with a time scale with periods of normal and reversed magnetic field. We thus find that we can divide geological time into long periods with dominantly normal or reversed polarity (Fig. 7.11). Within these we also find several shorter intervals when the magnetic field switched between the two polarities. Since we must assume that the switching between normal and reversed magnetism has taken place simultaneously and suddenly all over the world, such physical changes offer an ideal basis for correlation.

There are often major practical problems, however, since many periods of the Earth's history are characterised by a predominance of successions with rapidly changing reversals. Where we have many measurements and continuous profiles, e.g. in deep-sea cores, we will be able to correlate with relative certainty on the basis of the longer periods of magnetic field stability. Volcanic rocks and sediments deposited in fluvial or shallow-water environments, however, will have numerous hiatuses between beds, hampering registration of continuous variations in the residual magnetism. During the last 700,000 years we have had apparently normal polarity, possibly with the exception of a short period about 200,000–300,000 years ago. If we find sediments or volcanic rocks with reversed magnetism, we know that they are highly probably more than 700,000 years old.

7.9 Sequence Stratigraphy

7.9.1 General Aspects

Sequence stratigraphy is defined as the subdivision of sedimentary basin fills into genetically related stratal packages bounded by unconformities and their correlative conformities. Thus, the concept of sequence stratigraphy is closely related to that of allostratigraphy. Allostratigraphic analysis applies bounding discontinuities, e.g. erosional surfaces and marine flooding surfaces, for recognition of sedimentary entities independent of any genetic model. Sequence stratigraphy applies allostratigraphic features to interpret the depositional origin of sedimentary packages by analysing these in a framework of transgressive-regressive developments producing base level changes.

The infilling of a basin is controlled by the interaction of tectonics and eustasy, producing base level changes which define the accommodation space for sediments to be deposited. This is the space or height between the seafloor and the sea level. Climate is an important factor determining the production and supply of sediments. The evolution of basin architecture is controlled by the balance between accommodation space and sediment supply. If sediment supply exceeds the accommodation space available, *progradational geometries* will be the result. If accommodation space and sediment supply are roughly balanced, *aggradational geometries* result. When sediment supply is less than the creation of accommodation space, *retrogradational geometries* are formed.

The major bounding and subdividing surfaces of a depositional sequence are commonly represented by: the lower and upper sequence boundaries, transgressive surfaces and maximum flooding surface (Fig. 7.12). These surfaces principally define three sediment bodies: lowstand systems tract, transgressive systems tract and regressive systems tract. The building blocks of the systems tracts are parasequences, forming parasequence sets.

7.9.2 Accommodation Space

Local accommodation space for sediments represents simply the water depth in the depositional area. A global factor influencing the accommodation space is the eustatic sea level stand which is defined by a combination of several factors. One of these is the volume of the ocean basins, which is believed to be mainly controlled by the rate of seafloor spreading. Young lithosphere is warm and buoyant, therefore it will rise and decrease the volume of the world ocean. On the contrary, old lithosphere is colder and denser, and sinks. Another factor contributing to ocean volume changes is the sedimentation rate.

The volume of water in the ocean basins is also a primary factor influencing eustatic sea level changes. Continental and mountain glaciations and deglaciations decrease and increase, respectively, the volume of ocean water. These developments are exemplified by the well-documented regressions and transgressions accompanying Quaternary glacial and interglacial periods (Fig. 7.13). Other factors influencing the volume of oceanic waters are the expansion of water with increasing temperature and the amount of continental groundwater and surface water.

Fig. 7.12 Depositional sequence portrayed in a depth-distance and a time-distance diagram. It shows the regional extent of the condensed section from deep to shallow water, with its time span strongly expanding from coastal to basinal areas. The time span of the sequence boundary unconformity decreases from marginal to basinal areas. Abbreviations of sequence elements: SB = sequence boundary, LST = low stand systems tract, TS = transgressive surface, MFS = maximum flooding surface, HST = high stand systems tract (modified after Loutit et al. 1988)

