

SEA LEVEL VARIATIONS OVER GEOLOGIC TIME

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Introduction

Sea level changes have occurred throughout Earth history. The magnitudes and timing of sea level changes are extremely variable. They provide considerable insight into the tectonic and climatic history of the Earth, but remain difficult to determine with accuracy.

Sea level, where the world oceans intersect the continents, is hardly fixed, as anyone who has stood on the shore for 6 hours or more can attest. But the ever-changing tidal flows are small compared with longer-term fluctuations that have occurred in Earth history. How much has sea level changed? How long did it take? How do we know? What does it tell us about the history of the Earth?

In order to answer these questions, we need to consider a basic question: what causes sea level to change? Locally, sea level may change if tectonic forces cause the land to move up or down. However, this article will focus on global changes in sea level. Thus, the variations in sea level must be due to one of two possibilities: (1) changes in the volume of water in the oceans or (2) changes in the volume of the ocean basins.

Sea Level Change due to Volume of Water in the Ocean Basin

The two main reservoirs of water on Earth are the oceans (currently about 97% of all water) and glaciers (currently about 2.7%). Not surprisingly, for at least the last three billion years, the main variable controlling the volume of water filling the ocean basins has been the amount of water present in glaciers on the continents. For example, about 20 000 years ago, great ice sheets covered northern North America and Europe. The volume of ice in these glaciers removed enough water from the oceans to expose most continental shelves. Since then there has been a sea level rise (actually from about 20 000 to about 11 000 years ago) of about 120 m (Figure 1A).

A number of methods have been used to establish the magnitude and timing of this sea level change.

Dredging on the continental shelves reveals human activity near the present shelf-slope boundary. These data suggest that sea level was much lower a relatively short time ago. Study of ancient corals shows that coral species which today live only in very shallow water are now over 100 m deep. The carbonate skeletons of the coral, which once thrived in the shallow waters of the tropics, yield a detailed picture of the timing of sea level rise, and, thus, the melting of the glaciers. Carbon-14, a radioactive isotope formed by carbon-12 interacting with high-energy solar radiation in Earth's atmosphere (*see Cosmogenic Isotopes*) allows us to determine the age of Earth materials, which are about 30 thousand years old.

This is just the most recent of many, large changes in sea level caused by glaciers, (Figure 1B). These variations in climate and subsequent sea level changes have been tied to quasi-periodic variations in the Earth's orbit and the tilt of the Earth's spin axis. The record of sea level change can be estimated by observing the stable isotope, oxygen-18 in the tests (shells) of dead organisms (*see Cenozoic Climate – Oxygen Isotope Evidence*). When marine microorganisms build their tests from the calcium, carbon, and oxygen present in sea water they incorporate both the abundant oxygen-16 and the rare oxygen-18 isotopes. Water in the atmosphere generally has a lower oxygen-18 to oxygen-16 ratio because evaporation of the lighter isotope requires less energy. As a result, the snow that eventually forms the glaciers is depleted in oxygen-18, leaving the ocean proportionately oxygen-18-enriched. When the microorganisms die, their tests sink to the seafloor to become part of the deep marine sedimentary record. The oxygen-18 to oxygen-16 ratio present in the fossil tests has been calibrated to the sea level change, which occurred from 20 000 to 11 000 years ago, allowing the magnitude of sea level change from older times to be estimated. This technique does have uncertainties. Unfortunately, the amount of oxygen-18 which organisms incorporate in their tests is affected not only by the amount of oxygen-18 present but also by the temperature and salinity of the water. For example, the organisms take up less oxygen-18 in warmer waters. Thus, during glacial times, the tests are even more enriched in oxygen-18, and any oxygen isotope record reveals a combined record of changing local temperature and salinity in addition to the record of global glaciation.

