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GEOCHEMICAL EVIDENCE OF QUATERNARY SEA-LEVEL CHANGES

Introduction

- As we know that the 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.
- 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.
- 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).

Introduction

- 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.
- Paleoenvironmental 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.
- During successive Pleistocene glaciations, at times of maximum ice sheet development, major falls in sea level (lowstands) exposed continental shelves.

Introduction

- As rivers extended across continental shelves during the Last Glacial Maximum (LGM) many followed significantly different courses in their lower reaches.
- There are some examples which belongs to the changes: 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.
- 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 −120m during the LGM (Lambeck and Chappell, 2001).

Introduction

- Sea level reoccupied its present position (the present highstand being close to the position of past high stands) only recently, during the past 6,000 years when the northern hemisphere polar ice sheets that were kilometers thick during the glaciations had almost completely melted, except for Greenland.
- 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 behavior 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).
- 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.

Introduction

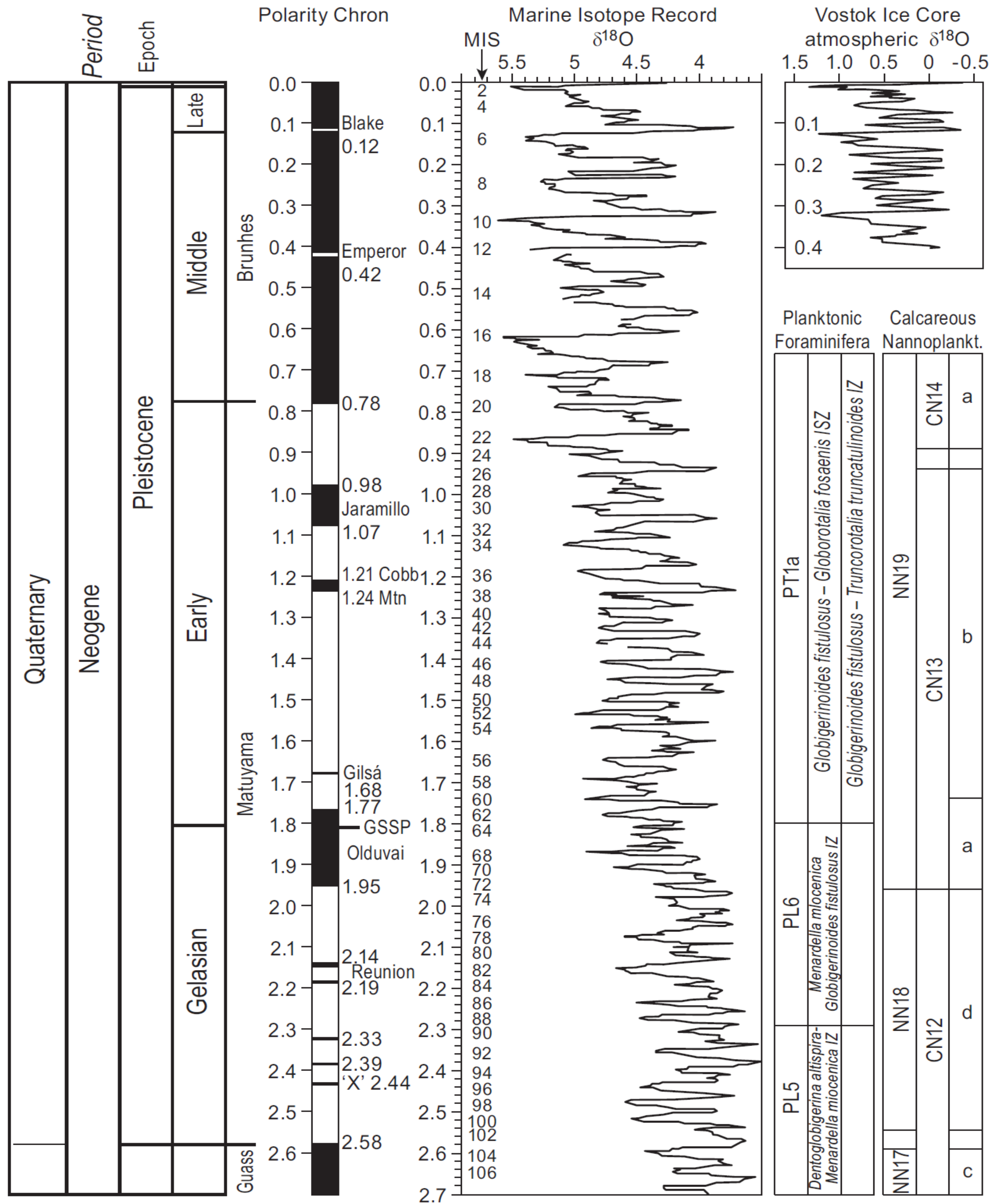
- In these years, the realization that human activities might be warming the planet and the prospect of future enhanced greenhouse-induced sea-level rise have raised considerable concern. Climate modelling and associated projections of a possible range of sea-level rise scenarios indicate that globally mean sea level might rise by as much as 80 cm or more by 2100.