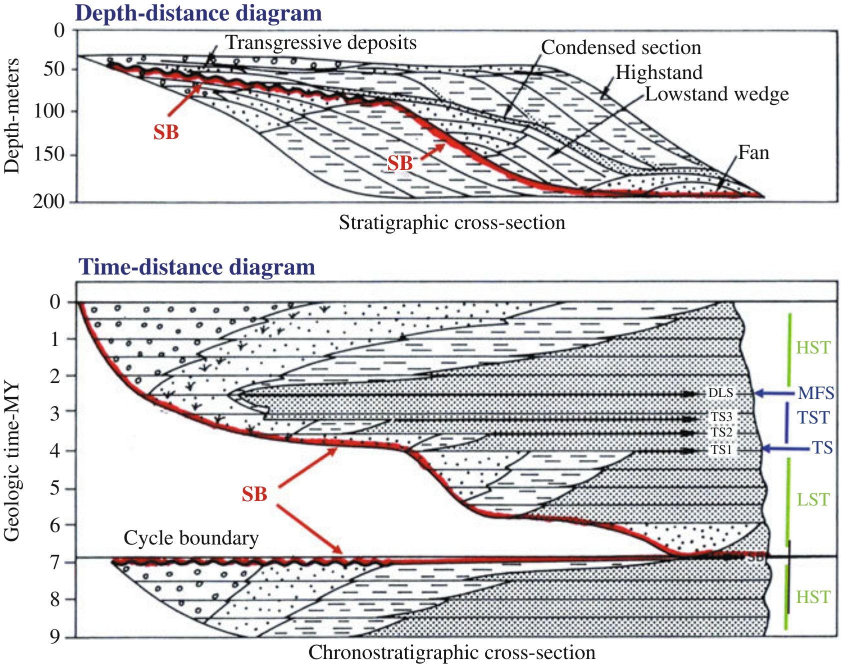
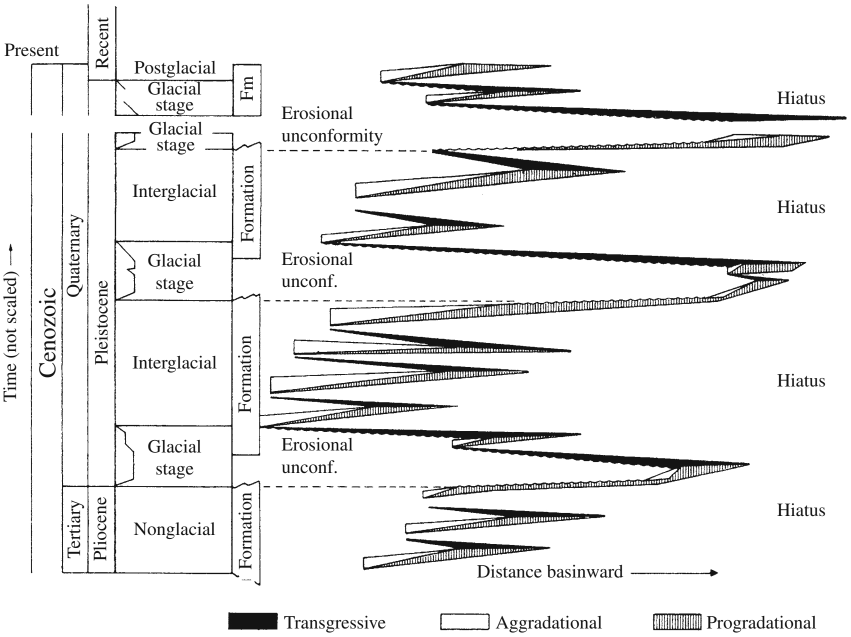


Fig. 7.13 Schematic illustration of transgressive-regressive cycles in the Quarternary, resulting from glacially-induced changes of the volume of ocean water. During a complete cycle, sedimentation takes place only during short episodes (note the three types of depositional architecture). During most of the time there is non-deposition or erosion (hiatus)



Tectonic movements result in transgressions and regressions of local to regional nature. These movements are driven by factors that affect how continental lithosphere floats on the asthenosphere, which is controlled by three main mechanisms: (1) Stretching of continental lithosphere resulting in replacement of continental lithosphere by denser and thinner astenosphere which sinks. (2) During stretching, continental lithosphere is heated, becomes less dense and tends to uplift. Subsequent cooling results in subsidence. (3) Weight of tectonic load added to lithosphere can produce subsidence e.g. wedges of fold and thrust belts pushed into foreland basins.