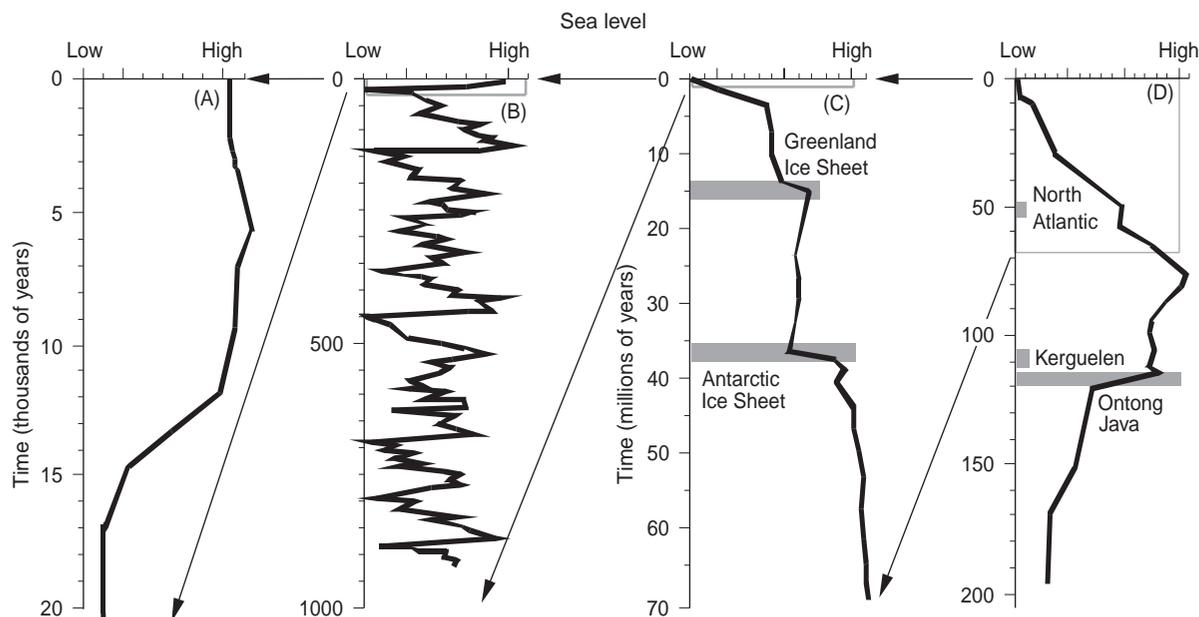


Figure 1 (A) Estimates of sea level change over the last 20,000 years. Amplitude is about 120 m. (B) Northern Hemisphere glaciers over the last million years or so generated major sea level fluctuations, with amplitudes as high as 125 m. (C) The long-term oxygen isotope record reveals rapid growth of the Antarctic and Greenland ice sheets (indicated by gray bars) as Earth's climate cooled. (D) Long-term sea level change as indicated from variations in deep-ocean volume. Dominant effects include spreading rates and lengths of mid-ocean ridges, emplacement of large igneous provinces (the largest, marine LIPs are indicated by gray bars), breakup of supercontinents, and subduction of the Indian continent. The Berggren *et al.* (1995) chronostratigraphic timescale was used in (C) and (D).

Moving back in time through the Cenozoic (zero to 65 Ma), paleoceanographic data remain excellent due to relatively continuous sedimentation on the ocean floor (as compared with shallow marine and terrestrial sedimentation). Oxygen-18 in the fossil shells suggests a general cooling for about the last 50 million years. Two rapid increases in the oxygen-18 to oxygen-16 ratio about 12.5 Ma and about 28 Ma are observed (Figure 1C). The formation of the Greenland Ice Sheet and the Antarctic Ice Sheet are assumed to be the cause of these rapid isotope shifts. Where oxygen-18 data have been collected with a resolution finer than 20,000 years, high-frequency variations are seen which are presumed to correspond to a combination of temperature change and glacial growth and decay. We hypothesize that the magnitudes of these high-frequency sea level changes were considerably less in the earlier part of the Cenozoic than those observed over the last million years. This is because considerably less ice was involved.

Although large continental glaciers are not common in Earth history they are known to have been present during a number of extended periods ('ice house' climate, in contrast to 'greenhouse' or warm climate conditions). Ample evidence of glaciation is

found in the continental sedimentary record. In particular, there is evidence of glaciation from about 2.7 to 2.1 billion years ago. Additionally, a long period of glaciation occurred shortly before the first fossils of multicellular organisms, from about 1 billion to 540 million years ago. Some scientists now believe that during this glaciation, the entire Earth froze over, generating a 'snowball earth'. Such conditions would have caused a large sea level fall. Evidence of large continental glaciers are also seen in Ordovician to Silurian rocks (~420 to 450 Ma), in Devonian rocks (~380 to 390 Ma), and in Carboniferous to Permian rocks (~350 to 270 Ma).

If these glaciations were caused by similar mechanisms to those envisioned for the Plio-Pleistocene (Figure 1B), then predictable, high-frequency, periodic growth and retreat of the glaciers should be observed in strata which form the geologic record. This is certainly the case for the Carboniferous through Permian glaciation. In the central United States, UK, and Europe, the sedimentary rocks have a distinctly cyclic character. They cycle in repetitive vertical successions of marine deposits, near-shore deposits, often including coals, into fluvial sedimentary rocks. The deposition of marine rocks over large areas, which had only recently been

nonmarine, suggests very large-scale sea level changes. When the duration of the entire record is taken into account, periodicities of about 100 and 400 thousand years are suggested for these large sea level changes. This is consistent with an origin due to a response to changes in the eccentricity of the Earth's orbit. Higher-frequency cyclicity associated with the tilt of the spin axis and precession of the equinox is more difficult to prove, but has been suggested by detailed observations.

It is fair to say that large-scale (10 to > 100 m), relatively high-frequency (20 000–400 000 years; often termed 'Milankovitch scale') variations in sea level occurred during intervals of time when continental glaciers were present on Earth (ice house climate). This indicates that the variations of Earth's orbit and the tilt of its spin axis played a major role in controlling the climate. During the rest of Earth history, when glaciation was not a dominant climatic force (greenhouse climate), sea level changes corresponding to Earth's orbit did occur. In this case, the mechanism for changing the volume of water in the ocean basins is much less clear.

