3 Sea-level change

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'Time and tide wait for no man.' Anon., 16th century proverb.

In Chapter 1, the fact that sedimentary deposits record changes in sea-level was introduced. In the first part of this Chapter, this scenario will be turned around. We know that sea-level has changed within the lifetime of humans, because such changes have been recorded, and in some cases directly measured with instruments. Understanding the effects of these recent sea-level changes on the sedimentary record gives us clues for interpreting sea-level changes from the geological record. This Chapter ends by using some of these clues to show how an example of cyclic sediments from the Carboniferous can be interpreted in terms of cycles of sea-level change. This example is revisited in Chapters 4 and 5, after further techniques have been introduced.

3.1 Noah's flood: a record of sea-level change

Noah's flood is one of the most widely reported changes in sea-level in the historical record. It is described most famously in the Old Testament of the Bible but similar accounts exist in ancient Greek and Middle Eastern literature. However, neither the timing nor geographical location of the flood is clear and several explanations for the flood have been proposed. Traditionally, the area of Noah's flood has been proposed as being in lower Mesopotamia (Figure 3.1) on top of the recently built-up delta area of the Euphrates, Tigris and Kurun rivers. For many thousands of years, this area has been a marshy, flat, low-lying plain a few feet above sea-level in the Arabian Gulf. The tale of the flood is supposed to have been told by the inhabitants of the area (Sumerians) from at least 4000 BC. Many historians believe that it was the same event that was later recorded on clay tablets engraved around 2000 BC that recount the tale of Gilgamesh, an ancient Babylonian king. It has been postulated that flooding of lower Mesopotamia by the sea occurred because of an earthquake in the area, which generated a large tsunami (tidal wave). The narrowness of the Arabian Gulf would have increased the height and therefore the destructive power of such a wave. However, it is also possible that the delta could have been flooded by: (i) a storm surge from the sea; (ii) flooding of the rivers due to heavy rainfall; or (iii) a rise in sea-level when glaciers melted, although the latter would have caused only a gradual inundation of the area because the Arabian Gulf is open to the ocean. The problem with all these theories is that because Mesopotamia is such a low-lying area they are all events that are likely to have happened a number of times and thus do not necessarily stand out as particularly dramatic and worthy of being recorded.

More recently, two American scientists, Bill Ryan and Walter Pitman, have uncovered and published (Ryan and Pitman, 1998) new evidence that the water level in the Black Sea (Figure 3.1) rose dramatically about 7600 years ago (i.e. about 5600 BC). They postulate that this flooded more than 100 000 km^2 of land in a matter of months, and most startling of all that this great volume of water could have only poured into the Black Sea through a narrow valley called the Bosporus (Figure 3.1) in a flow that probably reached the equivalent of 200 Niagara Falls! Prior to this flood, there is good evidence from fossils that the Black 'Sea' was actually a freshwater lake isolated from the saline waters of the Mediterranean (Figures 3.1, 3.2). At the time of the flood, sea-level in the Sea of Marmara (Figure 3.1) is interpreted to have gradually risen until it was poised to invade the Bosporus valley. At first, the seawater would have swept through the Bosporus valley carrying with it the soil and debris that once dammed it before plunging 150 m down into the Black Sea. The debris-laden fast-flowing torrent would have rapidly eroded the bedrock of the Bosporus valley: the deeper it cut the faster it flowed, and the faster it flowed the deeper it cut until there was a channel up to 85 m wide and 145 m deep. Ryan and Pitman hypothesize that this was the flood that was later recounted in Mesopotamia by the Sumerians and recorded in the tales of Gilgamesh. Certainly, it seems probable that such a dramatic event would be told and retold and could have eventually evolved into the biblical story.

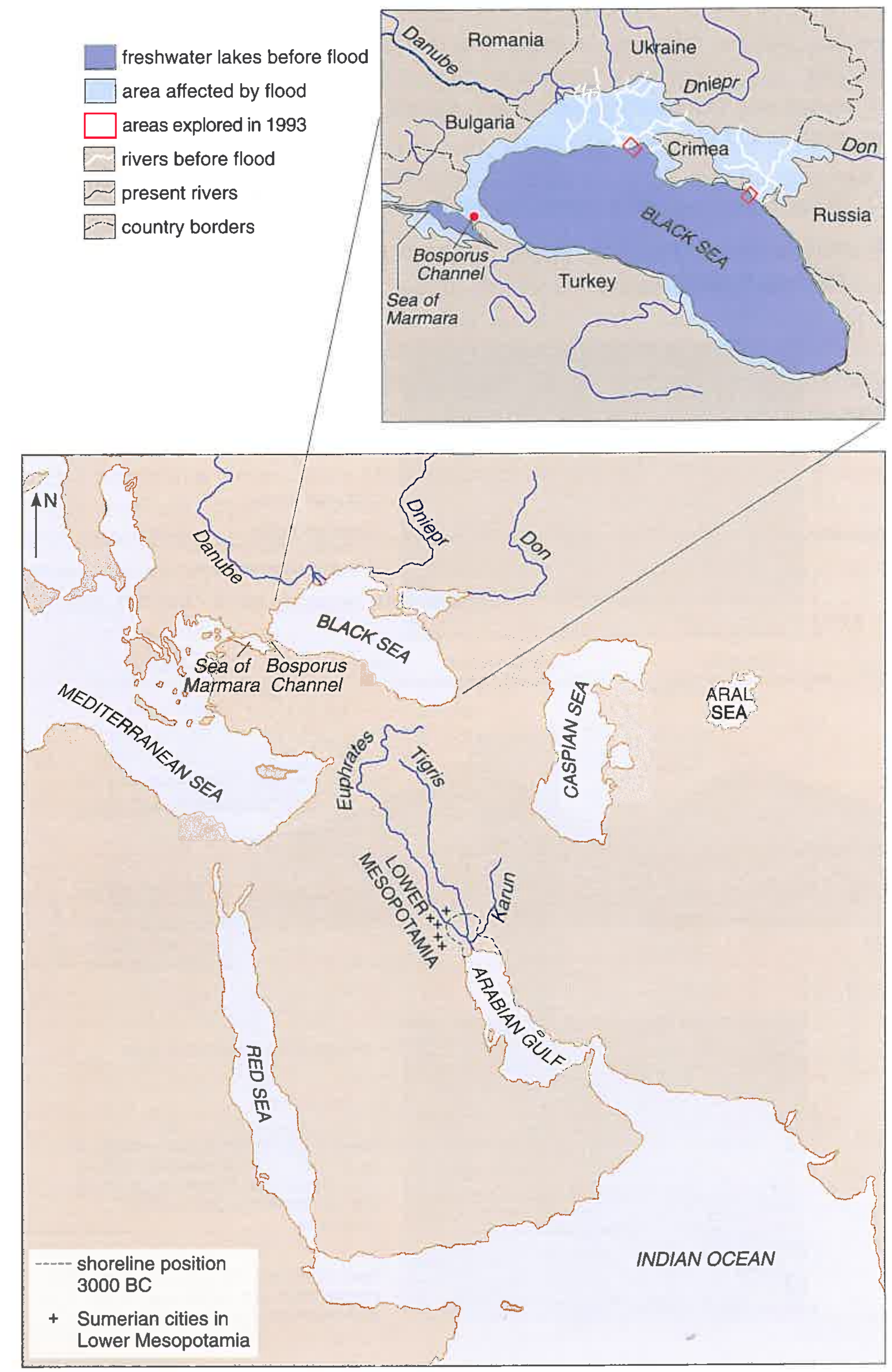


Figure 3.1 Present-day map of the Middle East and Eastern Europe showing the position of lower Mesopotamia at the head of the Arabian Gulf. Detailed map shows the extent of the two freshwater lakes (dark blue) and rivers around the Black Sea area prior to the flood compared to the area supposedly affected by it. Note that the water level after the flood in the Black Sea was higher than the present day. *(Detailed map: Mestel, 1997.)*

- ❍ So, what evidence could you look for to establish if there was a rapid rise in water level in the Black Sea thousands of years ago?
- ● Several different lines of evidence could be used: a change in the sedimentary record at the bottom of the Black Sea; buried shorelines nearer the middle of the Black Sea than the current-day shoreline; a change in salinity from freshwater to brackish; and flooded human settlements.

This is exactly what Ryan and Pitman looked for in the summer of 1993. They joined a Russian ship completing other scientific research in the Black Sea. They drilled many shallow boreholes (1–3 m deep) to recover sedimentary deposits on the sea-floor and they used an instrument that sends sound waves down through the water and sedimentary deposits to map out the sea-bed. A summary of some of the key results indicating there was a sudden flood in the Black Sea 7600 years ago is shown in Figure 3.2.

- ❍ What common feature marks the flood event?
- ● A ubiquitous layer of olive-grey homogeneous mud that drapes over all the previous deposits.

