A list of features which can be observed (measured or registered) in sedimentary rocks:

1. Textures – grain size, sorting, grain shape etc.
2. Grain orientation – fabric.
3. Sedimentary structures and their orientation.
4. Fossils.

   A Preservation or impressions, casts, or the fossils themselves, and their mode of occurrence.
   B Trace fossils.

5. Colour.
6. Resistance to weathering and erosion.
7. Composition (a) Mineral (b) Chemical.
8. Thickness and geometry of beds.
9. Variations in texture and composition within a bed, e.g. increase in grain size upwards or downwards in the bed (grading or inverse grading).
10. Type of contact between beds (e.g. erosional contact, conformable contact, gradational contact).
11. Association or any tendency to statistical periodicity in the features of the strata in a profile – bed types, structures.

These observations form the basis for defining facies, which are a synthesis of all the data listed above which can be used to group certain types of rocks. They may be genetic facies, i.e. strata which one assumes have formed in the same manner. All strata which contain criteria which indicate that they were deposited in shallow water can be described (in reality interpreted) as shallow water facies. In the same way we have fluvial facies, deep water facies, evaporite facies, and so on. The facies concept can also be used to distinguish between different rock compositions (lithologies), e.g. carbonate facies, sandstone facies.

2.16 Sedimentary Structures

By sedimentary structures we mean structures in sedimentary rocks which have formed during or just after deposition. We distinguish between *primary* structures which are formed at the time of deposition of the sediments, and *secondary* structures which are formed after deposition.

2.17 Layering and Lamination

Most sedimentary rocks exhibit some lamination or bedding, but we also have massive (unlaminated) rocks. Lamination records variations in the sediment composition as successive depositional layers are draped over the contours of the sedimentary surface. The variations may reflect different grain sizes, sorting, mineral composition or organic matter. *Laminae* are less than 1 cm thick. Units greater than 1 cm are called *beds*. A bed will contain sediments which have been deposited by the same sedimentary processes. Some sedimentary processes, for example deposition of a turbidite bed, may be fairly rapid. Migration of a sand dune to give cross-bedding takes somewhat longer, while deposition of a clay bed from suspended material may take a very long time.

Graded beds have a grain size which tends to decrease upwards within the bed. The opposite is called *inverse grading. Normal grading* may be due to deposition from suspension, when the largest particles tend to fall to the bottom first, as with turbidites, or to flow velocities dropping off during deposition in a river.

Inverse grading may be due to increasing flow velocity but if the increase in velocity is too high, the result will be erosion. The supply of coarse material during transport and deposition may also produce inverse grading. In high density sediment currents (debris flows) we may get inverse grading; smaller particles sink more easily to the bottom between the large particles. Massive beds, or at any rate reasonably massive beds without visible lamination or bedding, may be formed during very rapid deposition of sediments from suspension. X-ray photography of apparently massive sediments nevertheless usually reveals the presence of weak lamination even in sand. Massive sand beds occur due to rapid fall out from suspension. In mudstones the primary lamination may be destroyed by intense bioturbation.

On the surface of laminated sediment we may find erosion structures.

Water running over a plane surface, e.g. beach sand, will produce small-scale, branched (dendritic) erosion marks called *rill marks*. The flow of water may be due to runoff from big waves or from groundwater seepage at low tide. These structures are good indicators of inter- or supratidal environments, but they are seldom preserved because they are usually destroyed when the water level rises again. Raindrop imprints are often preserved on bedding surfaces, and are good indicators of subaerial exposure.

2.18 Bedforms

Bedforms are morphological features resulting from the interaction between particular types of flow and the sediment grains on the bottom. A specific type of bedform will only form within a limited flow velocity range and is also dependent on the availability of grain sizes which can be moved by that flow.

Current ripples form in fine-grained sand when the velocity exceeds the lower limit for sediment movement.

Ripples and dunes have a stoss side upstream where erosion takes place and a lee side on which deposition takes place (Fig. 2.14). They therefore migrate as a result of the combined effects of erosion and deposition. Current ripples form in fine-grained sand when the velocity exceeds the lower limit for sediment movement. Sections through ripples show inclined foreset laminae, a structure called "small-scale cross-lamination". Ripples may also form in coarser sand but there is an upper limit of 0.6–0.7 mm for the grain diameter. Ripples are less than 3–5 cm high, and may