There is no geological record of continental ice sheets in many portions of Earth history. These time periods are generally called 'greenhouse' climates. However, there is ample evidence of Milankovitch scale variations during these periods. In shallow marine sediments, evidence of orbitally driven sea level changes has been observed in Cambrian and Cretaceous age sediments. The magnitudes of sea level change required (perhaps 5–20 m) are far less than have been observed during glacial climates. A possible source for these variations could be variations in average ocean-water temperature. Water expands as it is heated. If ocean bottom-water sources were equatorial rather than polar, as they are today, bottom-water temperatures of about 2°C today might have been about 16°C in the past. This would generate a sea level change of about 11 m. Other causes of sea level change during greenhouse periods have been postulated to be a result of variations in the magnitude of water trapped in inland lakes and seas, and variations in volumes of alpine glaciers. Deep marine sediments of Cretaceous age also show fluctuations between oxygenated and anoxic conditions. It is possible that these variations were generated when global sea level change restricted flow from the rest of the world's ocean to a young ocean basin. In a more recent example, tectonics caused a restriction at the Straits of Gibraltar. In that case, evaporation generated extreme sea level changes and restricted their entrance into the Mediterranean region.

Sea Level Change due to Changing Volume of the Ocean Basin

Tectonics is thought to be the main driving force of long-term (≥ 50 million years) sea level change. Plate tectonics changes the shape and/or the areal extent of the ocean basins.

Plate tectonics is constantly reshaping surface features of the Earth while the amount of water present has been stable for about the last four billion years. The reshaping changes the total area taken up by oceans over time. When a supercontinent forms, subduction of one continent beneath another decreases Earth's ratio of continental to oceanic area, generating a sea level fall. In a current example, the continental plate including India is diving under Asia to generate the Tibetan Plateau and the Himalayan Mountains. This has probably generated a sea level fall of about 70 m over the last 50 million years. The process of continental breakup has the opposite effect. The continents are stretched, generating passive margins and increasing the ratio of continental to oceanic area on a global scale (Figure 2A). This results in a sea level rise. Increments of sea level rise resulting from continental breakup over the last 200 million years amount to about 100 m of sea level rise.

Some bathymetric features within the oceans are large enough to generate significant changes in sea level as they change size and shape. The largest physiographic feature on Earth is the mid-ocean ridge system, with a length of about 60 000 km and a width of 500–2000 km. New ocean crust and lithosphere are generated along rifts in the center of these ridges. The ocean crust is increasingly old, cold, and dense away from the rift. It is the heat of ocean lithosphere formation that actually generates this feature. Thus, rifting of continents forms new ridges, increasing the proportionate area of young, shallow, ocean floor to older, deeper ocean floor (Figure 2B). Additionally, the width of the ridge is a function of the rates at which the plates are moving apart. Fast spreading ridges (e.g. the East Pacific Rise) are very broad while slow spreading ridges (e.g. the North Atlantic Ridge) are quite narrow. If the average spreading rates for all ridges decreases, the average volume taken up by ocean ridges would decrease. In this case, the volume of the ocean basin available for water would increase and a sea level fall would occur. Finally, entire ridges may be removed in the process of subduction, generating fairly rapid sea level fall.

Scientists have made quantitative estimates of sea level change due to changing ocean ridge volumes. Since ridge volume is dependent on the age of the