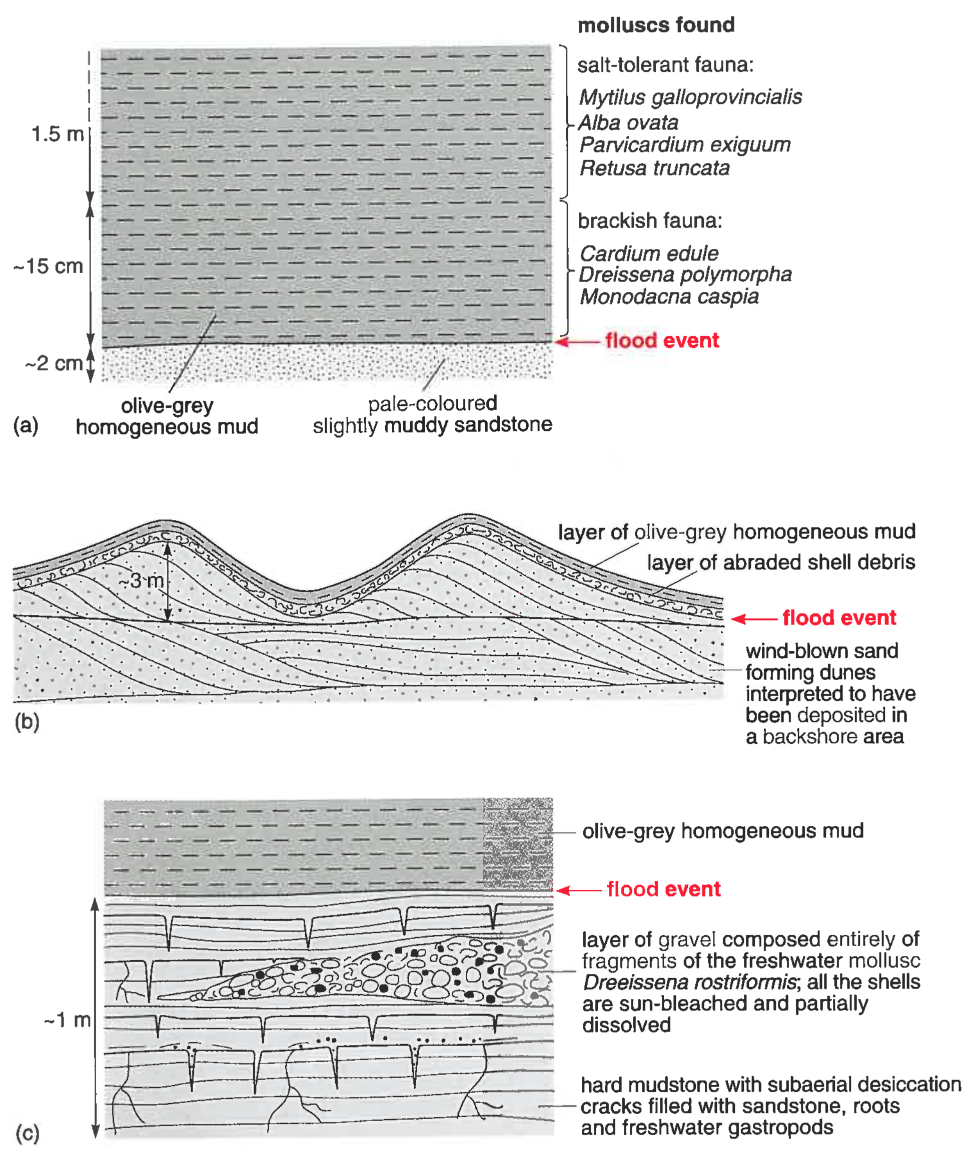


Figure 3.2 Sketches of some of the features found in different parts of the Black Sea demonstrating a flood and change from freshwater to marine conditions 7600 years ago based on information presented in Ryan and Pitman (1998). (a) 68 m water depth near the palaeomouth of the Don river (Figure 3.1); (b) 76 m water depth; (c) 100 m water depth near the mouth of the Dneister (Danube) and Dniepr rivers (Figure 3.1). The lowermost sedimentary deposits and fossils recovered indicate the shores of a freshwater lake whereas the uppermost sedimentary deposits and fossils indicate marine conditions. Carbon-14 (^{14}C) dating of mollusc shells from the very base of the olive-grey homogeneous clay indicates an age of 7600 years.

- ❍ What is the evidence that there was a change in salinity in the lake from freshwater to marine?
- ● The different types of mollusc found.
- ❍ How did the scientists determine the timing of the flood?
- ● By dating the mollusc shells using ^{14}C radiometric dating.

The results of all their coring and surveys demonstrated that prior to the flooding the level of the Black Sea shoreline was somewhere between 160 and 170 m below its present sea-level. The rapid rise in water level is estimated to have been up to 15 cm per day, and to have moved inland by as much as a mile a day; this would have had a devastating effect on any local communities that lived close to the shores of the lake. However, Ryan and Pitman also discuss evidence to show that this was not all 'doom and gloom' and that the flood probably led to the migration of people and spread of farming from the Middle East and Eastern Europe into Central and Western Europe, Asia, Egypt and Mesopotamia, thus marking an important event in the history of civilization.

Two key questions remain: (i) what was the primary cause of a sea-level rise in the Mediterranean at 7600 years ago? and (ii) was there a documented global event at the time? Climate proxies indicate the flooding event occurred about 200 years after the initiation of a particularly marked increase in global temperature (Figure 3.3), which culminated in the Holocene thermal maximum (i.e. the warmest part of the Holocene). Thus, what appears to have happened is that during the Holocene thermal maximum it was sufficiently warm to cause global sea-level to rise (through melting of ice caps) to such a height that the sea in the Mediterranean flooded over the top of the Bosporus valley threshold, created a channel and poured into the Black Sea. During this and other warm interglacial periods, the climate was both warmer and wetter. This may well be the reason that the legend mentions 40 nights and days of rain, though clearly, as in many legends, the time-scale seems to have been somewhat foreshortened.

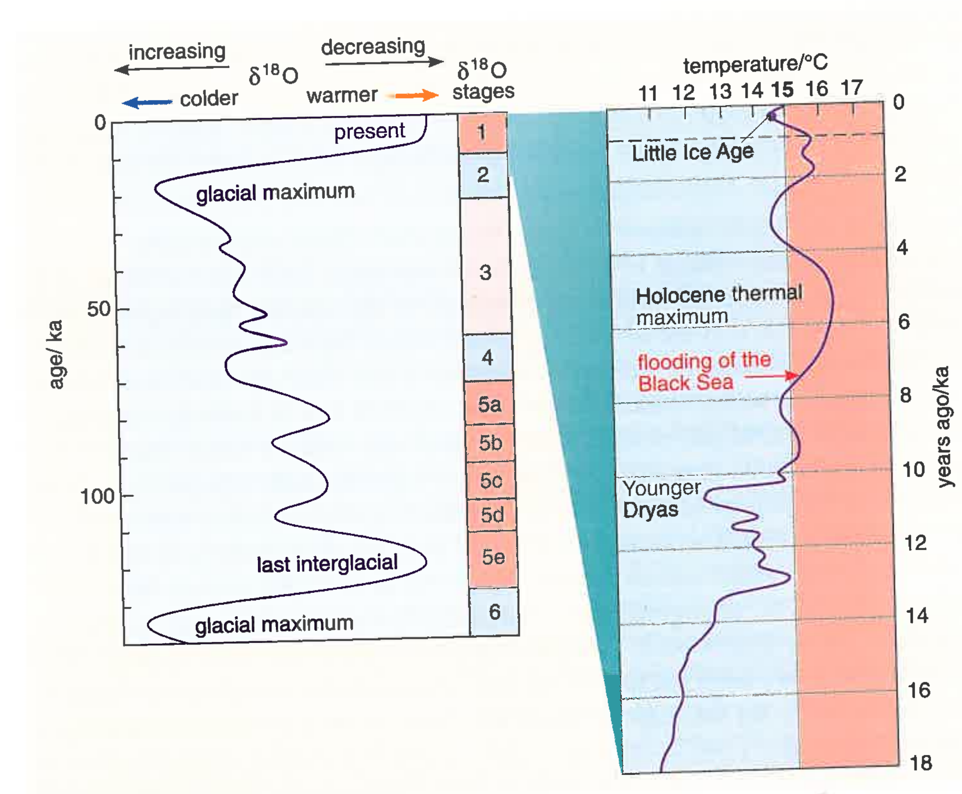


Figure 3.3 Relationship between flooding of the Black Sea, oxygen isotopes over the past 140 ka (left), and average global temperature interpreted from climate proxy records for the past 18 ka (right). Global mean surface temperature today is 15 °C. Oxygen-isotope stages 1 and 5 were warm periods, stage 3 was intermediate, and the rest were cool periods. Note that the maximum and minimum oxygen-isotope values define the isotope stages and that the boundaries between them are taken at the midpoint between maximum and minimum. Technically, this means that the boundary between isotope stages can vary between different records because the amplitude of the signal varies from record to record. See Section 3.2.1 for further discussion of oxygen isotopes. *(Left: Lowe and Walker, 1997 based on Martinson et al., 1987; right: Duff, 1994.)*

Ryan and Pitman end their book on the flood by reflecting that although the scientific evidence for Black Sea flooding is good, as yet no direct evidence has been found for Neolithic settlements and human occupation in the area, mainly because the area has been flooded. However, the *Sunday Times* of 17 June 2001 reported that beams, fragments of walls, stone tools and a rubbish dump had been found about 100 m below the water level in the Black Sea, indicating the area was probably inhabited at the time of the flood. This evidence was found by the same team who located the wreck of the *Titanic*. They are now searching for further evidence that significant numbers of people lived in fairly permanent dwellings on the shores of the Black Sea before the water level increased so dramatically.

Whether or not the Black Sea was the site of Noah's flood, there is clear sedimentary and palaeontological evidence that 7600 years ago the water level in the Black Sea increased dramatically and it became saline.

Clues for interpreting sea-level and salinity change from the sedimentary record:

- *Water-level rise can lead to deposition of lithologically uniform sediments over a wide geographical area (olive-grey mud, Figure 3.2a–c);*
- *Fossils can indicate changing conditions from freshwater to brackish to marine, and are useful for dating (Figure 3.2a);*
- *Rapid water-level rise may lead to deposition of a winnowed lag of previously deposited material (layer of abraded shell debris, Figure 3.2b);*
- *Rapid water-level rise does not always erode previously deposited sediments, even where they have a topography (sand dunes, Figure 3.2b).*

3.2 Measurement of sea-level change

3.2.1 Oxygen isotopes

For much of the Neogene and all the Quaternary, the oxygen-isotope record of marine fossils can provide a valuable insight into the volume of polar ice sheets which in turn can be directly linked to sea-level change. This is because the more water that is locked up in polar ice-caps and glaciers, the less water there is in the oceans.