The Quaternary Period

- The Quaternary Period was characterized by repeated growth and decay of continental ice sheets and substantial fluctuations in sea level at a global scale.
- The stratigraphically record from the Quaternary Period has been subdivided on the basis of paleoclimatic inferences. It is the evidence for sea-level changes during this period, their nature, timing and geomorphological significance.
- 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 Quaternary Period

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).



Sea-level changes: historical development

- Three examples who could be considered to historical development.
- 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 km2) 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.
- Paleoenvironments 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±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 20m 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.

Sea-level changes: historical development

- Postglacial sea-level rise within the Persian Gulf and the emergence of civilization in the Fertile Crescent. The present shoreline of the Persian Gulf was established sometime shortly before 6,000 years BP (14C years).
- 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 honored 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.

Observations from classical antiquity until the 19th century

- 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 emphasized 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.

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.
- 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.

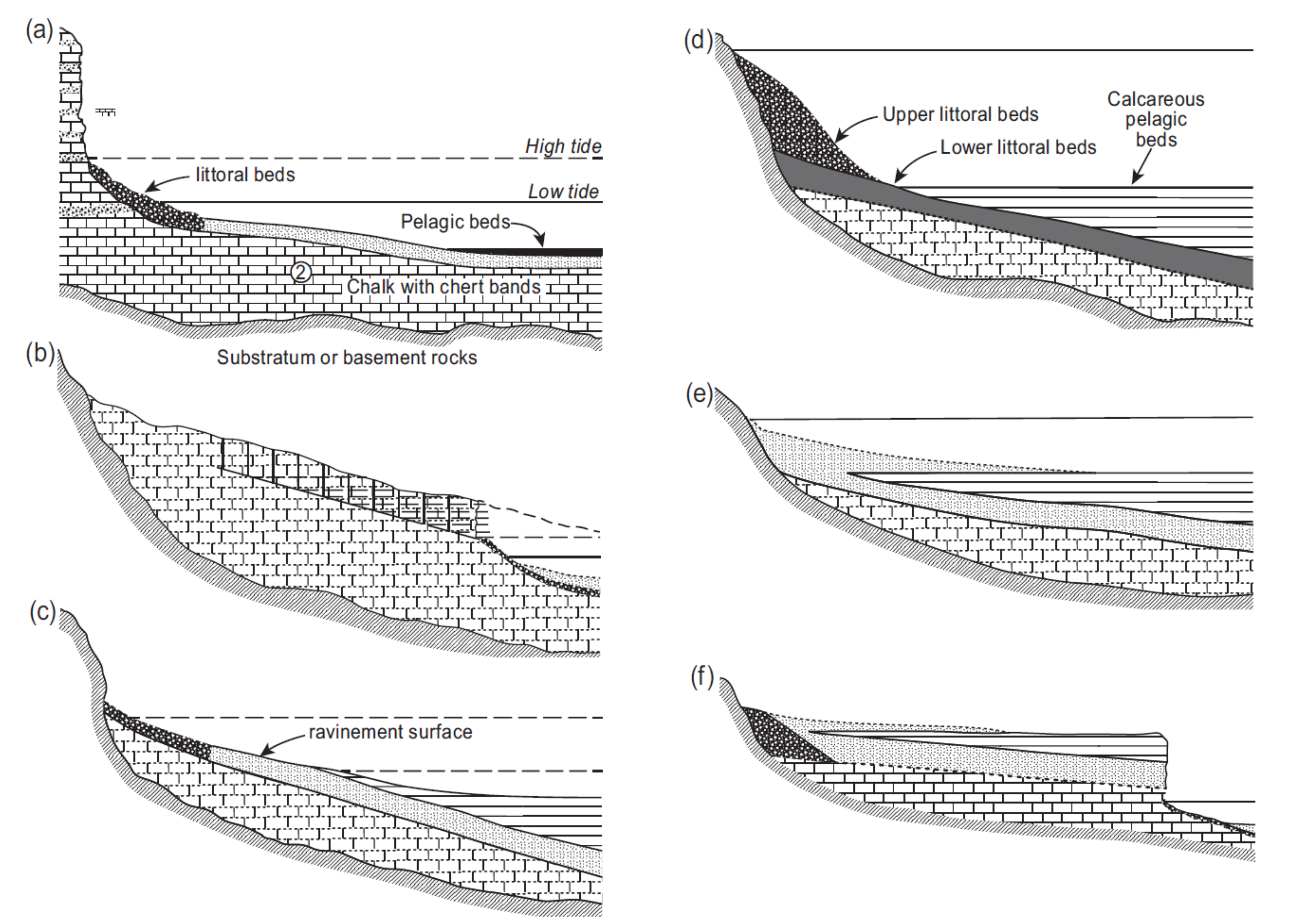
the concepts of transgression and regression