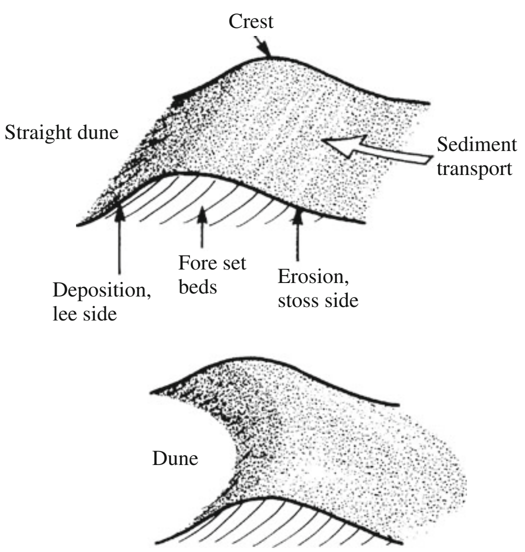

Fig. 2.14 Principle illustration of dune and cross-bedding

Fig. 2.15 Aeolian dunes several metres high in the Navajo Sandstone (Jurassic)

have a wavelength of up to 40 cm. The ripple index is an expression of the ratio of the wavelength divided by the wave height, and varies between 10 and 40. Waves may generate oscillatory flow that produces symmetrical ripples, which have foreset laminae pointing in both directions.

Dunes are similar to ripples in shape and structure, and form in coarse-, medium- and fine-grained sand, but require significantly higher flow velocities for their formation. Dunes range in height from 5 cm up to several metres, and wavelengths may exceed 10 m (Fig. 2.15).

Cross-bedding (large-scale cross-stratification) is seen in cross-sections through dunes (Fig. 2.16). Each lamination is called a *foreset bed* and represents the lee-side surface of a migrating dune. If the dunes have straight crests the foreset beds on the lee side will form a straight transverse plane (*tabular cross-bedding*). Curved dunes have rounded foreset beds, and in *trough cross-bedding* the laminae have a rounded surface which is concave in the downstream direction. The foreset lamination may form a relatively sharp angle with the underlying bed, or may have a more tangential contact. The latter is typical of trough-shaped sets.

Aeolian dunes may be many metres high, and their cross-bedding will then be correspondingly large (Fig. 2.15).

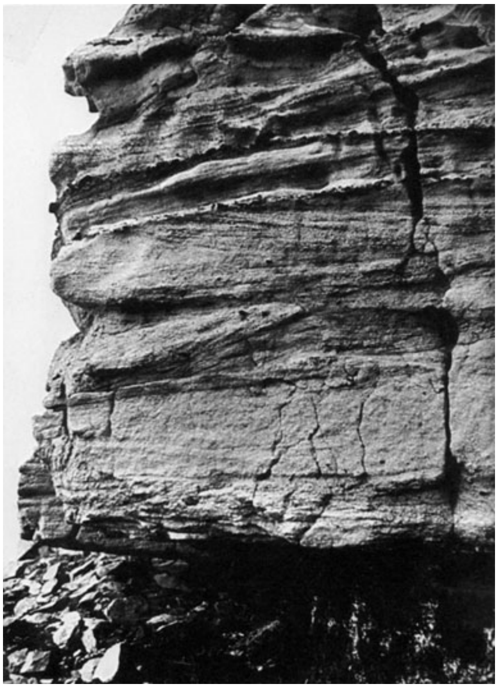

Fig. 2.16 Cross-bedded sandstone which represents the filling of a fluvial channel above a coal bed. The grain size fines upwards somewhat. It is largely trough cross-bedding represented here. From the Tertiary sequence of Spitzbergen. (Photo A. Dalland)

Whatever the size of the bedform, ripple movement provides the basic mode of migration. Seabed survey profiling records clearly show smaller ripples climbing the stoss sides of larger ones (so-called "megaripples", i.e. small dunes), which in turn are climbing the stoss sides of sandwaves.

Cross-sections through dunes show "large-scale cross-stratification", which is often referred to as "cross-bedding". This can be observed in real time on seabed video recordings made during periods of strong tidal current flow, where gradual forward movement of "megaripples" is seen, caused by sand cascading down the lee side after reaching the crest.

"Plane beds" (upper stage) may form when the shear stress against the bed exceeds the values which produce dunes. In cross-section we only see planar lamination, which is an internal structure, but on the bedding surface we may see very small ridges, which define a lineation called primary current lineation, parallel to flow.

At even higher velocities in relatively shallow water, standing waves may produce antidunes when the Froude number exceeds 0.8. The antidunes which are produced when standing waves are in phase with the bedforms develop resulting in low-angle cross-lamination which dips up-current.

Both ripples and dunes are formed through sand being transported along the bottom and deposited in sloping strata on the lee side of the structure. In consequence they always have dipping laminations *(foreset beds)* which may lie at an angle (angle of repose) of up to 35° to the surface of the bed, though such high angles are rather rare. Current ripples in plan view may be straight, or form curved patterns *(sinuous crests)*. Ripples with a symmetrical cross-section (symmetrical ripples) are formed by waves as a rule. Asymmetrical ripples are formed by a predominantly unidirectional current and their steeper side faces downstream. Ripples with a high sinuosity are also asymmetrical in most cases.

