REVIEW SUMMARY

SEA LEVEL CHANGE

Inherited landscapes and sea level change

Sierd Cloetingh and Bilal U. Haq*

BACKGROUND: Knowledge of past sea level fluctuations is fundamental to geosciences and for exploration of Earth-bound resources. Recent years have seen a convergence of views between stratigraphers (who measure past sea level changes in marine strata) and geodynamicists (who investigate surficial expressions of lithospheric and mantle processes) with the realization that without understanding inherited topographies, their causal mechanisms and operative time scales, palinspastic (pre-diastrophic) reconstructions of the past landscapes and seascapes remain inchoate at best.

Sequestrations of seawater on land or its subduction-related entrainment in the mantle are two direct means of lowering global sea level. Sea level can also be changed by modifying the container capacity of the ocean through numerous interconnected solid-Earth processes. Some of these can only refashion landscapes regionally, thus affecting local measures of sea level change. Disentangling these processes to uncover the likely cause(s) for the resultant topography poses considerable challenges.

ADVANCES: Recent developments in seismic tomography and high-speed computing that allow detailed forward and inverse modeling, combined with new concepts in stratigraphy and geophysics that permit envisioning large-scale transfers of material among depositional centers, have brought us closer to understanding factors that influence landscapes and sea levels and the complex feedbacks. As a result, estimates of the amplitude of long-term eustatic changes have converged using different data sets. We have learned that solid-Earth processes operating on decadal to multimillion-year time scales are all responsible for retaining lithospheric memory and its surface expression: On time scales of tens to hundreds of years, glacial isostatic adjustments cause local topographic anomalies, whereas postglacial rebound can be enhanced by viscous mantle flow on time scales of thousands to hundreds of thousands of years; on time scales of more than 1 million years, oceanic crustal production variations, plate reorganizations, and mantle-lithosphere interactions (e.g., dynamic topography) become more influential in altering the longer-wavelength surface response. Additionally, the lithosphere's rheological heterogeneity, variations in its strength, and changes in intraplate stress fields can also cause regional topographic anomalies, and syn-rift volcanism may be an important determinant of the long-term eustatic change on time scales of 5 to 10 million years.

OUTLOOK: Despite these remarkable advances, we remain far from resolving the causes for third-order quasi-cyclic sea level changes (~500,000 to 3 million years in duration). Ascertaining whether ice volume changes were responsible for these cycles in the Cretaceous will require discerning the potential for extensive glaciation at higher altitudes on Antarctica by modeling topographic elevation involving large-scale mantle processes. Extensive sea floor volcanism, plate reorganizations, and continental breakup events need to be better constrained if causal connections between tectonics and eustasy have to be firmly established. Another promising avenue of inquiry is the leads and lags between entrainment and expulsion of water within the mantle on third-order time scales. Future geodynamic models will also need to consider lateral variations in upper mantle viscosity and lithosphere rheology that require building on current lithospheric strength models and constructing global paleorheological models. Deep-drilling efforts will be of crucial importance for achieving the integrative goals. ■

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Earth's sea level history is archived in sedimentary sections. This example is from the Umbrian Apennines near Gubbio, Italy, that was a part of the ancient Tethys Ocean. It preserves a continuous and nearly complete Cretaceous pelagic record, and its contained microfossils and stable isotopes provide valuable clues about paleoceanography, paleoclimatology, and sea level history of the region. The finer-grained sediment near the base marks the boundary between the Cenomanian and Turonian stages, at which time the highest sea levels of the Cretaceous have been documented around the world. Evidence and measure of the amplitude of this eustatic high based on geodynamics and stratigraphic data have converged.

