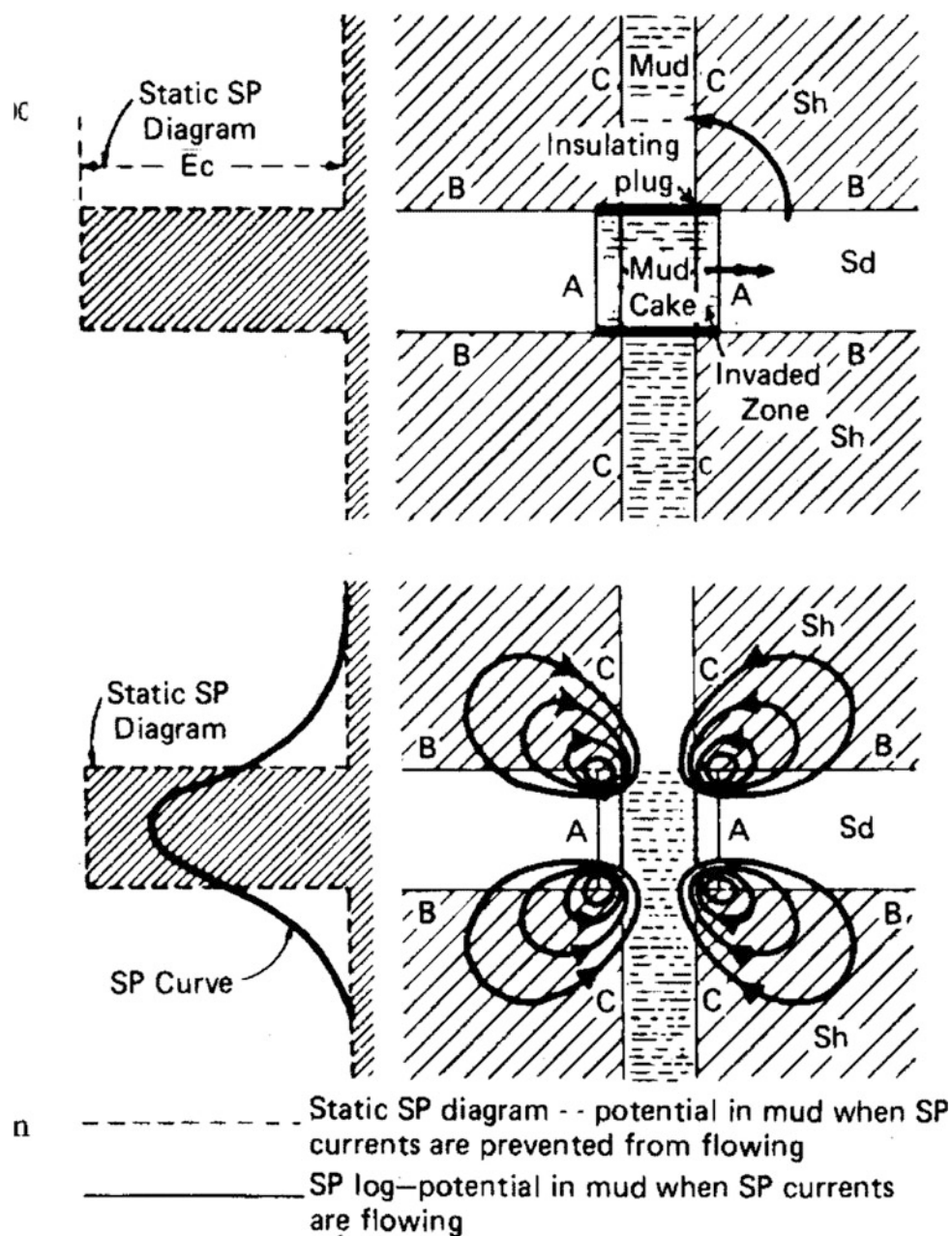


Fig. 2.34 The principle of the SP log

a computer in the recording truck at the wellhead integrates the travel time over each increment of depth as the survey is run. Every time this amounts to 1 ms a small pip appears on a track down the center of the log.

