The Phanerozoic Record of Global Sea-Level Change

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We review Phanerozoic sea-level changes [543 million years ago (Ma) to the present] on various time scales and present a new sea-level record for the past 100 million years (My). Long-term sea level peaked at 100 ± 50 meters during the Cretaceous, implying that ocean-crust production rates were much lower than previously inferred. Sea level mirrors oxygen isotope variations, reflecting ice-volume change on the 10^4- to 10^6-year scale, but a link between oxygen isotope and sea level on the 10^7-year scale must be due to temperature changes that we attribute to tectonically controlled carbon dioxide variations. Sea-level change has influenced phytoplankton evolution, ocean chemistry, and the loci of carbonate, organic carbon, and siliciclastic sediment burial. Over the past 100 My, sea-level changes reflect global climate evolution from a time of ephemeral Antarctic ice sheets (100 to 33 Ma), through a time of large ice sheets primarily in Antarctica (33 to 2.5 Ma), to a world with large Antarctic and large, variable Northern Hemisphere ice sheets (2.5 Ma to the present).

Fluctuations in global sea level (eustasy) result from changes in the volume of water in the ocean or the volume of ocean basins (Fig. 1) (*1–4*). Water-volume changes are dominated by growth and decay of continental ice sheets, producing high-amplitude, rapid eustatic changes [up to 200 m and 20 m per thousand years (ky)]. Other processes that affect water volume occur at high rates (10 m/ky) and low amplitudes (~5 to 10 m): desiccation and inundation of marginal seas, thermal expansion and contraction of seawater, and variations in groundwater and lake storage. Changes in ocean basin volume are dominated by slow variations in sea-floor spreading rates or ocean ridge lengths (100 to 300 m amplitude, rates of 10 m/My). Variations in sedimentation cause moderate amplitude (60 m), slow changes (10 m/My). Emplacement of oceanic plateaus produces moderately rapid rises (60 m/My) but slow falls due to thermal subsidence (10 m/My).

Eustatic variations can be estimated from satellite measurements, tide gauges, shoreline markers, reefs and atolls, oxygen isotopes ($\delta^{18}O$), and the flooding history of continental margins and cratons. Satellite measurements are limited to the past 10 years (*5*), whereas tide gauge records extend back only ~150 years (*3*). The most recent pre-anthropogenic sea-level rise began at about 18 ka and can be measured by directly dating shoreline markers (fig. S1). Tropical reefs and atolls (fig. S2) provide the most reliable geological estimates by dating "fossil sunshine" (e.g., shallow-dwelling corals) and have provided a precise estimate for the last sea-level lowstand (120 ± 5 m below present at 18 ka) (fig. S2) (*6*, *7*). However, most coral records are from regions with complicated uplift/subsidence histories, are difficult to recover and date (particularly beyond a few 100 ky), and have poorly preserved lowstand deposits.

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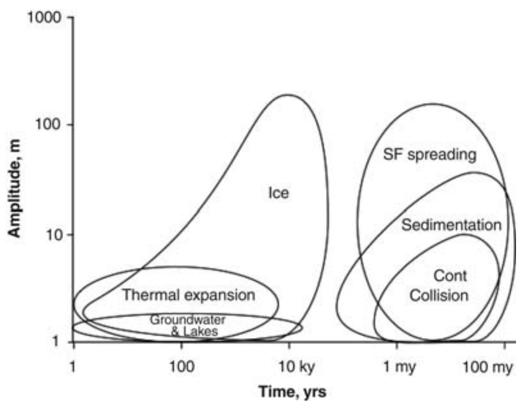

Fig. 1. Timing and amplitudes of geologic mechanisms of eustatic change derived from (*1–4*). SF, sea floor; Cont, continental.

The growth and decay of continental ice sheets causes eustatic changes that are indirectly recorded in the chemistry of foraminifera because ice has lower $\delta^{18}O$ values than seawater (fig. S2) [e.g., (*8*, *9*)]. Oxygen isotope values provide a proxy for glacioeustasy, but $\delta^{18}O$-based reconstructions are subject to several uncertainties: (i) Calcite $\delta^{18}O$ values also vary as a function of temperature. (ii) Surface-ocean $\delta^{18}O$ values are influenced by local evaporation-precipitation effects on seawater. (iii) Postdepositional alteration (diagenesis) may overprint original $\delta^{18}O$ values, limiting useful records to sediments younger than 100 My.

Continents have been flooded many times in the geologic past (Fig. 2). However, the flooding record is not a direct measure of eustatic change because variations in subsidence and sediment supply also influence shoreline location. Regional unconformities (surfaces of erosion and nondeposition) divide the stratigraphic record into sequences and provide a key to eustatic change. Unconformities result from sea-level fall or tectonic uplift (*10–12*). Similar ages of sequence boundaries on different continents have been interpreted as indicating that the surfaces were caused by a global process, eustasy [e.g. (*10*, *11*)]. The linkage with $\delta^{18}O$ increases for the past 40 My (*13*) indicates that most sequence boundaries resulted from eustatic falls driven by the growth of continental ice sheets.

Although unconformities potentially provide the timing of eustatic lowstands, extracting global sea-level history from the stratigraphic record requires a quantitative method that distinguishes the contributions of eustasy, subsidence, and sediment accumulation. Backstripping is an inverse technique that can be used to quantitatively extract sea-level change amplitudes from the stratigraphic record. It accounts for the effects of sediment compaction, loading (the response of crust to overlying sediment mass), and water-depth variations on basin subsidence (*14*). Tectonic subsidence at a passive margin is modeled with thermal decay curves and removed