The ratio of the stable isotopes ^{16}O and ^{18}O in water varies with salinity, temperature and the volume of ice. As water evaporates, molecules with the lighter oxygen isotope ^{16}O evaporate more readily (because of their higher vapour pressure) so that the co-existing water vapour becomes enriched in this isotope. The enrichment of ^{16}O in water vapour in the atmosphere is enhanced by the fact that when water condenses, and falls as either rain or snow, the heavier oxygen isotope ^{18}O is preferentially precipitated back into the water. The continued preferential removal of ^{16}O from the water through repeated evaporation and precipitation results in the water vapour becoming more and more depleted in ^{18}O. This process is limited: first, by an oppositely directed isotope exchange which causes the amount of ^{18}O in the water to peak when the liquid is 15–25% of its original mass, and secondly by the possible addition of freshwater during evaporation. Towards the Earth's poles, the water vapour becomes even more depleted in ^{18}O because of the selective removal of ^{18}O in initial condensates for the reasons described above, as well as for the following additional reasons:

1 enrichment of the lighter isotope in water vapour increases with decreasing air temperature;

2 evaporation into undersaturated air leads to additional kinetic fractionation;

3 re-evaporation of water from rain droplets and from surface water; and

4 evapotranspiration from plants which favour the lighter isotope.

Thus, when the water vapour is precipitated as snow in the polar regions, it is much depleted in the ^{18}O isotope relative to the oceans. The larger the ice-caps, the higher the relative proportion of ^{18}O in seawater and the lower the relative proportion of ^{18}O in ice-caps.

The proportion of ^{18}O isotope to the ^{16}O isotope is determined with respect to a standard and so is noted as the change relative to the standard in parts per thousand (per mil or ‰) as:

$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{standard}}{(^{18}O/^{16}O)_{standard}} \times 1000$$

Because it is the isotopic change that is measured, the $\delta^{18}O$ value (i.e. the oxygen-isotope composition) can be either positive or negative. The standards used are generally either, for water, silicates and ice records, seawater today (standard mean ocean water, SMOW) or, for carbonates and organic matter, a particular belemnite fossil (a type of mollusc) known as the Pee Dee Belemnite (PDB).

Changes in the oxygen-isotope composition of seawater through geological time as the ice-caps have changed in size are preserved in calcium carbonate that precipitated in the seawater. The seawater signal is only well preserved if the calcium carbonate does not suffer later diagenesis. For this reason, most studies involving oxygen isotopes have concentrated on the recent geological past, particularly the Quaternary (1.81 Ma to the present day). The calcareous skeletons of microfossils, particularly benthic and planktonic foraminifers which are found throughout marine Cainozoic sediments, have been favoured as they are abundant in both time and space, and any diagenetic alteration is relatively easy to detect. The exchange of oxygen isotopes between water and dissolved inorganic species such as carbonate is rapid. Hence, the $\delta^{18}O$ value of the water will determine the $\delta^{18}O$ value of the precipitated minerals. Carbonate is enriched in ^{18}O isotope compared to the water it precipitated from, due to mineral–water fractionation factors and the fact that $\delta^{18}O$ value of the carbonate is also dependent on temperature. As temperature rises, the activity of the ^{16}O isotope increases relative to that of ^{18}O isotope resulting in carbonate that forms at a higher temperature containing a higher proportion of ^{16}O than if it formed at a lower temperature. Because the $\delta^{18}O$ values of marine fossils are affected by both temperature and ice volume, more reliable estimates of ice volume can be obtained by using $\delta^{18}O$ values from benthic organisms rather than from planktonic organisms. The reason for this is that there is less temperature variation in the bottom waters of the oceans than there is in the surface waters. From this discussion, it follows that the higher the $\delta^{18}O$ values in benthic marine fossils, the greater the enrichment of ^{18}O isotope in seawater and the larger the ice-caps are. On average, a 1 °C change in temperature causes a 0.2‰ change in $\delta^{18}O$ value whereas typical changes in ice volume between glacials and interglacials result in a 1.2‰ shift. This indicates that ice volume has a more significant effect on $\delta^{18}O$ values than changes in temperature. Thus, by measuring the $\delta^{18}O$ value of benthic organisms during periods when there are polar ice-caps, we can obtain a good proxy for changes in ice volume and hence global sea-level. It has been calculated that a 1‰ change in $\delta^{18}O$ value is equivalent to about a 100 m change in global sea-level.

The oxygen-isotope composition also varies with salinity. More saline waters are enriched in the heavier isotope because, as already described, the ^{16}O isotope evaporates more easily. Thus, river water has a lower $\delta^{18}O$ value than seawater. Such factors need to be taken into account in oxygen-isotope studies where there is potentially any salinity variation, or in arid climatic conditions where there is increased evaporation, or where there is a large river water flux into the ocean, for instance near deltas.

Studies of Cainozoic marine sedimentary deposits have been completed in hundreds of cores from the world's oceans, as part of a large international project (the Deep Sea Drilling Program which was later replaced by the Ocean Drilling Program). The oxygen-isotope composition of foraminifers within the deposits has been measured and this has lead to the construction of a precise oxygen-isotope curve for much of the last 20 Ma (small parts of this are shown in Figures 3.3 and 3.4). This curve has been used to understand the timing and duration of glacials/interglacials and as an indication of sea-level change.

Additional oxygen-isotope data for the last 400 ka come from ice cores that were drilled from present-day ice-caps. One project was based in Greenland (Greenland Ice Core Project, or GRIP) and one in Antarctica at the Russian Vostok research station. The oxygen-isotope composition of the ice was measured at regular intervals, and a curve was obtained. As larger ice-caps preferentially store more of the lighter ^{16}O isotope, the glacial and interglacial episodes can be detected. In addition, the ice cores contain dust incorporated into the ice during colder periods when the wind was stronger. These ice-core data have been correlated with the data from sedimentary deposits using a variety of stratigraphical techniques.

Figure 3.4 shows an example of part of a calibrated benthic oxygen-isotope curve and its correlation to shallow-marine sedimentary cycles in New Zealand. The lowest $\delta^{18}O$ values which infer high sea-level correspond to the deepest-water facies — the shelf siltstones. Increases in $\delta^{18}O$ values inferring decreasing sea-level correspond to the change from shelf siltstones to shoreline sandstones, indicating a shallowing-upward succession that is entirely consistent with decreasing sea-level. The highest $\delta^{18}O$ values inferring lowest sea-level correspond to erosion surfaces interpreted to have formed at the lowest sea-level. Decreasing $\delta^{18}O$ values inferring relative sea-level rise correspond to shell beds deposited during transgression. Note also that the highest $\delta^{18}O$ values at oxygen-isotope stages 78 and 82 (oxygen-isotope stages are explained in the captions to Figures 3.3 and 3.4) correspond to the preservation of less shoreline sandstone facies (probably because of more erosion during the relative sea-level fall) than the smaller-magnitude isotopic maximum at stages 80 and 84.

In Chapter 6, we will consider oxygen-isotope and sedimentological data from sediments deposited during the Quaternary on the edge of the Mississippi delta.

Clues for interpreting sea-level change from the sedimentary record:

- *Oxygen-isotope records from fossils record temperature and ice-volume changes and can therefore also yield information about sea-level change.*
- *Sedimentary facies can indicate changes in sea-level.*

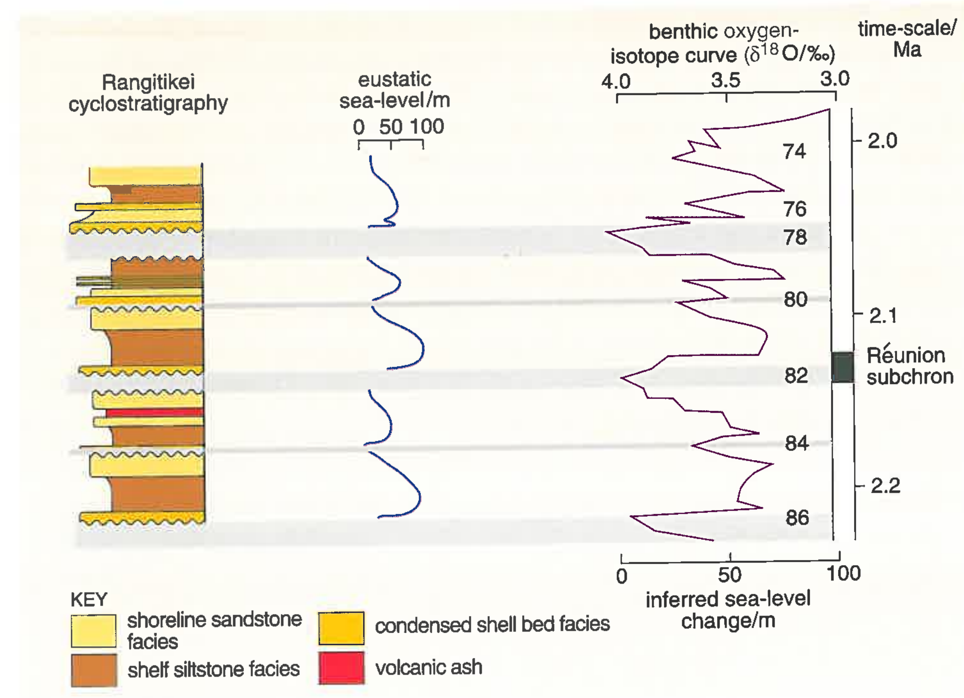


Figure 3.4 Example of the correlation between the benthic oxygen-isotope record for c. 2–2.2 Ma from which changes in sea-level related to ice-cap and glacier volume can be inferred, and sea-level change interpreted from the sedimentary record in New Zealand. The column on the left is a graphic log of the sedimentary facies with erosion surfaces in the succession shown as grey shaded areas. The eustatic (global) sea-level curve to the right of the graphic log is interpreted directly from these sediments and their fossils. On the right is a benthic oxygen-isotope curve. The sea-level that can be inferred directly from this benthic oxygen-isotope curve is shown on the horizontal scale. The maximum and minimum oxygen-isotope values are known as isotope stages ($\delta^{18}O$ stages): maxima (corresponding to cool periods) have even numbers and the minima (corresponding to warm periods) odd numbers. *(Naish, 1997.)*

3.2.2 Coastline maps and coastal sediments

We can easily see that sea-level has changed over the last few decades by comparing coastline maps plotted at different times. A worldwide plot of the coastline at particular points in time would allow changes in global sea-level to be deduced. This principle of plotting the coastline can be applied throughout geological time by identifying sediments that were deposited along the coast and thereby reconstructing a palaeocoastline map. The problem with this is that the data set is often incomplete because of later erosion but nevertheless the technique has been used to construct some sea-level curves.

