# 6 Silent, strong and deep

## The mystery of how basins fill

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## INTRODUCTION

There are many different types of basin – continental or marine, deep or shallow, large or small, long-lived or ephemeral. All represent regions of topographic or bathymetric low and all, therefore, will receive an input of sediment from the surrounding basin catchment area and, with continued sedimentation over time, become sedimentary basins. Only some basins will eventually fill completely, whereas many others will remain only partially filled. Some are preserved in the ancient rock series, even though they may have become fragmented in the process; others are subducted and lost.

In this chapter I focus on deep-sea basins and on the several different processes responsible for the input and accumulation of sediment. These processes and their resultant deposits have been the subject of study since HMS *Challenger* circumnavigated the world between 1872 and 1876 and returned with many sediment samples from the ocean depths (Stow, Reading and Collinson 1996). However, because of the nature of the samples recovered (red clays and biogenic oozes), the main sedimentary process active in all deep-sea basins was believed to be the slow, continuous, vertical fall-out of material by pelagic settling. Only much later and after many more years of research on both modern and ancient series were turbidity currents, one of a family of downslope processes first recognized in 1950, accepted as a principal agent of basin fill. In the mid-1960s, contour-following bottom currents were recognized as important in shaping the fill. Hemipelagic advection, volcanic fall-out, glacial input, chemical precipitation and hemiturbiditic processes are all now known to contribute to basin fill, the last of these being recognized as late as 1990 (Stow and Wetzel 1990).

The nature of the sediment fill is illustrated by examining case studies of existing and ancient basins on which the author has worked. This brief survey is no more than a very eclectic view of a subject of increasing importance. The study of sedimentary basins as a separate discipline has received great impetus in recent years because of their economic importance for oil, gas and mineral deposits, and several important publications on the topic have appeared in the 1990s (Allen and Allen 1990, Miall 1990, Busby and Ingersoll 1995).

## SEDIMENT SUPPLY

Many different types of material find their way eventually into deep-sea basins. Terrigenous material is derived primarily from the physical and chemical weathering and erosion of pre-existing rocks – igneous, metamorphic and sedimentary alike. Collectively, the world's rivers transport the bulk of this detritus across vast areas of continental drainage basin to the sea. The suspended loads are deposited first in coastal and shelf areas, only slowly moving seaward to the brink of the abyss under the constant influence of currents, tides and waves. Dissolved loads add their individual chemistry to that of the global ocean and may remain in solution for many aeons before being fixed into the sediment pile by organic or inorganic precipitation.

At high latitudes, the processes of melting and calving from glaciers and floating ice add much particulate material directly to both shelf and deep-sea deposition, but introduce far less dissolved solute. Wind-blown dust from arid and semi-arid low-latitude land masses, as well as from explosive volcanic eruptions, may travel far into the neighbouring ocean basin. The wave-pounding, undercutting and erosion of coastal cliffs, particularly effective during major storms or hurricanes, are a further source of detritus that may find its way ultimately to an abyssal sink. The relative input from these different sources is only poorly constrained at present (Table 6.1) and will have varied markedly in the past.

Material of biological origin (biogenic), including siliceous and calcareous tests of planktonic plants and animals as well as soft organic tissue, is supplied to the deep sea following primary productivity in the surface waters. Other important sources are organic growth in shoal areas with subsequent erosion and resedimentation, and run-off from biogenic-rich areas of the continents and coastline (e.g. mangrove or other swamps and rainforests, river weed and associated fauna, shoreface molluscs, and so on). The figures estimated for the flux of this material into the ocean basins (Table 6.1) are subject to a relatively wide margin of error as so much is dissolved and recycled, often many times over, before reaching the basin floor.

The ocean waters above any sedimentary basin have an enormous range of dissolved chemicals but a relatively constant ionic composition. This has been built up from the dissolved loads of riverine and groundwater input, wind dispersal of evaporitic salts from arid lands, dissolution of biogenic tests and organic matter, progressive corrosion of the more unstable terrigenous and volcaniclastic components such as ferromagnesian minerals, feldspars, glass and amorphous compounds, and by primary volcanic and hydrothermal emissions from mid-ocean ridges and active plate margins. A crude steady-state chemical balance is maintained within the oceans over long periods of geological time, subject always to large material flux in and out of solution, together with minor local variability between basins and between different layers or water masses within the oceans (Table 6.2).

*Table 6.1* Sediment flux to the ocean basins (From Stow 1994.)

| *Source* | *Supply* $\times 10^9$ *t year*$^{-1}$ |
|---|---|
| Rivers (suspended load) | 18.3 |
| Rivers (solution load) | 4.2 |
| Groundwater (solution load) | 0.48 |
| Ice (ice shelves and bergs) | 3.0 |
| Coastal erosion | 0.25 |
| Wind-blown dust | 0.6 |
| Volcanic ejecta | 0.15 |
| Biogenic carbonate | 1.4 |
| Biogenic silica | 0.49 |

Data from Goldberg (1974) and Open University (1984).

*Table 6.2* Principal properties of sea water (From Stow 1994.)

| | |
|---|---|
| *Salinity* | |
| General average | 35‰ |
| Surface waters | 32.4–39.8‰ |
| Deep water (>1000m) | 34.5–35‰ |
| *Temperature* | |
| General average | 3.52 °C |
| Surface range | – 1.87°–30.0 °C |
| Deep water (>1000m) | – 3.56°–8.9 °C |
| *Density* | |
| (expressed as specific gravity) | 1.024–1.029 |
| *pH* | |
| General average | 8.0 |

## SEDIMENTARY PROCESSES

Once material has been supplied to a basin or its margins, the range of sedimentary processes that operate within that basin (Fig. 6.1) can be divided into four main groups. These are: (1) downslope (or resedimentation) processes, (2) bottom current processes, (3) pelagic and hemipelagic settling, and (4) chemogenic processes. These affect different basins or parts of basins, involve very variable amounts of sediment, may be sudden and catastrophic or slow and continuous, and are subject to varying allogenic and autogenic controls. The brief review below draws heavily on previous work by the author (Stow 1985, 1986, Stow et al. 1996).