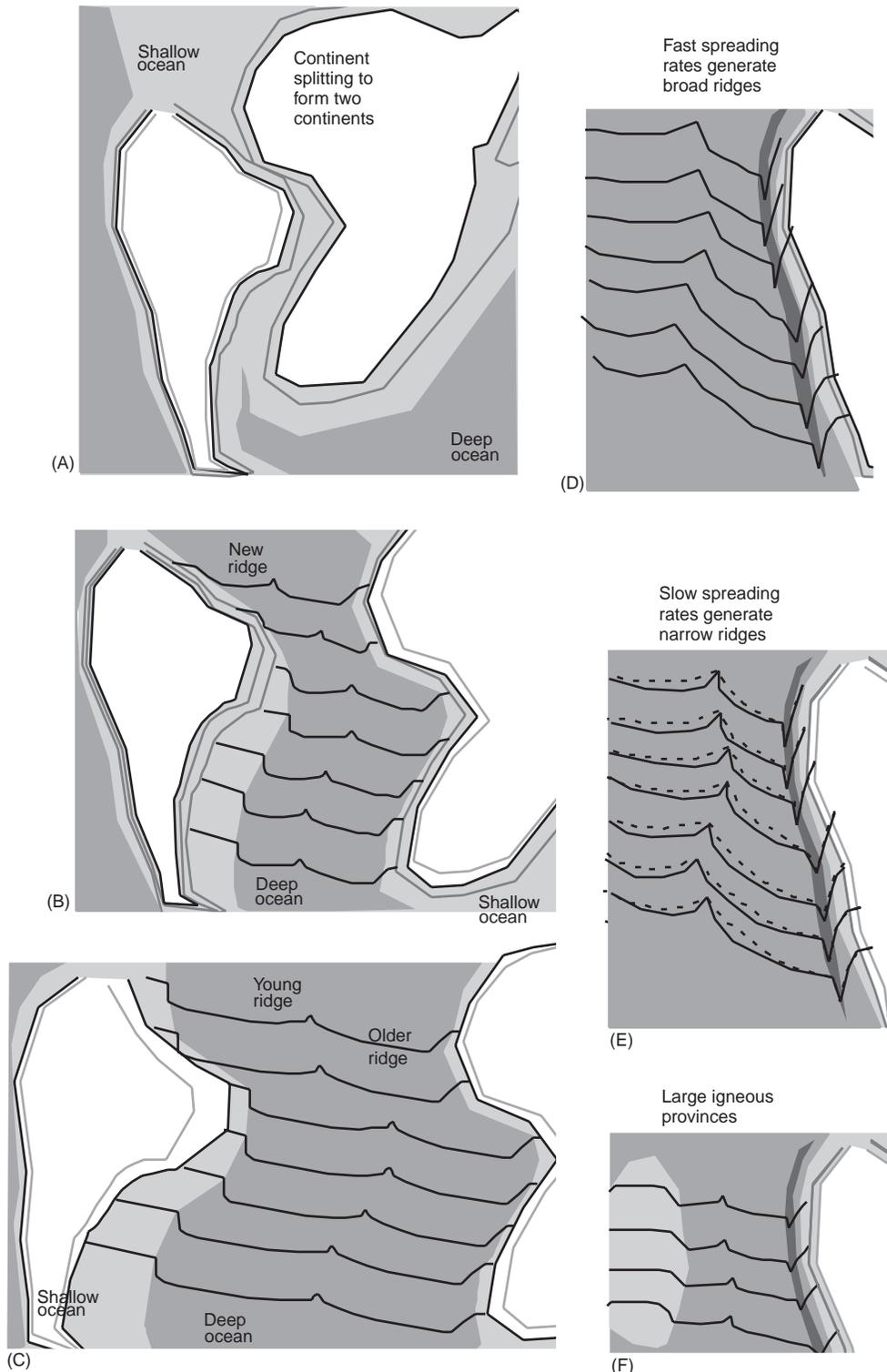


Figure 2 Diagrams showing a few of the factors which affect the ocean volume. (A) Early breakup of a large continent increases the area of continental crust by generating passive margins, causing sea level to rise. (B) Shortly after breakup a new ocean is formed with very young ocean crust. This young crust must be replacing relatively old crust via subduction, generating additional sea level rise. (C) The average age of the ocean between the continents becomes older so that young, shallow ocean crust is replaced with older, deeper crust so that sea level falls. (D) Fast spreading rates are associated with relatively high sea level. (E) Relatively slow spreading ridges (solid lines in ocean) take up less volume in the oceans than high spreading rate ridges (dashed lines in ocean), resulting in relatively low sea level. (F) Emplacement of large igneous provinces generates oceanic plateaus, displaces ocean water, and causes a sea level rise.

ocean floor, where the age of the ocean floor is known, ridge volumes can be estimated. Seafloor magnetic anomalies are used to estimate the age of the ocean floor, and thus, spreading histories of the oceans (*see Magnetism*). The oldest ocean crust is about 200 million years old. Older oceanic crust has been subducted. Thus, it is not surprising that quantitative estimates of sea level change due to ridge volumes are increasingly uncertain and cannot be calculated before about 90 million years. Sea level is estimated to have fallen about 230 m (± 120 m) due to ridge volume changes in the last 80 million years.

Large igneous provinces (LIPs) are occasionally intruded into the oceans, forming large oceanic plateaus (*see Igneous Provinces*). The volcanism associated with LIPs tends to occur over a relatively short period of time, causing a rapid sea level rise. However, these features subside slowly as the lithosphere cools, generating a slow increase in ocean volume, and a long-term sea level fall. The largest marine LIP, the Ontong Java Plateau, was emplaced in the Pacific Ocean between about 120 and 115 Ma (**Figure 1D**). Over that interval it may have generated a sea level rise of around 50 m.

In summary, over the last 200 million years, long-term sea level change (**Figure 1D**) can be largely attributed to tectonics. Continental crust expanded by extension as the supercontinents Gondwana and Laurasia split to form the continents we see today. This process began about 200 Ma when North America separated from Africa and continued with the East African Rift system and the formation of the Red Sea. The generation of large oceans occurred early in this period and there was an overall rise in sea level from about 200 to about 90 million years. New continental crust, new mid-ocean ridges, and very fast spreading rates were responsible for the long-term rise (**Figure 1D**). Subsequently, a significant decrease in spreading rates, a reduction in the total length of mid-ocean ridges, and continent–continent collision coupled with an increase in glacial ice (**Figure 1C**) have resulted in a large-scale sea level fall (**Figure 1D**). Late Cretaceous volcanism associated with the Ontong Java Plateau, a large igneous province (*see Igneous Provinces*), generated a significant sea level rise, while subsequent cooling has enhanced the 90 million year sea level fall. Estimates of sea level change from changing ocean shape remain quite uncertain. Magnitudes and timing of stretching associated with continental breakup, estimates of shortening during continental assembly, volumes of large igneous provinces, and volumes of mid-ocean ridges improve as data are gathered. However, the exact configura-

tion of past continents and oceans can only be a mystery due to the recycling character of plate tectonics.