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REVIEW

SEA LEVEL CHANGE

Inherited landscapes and sea level change

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Enabled by recently gained understanding of deep-seated and surficial Earth processes, a convergence of views between geophysics and sedimentary geology has been quietly taking place over the past several decades. Surface topography resulting from lithospheric memory, retained at various temporal and spatial scales, has become the connective link between these two methodologically diverse geoscience disciplines. Ideas leading to the hypothesis of plate tectonics originated largely with an oceanic focus, where dynamic and mostly horizontal movements of the crust could be envisioned. But when these notions were applied to the landscapes of the supposedly rigid plate interiors, there was less success in explaining the observed anomalies in terrestrial topography. Solid-Earth geophysics has now reached a developmental stage where vertical movements can be measured and modeled at meaningful scales and the deep-seated structures can be imaged with increasing resolution. Concurrently, there have been advances in quantifying mechanical properties of the lithosphere (the solid outer skin of Earth, usually defined to include both the crust and the solid but elastic upper mantle above the asthenosphere). The lithosphere acts as the intermediary that transfers the effects of mantle dynamics to the surface. These developments have allowed us to better understand the previously puzzling topographic features of plate interiors and continental margins. On the sedimentary geology side, new quantitative modeling techniques and holistic approaches to integrating source-to-sink sedimentary systems have led to clearer understanding of basin evolution and sediment budgets that allow the reconstruction of missing sedimentary records and past geological landscapes.

The interdisciplinary dissension between solid-Earth geophysics and soft-rock geology was at least partly due to the prevalent view within the sedimentological community that post-rift tectonic processes are normally too slow to contribute to punctuated stratigraphy. This was a likely outgrowth of the first generation of basin evolution models that implied steady long-term thermal subsidence of rifted margins. Another reason may have been that the solid-Earth geophysics community did not always appreciate variable time scales of basin-fill processes or lacked awareness of advances in sedimentary geology that now allowed the deciphering of the record of mass transfer at the scale of an entire continental margin or interior basin. In the past few decades, conceptual models as well as empirical evidence indicate that post-rift tectonic processes act on multiple scales. These lead to episodic vertical movements on shorter time scales, as well as far-field effects that may transform local topographies on longer spatial and temporal wavelengths. This newfound cognizance of the vertical movements of landscapes and seascapes at various time scales has indeed been a bridging factor between these two communities.

Sequence stratigraphy that facilitates stratigraphic estimates of past sea level changes (*1*, *2*) and geodynamic lithospheric models of continental margins and interiors [see, e.g., (*3*)] have had parallel histories of advancement over the past four decades, which in turn have led to a number of major breakthroughs in basin analysis. Indeed, this trend toward increasing synergy between stratigraphy and tectonics, crustal geophysics, paleoclimatology, and numerical modeling, where stratigraphic data had begun to play an important role in providing constraints for geodynamic models, was already alluded to by Miall (*4*). In the past two decades, progressively improving resolution of seismic tomographic images of the mantle (*5*–*8*) has provided better constraints for absolute plate motions (*9*), as well as revolutionary insights into the causes for dynamic vertical movements of continental and oceanic lithosphere (Fig. 1) at wavelengths that can affect both eurybatic (regional) and eustatic (global) sea level signals (*10*). [Eurybatic is a term introduced by Haq (*10*) to distinguish local or regional measures of sea level change from eustatic (global) changes.] This in turn has reinforced the notion of intimate coupling between Earth's mantle and surface processes (*11*–*13*). In addition, the holistic source-to-sink approach and process-based studies on several active and passive continental margins have also helped to reveal the connection of surface topography and basin subsidence [see, e.g., (*14*, *15*)]. At the same time, numerical simulations of the viscous response of the upper mantle to crustal loading and unloading [i.e., ice (*16*, *17*), sediments (*18*, *19*), and subduction of oceanic slabs underneath the continental crust (*20*)] have led to new insights into how surface topography reacts dynamically to both isostasy and mantle flow, producing regionally extensive landscape anomalies at both shorter and longer time scales. This response of the landscape to mantle flow has been broadly termed as dynamic topography (*11*), which thwarts straightforward measures of sea level changes based on stratal patterns and thickness of stratigraphic sequences along continental margins, even when corrected for thermal and flexural subsidence and other local factors (*21*). Also important to this discussion is the inherited rheological heterogeneity of lithosphere (*22*, *23*) due to intrinsic variations in the density and thermal regimes (*24*, *25*) (Fig. 2).