When analysing sedimentary successions, it is usually extremely difficulty to distinguish between the effects of eustatic sea level changes and tectonic movements. Therefore, in sequence stratigraphic studies, the phrase "relative sea level" is used to express the local sum of global sea level and tectonic movements.

7.9.3 Parasequences

Parasequences are sediment packages of genetically related beds representing a single minor transgression event followed by sediment progradation. In the marine realm parasequences are bounded by flooding surfaces. Most of the marine parasequences are formed in offshore shelf to shoreface environments, and show an upwards-coarsening development (Fig. 7.14). In coastal areas upwards-fining parasequences are formed during transgressions, encroaching over the supratidal zone, and contain shallowing-up subtidal, intertidal to supratidal strata (Fig. 7.15).

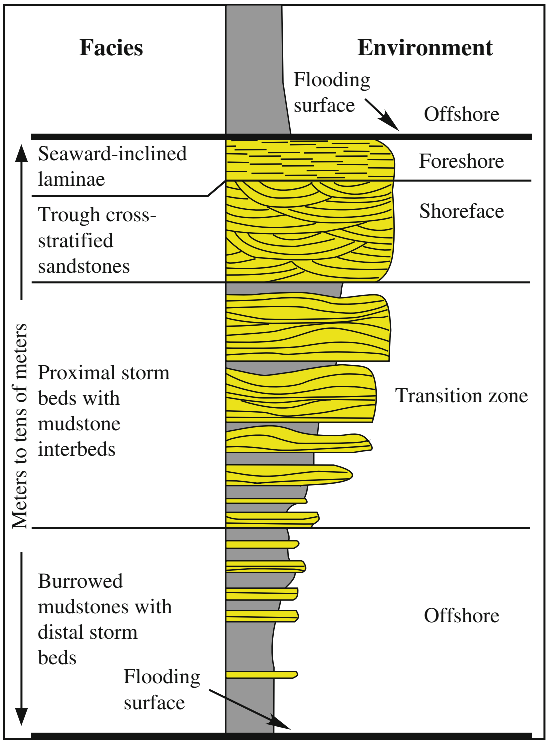


Fig. 7.14 Example of marine parasequence showing coarsening- and shallowing-upwards from offshore shales to foreshore sandstones (from University of Georgia web site, 2009)

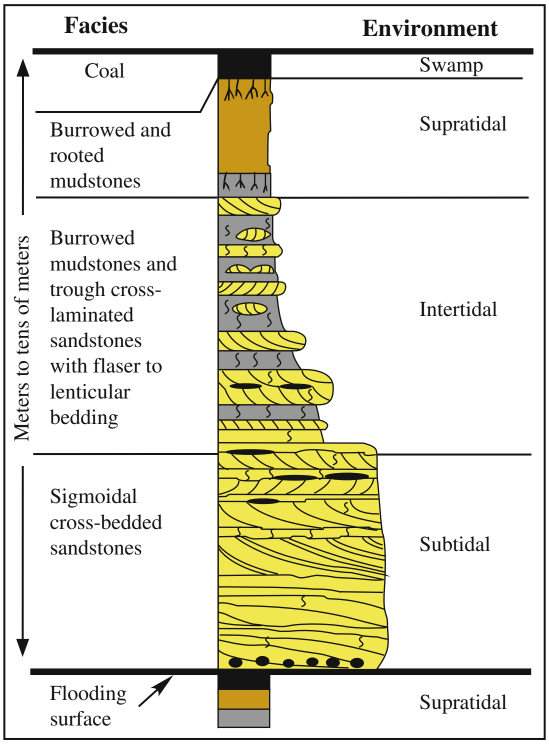


Fig. 7.15 Example of coastal parasequence showing fining- and shallowing-upwards from subtidal sandstones to supratidal swamp deposits (from University of Georgia web site, 2009)

Stacked parasequences form parasequence sets, which show stacking patterns according to their position in the sequence stratigraphic architecture (Fig. 7.16). If sediment supply exceeds the available accommodation space, progradational stacking geometry will be the result. If accommodation space and sediment supply are roughly balanced, aggradational geometries occur. When sediment supply is less than the creation of accommodation space, retrogradational stacking geometries are formed.