Sea Level Change Estimated from Observations on the Continents

Long-term Sea Level Change

Estimates of sea level change are also made from sedimentary strata deposited on the continents. This is actually an excellent place to obtain observations of sea level change not only because past sea level has been much higher than it is now, but also because in many places the continents have subsequently uplifted. That is, in the past they were below sea level, but now they are well above it. For example, studies of 500–400 million year old sedimentary rocks which are now uplifted in the Rocky Mountains and the Appalachian Mountains indicate that there was a rise and fall of sea level with an estimated magnitude of 200–400 m. This example also exemplifies the main problem with using the continental sedimentary record to estimate sea level change. The continents are not fixed and move vertically in response to tectonic driving forces. Thus, any indicator of sea level change on the continents is an indicator of relative sea level change. Obtaining a global signature from these observations remains extremely problematic. Additionally, the continental sedimentary record contains long periods of non-deposition, which results in a spotty record of Earth history. Nonetheless a great deal of information about sea level change has been obtained and is summarized here.

The most straightforward source of information about past sea level change is the location of the strand line (the beach) on a stable continental craton (a part of the continent, which was not involved in local tectonics). Ideally, its present height is that of sea level at the time of deposition. There are two problems encountered with this approach. Unfortunately, the nature of land–ocean interaction at their point of contact is such that those sediments are rarely preserved. Where they can be observed, there is considerable controversy over which elements have moved, the continents or sea level. However, data from the past 100 million years tend to be consistent with calculations derived from estimates of ocean volume change. This is not saying a lot since uncertainties are very large (*see above*).

Continental hypsography (cumulative area versus height) coupled with the areal extent of preserved marine sediments has been used to estimate past sea