Below, we review the relationship between inherited topography, caused both by deep-Earth and surficial processes, and sea level change, using the Cretaceous Period as the key example for several reasons: The Cretaceous is known to have been a period of warm climate when Earth was largely ice-free, with the possible exception of Antarctica (*26*). This makes the Cretaceous suitable for testing various tectonic models without the complications of ice cover in the Northern Hemisphere. The Cretaceous was also a period of extensive sea floor volcanism (*27*, *28*) associated with upper mantle instabilities and rifting and continental breakup (*29*) that is often accompanied by volcanic activity (*30*). Additionally, not all of the Cretaceous sea floor has been subducted, and the missing fragments can be reconstructed (*31*) or alternatively, some of the subducted slabs of this age can be imaged and modeled in mantle graveyards (*20*). The Cretaceous is also of considerable paleoclimatological interest, as it may be an appropriate analog for a greenhouse climate, a direction in which our planet currently seems to be headed. The presence of Cretaceous petroleum systems, both in terrestrial and offshore plays, also makes this interval of high interest to the hydrocarbon industry, where knowledge of the chronology of eustatic variations and their amplitudes is considered an indispensable component of the explorationists' toolbox, allowing them to broadly anticipate several exploration criteria (*10*). In this Review, we examine the record of both horizontal and vertical motions of the lithosphere with a focus on the Cretaceous record that could have influenced far-field sea level changes. We conclude by identifying unresolved questions and areas of future research.

Mechanisms and measures of sea level change

Known mechanisms capable of generating a global signature in the stratigraphic record fall into two categories: those caused by substantial changes in the volume of water in the oceans, and those driven by changes in the volume of the ocean basins, (i.e., their container capacity) [see also (*32*) for a recent review, and Table 1 for

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a summary of known operative mechanisms of sea level change].

Water sequestration on land

The simplest means of transferring a substantial amount of seawater to land (so as to be observable in the sedimentary record) is by sequestering it as ice on the continents during glacial episodes. [Smaller amounts of water can also be sequestered on shorter time scales (hundreds to thousands of years) in terrestrial aquifers and lakes (*33*–*36*), but the current consensus dictates that this does not produce an appreciable global stratigraphic signal, although it could be relevant to higher-frequency Milankovitch-scale cyclicity reflecting swings between dry and wet periods.] Our knowledge of Earth's glacial history is still fragmentary; nonetheless, glacial episodes with varying degrees of ice cover are known to have occurred in the Late Ordovician–Early Silurian interval, in the Late Devonian, through much of the Carboniferous and Permian, and in the Late Paleogene–Neogene, in addition to the development of bipolar ice cover in the Late Neogene [see, e.g., (*37*)]. In the Late Cretaceous, ephemeral Antarctic glacial episodes have been hypothesized (*38*–*41*).

The second process capable of redistributing a substantial volume of free water in the oceans over relatively longer time scales (on the order of millions of years) is the potential of imbalance of ocean's water exchange with deep mantle. This is not a well understood process (*32*), and in the absence of reliable models or the knowledge of operative time scales, this exchange (i.e., water subducted down with hydrated minerals versus water released from mantle into the ocean by degassing) is expediently considered to be in balance over very long time scales (10 million years or more). But it stands to reason that during intervals of anomalously high oceanic crustal production, as in the case in the Late Cretaceous, there would be a net gain of deep-sourced water in the oceans on the relevant time scales, which would balance out by net loss following increased subduction, presumably after a time lag (*10*). This is a promising area for future investigation.