7.9.4 System Tracts

The lowstand systems tract is bounded by the sequence base and the transgressive surface (Fig. 7.12). It was deposited when the sea level was located at or below the shelf break. The shelf was exposed to erosion and crossed by rivers eroding incised valleys and transporting sediments to the shelf margin. The lowermost part of the lowstand systems tract is the basin floor fan,

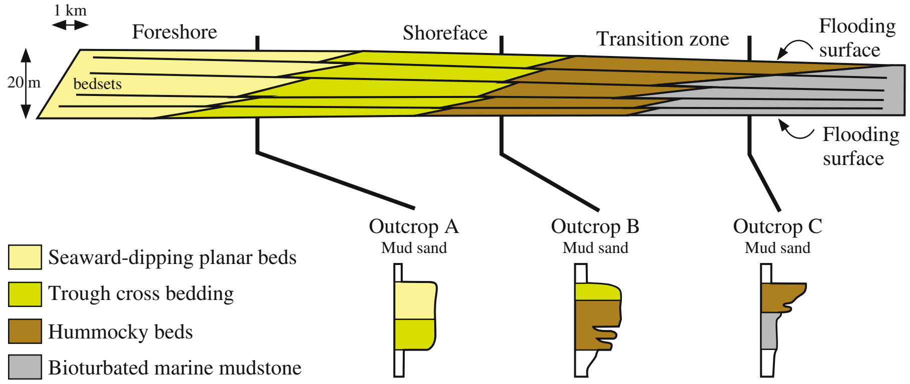


Fig. 7.16 Lateral and vertical relationships between parasequences forming a parasequence set, which progrades from foreshore to offshore shelf (from University of Georgia web site, 2009)

dominated by gravity-driven deposition of turbidite lobes and in feeder channels. The upper part of the lowstand systems tract is the lowstand wedge, which consists of progradational parasequences. Uppermost, estuarine sediments are deposited in drowned incised valleys (Fig. 7.17).

The transgressive systems tract is bounded by the transgressive surface and the maximum flooding surface. It is composed of retrogradational parasequence sets showing a generally upward-fining and upward-deepening development. This systems tract is generally thin because much sediment is trapped in estuaries, and the advancing transgression successively creates new accommodation space.

The highstand systems tract is developed between the maximum flooding surface and the upper sequence boundary. This systems tract represents a relatively thick succession of progradational parasequences showing an upward-coarsening and upward-shallowing development (Fig. 7.17). The parasequences downlap to the maximum flooding surface. The estuaries are now filled up by sediments, therefore the systems tract is characterised by outbuilding of deltas and shorelines.

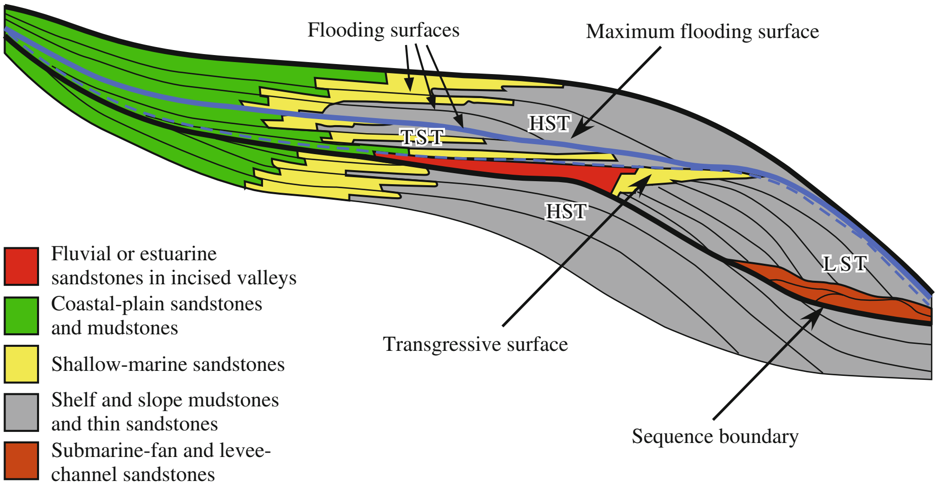


Fig. 7.17 Depositional sequence (type 1) portrayed as a down-dip section across an idealised passive continental margin with shelf break. The diagram shows sequence boundaries, systems tracts and parasequences. LST = low stand systems tract, TST = transgressive systems tract, HST = high stand systems tract (from University of Georgia web site, 2009)