### Downslope processes

Downslope (or resedimentation) processes are those that move material from the basin margins down a slope under the influence of gravity. They are mainly episodic, short-duration events that are typically dramatic in their nature and effect and generally introduce by far the greatest volume of material into the receiving basin. Distinct processes can be recognized within the downslope family, although in nature there is overlap between these end-members, such that a process continuum of mechanical behaviour exists from elastic through plastic deformation to viscous flow (Fig. 6.2).

Two very different end-members that are generally of only minor importance in terms of volume of material moved are rock falls and sediment creep. Rock falls are sudden, rapid, freefall events that can occur only on steep slopes, triggered by undercutting and erosion or by earthquake shocks. Single displaced clasts may be very large (> 10m) and bounce or roll downslope for several tens or hundreds of metres, in some cases dislodging other loose debris to create a submarine avalanche. Talus slopes of rockfall debris are common off coral reef mounds and volcanic sea-mounts. Sediment creep is an extremely slow, continuous process analogous to soil creep on land, that occurs over wide areas of even very gentle basin-margin slopes, wrinkling the surface and gradually displacing the upper few tens of metres of sediment. It may be an important precursor to slides and debris flows on unstable slopes.

Sliding and slumping are extremely common on most submarine slopes and involve the

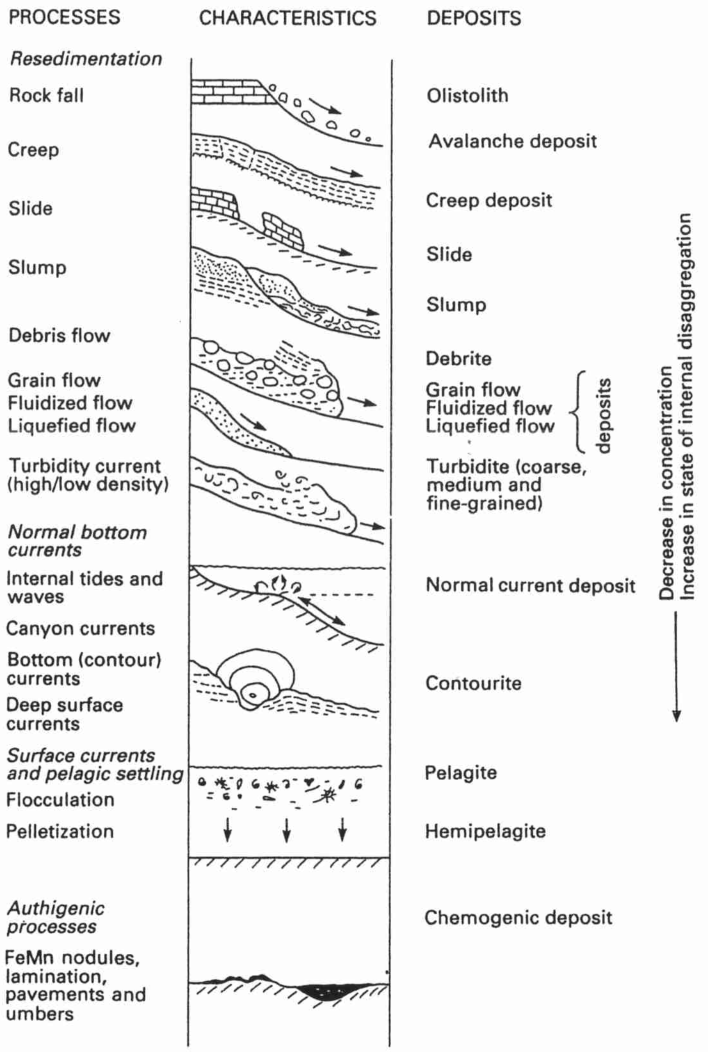

*Figure 6.1* The range of processes that operate in deep-sea basins and their deposits. (From Stow 1994.)

sudden downslope displacement of the upper layers of sediment along a basal shear plane. In slides the internal disturbance of these upper layers is minimal, whereas slumps show more internal disruption. Single slide masses range from very small (< $1 m^3$) localized displacements to very large (> $100 km^3$) and often complex bodies that may be as much as several hundred metres in thickness. Catastrophic slides in human terms have involved the complete loss of a drilling platform with all hands on board off the Mississippi Delta on the northern slope of the Caribbean Basin, the removal of half the new runway at Nice Airport in southern France and its disappearance downslope towards the Alboran Basin, and the overnight vanishing of a Ukrainian village from the Crimean Peninsula as it slid towards a watery grave in the Black Sea Basin. Such large-scale slides can lead to the generation of major tsunamis and further disastrous effects around the periphery of semi-enclosed basins.