Variations in container capacity of the oceans

The geologically rapid elastic isostatic response (on time scales of tens to hundreds of years) to ice unloading during deglaciations can be distinguished from what follows (*32*) as the viscous post-deglacial response (on time scales of thousands to hundreds of thousands of years) of mass redistribution and vertical displacements along continental margins (*42*–*44*). These effects do not influence the ocean volume on the broader scale per se, but can cause regional anomalies in sea level measurements along a particular margin. Even on the somewhat longer time scales (million years or more) of third-order sea level changes, the long-wavelength warping effect due to mantle convection flow patterns in response to upwellings and downwellings and movements of plates over subduction graveyards [i.e., dynamic topography (*20*, *45*, *46*)] can cause regional anomalies along affected continental margins. It should be noted, however, that numerical modeling studies of glacial isostatic adjustment (GIA) after deglaciation show that the initial elastic rebound and the consequent viscous mantle flow under deglaciated areas are essentially completed within thousands to hundreds of thousands of years post-glacial (*16*, *17*). On these time scales, GIA also shows a strong dependence on distance from the ice sheet. Thus, by ~100,000 years post-glacial, the effects of GIA largely reach equilibrium, and for third-order cyclicity they become part of the steady-state background.

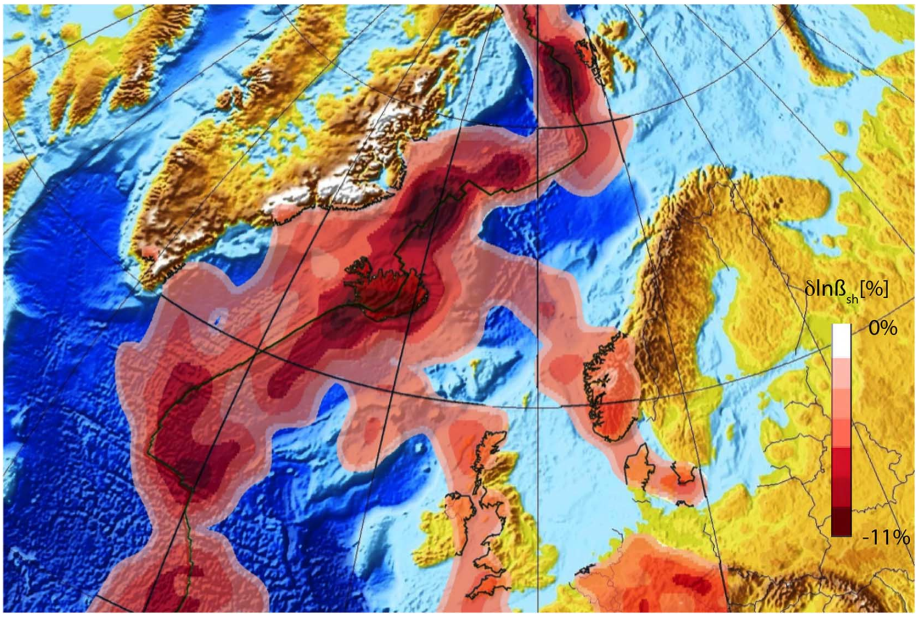


Fig. 1. A recent example of the resolving power of seismic tomography delineating a zone of mantle upwelling under the North Atlantic and adjacent continental areas [adapted from (8)]. Seismic velocity perturbations from full waveform inversion are shown for a depth slice at 120 km. Red areas depict location of Iceland plume and its side lobes extending into southern Norway, the British Isles, and central Europe. All of these areas are undergoing recent uplift in an intraplate tectonic setting, far from plate boundaries, thus affecting any measure of sea level change gauged along these margins. Perturbations are with respect to the reference velocity indicated in the figure.

