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Sea-level changes: the emergence of a Quaternary perspective

And so the relation of land to sea changes too and a place does not always remain land or sea throughout all time, but where there was dry land there comes to be sea, and where there is now sea, changes to follow some order and cycle.

(Aristotle *in Barnes, 1984, p. 572*)

1.1 Introduction

The sea is rarely level. Its surface is perturbed in many ways over contrasting spatial and temporal scales. The wind ruffles the surface of the water generating waves, which travel across the oceans as swell. Groups of waves propagating from one storm interact with wind waves and swell from other directions generated by other storms, and account for the irregular surf where they meet the shoreline. Superimposed on these most obvious of oscillations are longer-term variations in water level. Tides are the most regular of these variations, represented by a rise and fall of the surface of the sea as a consequence of the gravitational forces imposed by the Moon and the Sun. Tidal range is generally small in the open ocean; it is negligible at nodal points (called amphidromic points), but increases with distance from them. It is amplified in shallow coastal regions to reach more than 15 m during spring tides in a few embayments around the world. The tidal stage can be predicted with considerable accuracy because the orbital relationships between Sun, Earth, and Moon, and the harmonics which give rise to tidal variations, are known. However, calculation of mean sea level, the average level of the sea without wave or tide, requires 18.6 years of observations to account for the lunar nodal cycle (Pugh, 1987). The sea surface is subject to other perturbations; it responds to atmospheric conditions, such as barometric pressure, regional wind field, and dynamic oceanographic factors that vary with ocean currents. Of particular concern are unusually high water levels, such as storm surges which inundate coastal settlements, and tsunami, which are long wavelength waves caused by earthquakes, submarine landslides involving large sediment masses, or extraterrestrial impacts from space (Bryant, 2001; Owen *et al.*, 2007). The Aceh tsunami of 26 December 2004, which resulted in the death of more than 250,000 people, and the Tohoku tsunami of 11 March 2011, which killed more than 25,000 people, are tragic reminders of the destructive power of these extreme inundation events.

Sea level determines the present geographical outline of continents. The shoreline occurs where the sea meets the land. The shoreline is characterised by distinctive coastal landforms shaped by a range of processes that extend beyond the upper and lower limits of the water surface. Cliffs, beaches, and muddy shorelines undergo gradual changes in response to the oscillatory action of waves as they approach the shoreline and subaerial processes above the water line, such as swash, the run-up of the waves, salt spray, wind action that builds dunes, and other processes. Coastlines are some of the most dynamic places on Earth, as captured in the quotation from Aristotle above, not only because of the variability in water level from day to day, and the suite of associated coastal processes, but also because the level of the sea has undergone changes over longer timescales.

The level of the sea represents the ultimate base level determining the lower limit of continental denudation, to which fluvial and other weathering processes can erode landscapes. Before it was realised that sea level itself had varied, landscapes were viewed in terms of a cycle of erosion (the geographical cycle) culminating in a broad plain, termed a peneplain, at or close to sea level (Davis, 1899). Landscapes were thought to be infrequently rejuvenated by tectonic uplift. These erosional processes determine the volume and nature of terrestrially derived sediment that may be deposited within coastal environments. Geologists have understood for a long time that many sedimentary rocks accumulated in marine or coastal basins when the sea was at a different level to that which it occupies at present. Palaeoenvironmental inferences about global sea-level changes derived from the pre-Quaternary record have provided a coherent and integrated basis for developing models for hydrocarbon exploration, termed sequence stratigraphy, based on mapping of unconformity-bounded sedimentary sequences (Van Wagoner *et al*., 1988; Catuneanu, 2006). Many principles derived from pre-Quaternary sedimentary successions also apply to the Quaternary Period.