2.4.5 Formation Density Log

The tool contains a radioactive source emitting gamma rays. These penetrate the formation and collide with it, in a process known as Compton scattering. The deflected gamma rays are recorded at a detector on the tool. The rate of

scattering is dependent on the density of the electrons in the formation with which the gamma rays collide. This, in turn, depends on rock density, porosity, and composition of the formation fluids.

2.4.6 Neutron Log

For this log, a radioactive source emitting neutrons is used. These collide with the nuclei of the formation material, with a consequent loss of energy. The greatest loss of energy occurs when the neutron collides with a hydrogen nucleus,

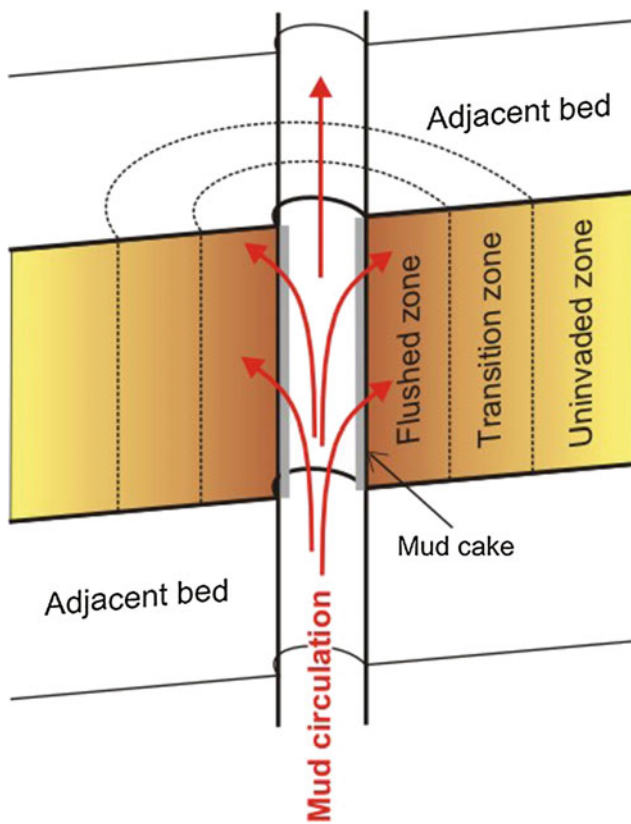


Fig. 2.35 Porous beds adjacent to a drill hole are flushed and filled with the drilling mud. This also leaves a “mud cake” adhering to the wall of the hole

and so the total loss of energy depends mainly on the amount of hydrogen present, either in formation waters, hydrocarbons, or bound water in clay minerals, gypsum, etc. The detector measures either the amount of scattered low-energy neutrons or the gamma rays emitted when these neutrons are captured by other nuclei.

2.4.7 Crossplots

Where the formation is known to consist of only two or three rock types, such as sandstone-siltstone-mudstone or limestone-dolomite, combinations of two or more logs can be used to determine lithology, porosity, and hydrocarbon content. These crossplots are therefore of considerable stratigraphic use where only generalized lithologic information is available from well cuttings.

For clean, nonmuddy formations, combinations of the sonic, formation density, and neutron logs are the most useful. For example, Figs. 2.38 shows the neutron-density combination. These logs are commonly calibrated in terms of apparent limestone porosity; that is, if the rock is indeed limestone, its porosity has the value indicated. For other lithologies, the porosity estimate will be in error, but by reading values for both logs, it is possible to determine both lithology and correct porosity. The curves in Fig. 2.38 give ranges of actual porosity readings for four principal rock types. To show how this graph can be used, compare it to the neutron-density overlay given in Fig. 2.38. Such overlays may be provided on a routine basis by the logging company or can be redrawn on request. The thick sandstone interval at the top can be recognized by the distinctly higher readings on the density curve. Values range from about 4 to 12, whereas those on the neutron curve are mostly close to zero. Examination of Fig. 2.38 shows that only sandstone can give this combination. The thick limestone at the bottom of the overlay in Fig. 2.38 is indicated by the near coincidence of the two curves. Dolomite or anhydrite would be suggested by relatively higher neutron readings. Mudstones can commonly be recognized by very high neutron readings relative to density, because of the abundant water in the clay mineral lattice. This would be confirmed by the gamma ray response or the SP or caliper log, if available.