Factors that can modify the ocean's container capacity with the potential to cause eustatic variations on relatively longer time scales of several million years include variations in oceanic crustal production rates (including volume of mid-ocean ridges and extruded igneous material on the sea floor) and net dynamic uplift and subsidence of the ocean floor due to long-wavelength dynamic topographic effects. It has long been reasoned that variability in rates of oceanic crustal formation at mid-ocean ridge systems (i.e., rates of spreading and total ridge length) would affect the total volume of these subsea features and thus eustatic sea level on relatively longer time scales (~10 million years) (*47*, *48*). Estimating ridge volume from older, now-subducted sea floor poses considerable challenges. Nevertheless, ridge volume variability from the Cretaceous to the present has been modeled (*49*) and, despite some difference of opinion (*50*), a number of independent estimates have reached the conclusion that there has been a slowdown in ridge spreading rates (and thus effective ridge volume) of 60 to 80% since the Late Cretaceous (*31*, *32*, *51*). Other ocean floor volcanic activities that can effect change in the ocean's container capacity include emplacements of large igneous provinces (LIP) and hotspot activity on the sea floor. In the Early Cretaceous, LIP activity was particularly pronounced, which manifested itself in the emplacement of Shatsky Rise [~137 to 131 million years ago (Ma)] and Ontong-Java and Manihiki Plateaus (episodically from ~122 to 90 Ma) in the Pacific that are interpreted to have been emplaced over relatively long durations (*28*). The Deccan Traps region in the Indian Ocean, on the other hand, was emplaced in a relatively short time (several hundred thousand years) in the latest Cretaceous, both on the ocean floor and along the western Indian margins (*52*).

Mantle-lithosphere interactions

An important development in geosciences in recent years has been the recognition that mantle-lithosphere interactions can have important consequences for long-wavelength surface topography on the sea floor and the continents, with implications for long-term (time scales of >5 million years) sea level variations. This applies to zones of mantle upwelling as well as downwelling, as documented by high-resolution seismic tomography (*7*, *8*). Continental interior and marginal surface topography can be modified when large features, such as a subducting slab, are traversed over by an overriding continent. This has been modeled and interpreted to be the case for the westward movement of North America over the remnants of the Farallon subduction slab (Fig. 3). This was inferred to have induced substantial far-field subsidence along New Jersey and adjacent margins since the Late Cretaceous, as modeled by a number of dynamic topographic studies (*20*, *31*, *53*–*55*). Although dynamic topography can produce both local and global effects, it is mainly relevant to long-term sea level trends and less so for the punctuated shorter-term third-order events, as long as it is recognized that the far-field warping effect that it can produce needs to be taken into account when measuring sea level change locally.

Thermomechanical models of mantle-lithosphere interactions predict vertical crustal movements within the same amplitude range as the third-order cycles, but they are not likely to be repetitive (*56*, *57*). For example, plume emplacement, slab detachment, or folding instabilities within the lithosphere are not likely to repeat in a strictly cyclic manner. However, one intriguing dynamic that seems worthy of consideration is the direct correlation between strong lithosphere and higher continental topography, and the association of low-strength lithosphere with lower topography that may allow access to oceanic flooding (*58*, *59*). The Cretaceous Period had inherently weaker lithosphere in the broad sense, due to widespread continental breakup and high oceanic crustal production rates. If this is combined with the potential for higher water expulsion rates from the mantle in the Late Cretaceous, weakening the lithosphere still further by water entrainment, the Late Cretaceous topography in general would have been lower and the global sea levels higher (*58*) (Fig. 4). Paleorheology varies in the Cretaceous, and the lithosphere as a whole becomes relatively stronger near the end of the Cretaceous. In addition, there is a feedback between stress and rheology (stresses weaken plates), thereby indirectly affecting topography. And as noted earlier, plume emplacements and their timing also play a role is resetting the thermomechanical structure. The plume emplacement effect dictates that there would be uplift in the earlier stages, followed by differential motions, including subsidence on the continents and margins (*56*). According to this tenet, we should expect shorter-wavelength (and higher-amplitude) changes in the earlier Cretaceous, and longer-wavelength (and lower-amplitude) changes in the later Cretaceous. On the ocean floor, swelling occurs during plume emplacement and subsidence follows only when the plume dies out (Fig. 5).