- The French chemist Antoine Lavoisier [1743–1794] examined the Tertiary successions of the Paris Basin and made several profound observations about relative sea-level changes (Carozzi, 1965; Friedman et al., 1992; Gould, 2000).
- He explained the relative stratigraphical relationships of pelagic shelly limestones (bancs calcaires), littoral sands and gravel and clay (galets, sable grossier, sable fin, argile), and pelagic chalk with flint (craie avec cailloux) in the context of relative sea-level changes, a concept that was revolutionary for its time (Figure 1.2).
- The sequence of changes involved (a) erosion of chalk coastal cliffs and deposition of gravel, sand and clay in the littoral zone, not necessarily under conditions of rising sea level; (b) a period of slow relative sea-level rise, coastal erosion and shoreline retreat accompanied by the deposition of a laterally persistent seaward-dipping, littoral deposit; and (c) continued relative sea-level rise resulting in the shoreline forming near mountains.
- During a sea-level highstand (d), terrigenous clastic sediment is shed from the mountain range and deposited within the coastal environment resulting in a younger succession of littoral sediments (Upper littoral beds), which overlie an older succession of littoral sediments (Lower littoral beds) with development of a thicker succession of calcareous pelagic beds in deeper water.

the concepts of transgression and regression

- Accompanying a relative fall in sea level (e), sediments within the littoral environment are progressively deposited on the deeper-water calcareous pelagic beds, resulting in a well-defined sediment wedge; and (f) represents the final product of this sequence of depositional episodes as described by Lavoisier (1789) following a period of subaerial erosion (Carozzi, 1965).
- Lavoisier's field observations preceded the contributions of Johannes Walther [1860–1937], who is generally credited for formulation of the concept of lateral facies succession: the notion that adjacent sedimentary environments and their preserved sediments, when viewed in a vertical stratigraphical profile, are seen to be superposed.
- Lavoisier's contribution is significant for recognizing the possibility of cyclic sedimentation in response to sea-level changes (Carozzi, 1965; Gould, 2000), and also introduced the concept of an equilibrium cross-shore profile in response to sea-level changes (i.e. erosion, shoreline retreat and the landward translation of coastal sediments accompanying a relative rise in sea level).

the concepts of transgression and regression



Insights from around the world

- As evidence for worldwide changes in sea level became more widely accepted, it was considered that diastrophism (ocean crustal movements) was responsible. Eduard Suess [1831–1914] noted that transgressions and regressions from many widely separated regions were broadly coeval globally (Suess, 1888). On this basis, Suess formalized the notion of eustatisch (eustatic or worldwide) changes in sea level and considered that altered volume of the ocean basins caused sea-level changes in the longer-term geological record.
- Woods also suggested that (1) ongoing uplift of the coastal plain explained the origin of the raised beaches, coastal lagoons and salinas; (2) each range corresponded with a former coastline; and (3) the flats on the landward side of each barrier represented former estuaries.