Sediments deposited along the coastline and in shallow-marine areas are the most sensitive to changes in sea-level. As the coastline sediments change position as sea-level rises and falls, so do all the other adjacent alluvial and marine facies belts. Sedimentary facies and the amount of encroachment of shoreline facies along cross-sections perpendicular to continental margins have been examined and used to interpret sea-level change. How the sedimentary record may be analysed in detail to determine sea-level changes is covered in Chapter 4.

Clues for interpreting sea-level change from the sedimentary record:

- *Maps of the distribution of coastal sediments can show how sea-level has changed through time.*
- *The vertical and horizontal movement of sedimentary facies in space, particularly shallow-marine sediments, indicates how sea-level has changed.*

3.2.3 Tide-gauge records

If you spend a day on the beach, you may witness clear evidence for sea-level change. Twice a day, the tides force sea-level to rise, driving you up the beach before the subsequent fall. This is sea-level change on a very short (diurnal) time-scale and it is clear that the sea is rising and falling with respect to the land. Tide gauges can be used to measure this short-term tidal variation in sea-level, but they can also show the longer-term variation in sea-level if used over an extended period. The results from some such instruments are shown in Figure 3.5. It is the longer-term sea-level variations that we are interested in extracting.

Figure 3.5 clearly shows that sea-level has changed between 1890 and 1970. However, the records also show that whilst at one locality sea-level is nearly constant, it is falling significantly at others.

❍ What might cause sea-level changes to apparently differ at various localities on the same continent?

● The local tectonic setting.

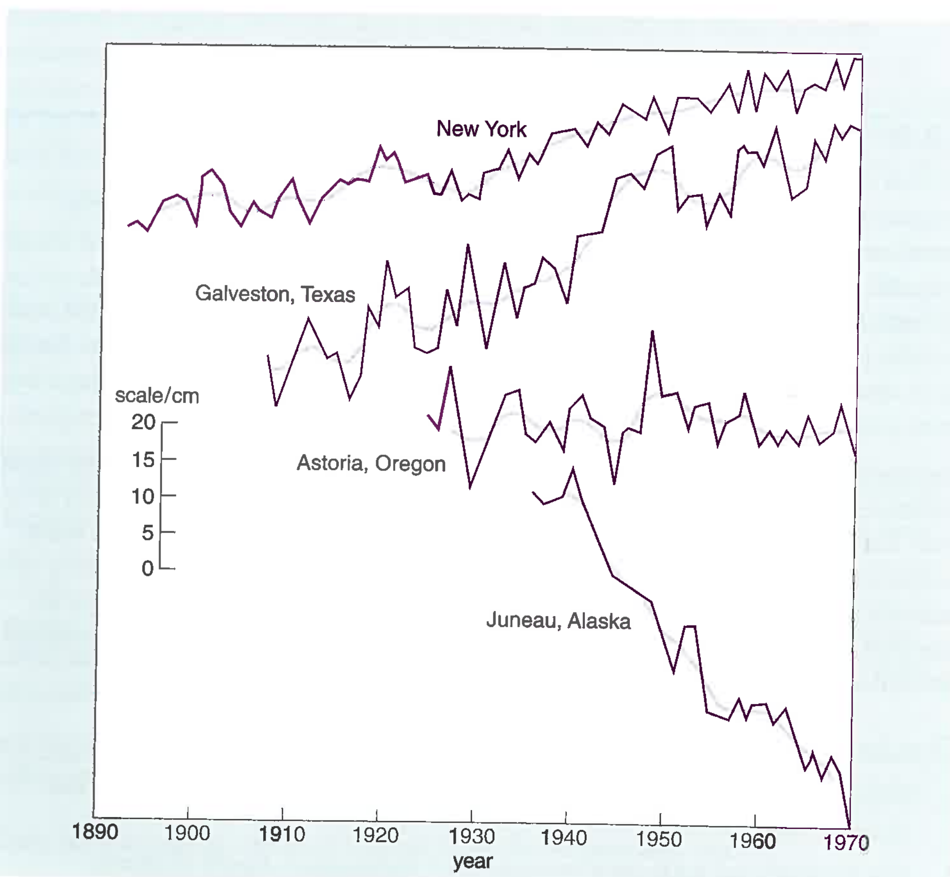


Figure 3.5 Tide-gauge records of annual mean sea-level (purple) from selected coastal localities in the USA. The large annual range is caused by meteorological changes (e.g. low pressure causing higher sea-levels, and onshore winds, which can drive water up against coasts). The smoother pale-blue curves indicate a five-year average. *(Davis, 1994.)*

The sea-level measured at one particular location on the Earth is not necessarily going to be a global signal. It may be affected by glacial rebound, as is the case for Juneau, Alaska, or by tectonic uplift, e.g. Astoria in Oregon. The curve for New York actually corresponds more or less to the global average because it is on a stable continental crust. The similar but slightly higher rate of sea-level rise at Galveston, Texas, is interpreted to be due to the added effect of subsidence because of extraction of oil and/or groundwater.

This discussion poses three questions: (i) What are the processes causing sea-level change? (ii) How do we separate the different processes that are contributing to a change in sea-level at any one location? And (iii) how do we obtain a global signal?

The answers to these questions are complex issues which will be briefly introduced in Section 3.3 and then discussed more fully in the rest of the book.

Clue for interpreting sea-level change from the sedimentary record:

- *The data from any one geographical location do not give a global signal of sea-level change as this may be influenced by local processes.*

3.3 Why does sea-level change?

The example shown in Figure 3.5 indicates that long-term sea-level changes may result either from the level of the sea or the elevation of the land changing. This leads to the conclusion that processes controlling sea-level change are of two types: those which require the volume of seawater to change and those which require the total volume of basins containing seawater to change (see Box 3.1 for an explanation of different types of basin).

Changes in the volume of seawater

Whilst water can be added to the oceans through volcanism, and removed during the subduction of oceanic crust at destructive plate margins, these processes only cause minor fluctuations on the thousand to million-years time-scale that we are interested in. The principal cause of variation in the volume of seawater is through the formation and melting of ice-caps and glaciers. Complete melting of the present-day Antarctic ice-cap and Greenland ice sheet would lead to a sea-level rise of *c.* 60–80 m, sufficient to reduce the global land area by about 20%! Another mechanism for changing the volume of seawater is thermal expansion; an increase in average global ocean water temperature of 10 °C would cause sea-level to rise by about 10 m.

It should be clear from this brief introduction that there is a close link between climatic processes and sea-level. When global temperatures increase, the volume of seawater expands and polar ice-caps melt, both of which in turn cause global sea-level to rise. Conversely, when global temperatures decrease or polar ice-caps grow, the volume of seawater decreases which causes global sea-level to fall.

Changes in the volume of basins containing seawater

The second mechanism we need to consider is how the size and shape of basins (Box 3.1) containing seawater can change. These can either be ocean basins formed on oceanic crust or continental basins formed on continental crust. The major changes in volume are due to ocean basins changing in size and shape.

Complete desiccation of a basin containing seawater can result in redistribution of the seawater into other basins.

- ❍ What is the main process that controls changes in volume of the seawater-filled basins?
- ● Plate tectonics.

During continental break-up, an increased length of mid-ocean ridge spreading centres or an increase in the rate of sea-floor spreading will decrease the volume of the ocean basins. This is because the hot rising magma causes the lithosphere to be uplifted along the mid-ocean ridges, thus decreasing the volume that the ocean basins occupy, causing the oceans to flood the continental margins. Conversely, during continental collision, orogenic (mountain-building) episodes will decrease the area taken up by the newly formed continent (relative to the two old continents from which it was formed). This will increase the volume of the ocean basin, causing a fall in sea-level. Furthermore, the respective thickening and thinning of the continental crust that this entails will lead to changes in the elevation of coastal regions. This process is counteracted by the subsequent erosion of the newly formed mountain chain. As sediment is deposited, it will decrease the volume of the basin.

We will not consider the reasons for the change in continental elevation in any detail, though you should be aware of the following mechanisms:

- Fault movement along coastal regions may cause rapid tectonic uplift or depression of part of a continent's margin.
- Loading of the continents by glaciers causing them to subside, and isostatic rebound (uplift) following glacial melting.
- Sediment loading within a sedimentary basin: as sediment is deposited within a basin, the added weight causes the basin and its margins to subside.

These mechanisms all act on different time-scales; in addition, some are global whereas others influence sea-level in just one location. It is clearly important to try to discriminate between global sea-level changes, due to 'true' sea-level fluctuation, and local or regional changes, due to the vertical motion of a particular continent.

In Chapter 5, we will return to the issues briefly outlined above in an attempt to understand the causes of sea-level change and the time-scale on which each of these causes acts.