In this context, it is becoming evident that the assumption of rigid lithospheric plates may be an oversimplification, and the isostatic response to loading and unloading would depend strongly on rheological stratification of the lithosphere (*56*). As a result of the large number of rifted margin studies carried out in recent decades, it is becoming clear that traditional concepts resulting from the early stretching models (*60*), implying instantaneous rifting followed by a post-rift phase of steadily decaying thermal subsidence, require some additional thought. The duration of syn-rift phases can last up to hundreds of millions

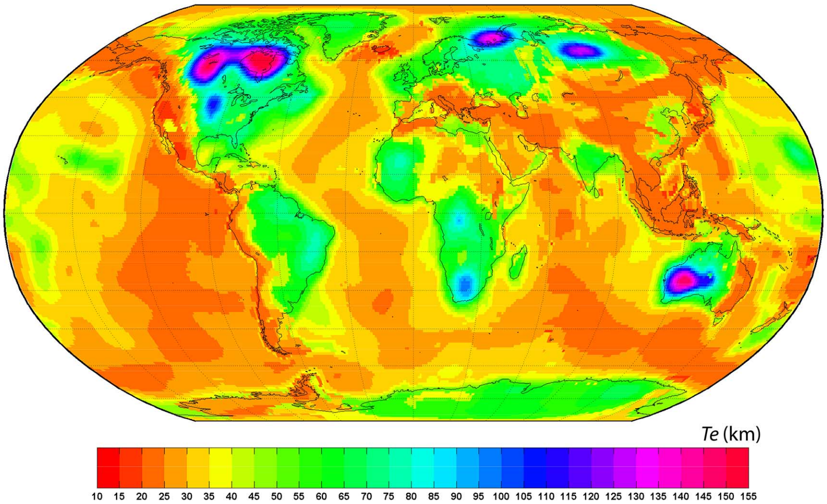


Fig. 2. Map of global modeled lithospheric rigidity (strength) expressed in term of effective elastic thickness (T_e) of oceans and continents, showing pronounced spatial variations from strong continental cratonic areas to weak alpine belts and young oceanic lithosphere [adapted from (*23*)]. Such variations have strong impact on the loading capacity of the lithosphere to support topography, ice caps, and sedimentary loads. Weak areas frequently manifest lithospheric domains (e.g., Iceland in the North Atlantic) that are subject to upwelling, whereas strong cratonic areas (such as the Canadian Shield) retain long-term memory of relative tectonic quiescence and the presence of a cold upper mantle underneath. Weak areas are also locus of intraplate deformation and associated vertical motions affecting inherited landscapes.

Table 1. Various mechanisms that can modify local/regional (eurybatic) and global (eustatic) sea levels, their time scales, their magnitude of change, their extent, and the mechanism's relevance to the Cretaceous Period under discussion in this Review. Data are from several sources, including (*32*, *47*, *48*, *84*); GIA, glacial isostatic adjustment; LIPS, large igneous provinces; My, millions of years.

Mechanism	Operative time scale	Order of magnitude of change	Potential extent	Cretaceous relevance
Water sequestration on land and in mantle				
Terrestrial aquifers and lakes	<0.01 My	Up to 10 m (? higher)	Global	?
Glaciations/deglaciations	0.01 to 0.1 My	100 to 250 m	Global	?
Water exchange with mantle	0.1? to 1.0 My	Unknown	Global?	++
Changes in container capacity of oceans				
GIA: Elastic rebound	0.00001 My	Up to 100 m	Regional	?
GIA: Viscous mantle flow	0.0001 to 0.1 My	Up to 100 m	Regional	?
Mean age of oceanic crust	50 to 100 My	100 to 300 m	Global	+++
Ridge production rate changes	50 to 100 My	100 to 300 m	Global	+++
Ocean floor volcanic activity (LIPS)	1 to 10 My	500 to 1000 m	Global	+++
Mantle/lithosphere interactions	1 to 10 My	10 to 1000 m	Regional/global	+++
Intraplate deformation	1 to 10 My	10 to 1000 m	Regional/global	+++
Dynamic topography	>5 My	Up to 1000 m	Regional/global	+++
Sedimentation	1 to 10 My	50 to 100 m	Global	+