Sea-level changes have far-reaching effects on both coastal and terrestrial environments. During successive Pleistocene glaciations, at times of maximum icesheet development, major falls in sea level (lowstands) exposed continental shelves. This was associated with lateral shifts in vegetation communities, and created land bridges enabling migration of taxa between formerly isolated regions; for example, Britain was connected to continental Europe and the island of New Guinea was connected to Australia. During these periods when base level was lowered, rivers eroded more vigorously in headwater and other regions. The significantly larger land areas of many continents at times of lower sea levels also led to greater aridity in the interior of Australia, Africa, the Americas, and Eurasia. As rivers extended across continental shelves during the Last Glacial Maximum (LGM) many followed significantly different courses in their lower reaches. For example, the island of Borneo was connected with Peninsular Malaysia forming a broad Sunda Shelf which was drained into the South China Sea by a river system called the Molengraaff River (Tjia, 1980), and the Rhine and Thames joined as tributaries to the Channel River in northwestern Europe (Coles, 2000). Terrigenous sediments, the product of prolonged continental denudation, were carried onto, or well beyond the continental shelves and deposited in deeper water, such as the Bengal Fan in the Bay of Bengal (Kuehl *et al*., 1989) and the River Murray at the shelf edge in southern Australia (Hill *et al*., 2009; Schmidt *et al*., 2010).

Sea level has been close to, or above, present levels for $<15\%$ of the past 128,000 years (the last glacial cycle). Sea levels fluctuated considerably for the majority of this period and were significantly below present reaching a maximum of about −120 m during the LGM (Lambeck and Chappell, 2001). Sea level reoccupied its present position (the present highstand being close to the position of past highstands) only recently, during the past 6,000 years when the northern hemisphere polar icesheets that were kilometres thick during the glaciations had almost completely melted, except for Greenland. The past few thousand years have been relatively stable in terms of climate, in contrast to much of the last glacial cycle, during which sea level has oscillated significantly in response to repeated climate changes. There have also been subtle geographical variations in relative sea-level change which have been a function of the complex crustal response to changing ice and water loads on the surface of the Earth (glacio-hydro-isostatic adjustment processes). Sea-level studies provide independent evidence for these geophysical adjustments, and are an invaluable means of quantifying mantle rheology (Lambeck and Johnson, 1998).

Viewed at a global scale, redistribution of water masses accompanying glacio-eustatic sea-level changes affects the Earth's rotation as well as perturbing near-Earth satellites in an otherwise time-constant gravity field. Earth rotational changes involve variations in angular velocity about the rotation axis (length of day) and the orientation of the rotation axis (polar motion). Rates of weathering, planetary albedo at a global scale, as well as the rotational behaviour of the planet are also influenced by changes in sea level. In addition, the rapid flooding of continental shelves has been linked to some episodes of volcanism (Nakada and Yokose, 1992; McGuire *et al*., 1997; Church *et al*., 2005).

Quaternary highstands of sea level have coincided with interglacials, the warmer periods during the Ice Ages. The vestiges of past periods of high sea level are recorded in the varied landforms and sedimentary deposits preserved along the world's diverse coastlines. Fluctuations in relative sea level can also shift laterally the area affected by hazards such as storm surge and tsunami, especially along low gradient coastlines.

In recent years, the realisation that human activities might be warming the planet and the prospect of future enhanced greenhouse-induced sea-level rise have raised considerable concern. Climate modelling and associated projections of a possible range of sea-level rise scenarios indicate that globally mean sea level might rise by as much as 80 cm or more by 2100 (IPCC, Third Assessment Report, 2001, and Fourth Assessment Report, 2007 which produced slightly different projections, see Chapter 8). These projections have caused concern for people living in coastal lowland regions and oceanic islands, exacerbating the impact of coastal hazards to which they are already exposed (Nicholls *et al*., 2007). A disproportionate percentage of the world's population resides in coastal lowland regions close to present sea level.

1.2 The Quaternary Period

The Quaternary Period was characterised by repeated growth and decay of continental icesheets and substantial fluctuations in sea level at a global scale. The stratigraphical record from the Quaternary Period has been subdivided on the basis of palaeoclimatic inferences derived from sedimentary successions (Bowen, 1985; Lowe and Walker, 1997; Bradley, 1999; Cronin, 2010). It is the evidence for sea-level changes during this period, their nature, timing and geomorphological significance, and the methods used to study them that are the principal focus of this book.