3.4 What do we mean by 'sea-level'? Definitions of eustasy, relative sea-level and water depth

Following on from the above discussion, it is clear that it is useful to define different types of sea-level change. Eustatic sea-level, relative sea-level and water depth all have specific meanings. *Eustatic sea-level* (or eustasy) is global sea-level and is a measure of the distance between the sea-surface and a fixed datum, usually taken as the centre of the Earth (Figure 3.6). Variations in eustasy

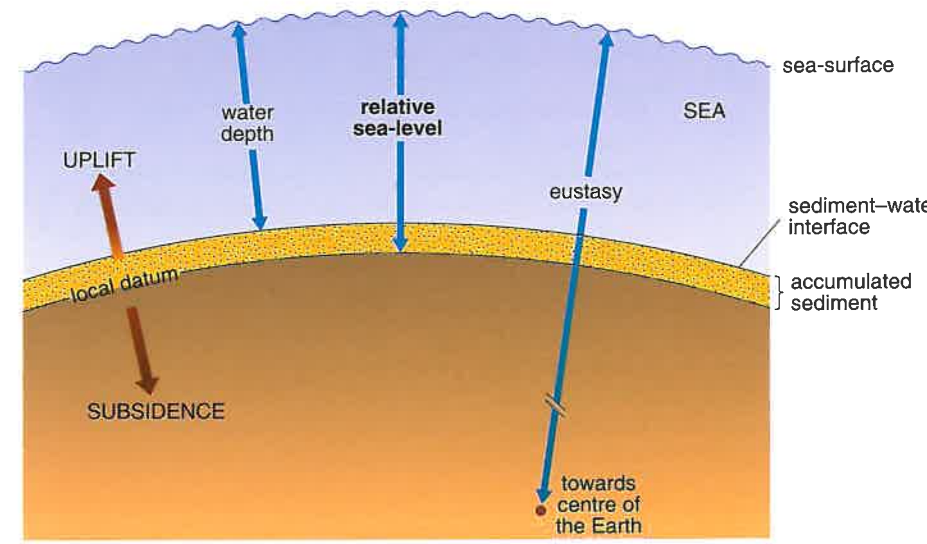


Figure 3.6 Cartoon showing the relationship between relative sea-level, water depth, eustatic sea-level, tectonics (uplift and subsidence), and accumulated sediment. Note that relative sea-level incorporates subsidence and/or uplift by referring to the position of sea-level with respect to the position of a datum at or near the sea-floor (e.g. basement rocks, top of previous sediment package) as well as eustasy. Eustasy (i.e. global sea-level) is the variation of sea-level with reference to a *fixed* datum, for example the centre of the Earth.

are controlled by changes in ocean-water volume (e.g. by varying the volume of water locked up in glaciers, causing glacio-eustasy) and by changing the volume of the ocean basins (e.g. by varying the total length or rate of sea-floor spreading and therefore the volume of the world's ocean ridge systems, causing tectono-eustasy). *Relative sea-level* on the other hand is the distance between the sea-surface and a local datum, for example the top of the basement rocks in a sedimentary basin (Figure 3.6). Relative sea-level change is therefore influenced not only by eustasy, but also by changes in the elevation of continents and the sea-floor. Relative sea-level change is a useful term as it does not imply that a particular mechanism is responsible for the sea-level change or that it is global in extent. For instance, relative sea-level change rather than eustasy is a better term to use when considering sea-level change in a local area, as it accounts for both local subsidence (or uplift) and eustatic changes in sea-level.

- ❍ Describe a situation in a sedimentary basin whereby eustatic sea-level is falling during a relative sea-level rise.
- ● If eustatic sea-level is falling, then the only way that relative sea-level can rise is if the basin is subsiding at a higher rate than the eustatic sea-level fall. This will increase the distance between the sea-surface and the base of the basin.

Water depth is not the same as relative sea-level. Whilst the latter is the distance between the sea-surface and a fixed local datum, *water depth* is the distance between the sea-bed, i.e. the top of the sediments (Figure 3.6), and the sea-surface or water level. So even if basin subsidence and eustatic sea-level are static, water depth will be reduced as sediment fills the basin.

Box 3.1 Sedimentary basins

Sedimentary basins are generally regions of prolonged subsidence of the Earth's surface. They are the places where the majority of sedimentary rocks are found because they are essentially a 'hole' that gets filled. Sedimentary basins may be filled with either marine and/or non-marine sedimentary deposits and, of course, seawater and freshwater. Processes associated with plate tectonic motions within the cool, relatively rigid lithosphere are responsible for the formation of sedimentary basins. There are three basin-forming processes that may occur either independently or may change during the history of the basin. They are:

1 *Purely thermal mechanisms:* examples are the cooling and subsidence of ocean lithosphere as it moves away from mid-ocean ridge spreading centres, or thermal contraction causing sagging.

2 *Changes in crustal/lithospheric thickness:* thinning of the crust by mechanical stretching causes fault-controlled subsidence, whereas thinning of the lithosphere produces thermal uplift.

3 *Loading:* the lithosphere will be deflected or flexurally deformed as it is loaded. Examples include subsidence that occurs adjacent to mountain belts as they are forming, and loading of the crust by a volcano or seamount.

These mechanisms produce a range of different types of basin. The ones considered in this book include:

- *Ocean basins:* these are formed on oceanic lithosphere by purely thermal mechanisms. As the new oceanic lithosphere moves away from the mid-ocean ridge spreading centre, it cools and subsides, creating a basin either side of the spreading ridge over the entire ocean. The Atlantic Ocean is a modern-day example.
- *Rift basins:* these form as the lithosphere is thinned by mechanical stretching. Rift basins form part of an evolutionary sequence from the initial stages when stretching of the continental crust causes faulting and subsidence, to their possible evolution into oceanic spreading centres and an ocean basin if the stretching is strong and continuous enough. If new sea-floor does form, the faulted and subsided edge of the continent forms a passive continental margin or passive margin. The North Sea is an example of a failed rift basin, that is, it rifted but the stretching forces were never sufficient to form oceanic lithosphere. The formation and trapping of hydrocarbons has occurred in the North Sea because it is composed of a number of rift basins which filled with a thick pile of sediments having a range of compositions.
- *Strike–slip basins:* these are formed by local stretching in intricate fault zones. These basins tend to be complex; they form linked structural systems, in that each area of extension is balanced by compression. There are many such basins along the San Andreas fault system in California.
- *Foreland basins:* these form through flexure of the lithosphere as it is loaded in a continental collision zone during the formation of mountains. Modern examples of flexural basins can be found near the Alps and Himalayas. The sedimentary rocks of Book Cliffs covered in Part 3 were deposited in a foreland basin.
- *Fore-arc basins and deep oceanic trenches:* these are formed through flexure as the lithosphere approaches a subduction zone. The driving force is the loading of the lithosphere by the mass of the magmatic arc and/or the gravitational forces exerted by the downgoing slab.

For further information see Allen and Allen (1990) which provides a good summary of sedimentary basin formation and evolution.

3.5 An example of sea-level change from the Carboniferous sedimentary record

This Section presents an example of sedimentary cycles from the Namurian (part of the Carboniferous) of northern England. It will raise questions which will be answered more fully when we reconsider this example in Section 4.4.

During the late Carboniferous, deltas built out (or prograded) southwards from what is today Scandinavia and the North Sea to fill deep marine rift basins (see Box 3.1) that occupied the area that is now Britain (Figure 3.7). Progradation of these deltas was occasionally interrupted by regionally extensive, marine transgressions which pushed the delta shoreline back to the north. This was followed by a renewed phase of progradation in which the deltas again advanced southward.