of years (29); in the case of the Norwegian-Greenland Sea, the syn-rift phase lasted more than 200 million years, followed by a post-rift phase of 65 million years, leading to a complex pattern of subsidence and basin migration. Tectonic subsidence in the post-rift phase in many marginal systems also does not conform with the prediction of a steady decrease with time (61–65), but is instead often anomalous, implying that punctuated subsidence is not necessarily only a response to sea level fluctuations. Another factor that may be important in determining inherited landscape is the role of intraplate deformation and associated differential vertical motions. The wavelength and magnitude of lithospheric warping due to intraplate deformation and lithosphere-mantle interactions depend strongly on thermal age and rheology of the lithosphere and should not be ignored in geodynamic models (66, 67). In addition, better quantitative understanding of global effects of seemingly regional factors, such as stress field changes operating on plate scales and their effect on eustasy, is also needed. The same applies to the effects of major opening and closing of tectonic gateways (e.g., closure of neo-Tethys, closure of mid-America Seaway, breakup of North Atlantic, opening of Scotia Arc, etc.).

Dynamic topography

In practice, dynamic topography is what remains after shorter-term isostatic effects have been removed from the observed topography (68). Thus, dynamic topography complicates physical measures of sea level change based on stratal patterns, even when corrections for local factors have been applied. The long-wavelength warping effect of dynamic topography becomes notably apparent on the relatively longer time scales (multiple millions of years) and can dampen or enhance any underlying global signal of the third-order sea level events that occur on shorter time scales, but it rarely wipes out this signal completely. The U.S. East Coast provides an appropriate example of the influence of this factor because of the numerous modeling studies that followed the backstripped stratigraphic amplitude estimates along this margin. The modeled migration of the remnants of the Farallon Plate beneath North America (20) shows the effects of this dynamic passage on surface morphology since the Late Cretaceous. Assuming these models to be valid, this dynamic warping effect may have led the New Jersey margin to subside between 105 and 180 m since the late Cretaceous [see (10) for a discussion]. This example illustrates the considerable challenge involved in extracting a eustatic long-term sea level signal from local stratigraphic measurements.

Disentangling measures and mechanisms of Cretaceous sea level changes

It has become apparent that a measure of the amplitude of eustatic events cannot be gleaned from any one location, as discussed above. Instead, we have to resort to averaging it from global data after chronological consistency of events has been established. Nonetheless, the issue of the causes of third-order events (other than glacial sequestration of water on land) remains conjectural at this point. As mentioned earlier, at least in the Cretaceous, net gain and loss of water to the oceans from mantle sources due to the high crustal production rates remains a likely possibility that may have contributed to the long-term sea level highs and lows of that period.