Consistent with the terminology of the earlier Phanerozoic record, the Quaternary refers to the most recent interval of Earth history (Figure. 1.1), following the Tertiary Period (now re-named Neogene and Paleogene). The Quaternary has been assigned Period status; *periods* are chronostratigraphically defined intervals of time intermediate in status between Era and Epoch (Salvador, 1994). The Quaternary was defined by Desnoyers (1829) based on a flat-lying succession of sediments in the Paris Basin that overlie Tertiary strata. Charles Lyell subsequently defined the Pleistocene epoch in reference to marine strata containing up to 70% fossils represented by modern equivalents (Lyell, 1839). The Quaternary Period has become largely synonymous with the term Ice Age, as corroborated by oxygen-isotope evidence from deep-sea (Shackleton *et al*., 1990; Raymo, 1992) and ice cores (Barbante *et al*., 2010).

The Pliocene–early Pleistocene boundary has been antedated from 1.806 Ma to 2.59 Ma (Ogg *et al*., 2008). This is an outcome of much discussion (Gradstein *et al*., 2004; Pillans and Naish, 2004), and the recognition, based on a range of palaeoclimatic evidence, that the onset of northern hemisphere glaciation commenced earlier than originally appreciated. In assigning an older age to the base of the Pleistocene, the Gelasian Stage (formerly a terminal Pliocene Stage) has been reassigned to the Quaternary Period. The former base of the Quaternary was defined by a stratigraphical section of marine strata at Vrica in Calabria, southern Italy, with an assigned age of 1.806 Ma (Aguirre and Pasini, 1985). It was marked by the first appearance of elements of an Arctic fauna within the Mediterranean Basin including the marine mollusc *Arctica islandica* and the ostracod *Cytheropteron testudo*. The redefined base, coinciding with Marine Isotope Stage (MIS) 103, a slightly warmer interval with a basal age of 2.59 Ma, occurs at a globally recognisable geomagnetic reversal, the onset of the Matuyama Chron (interval of reversed geomagnetic polarity). This is stratigraphically more easily identified than the colder MIS 110 at 2.73 Ma.