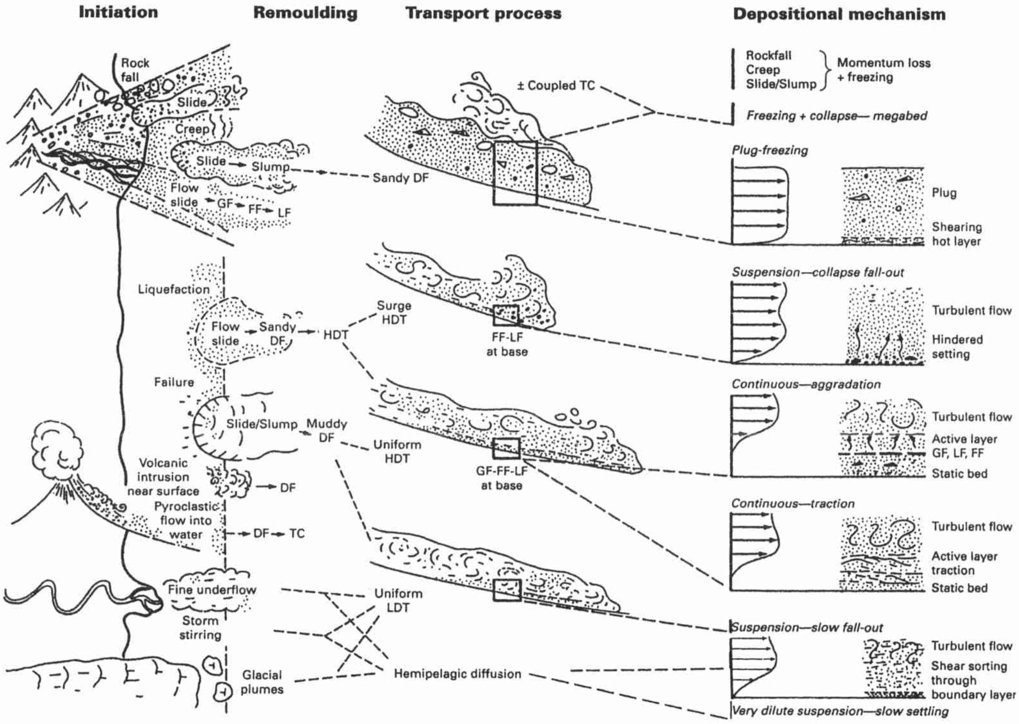

*Figure 6.2* Downslope processes responsible for basin filling: initiation, remoulding, transport and deposition. (From Stow et al. 1996.)

Destruction of the Minoan civilization on Crete some 3500 years ago is believed to have resulted from a combination of explosive volcanism and associated seismicity on the island of Santorini, followed by submarine sliding around the flanks of the caldera and the generation of devastating tidal waves (tsunamis).

Sediment instability on basin slopes is affected by a combination of interacting variables. These include: (1) the slope angle, (2) high rates of sedimentation leading to high water content and low shear strength, (3) seismic shock, (4) repeated cyclic stress (minor tremors, tides, and so on), (5) high primary productivity leading to high organic carbon flux, or deposition on the seabed of organic matter derived from plants and animals in the water column, (6) diapiric activity, or subsurface intrusions (usually sedimentary) causing doming in the overlying strata, and mud volcanoes, and (7) generation of gas in the sediment due to clathrate[1] decomposition. Interestingly, recent data suggest that gas-triggered slides on the Bermudan slope remove sufficient of the upper sediment layers to decapitate large areas of buried clathrates and hence release giant bubbles of methane gas. Further speculation links these natural events with the countless and mysterious disappearances of ships and even planes in the Bermuda Triangle (Anon. 1992).

Debris flows are highly concentrated slurry-like flows that advance down slopes in excess of only 0.5°, either rapidly and continuously (for at least a short time) or slowly and intermittently. Typically they have a mud-rich matrix that can support large boulders or slabs the size of a small car, potentially moving at speeds of 20m per second and eventually 'freezing' to leave deposits standing up to 30m or more above the surrounding sea floor, after downslope transport of tens or even hundreds of kilometres. Their chaotic bouldery mud deposits, known as debrites, are well documented from both modern and ancient systems throughout the world, although they may in places be confused with debris-flow deposits on alluvial fans, glacial tillites and sediment injection or mud-volcano bodies.

Turbidity currents and their deposits, turbidites, are one of the most common and best known features of deep-sea basins, although a full-size prototype has never yet been observed in nature. They are a type of density current in which the denser fluid is a relatively dilute suspension of sediment in sea water generated in the first instance in one of four main ways: (1) from the transformation of slumps and debris flows by excessive mixing with sea water; (2) from sand-spillover, grain flows and rip currents feeding sediments into the heads of submarine canyons; (3) from concentrated shelf or canyon nepheloid layers[2] built up by storm-stirring and biogenic suspension of unconsolidated sediment; (4) directly from suspended sediments delivered to the sea by flooding rivers, glacial meltwaters or volcanic plumes; and (5) from the transformation of pyroclastic flows and falls into or onto the sea.

Depending on the way in which the flow has been initiated and on the subsequent supply of sediment, two main types of turbidity current are recognized: short-lived surge-type flows and relatively long-lived steady or uniform flows. Both can occur on even the gentlest of slopes (<1°), but above a critical density the flow will 'ignite', increasing in density and velocity and achieving a state of autosuspension or flow self-maintenance. In this mode, a turbidity current can travel several thousands of kilometres downslope, across almost flat abyssal plains, and even upslope and over minor topographical obstacles for short distances. Truly large turbidity currents, generated perhaps from gigantic basin-margin slides, may reach over 500m in thickness, 10km in length and speeds of over 70km per hour, and eventually deposit a 2m thick layer of sand and mud over an area the size of England! If the receiving basin is small and confined, or if the flow does not reach ignition, then megaturbidites up to 25m thick, grading from coarse gravel and even small boulders at the base to fine silt and clay at the top, may be deposited by single flows. Such large-scale events are relatively rare, perhaps occurring once every 1000–3000 years, interspersed with more frequent small-scale flows. They occur more commonly during times of lowered sea level and in areas of high tectonic activity. All, however, form geologically instantaneous deposits, gravel and sand depositing within a matter of minutes to hours and even the very finest material settling over a period of a few days.

## Bottom currents

The second main group of processes that operate in deep-water basins, actively eroding, transporting and depositing sediment, are collectively known as bottom currents. These include all types of deep current driven by normal oceanographic forces such as winds, tides, waves and thermohaline circulation. Four main groups are recognized: (1) major surface currents, (2) internal tides and waves, (3) canyon currents, and (4) bottom (contour) currents. The last of these is the most important in shaping basin-fill and so forms the main focus for our discussion below. They tend to be semi-permanent in nature rather than episodic, although they typically display periods of greater and lesser intensity.

### *Bottom (contour) currents*

Ocean waters, shallow and deep, can be compartmentalized into different water masses formed in different places, each having distinctive salinity/temperature characteristics. The deepest water masses in each basin are formed by the cooling and sinking of surface waters at high latitudes and their subsequent slow thermohaline circulation, that is, gravitational exchanges of sea water throughout the world oceans caused by local variations in density, which is a function of both salinity and temperature (Figs 6.3a and 6.3b). Upward mixing leads to the formation of intermediate water masses, which may impinge directly on the sea floor on basin margin slopes. Highly saline but warm water also flows out of the Mediterranean Sea as an intermediate water mass.