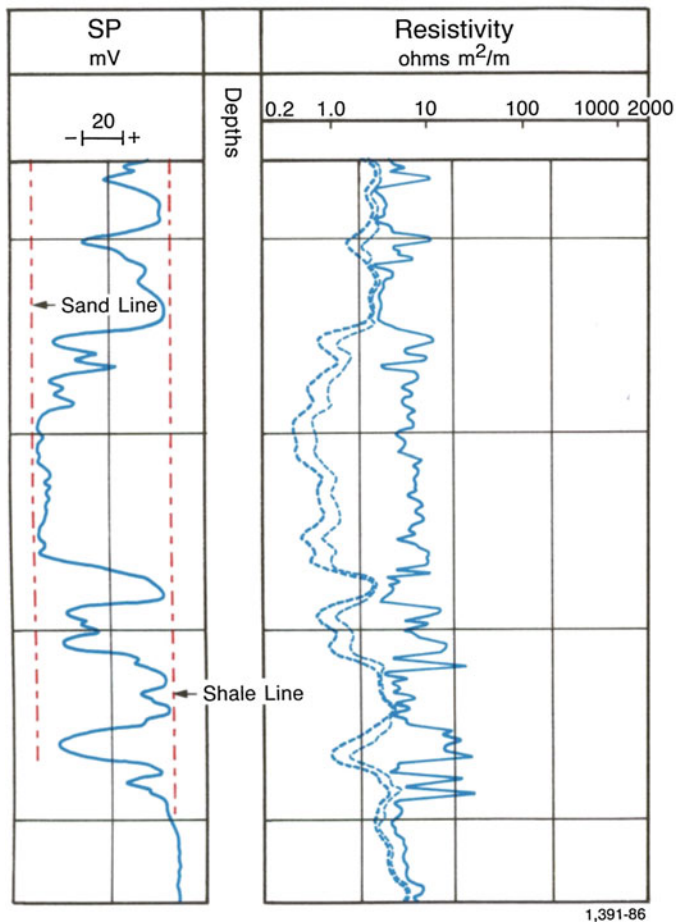
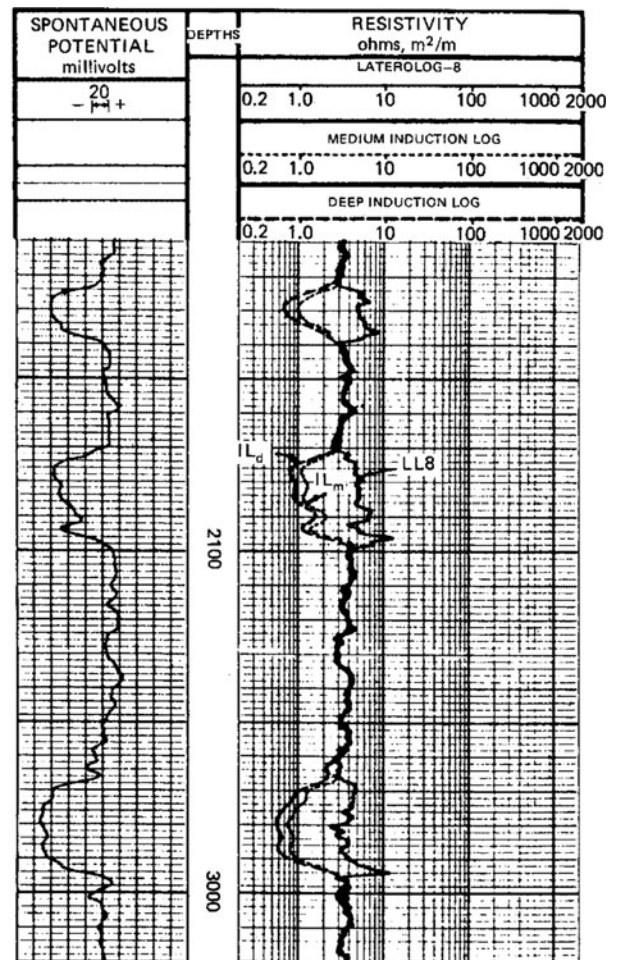