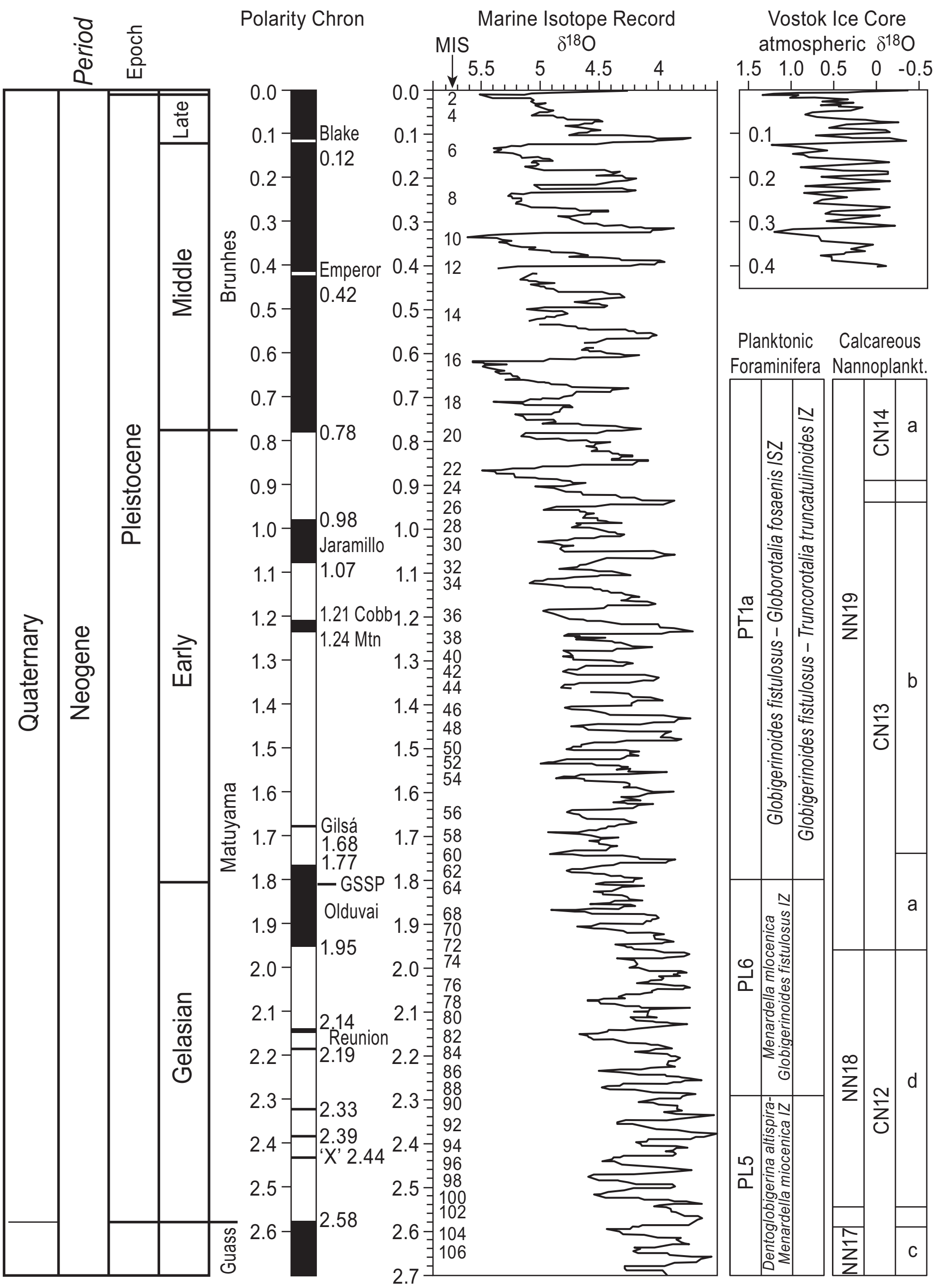

Figure 1.1 Global correlation time chart of the Quaternary Period showing the principal subdivisions of Quaternary time. The chart includes the geomagnetic polarity timescale, marine oxygen-isotope record, Vostock Ice Core, and marine biostratigraphy based on planktonic foraminifera and calcareous nanoplankton (*source*: modified after Gradstein *et al.*, 2004 to accommodate the revision to the Quaternary boundary).

The early–middle Pleistocene boundary is commonly defined by the Brunhes–Matuyama geomagnetic polarity reversal at 780 ka, although this has not been formally described. The middle–late Pleistocene boundary has been placed at about 126–128 ka (near the base of the Eemian Interglacial in Europe), although also the subject of renewed discussion (Gibbard, 2003; Pillans and Naish, 2004). The Holocene series (epoch) refers to the past 11,500 years (^{14}C years) (Figure 1.1). The Holocene has also been defined as a time of climatic amelioration following the Younger Dryas, which was a period of cooling during an overall trend of deglaciation following the LGM; it lasted approximately 1,500 years and ended some 11,500 years ago. The redefined Quaternary Period represents approximately 0.06% of Earth history. The subdivisions of the Pleistocene series (epochs in geochronological parlance) represent different percentages of Quaternary time, namely: early Pleistocene ~70%; middle Pleistocene ~25%; late Pleistocene ~4.5%, and the Holocene 0.5%.

1.3 Sea-level changes: historical development of ideas

Many cultures have recorded legends of floods, some of which were attributed to changes in sea level. More than 500 flood myths are known (Oppenheimer, 1998). Many of them are marine flood legends or descriptions of deluges (Ryan and Pitman, 1998; Burroughs, 2005). Few enable an estimation of the apparent timing of such flood events. Three examples are considered below.