Any slowly moving water mass is affected by the Coriolis force, caused by the Earth's spin, which deflects moving bodies to the right in the northern hemisphere and to the left in the southern hemisphere. The result of this is that the once slowly moving flows are banked up against the western slopes of ocean basins, unable to move upslope against gravity and so become restricted and hence intensified, forming more powerful currents up to several kilometres in width and tens to hundreds of metres in thickness, flowing at different levels in the water column. Bottom currents are also locally intensified by flow restriction through narrow passages in the deep sea, typically linking one deep basin with another, such as those through fracture zone gaps in the mid-ocean ridge system. The Mediterranean outflow forms a contour current and contourites on the eastern margin of the North Atlantic, off the Portuguese continental slope.

Whereas much of the ocean is swept by very slow currents (less than 2cm/s) that have very little effect on basin fill, the western boundary currents commonly attain velocities of 10–20cm/s and up to more than 100cm/s where the flow is particularly restricted. Clearly these currents are sufficiently competent to erode, transport and deposit material, although their variability in both velocity and direction leads to a similar complexity in their deposits – contourites. Both tidal and seasonal periodicities have been noted from direct measurements of bottom-current flow, whereas longer-term variations, perhaps linked to Milankovitch climatic cycles,[3] can be inferred from the sedimentary record. It is now also known that temporary very high surface-energy conditions, related to tropical storm build-up for example, can propagate downwards and induce high energy over the deep-sea floor. These lead to benthic storms that stir and erode sediment for periods of a few days at a time, interspersed with longer and quieter periods of contourite deposition (Gardner and Sullivan 1981).

Contourite deposits or drifts develop in small irregular patches commonly associated with deep-sea channels and moats, in very broad only slightly mounded sheets often covered by extensive sediment wave fields, and as distinct mounded elongate drifts typically aligned parallel or subparallel to the basin margin. Individual drifts may grow to over 1000km long, 150–200km wide and several hundreds of metres in thickness, at mean accumulation rates of 5–10cm per 1000 years for several million years. Some of the giant drifts of the North Atlantic basins, for example, have been established for over 25 million years, bearing witness not only to periods of slow semi-continuous accumulation but also to basin-wide episodes of much more vigorous bottom currents causing regional hiatuses to develop.

## Pelagic and hemipelagic processes

Slow vertical settling of microscopic biogenic and non-biogenic particles that occurs through the water column to any depth as a basin-wide continuous background sedimentation is known as pelagic settling. It involves the hard tests of calcareous and siliceous planktonic organisms and their associated soft body tissues, which have been biosynthesized in the surface layers of the oceans. These are mixed with small amounts of the very finest terrigenous, volcaniclastic and even cosmic materials, carried by surface currents or windblown and

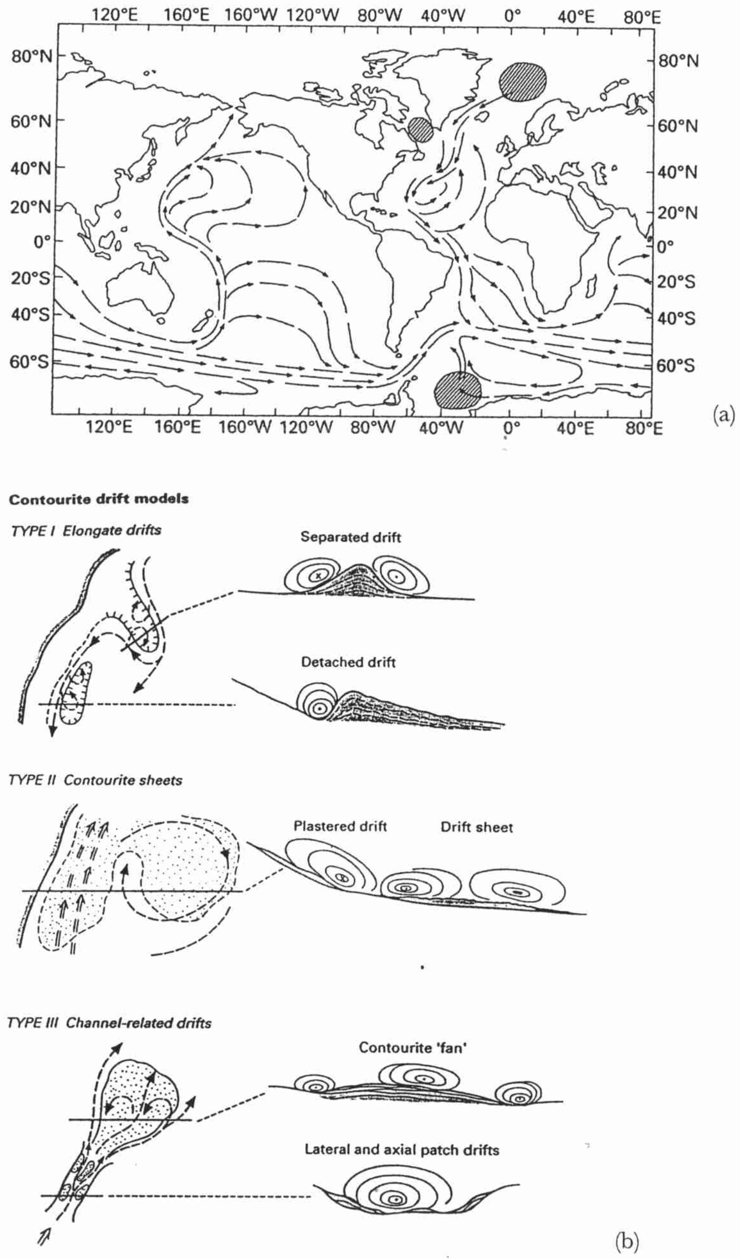

*Figure 6.3* Bottom current processes that shape the basin fill: (a) global pattern of deep thermohaline circulation in the ocean basins; (b) the nature of contourite drift deposits. (From Stow et al. 1996.)

then subject to the same very slow rates of settling, yielding mean accumulation rates for pelagic sediments of < 1cm per 1000 years.