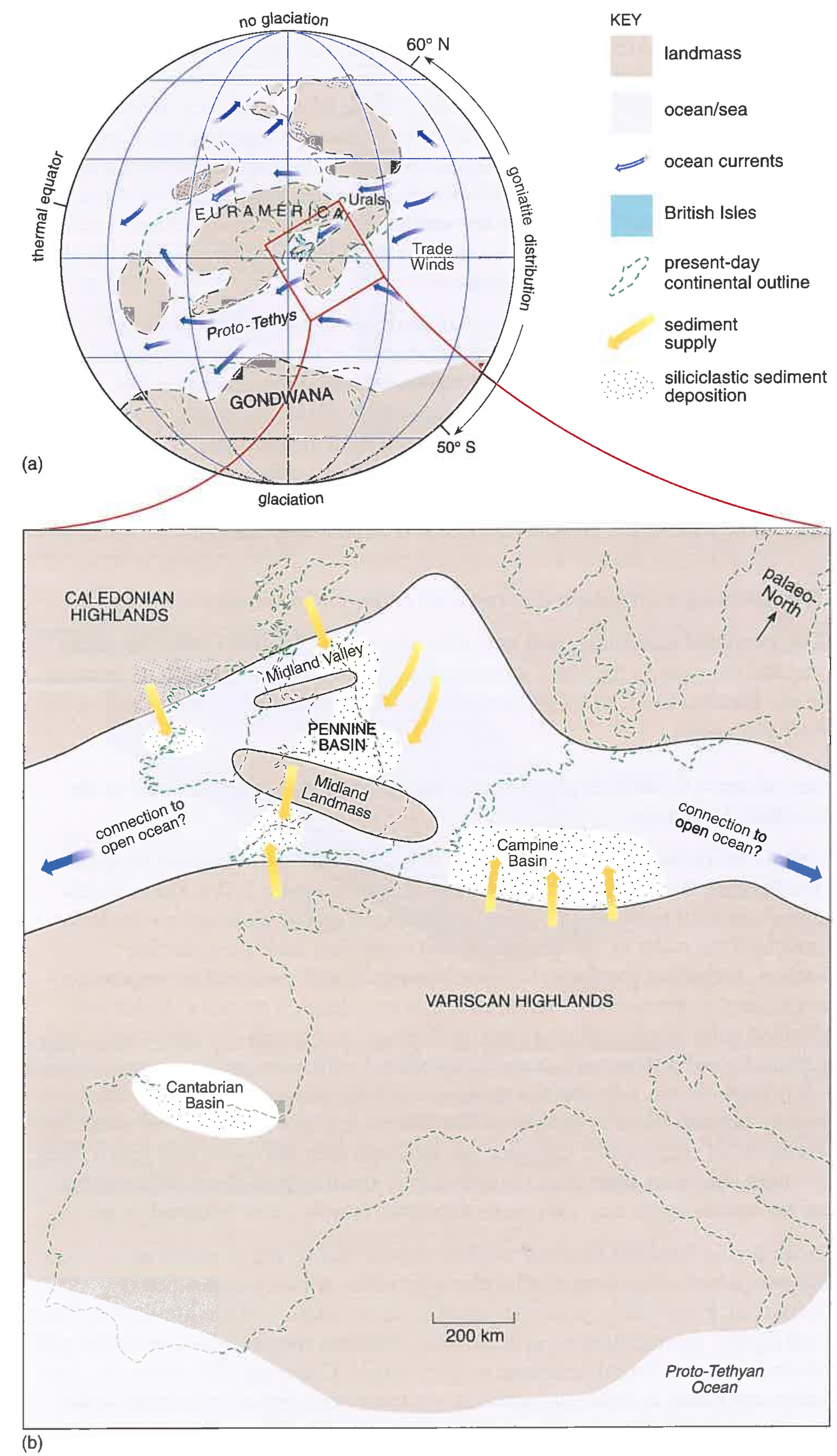


Figure 3.7 (a) The global distribution of continents and oceans during the Namurian. There is evidence of glaciation over the South Pole during the Namurian. The evidence is preserved in parts of the present-day continents (South America, Antarctica, Africa, Arabia, India and Australia) that made up the supercontinent Gondwana in the Namurian. The North Pole is not thought to have been glaciated at this time. This imbalance between north and south would have shifted the thermal equator some 10° to 20° north of the geographical equator. (b) Palaeogeographical map of north-western Europe during the Namurian indicating continents, seaways, oceans, marine sedimentary basins and areas of active sediment deposition. *((a) Ramsbottom, 1971; (b) Collinson, 1988 based on Anderton et al., 1979 and Ziegler, 1982.)*

From a global perspective, the supercontinents of Gondwana (comprising South America, Antarctica, Africa, Arabia, India and Australia) and Euramerica (comprising North America, North Asia and Europe) were separated by a 'Proto-Tethys' Ocean during the late Carboniferous (Figure 3.7a). Evidence of boulder clays, glacial tills and glacial striations in rocks of this age suggests that Gondwana was glaciated to varying degrees during the late Palaeozoic and underwent a longer episode of glaciation in the Namurian when most of Gondwana was covered in ice. Eustatic sea-level change induced by the waxing and waning of the Gondwanan ice sheet is therefore a mechanism that we need to consider to explain the periods of delta advance and marine transgression.

Figure 3.7b is a palaeogeographical map of north-western Europe during the Namurian. It was produced by mapping those areas of known sediment erosion (interpreted as continental) and those of sediment deposition (interpreted as marine). It shows an east–west elongate seaway, exceeding 3000 km in length, sandwiched between the Variscan and Caledonian highlands (each the product of two earlier ocean closures and orogenies). We know the seaway extended eastwards as far as the Urals in Russia (another 2200 km) because rocks of similar age, and suggesting similar deltaic conditions, are known to exist between there and Britain.

- ❍ Why are we not sure about the westward extension of the seaway?
- ● The westward extension leads into what is now the Atlantic Ocean, an ocean that did not exist in the late Carboniferous. Rifting associated with its opening in the Jurassic and Cretaceous would have destroyed much of the evidence for such a seaway.

Further evidence for this seaway emerges on the other side of the Atlantic in the Appalachian Mountains.

The deltaic successions now preserved in central and northern England prograded into the Pennine Basin from the north and north-east (Figure 3.7b). These deltaic sediments are built up of many cycles. An idealized deltaic sedimentary cycle for this area is in the order of 30–50 m thick and comprises dark-grey, marine mudstones containing goniatites (free-swimming, coiled-shell marine organisms closely related to ammonites). These pass upwards through prodelta mudstones, interbedded delta-front mudstones and sandstones, and mouth-bar sandstones, into delta-plain fluvial distributary channels associated with coals and palaeosols (Figure 3.8). It is important to note that the thickness of each interval often bears little relation to the time taken to deposit it. The marine mudstones containing goniatites are examples of condensed* deposits. So, although they may total less than a metre in thickness, they may have been deposited over thousands of years, whereas the rest of the deltaic cycle may have been deposited in only a few hundred years.

Exposure across northern England is often so poor that trying to match up sandstones (which often have similar characteristics) between exposures is problematical. Fortunately, goniatites greatly aid correlation of the lithologies. They evolved rapidly through time to give us many different species which are principally recognized by the different ornament on their shells. Consequently, where the same goniatites are found at different localities, we know that they represent the same marine transgression. This is an example of the use of biostratigraphy in the correlation of sediments (Section 2.1.2, Figure 3.8).

* Condensed is defined here as a long period of time being represented by a small thickness of sediment.

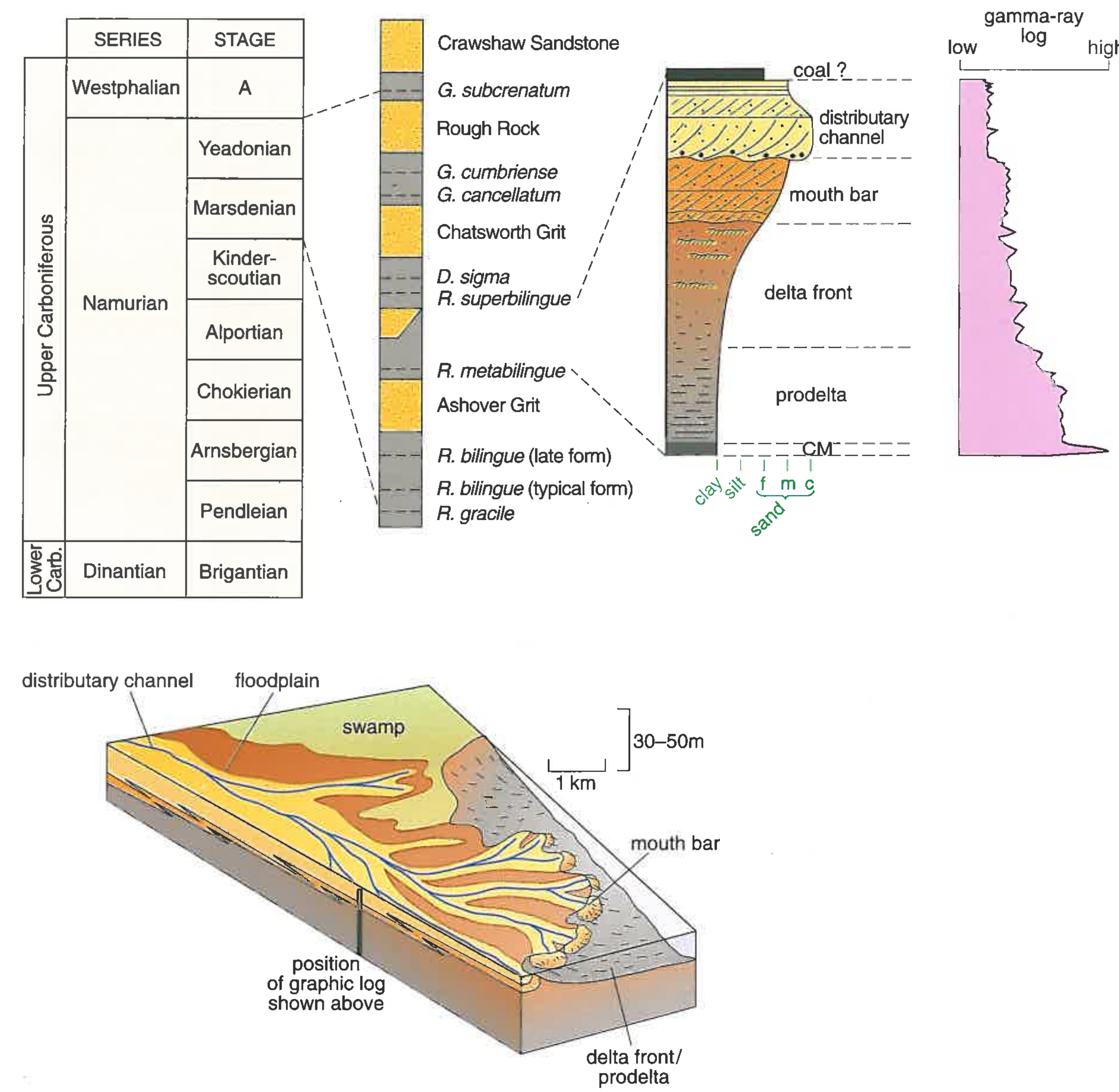


Figure 3.8 Namurian stages and an outline of the generalized stratigraphy of the Marsdenian and Yeadonian stages for central England. Each successive delta cycle has its own named sandstone, and each is terminated by a unique goniatite species. Also illustrated is a graphic log of a typical deltaic cycle showing the component facies and the typical corresponding gamma-ray log (Box 3.2). The lower part of the diagram shows a block diagram of a prograding delta. The position of the graphic log is marked. G = *Gastrioceras*; D = *Donetzoceras*; R = *Reticuloceras*; CM = condensed marine mudstones with goniatites.