In Australia, numerous Aboriginal dreamtime legends account for an episode of marine inundation which is most likely associated with the most recent deglaciation and early Holocene sea-level rise. Approximately one-seventh of the continent ($> 2,500,000$ km^2) was flooded resulting in a loss of low gradient, foraging land and the flooding of former river valleys (Cane, 2001). A dreamtime legend describes the filling of what is now Spencer Gulf, an elongate shallow marine embayment that extends some 300 km northwards into semi-arid southern Australia. According to the legend, a kangaroo-man used a thigh bone of a mythical ancestor to open an isthmus which separated the ocean from the valley and its protected shallow-water lagoons in order to establish harmony between birds and land-dwellers over disputed access to lagoons for freshwater (Roberts and Mountford, 1969). Palaeoenvironments inferred from benthic foraminifera provide scientific evidence for the marine flooding of northern Spencer Gulf, consistent with the dreamtime legend. A calibrated radiocarbon age of $12,630 \pm 230$ years BP (Before Present, which in the case of radiocarbon is before 1950 AD) on a specimen of the intertidal to shallow subtidal cockle *Katelysia* sp. from a vibrocore of estuarine carbonate lagoon sediments collected in a modern water depth of 20 m indicates marine flooding of the northern gulf by that time (Cann *et al*., 2000), and attests to the antiquity of the dreamtime legend.

Evidence for abrupt drowning of the Black Sea has been examined by Ryan *et al*. (1997) and Ryan and Pitman (1998), who argue that around 7,600 years ago, close to the culmination of the postglacial rise in sea level, seawater burst through the narrow straits of the Bosporus Valley. They argued that this event was responsible for many of the long-standing myths concerning floods, including the Epic of Gilgamesh. Before the flooding event, the Black Sea was a large freshwater lake of significantly smaller extent. Ryan and Pitman (1998) suggested that the lake level was up to 100 m below the sill which divides the Bosporus from the present Black Sea. They inferred that inflow of water from the Bosporus to the present Black Sea was of the order of 50–100 km^3/day (greater than 200 times the flux over Niagara Falls). A counter-argument was presented by Görür *et al*. (2001) suggesting that the event was not as dramatic as suggested by Ryan and Pitman (1998) and that the change in water level was only about 18 m. A large literature has emerged on the topic and some of the controversies surrounding the Black Sea flooding event have been exacerbated by uncertainties in the value of the marine reservoir effect adopted in radiocarbon dating (Nicholas *et al*., 2011).

The theme of flood legends is briefly explored by Lambeck (1996a) in the context of postglacial sea-level rise within the Persian Gulf and the emergence of civilisation in the Fertile Crescent. The present shoreline of the Persian Gulf was established sometime shortly before 6,000 years BP (^{14}C years). The rising sea inundated extensive low-lying areas of Lower Mesopotamia, and is likely to have constrained migration of people and establishment of the earliest settlements in Lower Mesopotamia. It is speculated that the gulf floor before sea-level rise would have represented a logical route for people travelling westward from the east of Iran during the late Palaeolithic (> 10,000 years BP) to early Neolithic (6,000 years BP). Excavations at the city of Ur have provided evidence for a flooding event some 5,000–6,000 years BP; the water god Enki (or Ea) appears to have been particularly honoured in the holy city of Eridu, which was situated at the mouth of the Apsu (Guirand, 1996), and it is possible that the Sumerian flood legend actually documents the culmination of postglacial sea-level rise.

1.4 Observations from classical antiquity until the nineteenth century

Since earliest antiquity, there have been suggestions of changes in the relative positions of land and sea. In his second book entitled *Euterpé*, Herodotus [c. 485–425 BC] refers to marine shells in the sediments beneath the plains of the Nile, as well as the hillslopes bounding the wide Nile Valley, and considered that the region had once been covered by the sea (Komroff, 1947). The eighteenth-century development of geology as a formal scientific discipline saw a series of refinements as observations in the field began to play a more significant role and replace a strict interpretation of biblical teaching. The Neptunist and Vulcanist schools of thought attempted to describe many seemingly disparate geological observations. The Neptunists emphasised the significance of marine agencies for the origin of rocks (exogenetic processes) whilst the Vulcanists appreciated the importance of igneous processes operative within the Earth's crust (endogenetic processes). Thus, relative changes in sea level were attributed to sea-surface variations by the Neptunists, and to crustal processes by the Vulcanists.