Normal settling rates are enhanced by physical mechanisms of flocculation, that is particle aggregation, and biogenic processes (e.g. faecal pellets), whereas overall sedimentation rates are increased by as much as a factor of ten in areas of high surface productivity associated with oceanic upwelling. Pelagites[4] in these regions have a high potential for preserving organic matter, particularly where bottom circulation is restricted and oxygen levels very low. In the central parts of deep oceanic basins, by contrast, not only is all the organic matter destroyed by oxidation during settling, but calcareous skeletons dissolve in the lower pH waters found below a level known as the carbonate compensation depth (CCD). Where siliceous organisms make a significant part of the plankton then the resulting pelagite is a siliceous ooze but, in the absence of this material, pelagic red clay is deposited. Very fine terrigenous material blown by winds or transported in surface ocean currents forms a large part of these red clays.

On the continental margins of large basins and in many smaller basins, silty terrigenous material can form a significant proportion of the settling material. In this case the resulting deposit is termed hemipelagic. At high latitudes, glaciogenic hemipelagites[5] are very common, whereas in active margin basins volcaniclastic material may be dominant. Hemipelagic processes typically involve a component of slow lateral advection in mid and bottom waters via suspension cascading, lutite flows of fine-grain material such as silt or clay, and canyon currents, as well as vertical settling. Rates of accumulation are typically between 5 and 10cm per 1000 years.

## Chemogenic processes

Although chemogenic processes and their deposits cannot be considered volumetrically important in terms of basin fill, they do serve to indicate significant environmental niches or events in basin history. Ferromanganese nodules and pavements grow very slowly by direct precipitation from sea water enriched in iron and manganese, together with the co-precipitation of a range of other metallic elements. For their growth there must be a complete absence of other sedimentary materials, perhaps in areas swept clean by slow bottom currents or far removed from continental input beneath areas of ocean desert, such as the Sargasso Sea in the central North Atlantic.

Metalliferous sediments or umbers are formed much more rapidly in localized ponds and patches associated with the upwelling of hot fluids into cold bottom waters primarily along mid-ocean ridge systems. These deep-seated hot fluids vent through dark encrusted chimney stacks known as black smokers, which have been constructed by earlier precipitates. They then play host to a weird and wonderful world of bizarre life forms that thrive in these lightless depths of high temperatures and enormous pressures (see Chapter 8).

Even the deepest basins will eventually close and become shallow when caught between the inexorable forces that weld plates together and force up mountain chains. In low latitude areas of low precipitation and high evaporation, an enclosed basin may evaporate to near dryness and natural sea salts begin to precipitate out from the concentrating brine solution. Chemogenic evaporites, such as gypsum, anhydrite and halite, are formed in this way. They are well known from the basal sections of many Atlantic margin basins, having formed during the incipient stages of basin development, and from the upper sections of Tethyan basins, formed during final isolation of the Mediterranean region from the global ocean that led to a major salinity crisis between 6.0 and 5.5 million years ago.

## BASIN DEVELOPMENT: CASE STUDIES

There is such a variety of deep-sea basins, both present-day and preserved in the ancient rock record, that it is hard to do justice in an article of this length to the many and varied styles of basin fill that we know to exist. The following summary case studies, therefore, are selected from those basins in which the author has worked himself, and comparisons are drawn with other systems as appropriate.

### Angola Basin, southeast Atlantic

The Angola Basin is one of the four main basins in the South Atlantic, having an area of some 1 million square kilometres lying below the 4000m isobath (marine depth contour) and a maximum depth in excess of 5500m (Fig. 6.4). In many ways it is typical of a modern ocean basin with a flat-lying central abyssal plain, bordered on the west by a mid-ocean ridge system and on the east by a major continental land mass. To the north and south the topographic barriers are now submerged but have been at least partially emergent in the past. The South Atlantic has been opening since the early Cretaceous over 110 million years

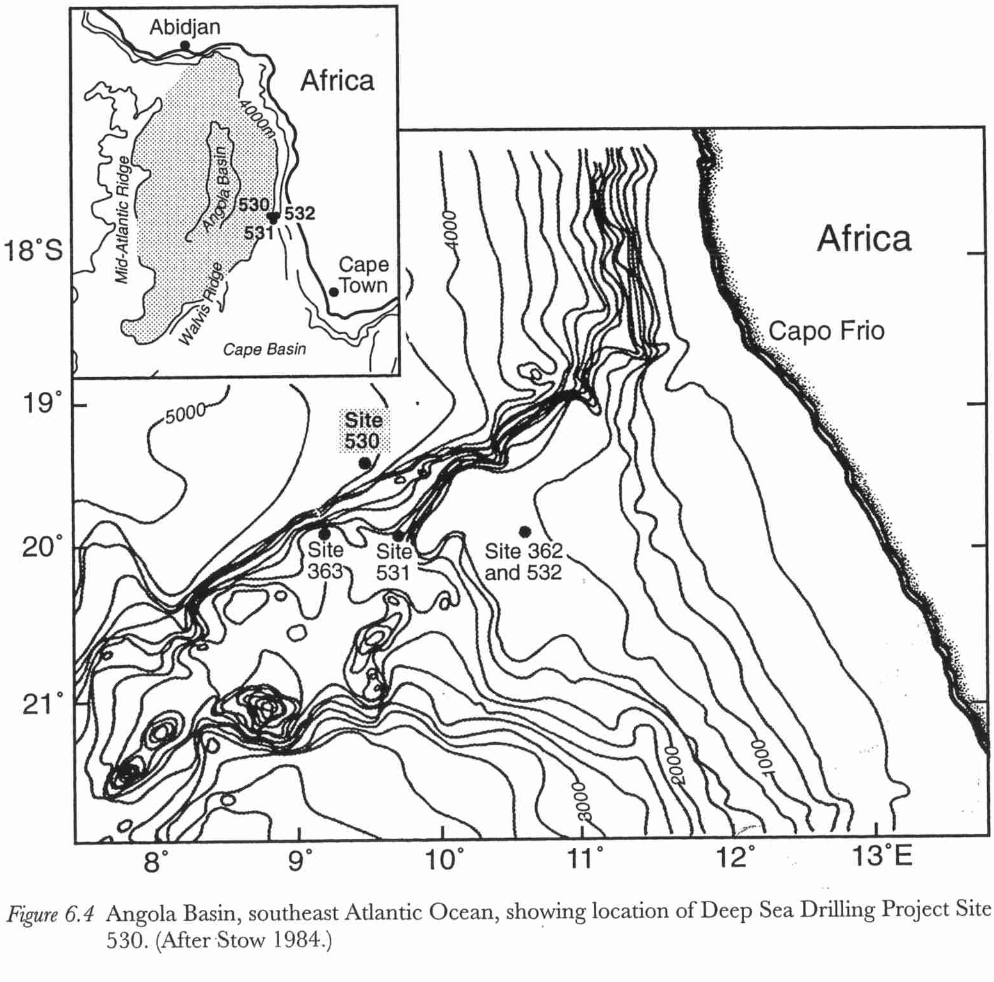

*Figure 6.4* Angola Basin, southeast Atlantic Ocean, showing location of Deep Sea Drilling Project Site 530. (After Stow 1984.)

ago, with the Angola Basin deepening progressively as the oceanic crust on which it formed cools and subsides, but also being slowly but steadily filled with sediment shed from its various margins.