Fig. 2.36 Examples of SP and resistivity logs. Impermeable beds, such as shales, are indicated where the Laterolog curves combine. This is confirmed by the deflection of the SP curve towards the shale line.



Permeable beds are indicated where the Laterolog curves diverge, indicating the different resistivity response between the invaded and uninvaded zone

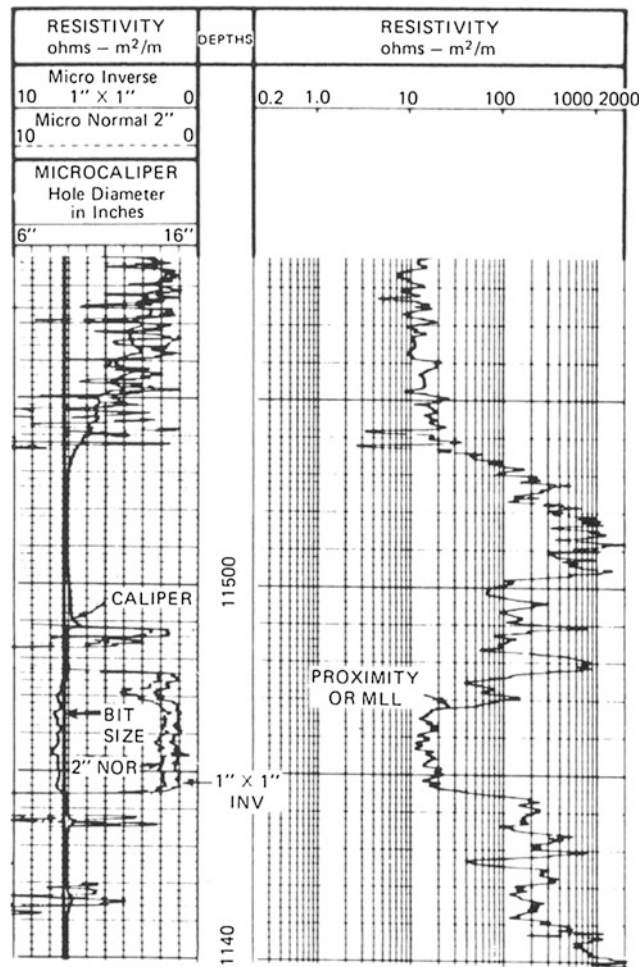
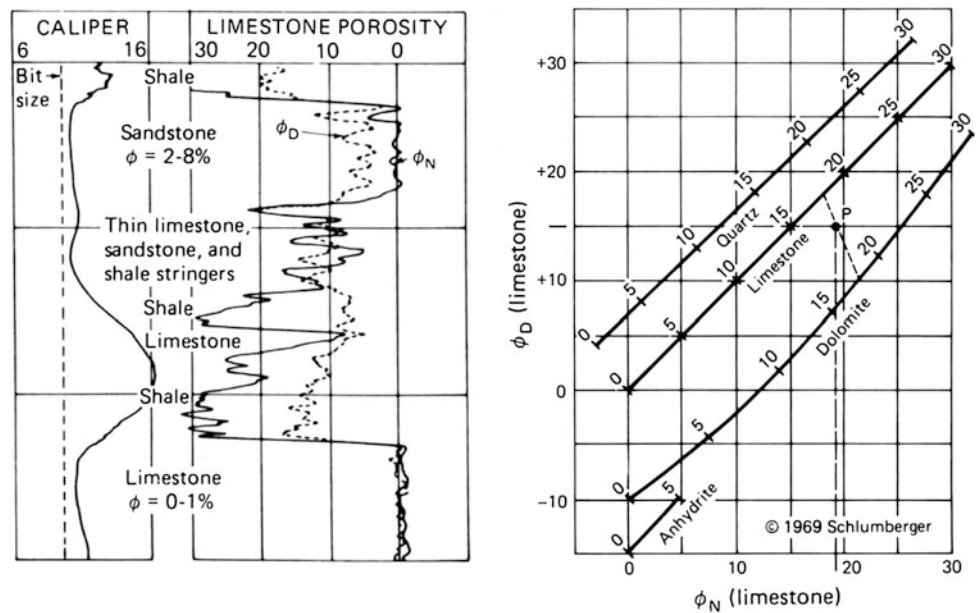