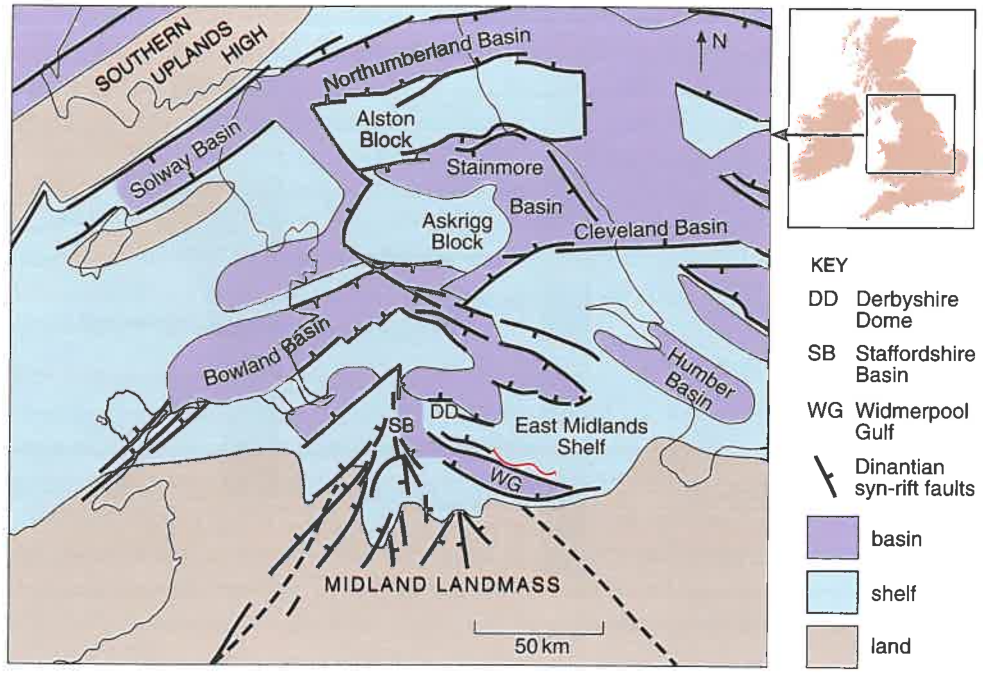


Figure 3.9 Structural map of the Pennine Basin (central and northern England) prior to the deposition of the Namurian deltas showing land areas and areas covered by sea which are divided into deeper fault-bounded basins or troughs and shallower shelf areas (shelf areas are also variously termed blocks, platforms, domes, highs). Note that the deltas prograded into the Pennine Basin from the north and north-east. Red line shows position of cross-section in Figure 3.10. *(Guion et al., 2000.)*

Figure 3.9 shows the structure of the Pennine Basin just prior to the deposition of the Namurian deltas. Far from being a flat surface in the middle of an ocean, there were a series of predominantly north-west–south-east oriented shelf areas and basins, each bounded by faults, with some of the basins showing marked asymmetry. It is known that these faults ceased to be active before the deltas prograded into the area. However, the difference in water depth (or palaeobathymetry) between the basins and shelf areas had a marked effect on the distribution of the earliest deltas which were restricted to the basins or only thinly developed over the shelf areas. We will focus our attention on the deltas deposited in the Widmerpool Gulf and on the East Midlands Shelf (Figure 3.9). The Derbyshire Dome (Figure 3.9) acted as a barrier to the southward advance of the deltas into the Staffordshire Basin and Widmerpool Gulf until the late Kinderscoutian (Figure 3.8).

Figure 3.10 is an interpreted cross-section through the Marsdenian and Yeadonian intervals of the Namurian and lowermost Westphalian (Figure 3.8). The cross-section is made up of data from nine boreholes, and consists of graphic logs constructed from cores and a natural gamma-ray log response (Box 3.2). Ignoring for a moment the sandstones marked in orange, Figure 3.10 shows ten goniatite-bearing marine mudstone layers, each of which is overlain by a new phase of delta progradation into the marine basin. Most of these progradation phases are shown as the colour change from grey below to yellow above, representing the coarsening-upward transition from prodelta mudstone/delta front sandstone (grey) to mouth bar/delta front/delta top sandstone (yellow). The most clearly defined parts of the progradational trends are shown by the black triangles labelled 1 to 9 on Figure 3.10. Some of these delta progradation intervals are very thin, being represented by a few metres of prodelta mudstone/delta front

Box 3.2 The gamma-ray log

Boreholes are drilled to find water, oil or gas. They also allow data to be gathered on the lithologies that they penetrate. Whilst this is most effectively done by extracting sections of core, it is also the most expensive way, and so coring is usually only undertaken for rocks of considerable interest. For oil companies, this might mean sandstones thought to be good hydrocarbon reservoirs. As an alternative, instruments may be lowered into the borehole after (or during) drilling to investigate remotely the properties of the surrounding rocks. One property routinely measured is the natural radioactivity of the rocks.

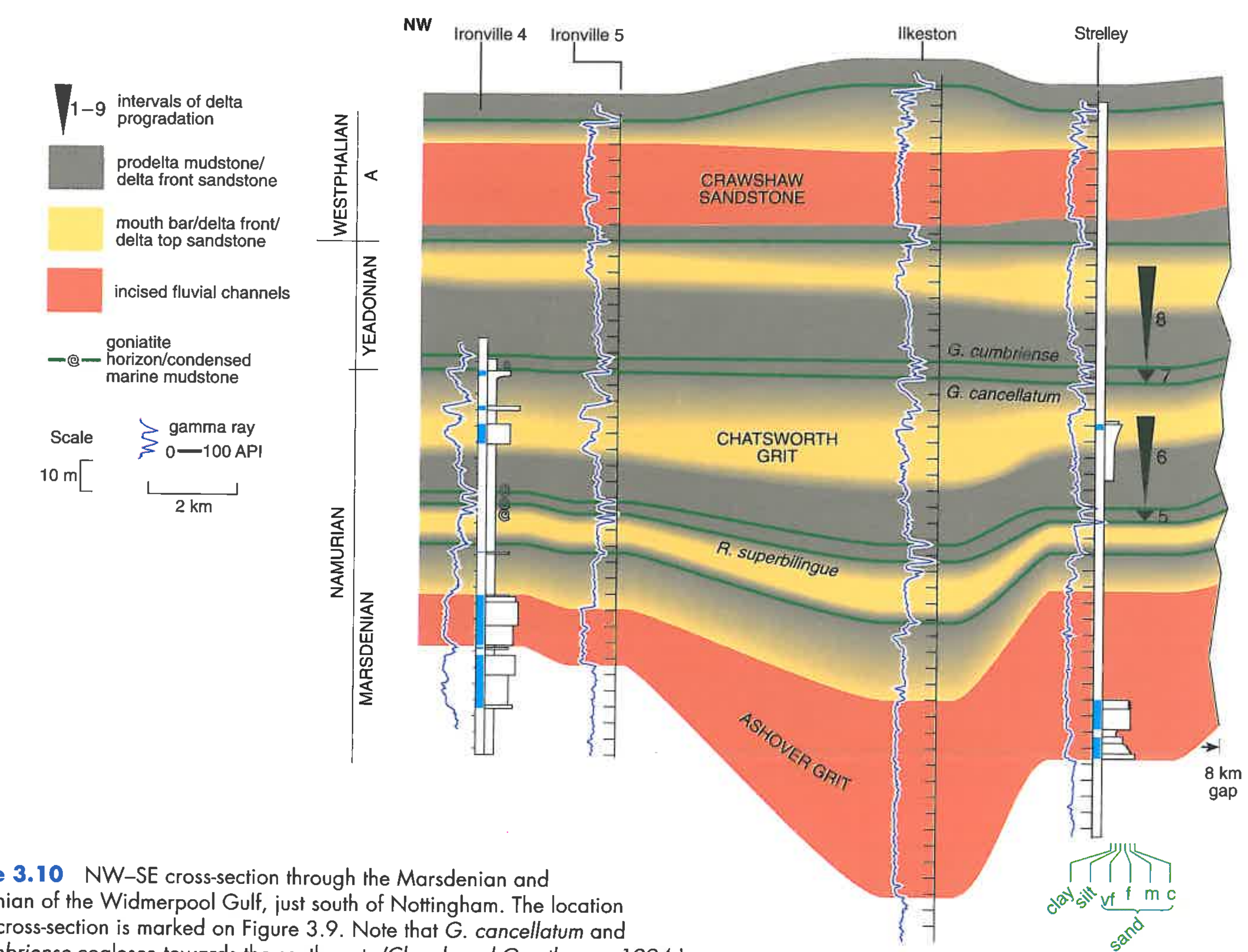
The gamma-ray log measures gamma rays emitted by small concentrations of naturally occurring radioactive elements, principally the isotopes of thorium (Th), potassium (K) and uranium (U). The logs in Figure 3.10 do not discriminate between the three isotopes though this is possible to do with spectral gamma-ray tools. Values are measured as a ratio against a standard sample held by the American Petroleum Institute (API) and are quoted in 'API' units.