At its thickest the sediment fill is little over 2km, but it is best known from the Deep Sea Drilling Project (DSDP) Site 530 in the southeast portion of the basin where 1.1km of sedimentary section was drilled, overlying ocean floor basalts of mid-Albian age (approximately 100 million years ago). Five main phases of basin fill can be recognized from the earliest sediments upwards (Figs 6.5a and 6.5b).

(1) The lowermost 200m of section comprises fine-grain mainly terrigenous sediments characterized by over 250 distinct beds of black shale having a mean organic carbon content of around 5 per cent. These were deposited by normal turbiditic and hemipelagic processes in a semi-restricted, narrow elongate Angola Basin, in which the bottom waters periodically became anoxic. Interestingly, the same mid-Cretaceous black-shale event can be recognized clearly throughout the Atlantic-Tethyan realm (including the Mediterranean and its predecessor, the Tethys) and, to a lesser extent, in other ocean basins.

(2) The overlying 250m is distinguished by an influx of greenish-coloured volcaniclastic turbidites derived from the Walvis Ridge volcanic chain to the south, which was active and partly emergent during late Cretaceous time. There is a progression upwards from

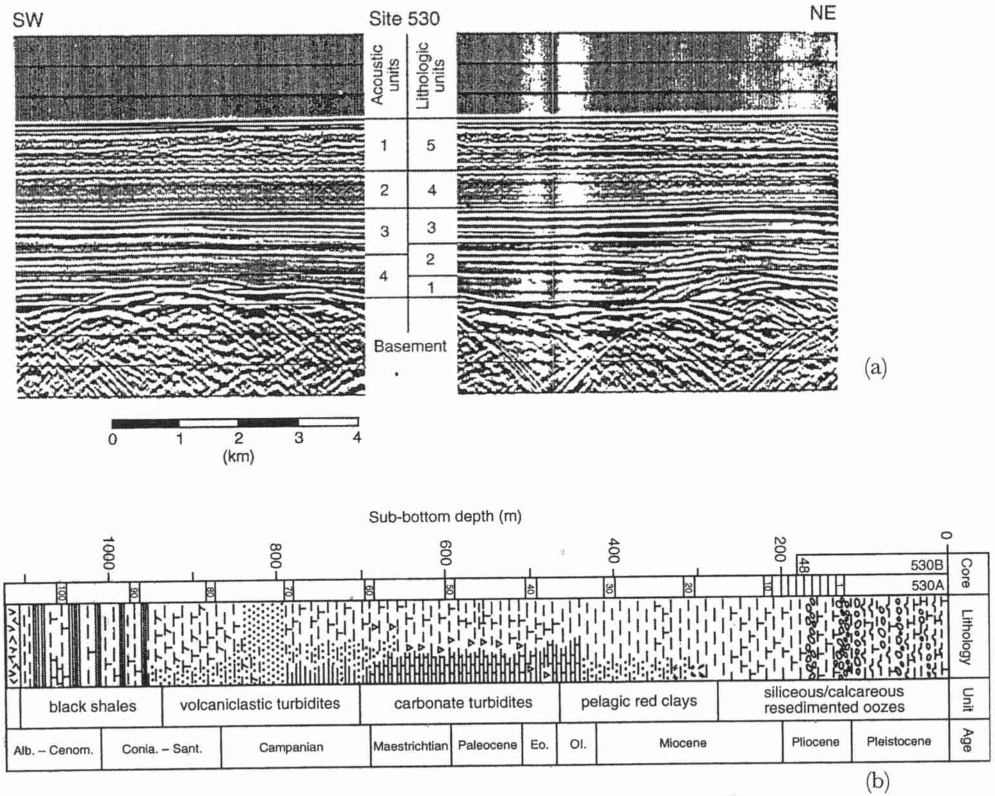

*Figure 6.5* Sections through Angola Basin fill: (a) seismic reflection profile showing 1100m sediment fill (horizontal reflectors) over ocean crust basalts (strong hyperbolic reflectors); (b) graphical representation of lithological section drilled at Site 530. Units 1–5 refer to the sediment fill units described in the text. (After Stow 1984.)

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thin-bedded fine-grained turbidites and interbedded hemipelagites, through a thick-bedded sand-dominated section, and then a return to thinner beds but of mixed vocaniclastic–carbonate composition, intercalated (layered) with very thin quartzo-feldspathic turbidites derived from the African mainland.

(3) Upwards, the mixed composition beds give way to purely carbonate turbidites made up of the fragmented remains of shallow-water organisms reworked from reefs and platforms that surrounded the now subsiding and inactive chain of volcanic sea-mounts. Individual calciturbidites are well separated by calcareous pelagites, the whole section extending for some 200m across the Cretaceous–Tertiary boundary. Careful micropalaeontological studies across this boundary reveal no particular lithological change and a rapid but phased transition from Mesozoic to Tertiary faunas. This is not consistent with a catastrophic end to the dinosaur era.

(4) The sudden end to this period of carbonate sedimentation occurred within the Oligocene period, when oceanographic changes, perhaps forced by climatic deterioration in Antarctica or major sea-level oscillation (or both), led to a dramatic shallowing of the carbonate compensation depth (CCD) in the South Atlantic and hence the non-preservation of any calcareous pelagites. One or two thin calciturbidites persisted, but the source area was clearly subsiding or exhausted and so these too disappeared. Meanwhile, the African continent bordering the Angola Basin had drifted northwards into the desert belt, so that little fluvial terrigenous material was available for redistribution. These events are reflected in the slow accumulation of some 200m of pelagic red clay.