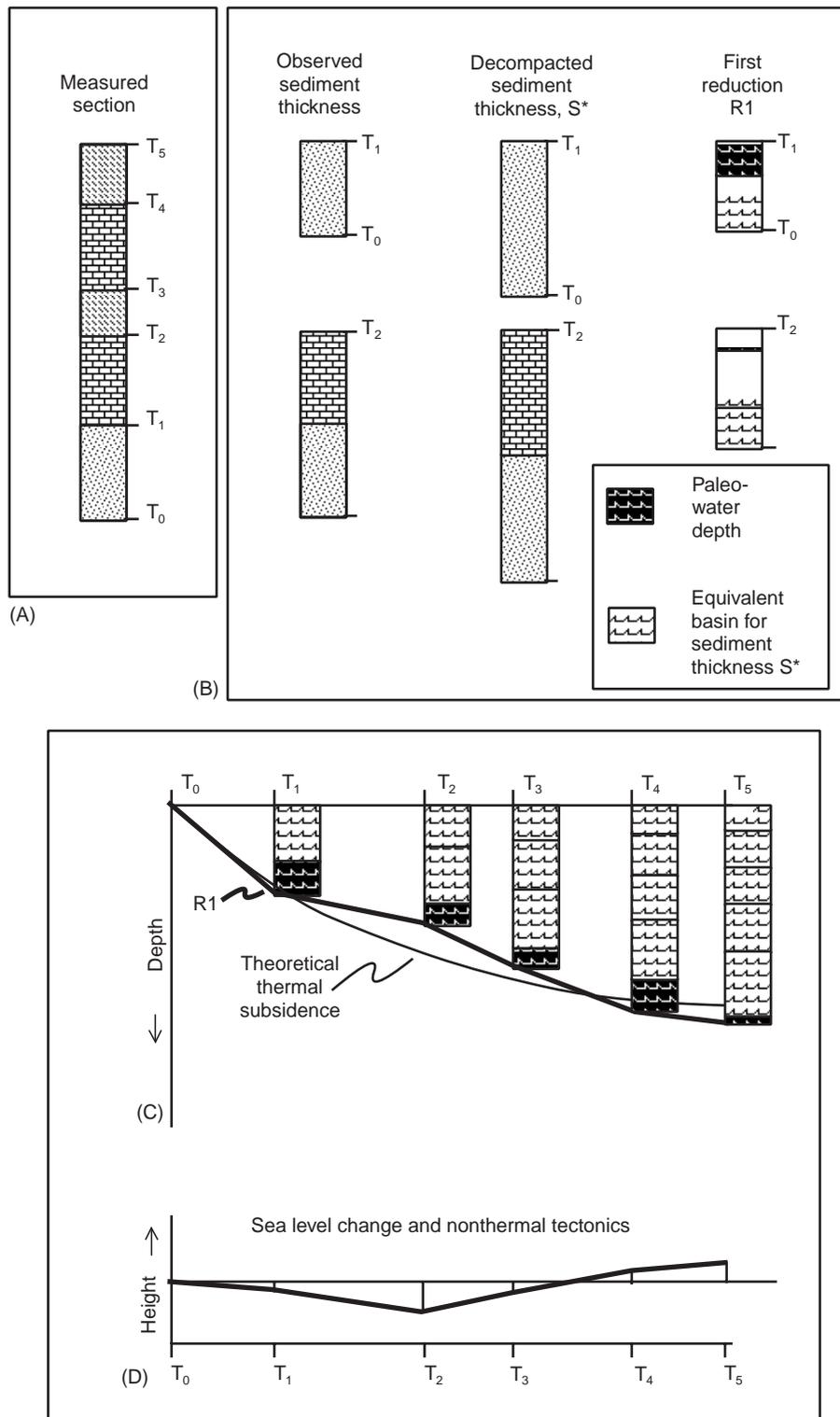


Figure 3 Diagrams depicting the backstripping method for obtaining sea level estimates in a thermally subsiding basin. (A) A stratigraphic section is measured either from exposed sedimentary rocks or from drilling. These data include lithologies, ages, and porosity. Note that the oldest strata are always at the base of the section (T_0). (B) Porosity data are used to estimate the thickness that each sediment section would have had at the time of deposition (S^*). They are also used to obtain sediment density so that the sediments can be unloaded to determine how deep the basin would have been in the absence of the sediment load ($R1$). This calculation also requires an estimate of the paleo-water depth (the water depth at the time of deposition). (C) A plot of $R1$ versus time is compared (by least-squares fit) to theoretical tectonic subsidence in a thermal setting. (D) The difference between $R1$ and thermal subsidence yields a quantitative estimate of sea level change if other, nonthermal tectonics, did not occur at this location.

level. In this case only an average result can be obtained, because marine sediments spanning a time interval (generally 5–10 million years) have been used. Again, uncertainties are large, but results are consistent with calculations derived from estimates of ocean volume change.

Backstripping is an analytical tool, which has been used to estimate sea level change. In this technique, the vertical succession of sedimentary layers is progressively decompacted and unloaded (Figure 3A, B). The resulting hole is a combination of the subsidence generated by tectonics and by sea level change (Figure 3B, C). If the tectonic portion can be established then an estimate of sea level change can

be determined (Figure 3C, D). This method is generally used in basins generated by the cooling of a thermal anomaly (e.g. passive margins). In these basins, the tectonic signature is predictable (exponential decay) and can be calibrated to the well-known subsidence of the mid-ocean ridge.

The backstripping method has been applied to sedimentary strata drilled from passive continental margins of both the east coast of North America and the west coast of Africa. Again, estimates of sea level suggest a rise of about 100–300 m from about 200–110 Ma followed by a fall to the present level (Figure 1D). Young interior basins, such as the Paris Basin, yield similar results. Older, thermally driven