Advances in geochemistry and geochronology

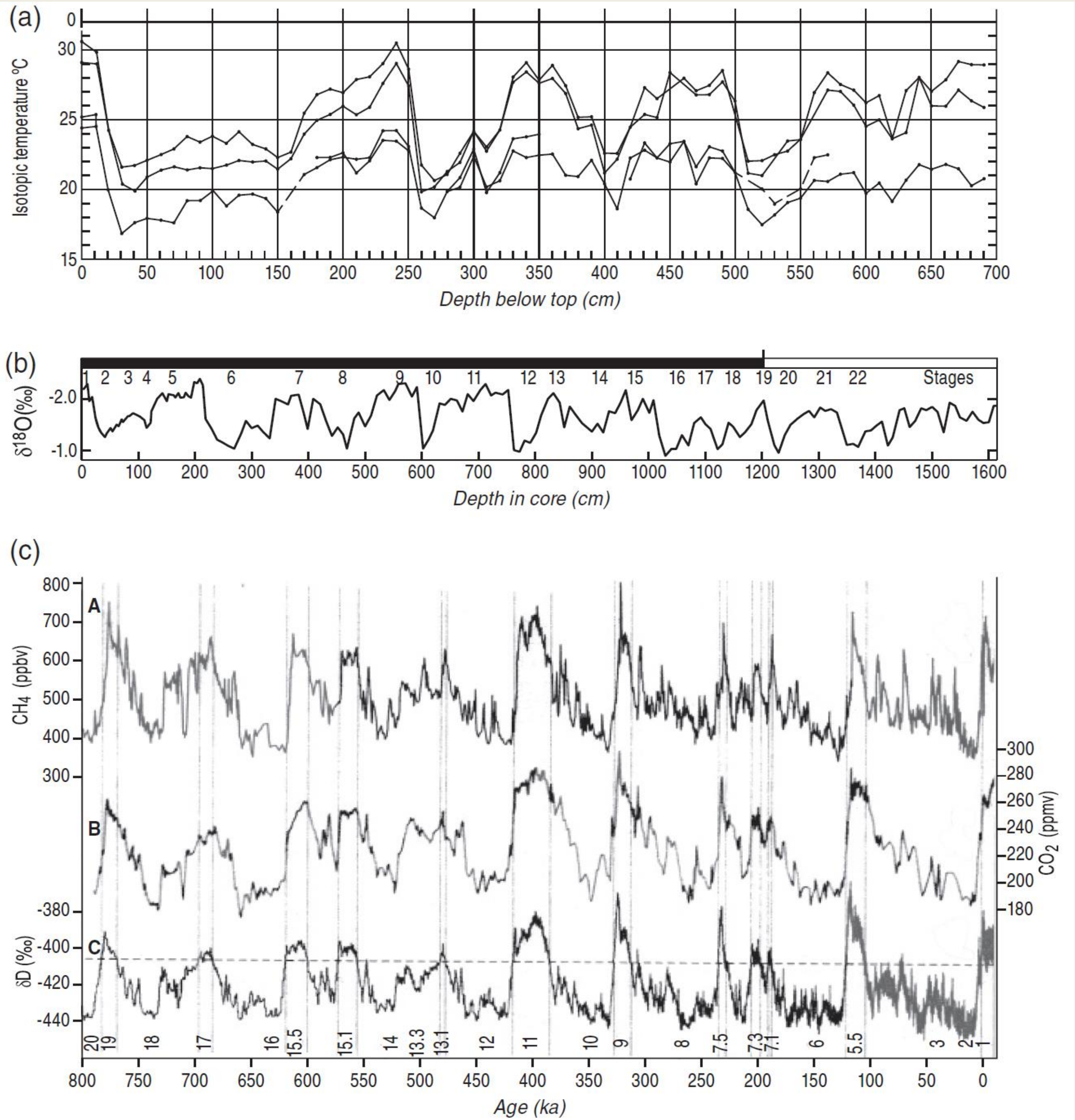
- The radiocarbon chronologies constrained the timing of geologically recent sea-level changes (for the past 50,000 years), and revealed that the most recent deglaciation occurred relatively rapidly with a concomitant rapid rise in sea level (Fairbanks, 1989; Chappell and Polach, 1991).
- There were some limitations to the radiocarbon studies, however; many early studies suggested the presence of high interstadial sea levels close to present sea level during the last glacial cycle (around 30,000 years ago) that are now known to be a result of sample contamination by younger carbon sources on fossil deposits actually of last interglacial age (125 ka).
- Uranium-series dating, and in particular the activity ratios of the isotopes of uranium and thorium, represented a further important method for determining the age of coastal deposits, particularly for corals that formed during the last two interglaciations. U-series dating provided the first compelling evidence for the age of last interglacial and penultimate interglacial deposits (Barnes et al., 1956; Veeh, 1966; Stearns, 1984). It also yielded preliminary numerical ages to assess the veracity of the Croll–Milankovitch Hypothesis as an explanation of long-term climate change. Since these early investigations, numerous publications have appeared on
- Corals were also soon realized to be particularly suitable for dating by the U-series method, and with detailed stratigraphical analysis, confident estimates of palaeo-sea level could be inferred from the palaeoecological context of the fossil reef complexes.