(5) Then, in the late Miocene, calcareous background pelagites returned as suddenly as they had disappeared. However, they are interbedded with an intriguing 250m thick re-sedimented pile of mud-rich turbidites and giant debrites containing abundant siliceous material of biological origin, together with high concentrations of organic carbon. These were derived from the Walvis Ridge and mark the onset and development of the cold water Benguela Current at the surface, which led to upwelling and enhanced primary productivity along the African margin, and hence increased deposition and preservation of biogenic material and organic matter. This system is still in existence today.

## Comparisons

Although there will be regional differences according to the different sources of sediment available for supply into the Angola Basin, the sort of history of sediment fill outlined above is believed to be characteristic. It also has many close similarities with the fill or partial fill of other open ocean basins worldwide, although some specific differences can be highlighted.

The northeast Indian Ocean basin, for example, is dominated by the world's largest submarine fan, the Bengal Fan, which has been receiving vast quantities of terrigenous sediment for the past 40–50 million years as a direct result of collision between the Indian and Eurasian plates and consequent uplift of the Himalayas. The fan itself covers over 1 million square kilometres and is up to 16km or more thick at its northern end. Most of the material is brought into the basin by turbidity currents, with slides and debris flows being more important across the northern slope, and pelagic interbeds thicker on distal parts of the fan. These typically occur as alternating layers of turbidites and pelagites.

In the North Atlantic Ocean basins there is no single dominant source of sediment and the varied input of material is swept along the margins in deep-water bottom currents constructing giant elongate drifts and contourite sheets. At certain periods, climatic and oceanographic changes have led to much intensified bottom currents and the occurrence of basin-wide hiatuses in the sediment record.

## Sorbas–Tabernas Basin, southeast Spain

The Sorbas–Tabernas Basin (here referred to as the Sorbas Basin for convenience) is an example of a relatively small, fully filled, ancient basin now exposed on land. It lies within the Betic Cordillera, an Alpine mountain chain resulting from the collision of the European and African plates, which began in late Mesozoic times. The Sorbas Basin formed as an east–west orientated transtensional half-graben from the mid-Miocene onwards, when there was a switch from compressional to strike slip tectonics. At its maximum extent it was some 15–20km wide and 30–40km long, and was partly interconnected with the Vera Basin to the east and the Andarax Basin to the west (Fig. 6.6). The chief phases of basin fill can be defined as follows (Fig. 6.7).

(1) Terrestrial coarse clastic deposits first marked the onset of basin development, deposited in alluvial fan to fan delta settings by terrestrial and then submarine debris flows and associated processes. Rapid basin deepening at this stage flooded the area with fully marine deep-water sediments.

(2) The succeeding 500–700m section comprises resedimented slides, slumps, debrites and turbidites, varying from very coarse-grained megabeds to thin silt and mud turbidites, deposited both as a slope-apron fringe and in a series of submarine fans extending across the full width and partly along the axis of the basin system. They are interbedded with and pass distally into hemipelagic marls, or calcareous mudstones, and limestones. Together, these represent the thickest and deepest marine phase of basin fill that is everywhere capped by an unconformity related to continued tectonic activity and basin uplift.

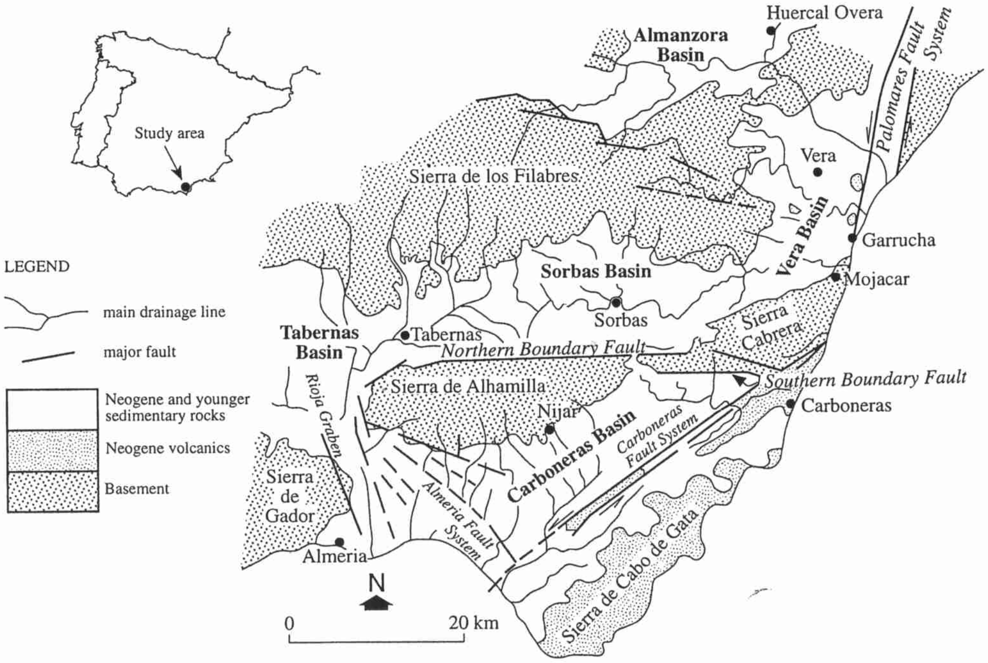

*Figure 6.6* Sorbas–Tabernas Basin, Andalucia, Spain. (After Harvey 1990.)