Tongue-shaped *(linguoid)* ripples have a very high sinuosity and asymmetry and are usually formed in shallower water or under higher velocities than straight-crested types. Wave ripples in particular may split laterally into two ripples. This is called bifurcation. In intertidal zones ripples formed at high tide may be eroded at low tide, and the crests become flattened. When the tidal flat is submerged at high tide it may also be below the normal wave base, resulting at slack water in deposition of clay which tends to collect in the ripple troughs. Current ripples with thin lenses of clay between them constitute *flaser bedding*. Wind may generate waves moving in different directions, particularly at very low water, so that we find two or more sets of ripples at an angle to each other *(interference pattern)*. In most cases each bed with current ripples represents a sort of equilibrium with deposits reflecting current patterns. Isolated sand lenses in clay are called *lenticular bedding*.

Normally current ripples form completely horizontal beds. In some cases, however, we find examples of current ripples appearing to climb downstream in relation to the horizontal plane. They form several sets of cross-laminated beds delimited by erosion boundaries, but with small internal erosion planes. These are called *climbing ripples* and are due to sedimentation taking place so rapidly that, in contrast to normal ripples, there is no equilibrium between erosion and

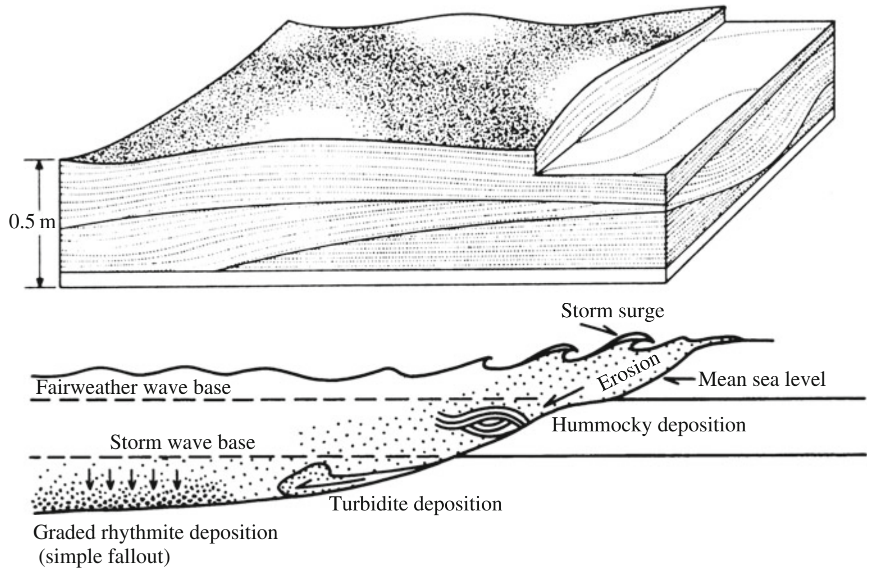

Fig. 2.17 Hummocky stratification (After Harms et al. 1975, Walker 1982)

sedimentation. Climbing ripples are therefore typical of environments with rapidly declining flow velocity and consequently a high rate of sedimentation.

Sandwaves are large-scale transverse bedforms, generally 2–15 m high, with a wavelength of 150–500 m. They may be formed at flow velocities of 65–125 cm/s. Cross-stratification may be symmetrical or asymmetrical on both sides of the sandwave, depending on the relative strength of the opposing currents.

At velocities of less than 1 m/s *sand ribbons* may be deposited – longitudinal bedforms developed parallel to the currents. Sand ribbons are typical of subtidal environments (20–200 m), and they may be up to 20 km long, 200 m wide and less than a metre thick.

Relatively low-energy environments (< 50 cm/s) are characterised by *sand patches* and mud. The sand forming the patches probably only moves during storms. Lateral structures are typically current ripples and small dunes.

Sandwaves often have current ripples ("smaller dunes") on their surface. This may also be the case with dunes. Bedforms are a function of both flow velocity and grain size. Current ripples are formed only in silt and medium-grained sand, while dunes require medium to coarse sand. Upper flow regime plane beds which have an internal structure of planar lamination are formed when the Froude number is about 0.6–0.8. Plane beds typically develop in beach sand. A well-developed lineation on the bedding surface parallel to the direction of sediment transport is typical of plane beds (Fig. 2.9). Antidunes are formed by higher velocities in the upper flow regime; the absolute flow velocities required are lower when the water is shallow.

Below the ordinary, fair-weather wave base we find different types of sedimentary structures from those formed through constant wave action. During storms in nearshore areas traction currents may develop and carry fine material (fine sand) from the beach out to greater depths. This material is deposited as *hummocks* consisting of parallel laminae which form dome-shaped structures (Fig. 2.17). Because deposition of beds of this type takes place during short periods during storms, they are often reworked by bioturbation near the top. Hummocky stratification is common in sections through some shallow marine deposits and wave-dominated deltas.

2.19 Erosion Structures on the Underside of Sand Beds *(Sole Structures)*

When sand is deposited rapidly over finer sediments (silt and clay) there will also in very many cases be an initial erosional phase, so that erosion hollows