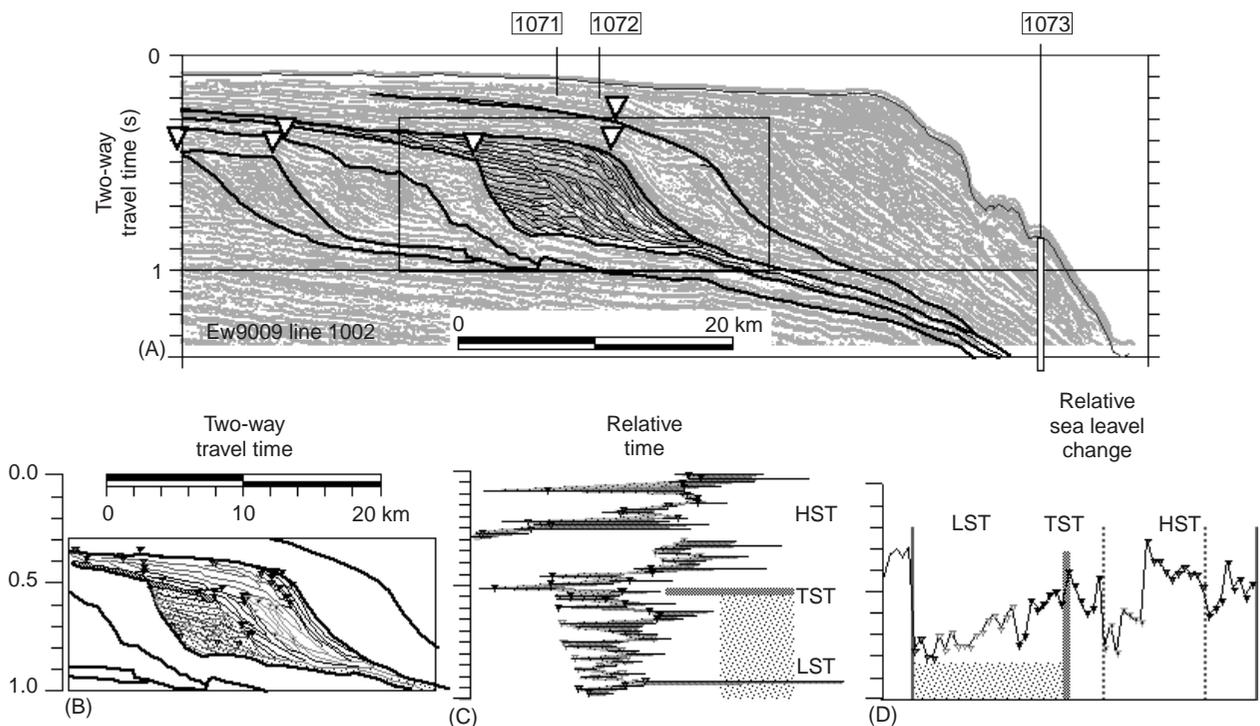


Figure 4 Example of the sequence stratigraphic approach to estimates of sea level change. (A) Multichannel seismic data (gray) from the Baltimore Canyon Trough, offshore New Jersey, USA (Miller *et al.*, 1998). Black lines are interpretations traced on the seismic data. Thick dark lines indicate third-order Miocene-aged (5–23 Ma) sequence boundaries. They are identified by truncation of the finer black lines. Upside-down deltas indicate a significant break in slope associated with each identified sequence boundary. Labeled vertical lines (1071–1073) show the locations of Ocean Drilling Project wells (**Deep-sea Drilling Methodology**), used to help date the sequences. The rectangle in the center is analyzed in greater detail. (B) Detailed interpretation of a single third-order sequence from (A). Upside-down deltas indicate a significant break in slope associated with each of the detailed sediment packages. Stippled fill indicates the low stand systems tract (LST) associated with this sequence. The gray packages are the transgressive systems tract (TST), and the overlying sediments are the high stand systems tract (HST). (C) Relationships between detailed sediment packages (in B) are used to establish a chronostratigraphy (time framework). Youngest sediment is at the top. Each observed seismic reflection is interpreted as a time horizon, and each is assigned equal duration. Horizontal distance is the same as in (A) and (B). A change in sediment type is indicated at the break in slope from coarser near-shore sediments (stippled pattern) to finer, offshore sediments (parallel, sloping lines). Sedimentation may be present offshore but at very low rates. LST, TST, and HST as in (B). (D) Relative sea level change is obtained by assuming a consistent depth relation at the change in slope indicated in (B). Age control is from the chronostratigraphy indicated in (C). Time gets younger to the right. The vertical scale is in two-way travel time, and would require conversion to depth for a final estimate of the magnitude of sea level change. LST, TST, and HST as in (B). Note that in (B), (C), and (D), higher frequency cycles (probably fourth-order) are present within this (third-order) sequence. Tracing and interpretations are from the author's graduate level quantitative stratigraphy class project (1998, Western Michigan University).

basins have also been analyzed. This was the method used to determine the (approximately 200 m) sea level rise and fall associated with the breakup of a Pre-Cambrian supercontinent in earliest Phanerozoic time.

Million Year Scale Sea Level Change

In addition to long-term changes in sea level there is evidence of fluctuations that are considerably shorter than the 50–100 million year variations discussed above, but longer than those caused by orbital variations (≤ 0.4 million years). These variations appear to be dominated by durations which last either tens of millions of years or a half to three million years. These sea level variations are sometimes termed second- and third-order sea level change, respectively. There is considerable debate concerning the source of these sea level fluctuations. They have been attributed to tectonics and changing ocean basin volumes, to the growth and decay of glaciers, or to continental uplift and subsidence, which is independent of global sea level change. As noted above, the tectonic record of subsidence and uplift is intertwined with the stratigraphic record of global sea level change on the continents. Synchronicity of observations of sea level change on

a global scale would lead most geoscientists to suggest that these signals were caused by global sea level change. However, at present, it is nearly impossible to globally determine the age equivalency of events which occur during intervals as short as a half to two million years. These data limitations are the main reason for the heated controversy over third-order sea level.

Quantitative estimates of second-order sea level variations are equally difficult to obtain. Although the debate is not as heated, these somewhat longer-term variations are not much larger than the third-order variations so that the interference of the two signals makes definition of the beginning, ending and/or magnitude of second-order sea level change equally problematic. Recognizing that our understanding of second- and third-order (million year scale) sea level fluctuations is limited, a brief review of that limited knowledge follows.