1.4.1 Early Mediterranean studies

Aristotle [384–322 BC] discussed the emergence of the coastal plains of Libya and noted that low-lying lands formed in response to formation of a 'barrier of silt' leading to the desiccation of lakes, and in his work on *Meteorology* was clearly aware of relative sea-level changes, as apparent from the quotation that heads this chapter. The geographer and historian Strabo [c. 64 BC–c. 23 AD] sought to explain by what processes marine shells became buried at high elevations in the landscape. He suggested that changes in land level were simultaneously accompanied by sea-level changes, such that the rise in the seafloor heralded a rise in sea level.

Leonardo da Vinci [1452–1519] described shell deposits at high elevations near Monferrato in Italy in his notebooks written sometime between 1470 and 1480. He reasoned that:

> *From the two lines of shells we are forced to say that the earth indignantly submerged under the sea and so the first layer was made; and then the deluge made the second.*
>
> (da Vinci, *VI Geological Problems, in Richter, 1970)*

Elsewhere, Leonardo had argued against a deluge for the origin of accumulations of shell; however, he may have made the reference above to maintain a religious correctness, as at the time it was unclear what exactly the impressions of fossils within rocks actually represented. There was a view that they had been placed within the rocks by a divine creator to test the religious faith of mortals.

1.4.2 Eighteenth-century writings on universal changes to the Earth

Although numerous workers articulated theories of the Earth in what is now regarded as the Neptunist School of thought, history has accorded Abraham Gottlob Werner [1750–1817] as the strongest proponent of the movement. As with other Neptunists, Werner was of the view that a universal ocean had formerly covered the entire surface of the Earth, and that land had periodically been exposed as a result of a progressive lowering of the world ocean (eustatic sea level in modern parlance). Werner suggested that granite and other crystalline rocks had been precipitated from the universal ocean giving rise to *primitive* rocks. A *transitional series* of strata were then deposited by subaqueous depositional processes, resulting in formation of steeply dipping strata on crystalline rock. With the progressive lowering of sea level, emergence of islands enabled subaerial processes to weather the primitive rocks and promote deposition of *secondary* formations. A continued fall in the level of the universal ocean, as receding waters were sequestered in subterranean caverns, resulted in formation of alluvial successions (Tertiary strata) flanking the crystalline massifs. A consensus emerged that there had been an overall fall in the level of the universal ocean throughout Earth history (Rudwick, 2005), although some scientists believed there had been periodic short-term rises.

Evidence for emergence of land, such as shell beds at high elevations in the landscape, and the stranding of harbours inland from the coastline, was linked to a gradual fall in the level of the 'universal ocean', termed the 'diminution of the sea' by the French diplomat and naturalist Benoît de Maillet [1656–1738]. In a book entitled *Telliamed* (published posthumously in 1748, the title being the author's surname spelt in reverse), de Maillet (1748) described a dialogue between a fictional Indian scholar named Telliamed and a French missionary (Carozzi, 1969, 1992; Oldroyd, 1996). A scholarly translation of the complete work is given by Carozzi (1968) with detailed re-interpretations of the observations made by de Maillet.

Fennoscandia features prominently in the early scientific literature on relative sea-level changes, because there are former shorelines now found elevated well above sea level (Celsius, 1743; Linné, 1745). During his travels, Celsius [1701–1744] made numerous observations of these former shorelines and the shallowing of formerly navigable channels. He concluded that sea level had fallen (the 'diminution' of water following the universal deluge) by up to 4.5 feet (1.37 m) during the previous 100 years. This value was subsequently revised to 4 feet and became widely known as the 'Celsius-value' (Wegmann, 1969). Celsius was instrumental in initiating the practice of recording water levels on rocks marking them with a line, inscribed with the date when the recording was made. This practice continued after Celsius and represents an important source of historical information on relative sea-level changes.