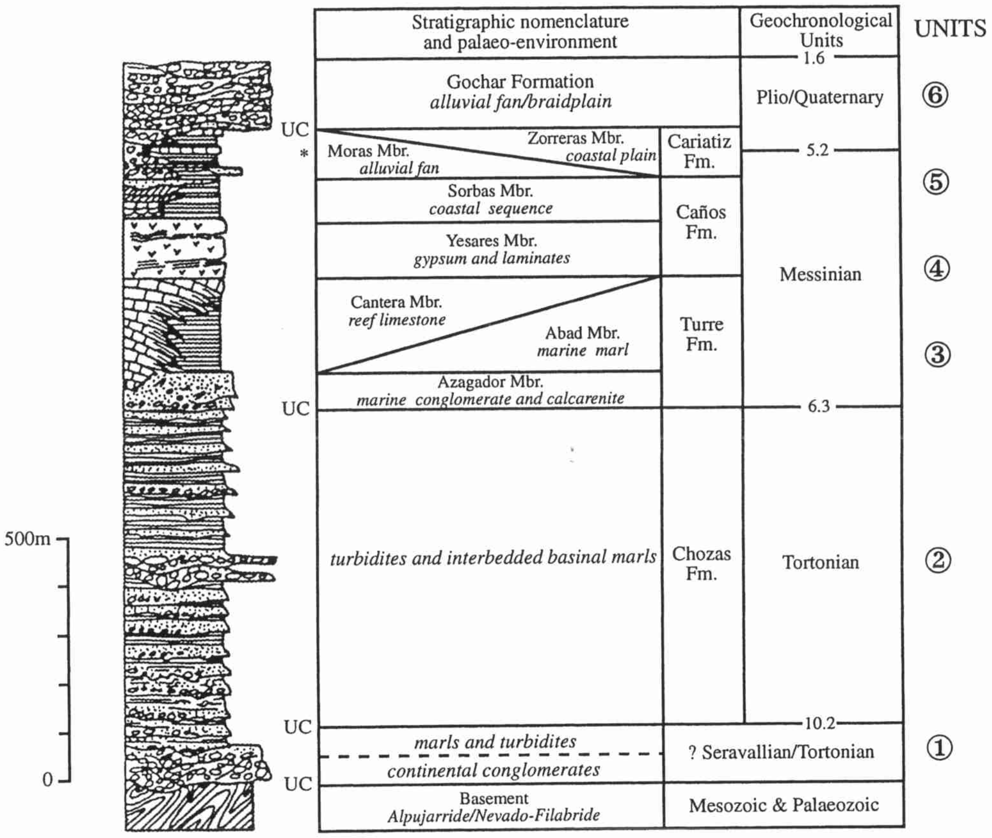

*Figure 6.7* Graphical representation of composite lithological section through the Sorbas Basin fill succession. Units 1–6 refer to the sediment fill units described in the text. (After Mather 1993.)

(3) The overlying series is represented by shallow-water reef limestones around the basin margins, fringed with resedimented coarse-grained reef talus that passes distally into marine marls of the basin centre.

(4) Continued tectonic activity led to isolation of the Sorbas Basin, together with a progressive shallowing, and the coincident isolation of the whole Mediterranean system. The result was a major phase of basin evaporation and the precipitation of gypsum–anhydrite evaporites in repeated cycles that indicate alternate evaporation and flooding events. This latest Miocene series is generally termed the Messinian salinity crisis throughout the Tethyan realm.

(5) A relatively thin (< 100m) shallowing upwards coastal sequence marks the end of marine conditions in the Sorbas Basin. Shallow marine sands, tidal sand barriers, and back-barrier lagoon sediments with birdfoot trails and fossil insects mark an intriguing conclusion of marine fill.

(6) In late Pliocene times the tectonic regime changed, with strike-slip transtension giving way to transpression and compressional tectonics so that regional uplift ensued. The former Sorbas Basin became a terrestrial basin for a brief period and was locally swamped by

alluvial fan and fluvial sediments from the uplifting basement areas to both north and south. Although the Sorbas Basin retains some topographic expression today and is clearly demarcated by the outcrops of metamorphic basement rocks in the bounding Sierras, it is essentially a filled basin that has moved into a phase of dissection and erosion.

The style of basin fill exemplified by the Sorbas Basin has many analogues in both modern and ancient systems worldwide. On the Pacific side of the San Andreas Fault system in North America, for example, there are numerous, relatively small, lozenge-shaped, fault-controlled basins in various stages of sediment fill. The exact nature of the sediment is variable, but all tend to pass from deep water through stages of progressive shallowing, followed by eventual uplift and emplacement on land. In island arc settings on compressive plate margins, small fault-controlled basins are formed and filled within a timespan of 5–15 million years. The Pohang Basin in southeastern Korea and the Miura Basin in south-central Japan are both arc-related basins of Miocene–Pliocene age (approximately 15–30 million years old) that filled with a mainly volcanic-rich suite of deep-water, shallow-water and finally terrestrial sediments.

## CONCLUSIONS

Although many different processes conspire to introduce much material over millions of years to the deep-sea floor, it is not possible to fill an open ocean basin by sedimentary means alone. Episodic turbidity currents can deliver 100 billion tons of detritus in a single event and construct submarine fans that extend over 2500km across the ocean floor. Semi-permanent bottom currents winnow, erode and reconstruct the ocean margins and can build giant contourite drifts over 1000 km in length. The ever-present slow pelagic rain of material onto the sea floor may be enhanced 100 times or more beneath areas of rich nutrient upwelling and high primary productivity. Where melting ice, strong winds or volcanic eruptions spread large amounts of terrigenous material across the ocean surface, rates of hemipelagic sedimentation are still greater. However, even given all these conditions, deep open ocean basins will not fill.

It is only where tectonic forces along active plate margins create small enclosed and semi-enclosed basins that the combined processes of sedimentation acting over a long enough period of geological time completely fill the basin. It is the record of this type of basin fill that is most readily preserved and easily recognized in ancient series on land.

## Notes

1 Clathrate: a gas hydrate deposit, mostly of methane trapped in frozen water molecules in the pore spaces of sediments.
2 Nepheloid layer: near-bottom water containing abundant suspended sediment.
3 This theory, put forward in the twentieth century by the Yugoslav scientist Milutin Milankovitch, ascribes variations in global climate and the onset of ice ages to cyclical changes in the Earth's orbit. An earlier version of this theory, by the nineteenth-century Scottish physicist James Croll, underlay a heated controversy that played a major part in the dispatch of the *Challenger* Expedition.
4 Pelagite: a sediment made up from the remains of dead pelagic (floating) planktonic organisms.
5 Hemipelagite: a sediment composed of a significant mixture of terrigenous detritus from land and the remains of pelagic (planktonic) organisms.

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