Sequence stratigraphy is an analytical method of interpreting sedimentary strata that has been used to investigate second- and third-order relative sea level changes. This paradigm requires a vertical succession of sedimentary strata which is analyzed in at least a two-dimensional, basinal setting. Packages of sedimentary strata, separated by unconformities, are observed and interpreted mainly in terms of their

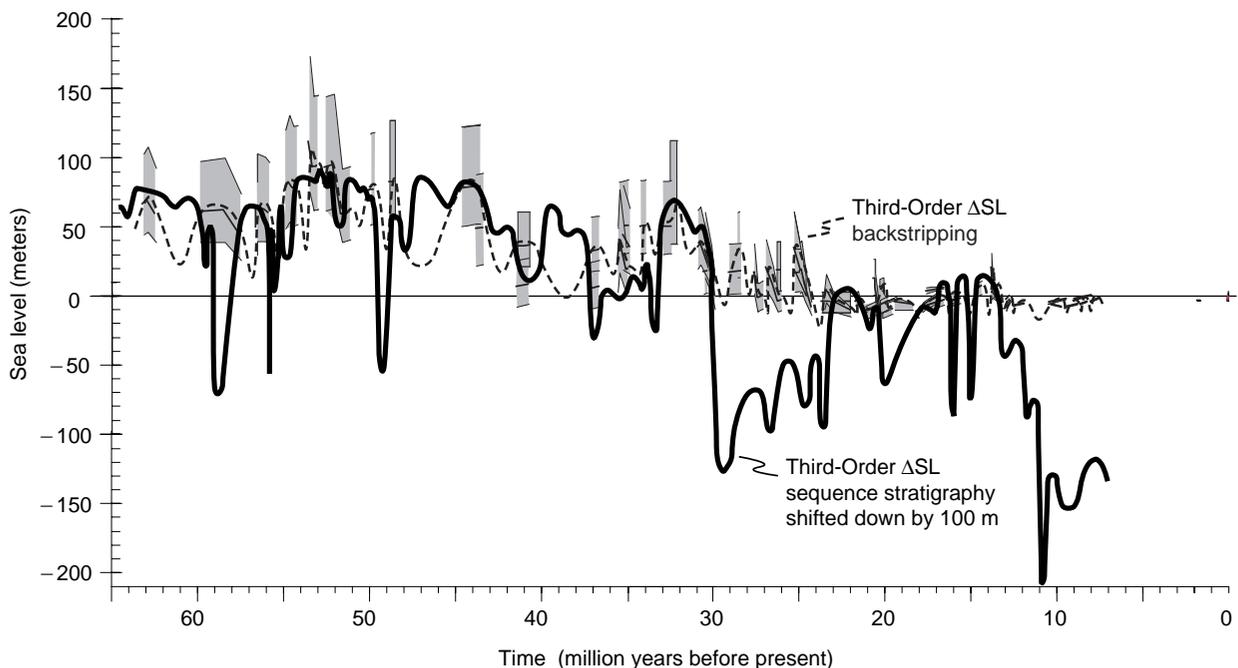


Figure 5 Million year scale sea level fluctuations. Estimates from sequence stratigraphy (Haq *et al.*, 1987; solid curve) have been shifted down by 100 m to allow comparison with estimates of sea level from backstripping (Kominz *et al.*, 1998; dashed curve). Where sediments are present, the backstripping results, with uncertainty ranges, are indicated by gray fill. Between backstrip observations, lack of preserved sediment is presumed to have been a result of sea level fall. The Berggren *et al.* (1995) biostratigraphic timescale was used.

internal geometries (e.g. Figure 4). The unconformities are assumed to have been generated by relative sea level fall, and thus, reflect either global sea level or local or regional tectonics. This method of stratigraphic analysis has been instrumental in hydrocarbon exploration since its introduction in the late 1970s. One of the bulwarks of this approach is the 'global sea level curve' most recently published by Haq *et al.* (1987). This curve is a compilation of relative sea level curves generated from sequence stratigraphic analysis in basins around the world. While sequence stratigraphy is capable of estimating relative heights of relative sea level, it does not estimate absolute magnitudes. Absolute dating requires isotope data or correlation via fossil data into the chronostratigraphic timescale (see **Geomagnetic Polarity Timescale**). However, the two-dimensional nature of the data allows for good to excellent relative age control.

Backstripping has been used, on a considerably more limited basis, in an attempt to determine million year scale sea level change. This approach is rarely applied because it requires very detailed, quantitative, estimates of sediment ages, paleoenvironments and compaction in a thermal tectonic setting. A promising area of research is the application of this method to coastal plain boreholes from the mid-Atlantic coast of North America. Here an intensive Ocean Drilling Project survey is underway which is providing sufficiently detailed data for this type of analysis (see **Deep-sea Drilling Methodology**). Initial results suggest that magnitudes of million year scale sea level change are roughly one-half to one-third that reported by Haq *et al.* However, in glacial times, the timing of the cycles was quite consistent with those of this 'global sea level curve' derived by application of sequence stratigraphy (Figure 5). Thus, it seems reasonable to conclude that, at least during glacial times, global, third-order sea level changes did occur.

Summary

Sea level changes are either a response to changing ocean volume or to changes in the volume of water contained in the ocean. The timing of sea level change ranges from tens of thousands of years to over 100 million years. Magnitudes also vary significantly but may have been as great as 200 m or more. Estimates of sea level change currently suffer from significant ranges of uncertainty, both in magnitude and in timing. However, scientists are converging on consistent estimates of sea level changes by using very different data and analytical approaches.

See also

Cosmogenic Isotopes. Deep-sea Drilling Methodology. Geomagnetic Polarity Timescale. Igneous Provinces. Magnetism.

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