In his *Oratio de Telluris Habitabilis Incremento*, published in 1743, Linné envisaged dry land appearing from a once almost universal ocean. Following on from the work of Celsius and Linné, the Swedish historiographer, Olof Dahlin, had caused political commotion with his reconstruction of the former shape of the Swedish kingdom (Wegmann, 1969). He concluded that the country was formerly an archipelago, and had existed in the form it did at the time at which he wrote for only a third of history since creation. This apparently caused scandal because people '. . . believed, the dignity of the kingdom had been challenged' (Wegmann, 1969, p. 391).

1.4.3 Diluvial Theory – the universal flood

A central tenet of the Diluvial Theory as propounded by Reverend William Buckland [1784–1856], Reader in Geology at Oxford University, was the notion that major changes on the Earth's surface could be readily understood through literal interpretation of the Bible, particularly the deluge recorded in Genesis (Buckland, 1823). This represented a significant intellectual constraint for the development of ideas about sea level, and environmental changes in general. Accordingly, in the eighteenth and early nineteenth centuries, many geomorphological features, such as isolated glacial erratics perched on hilltops, boulder clay (till), and related superficial moraine deposits, as well as erosional landforms, were attributed to the actions of a universal deluge (Conybeare and Phillips, 1822). Some attempted to explain the origin of poorly sorted superficial deposits mantling the landscape and erosional features such as striated bedrock surfaces as the product of a mega-tsunami (Diluvian waves) (Hall, 1815). The term 'drift', introduced by Roderick Murchison (1839) in his book, *The Silurian System*, was subsequently invoked to describe seemingly chaotic assemblages of poorly sorted, unconsolidated sediments formerly termed *diluvium* by Buckland, who believed they formed during Noah's Flood (the term drift is still used by the British Geological Survey for the mapping of unconsolidated deposits of Quaternary age irrespective of their mode of formation).

Timing of the deluge was constrained by literal interpretation of the Bible. Based on a combination of astronomical evidence, historical information and genealogical studies of the Bible, James Ussher, Archbishop of Armagh in Ireland, concluded that the '. . . beginning of time according to our Chronologie, fell upon the entrance of the night of the Julian Calendar, 710 (4004 BC)' (Ussher, 1658, p. 1) and accordingly, the 'flood deposits' must have been significantly younger. In 1647 John Lightfoot, Vice-Chancellor of the University of Cambridge, suggested that the moment of creation (i.e. age of the Earth) was on 26 October 4004 BC at 9 a.m. Ussher, however, is remembered for this calculation as it was included as a side note in the authorised King James I version of the Bible (Brice, 1982; Dalrymple, 1991).

The literalist interpretation of scriptures imposed a rigid explanation for human origins and an unrealistically short time interval for the development of landforms, the Earth's major relief and the sedimentary fill of large depositional basins. In addition, emergent shell beds were commonly regarded as contemporaneous with Noah's flood rather than as evidence for relative changes in sea level.

1.4.4 The Temple of Serapis: a compelling case for relative sea-level change

In the ninth edition of his celebrated work, *Principles of Geology*, published in 1853, Charles Lyell [1797–1875] described a market place, popularly known as the Temple of Serapis at Pozzuoli, near Naples in southern Italy, which provides evidence of a recent relative change in sea level during historical times. The monument has become immortalised as the foremost example of recent relative sea-level changes through its inclusion in the frontispiece, and as a gold embossed inlay on the cover of various editions of Lyell's *Principles of Geology*. A particularly detailed description of the site was also presented by the mathematician Charles Babbage [1792–1871] (Babbage, 1847), inventor of the adding machine and author of *Reflections on the decline of science in England* published in 1830. At a regional landscape scale, the Roman marketplace at Pozzuoli is situated within the centre of the Phlegrean Fields caldera in which Monte Nuovo and Solfatara occur, a feature about 13 km in diameter whose earliest phase of volcanism extends back around 60 ka (Morhange *et al*., 2006). The Roman marketplace was excavated in 1750 by removing volcanic ash which had partially buried the structure (see Figure 3.13a). Three vertical marble columns are covered in the markings made by marine bivalves, *Lithodomus* sp., the upper limit of which ranges between 5.68 and 5.98 m above present sea level