In general terms, the radioactive isotopes are concentrated in the micas and clay minerals in mudstones, so mudstones record high values of gamma rays, whilst sandstones record low values. The gamma-ray log thus records sandstones and mudstones as 'end-member' low and high values respectively. Intermediate values result from a mixture of lithologies, for example when sandstones and mudstones are interbedded. Though the log may appear to resemble a grain-size profile, its shape is in fact determined by changes in mineralogy. For this reason, mudstones of different clay minerals give different values. Organic carbon-rich mudstones often give particularly high gamma-ray values as they also tend to contain high concentrations of uranium because it is fixed in the sediment under anoxic conditions. The gamma-ray log is widely used as a correlation tool in the petroleum and coal industry.

sandstone sandwiched between goniatite-bearing marine mudstones (e.g. between the *R. gracile* and *R. bilingue* marine layers). These progradational intervals are nevertheless recognizable from the gamma-ray signal. Above most progradational intervals lies a transition back to prodelta mudstone and delta front sandstone (this is shown as a colour change from yellow below to grey above, e.g. above the *D. sigma* marine layer). These indicate an end to progradation and the gradual onset of transgression as the sea flooded (or transgressed) the top of the delta plain to deposit finer-grained sediments on what was formerly a terrestrial environment. In each case, the acme of the transgression is marked by the deposition of goniatite-bearing marine mudstones. In the Carboniferous, these marine mudstones are prominent on the gamma-ray log because they are enriched in uranium and so have very high gamma-ray log responses (Figures 3.8, 3.10). The pairing of delta progradational successions and marine deposits represents one depositional cycle.

- ❍ How might we explain the development of these depositional cycles in terms of relative sea-level change (i.e. subsidence and eustatic sea-level) and/or sediment compaction?

- ● Clearly, we need a mechanism to allow the sea to periodically transgress the land. This can be done either by allowing eustatic sea-level to rise in stages, or by keeping eustatic sea-level constant and allowing subsidence of the basin in stages, both cases equate to pulses of relative sea-level rise. Alternatively, relative sea-level could have remained constant and compaction of newly deposited sediment within the delta may have caused the delta to subside beneath the sea-surface.



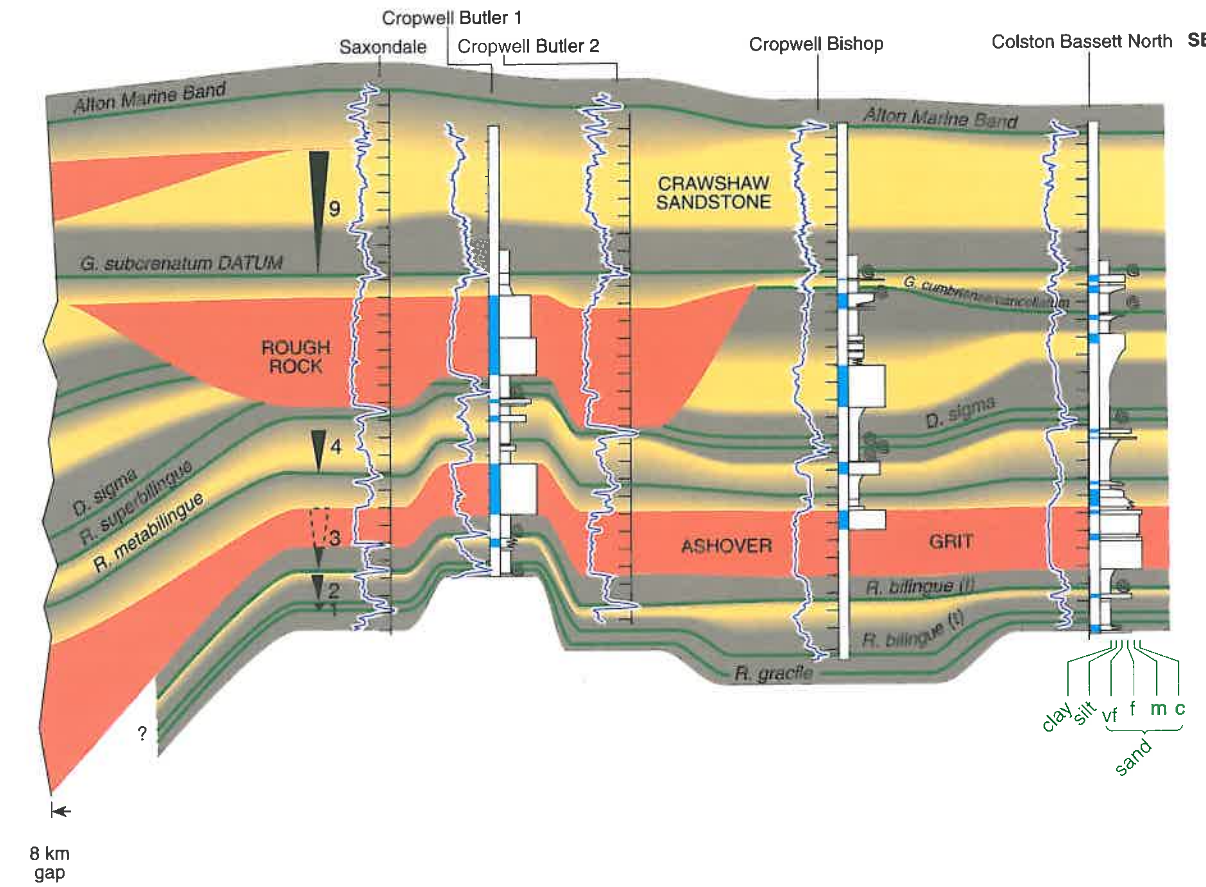


Figure 3.10 NW–SE cross-section through the Marsdenian and Yeadonian of the Widmerpool Gulf, just south of Nottingham. The location of the cross-section is marked on Figure 3.9. Note that *G. cancellatum* and *G. cumbriense* coalesce towards the south-east. *(Church and Gawthorpe, 1994.)*

Scientists still have difficulty agreeing on which of these mechanisms was dominant during the deposition of the Namurian in the Pennine Basin. Most would concede that as the South Pole was glaciated, the first option is more likely, simply because there is a mechanism in place that is capable of accounting for these observations. However, it may also be true that both tectonic subsidence and compaction of the sediment played some part in causing each of the transgressions.

Now consider the sandstones marked in orange on Figure 3.10. They contain sedimentary structures indicative of deposition within fluvial distributary channels. However, these sandstones appear to overlie erosively the delta deposits (which of course also contain their own distributary channel sandstones). This suggests that they cannot have been deposited concurrently with the underlying delta. Instead, they must have been deposited following a period of erosion which occurred after the delta prograded into the area.

○ Bearing in mind our conclusion regarding the fact that each depositional cycle represents progradation of the delta followed by flooding by the sea, what might have caused the erosion of its top?

● It could be argued that a fall in relative sea-level would leave the old delta plain stranded high above the sea-surface. As a consequence, rivers would incise down into the delta plain as they endeavoured to adjust to a new gradient consistent with a lowering of relative sea-level. As they did this, they would carve out new valleys, which would subsequently fill with fluvial sand, recreating what we see in Figure 3.10. This can be done simply by allowing eustatic sea-level to drop. Although tectonic uplift of the basin is another plausible mechanism, it is unlikely because it would require compression of a basin that we know to have been in extension at the time.

From this simple example, we have identified sedimentary cycles with varying thickness and facies development, and whose deposition was probably controlled by fluctuating relative sea-level. Each cycle is composed of a progradational phase (deposition of deltaic sediments), a transgressive phase (the transition back to prodelta and delta front sediments and the capping by a goniatite-bearing marine mudstone) and some have an erosive phase (fluvial channel sandstones lying within incised valleys), caused by a drop in relative sea-level. In the next Chapter, we will look at sedimentary cycles in general to see how they develop during one cycle of relative sea-level rise and fall, using the principles of sequence stratigraphy. In Section 4.4, we will return to our Carboniferous case study to apply these principles to the sedimentary cycles discussed in this Section.

3.6 Conclusion

As we move further back in time, we obviously lose the ability to measure sea-level change directly. However, as we have seen from the Black Sea example in Section 3.1, analysis of sedimentary successions themselves can indicate changes in sea-level. Interpretation of the sedimentary record in terms of sea-level change involves combining evidence from unconformities and sedimentary deposits so that we can obtain a holistic record (Chapter 1) together with integrating the appropriate part of the geological time-scale (Chapter 2). In Chapter 4, we will present the sequence stratigraphy model for interpreting changes in sea-level from the sedimentary record. In the remaining Chapters, we examine many case studies from the sedimentary record deposited over the past 350 Ma, in a variety of tectonic settings and depositional environments.

3.7 Summary

- There is sedimentological, palaeontological and archaeological evidence to suggest Noah's flood recorded in the Bible might well be related to flooding of the Black Sea 7600 years ago when seawater from the Mediterranean entered the area through the Bosporus valley. This event can be correlated with eustatic sea-level rise associated with the Holocene thermal maximum.
- Oxygen-isotope data, coastline maps, maps of the distribution of coastal sediments and tide gauge records can all provide information about sea-level change over long time periods.
- Data on sea-level change from any one particular point does not usually provide a eustatic sea-level signal. This is because local sea-level changes may be governed by a combination of eustatic changes, local tectonic movement and sediment compaction.
- Sedimentary basins are generally regions of prolonged subsidence of the Earth's surface; there are a variety of different types depending on tectonic conditions.
- Sea-level change is caused either by variations in the volume of basins filled by seawater or by alteration of the volume of seawater. The former is controlled by tectonic processes and the latter mainly by ice-cap and glacier growth and melting together with thermal expansion and contraction of seawater.
- Relative sea-level is the distance between the sea-surface and a local datum.
- Eustatic sea-level is the distance between the sea-surface and a fixed datum (usually the centre of the Earth).
- Water depth is the distance between the sea-surface and the top of the sediments.
- Cyclic deposition of deltaic, incised fluvial, and open-marine sediments which can be correlated across northern England using biostratigraphy, indicate that relative sea-level changed during the deposition of the Namurian in central and northern England. Evidence from continental areas that made up the supercontinent of Gondwana during the Namurian suggests that the South Pole was glaciated at this time. Fluctuation in the volume of the ice-cap due to climate change is the most likely mechanism of relative sea-level change during this period of Earth history.
- Gamma-ray logs provide additional information on the composition of sedimentary succession. They can often be used as a proxy for grain size (clay minerals give a high value whereas quartz gives a low value).

3.8 References

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