Oxygen-isotope records from marine sediments and ice cores

- Harold Urey [1893–1981] noted that when water is heated, the stable isotopes of oxygen undergo fractionation whereby the lightest isotope (16_{O}) is preferentially selected during evaporation, such that the remaining liquid is enriched in the heavier isotopes of oxygen (17_{O} and 18_{O}), a process termed isotopic fractionation.
- This fundamentally important discovery (Urey, 1948) prompted Cesare Emiliani [1922–1995] to investigate the geochemical potential of this fractionation reaction in understanding the dynamics and nature of long-term climate change during the Pleistocene (Emiliani, 1955).
- Emiliani (1955) examined the isotopic signature of fossils of the foraminifera Globigerinoides spp., Globigerina sp., and Globoratalia sp. from Globigerina ooze in 12 deep-sea cores from the Atlantic, Caribbean, and Pacific Oceans.
- He concluded that the down-core isotopic changes within the foraminiferal tests provided a signature of long-term ocean temperature changes, and, as a corollary, a proxy of glaciation and deglaciation (Figure 1.7).

Oxygen-isotope records from marine sediments and ice cores

Figure 1.7 (a) Oxygen-isotope inferred palaeotemperatures from the fossil foraminifera *Globigerinoides ruber*, *G. sacculifera*, *Globigerina dubia* and *Globorotalia menardii* from marine core A179–4 (Emiliani, 1955), compared with (b) the oxygen isotopic composition of the foraminifer *Globigerinoides sacculifera* in Core V28–238 from the Solomon (Ontong Java) Plateau, Equatorial Pacific Ocean (Shackleton and Opdyke, 1973). These classical marine isotopic records of global ice-volume change, and as a corollory, Quaternary sea-level changes are compared with (c) geochemical analyses from the European Project for Ice Coring in Antarctica (EPICA) Dome C ice core that provides a paleoclimatic record for the past 800 ka (Schilt *et al*., 2010). The records for (A) CH4 (ppbv), (B) CO2 (ppmv) and (C) D are shown. In the D curve, the dashed line highlights peaks that represent interglacials, with the timing of interglacials represented by the portion of the peak above the dashed line.



Oxygen-isotope records from marine sediments and ice cores

- His work revealed evidence for at least 15 glaciations during the Pleistocene, based on evidence from a Pacific deep-sea core, and therefore indicated repeated major changes in sea level at a global scale.
- These repeated changes in ice volume were described according to a numbering scheme that remains in use today, whereby even numbers designate cold, and odd numbers warm stages, respectively.
- Oxygen-isotope measurements were performed on specimens of the foraminifer Globigerinoides sacculifera.
- Noting that the isotopic changes evident within foraminifera were based on, essentially, globally synchronous events, Shackleton and Opdyke (1973, p. 48) concluded that:
- The higher resolution afforded by ice-core records has identified numerous interstadials involving tens of metres of relative sea-level change within a few thousand years that were not originally identified from oxygen-isotope records based on deep-sea sediments.

Theoretical concepts relevant to the study of Quaternary sea-level changes

- Many palaeo-sea-level interpretations are based on inferences derived from analysis of ancient facies and uniformitarian comparisons with modern sedimentary environments. Implicit within these studies is the assumption that ancient sedimentary facies formed under essentially the same conditions as their modern counterparts (e.g. water depths, salinities, geomorphological setting). Thus, the natural field context of modern facies provides a framework to infer sea level from early Holocene or last interglacial equivalents based on a comparative study of their sedimentary attributes.

Theoretical concepts relevant to the study of Quaternary sea-level changes

Relative sea-level changes over Quaternary timescales (ka) represented as a process–response system and illustrating the interrelationship between internal (endogenetic) and external (exogenetic) processes (after van de Plassche, 1982). The diagram reveals that numerous processes are responsible for sea-level changes.