Fig. 2.37 Example of a Microlog and Caliper log (reproduced courtesy of Schlumberger Inc.)

Fig. 2.38 *Left* a neutron (ON): density (OD) crossplot, showing how readings of the two logs can be used to determine lithology and porosity (reproduced courtesy of Schlumberger Inc.). *Right* example of a neutron: density overlay, illustrating how curve separation and deflections can be used to determine lithology (reproduced courtesy of Schlumberger Inc.).



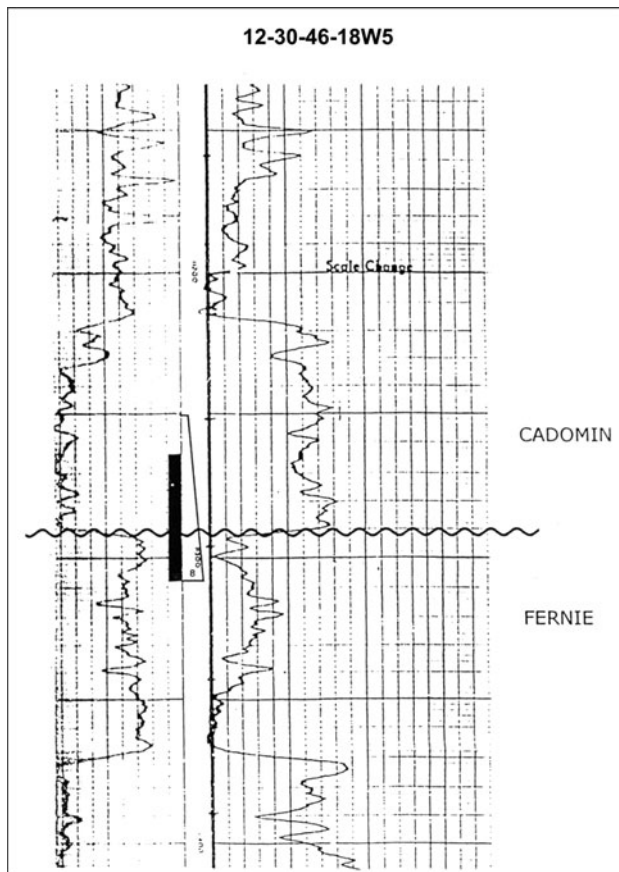


Fig. 2.39 Integrating core and log data is a very important and useful step in the documentation of subsurface stratigraphy and sedimentology. This example is from the Alberta Basin. The cored interval in the



well is shown by the *black bar* down the center of the wireline log. The contact between Fernie shales and siltstones and Cadomin conglomerates and sandstones is indicated on the core by a *red arrow*

2.4.8 Integrating Cores and Wireline Logs

The combination of core and petrophysical log data is a powerful one. An essential step is to locate the core on the petrophysical strip log by referring to the core depth information on the core box, as shown in Fig. 2.39. In this example, an important regional bounding surface and disconformity that can be traced for hundreds of kilometres shows up as a sharp discontinuity in the log and can be identified by a sharp lithologic break in the core (red arrow). Typically, regional cross-sections constructed from petrophysical logs (e.g., Figs. 5.4 and 5.5) are used to document the regional stratigraphic variability, while the core is used to highlight local facies characteristics, particularly vertical facies changes, contact relationships and sedimentary structures, including crossbedding and trace fossils.

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