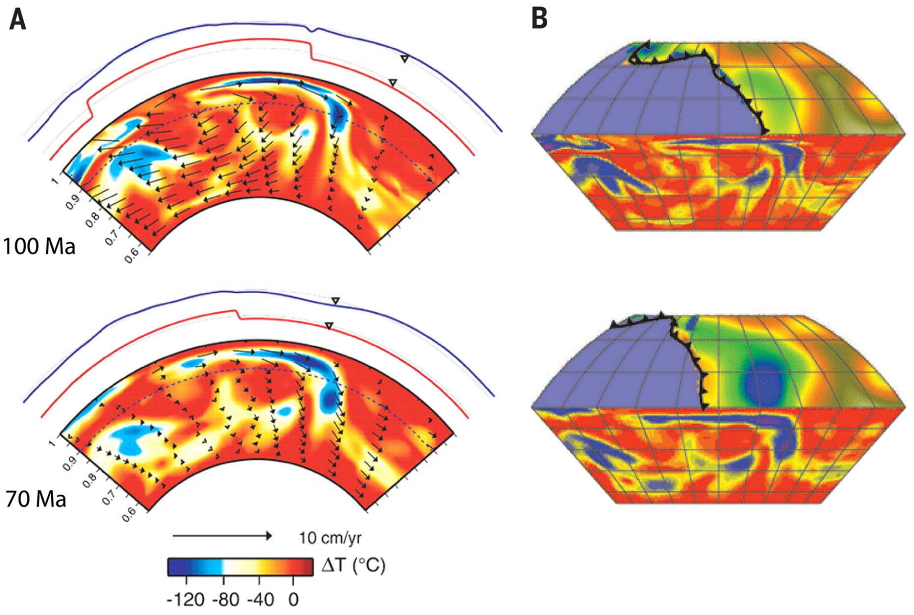


Fig. 3. Modeled temporal evolution of Farallon slab (shown in blue) subducting under North America leading to differential dynamic topography patterns, with down-warping of overlying continental lithosphere. (**A**) Results of a forward model, with a cross section showing temperature anomalies in the mantle, dynamic topography (blue line), and longitudinal component of plate motion (red line) during the Middle (100 Ma) and Late (70 Ma) Cretaceous [adapted from (20)]. (**B**) The same time slices with North America superimposed [adapted from (83)]. Oceanic lithosphere is subducted along a trench (solid line with triangles) on the western margin of the North American continent. During the Cretaceous, the topographic low (areas in green and blue) migrates east together with the remnants of the subducted plate.

Recently, an updated model of Cretaceous eustatic sea level variations based on a synthesis of broadly distributed stratigraphic database has been presented (10) (Fig. 6). This synthesis also took into account most of the published Cretaceous stable oxygen-isotopic data, plus an additional isotopic data set for a nearly complete Cretaceous pelagic carbonate section in Italy. Although such isotopic data (69) were not helpful in the estimation of amplitude of sea level changes [see discussion in (10)], major isotopic excursions aided in verifying the timing of the prominent shifts that were consistent with the stratigraphic data.

Long- and short-term trends

Constraints for the Cretaceous long-term eustatic curve were originally provided by continental flooding data and ridge volume estimates (47, 70). However, now that links with sea floor activities and ocean container capacity changes have been established, model reconstructions of the mean age of the oceanic crust and emplacement of substantial igneous accumulations on the sea floor (31, 71, 72) can provide additional constraints, but they do not change the overall shape of the original long-term curve (1) for the Cretaceous. Most recent estimates derived from geophysical models have now converged and are within the same range of amplitudes (e.g., the Cenomanian-Turonian all-time high in the Cretaceous is estimated at between 170 and 250 m above present-day mean sea level). A noticeable feature of the long-term envelope is that the mean sea level throughout the Cretaceous remained higher than at present, with a low in the Early Cretaceous and peak high in the late mid-Cretaceous. The updated Cretaceous short-term sea level curve is based on the premise that events that can be documented to be geologically synchronous in several, preferably noncontiguous, basins represent global rather than eurybatic events [see discussion in (10)].

Tectonics and eustasy: temporal connections

Figure 6 illustrates the revised eustatic curve for the Cretaceous Period (10) and the various potential mechanisms that could have been operative collectively to produce the resulting long-term sea level trends and possibly also contribute toward the short-term changes. Although the long-term trends can be explained by a number of these processes, individually or in combination, the reasons for shorter-term (third-order) cyclicity remain elusive. A simple comparison of the swing points (where the trends in sea level change) on the long-term eustatic curve with the timing of major tectonic events in the Atlantic domain (73) seems to suggest a connection between major plate reorganizations and initiation of rifting with these swings. Large-scale volcanic activity and continental breakup events (*29*) also seem to complement the overall trends. It should be noted that the onset of rifting in the Atlantic was followed by a prolonged sea floor–spreading phase that occurred over a wide realm that must have affected the Cretaceous record. In contrast to major plate reorganizations (and their related stress fields) with global implications, most stress regime fluctuations and their effect on the sea level were more likely of regional nature.

Discussion: Causal mechanisms operative in the Cretaceous

Multiple interrelated factors can account for the long-term changes, and some of them hold promise to shed light on the shorter-term sea level variations.

Water sequestration on land

During the Cretaceous, the Northern Hemisphere was ice-free while the Southern Hemisphere had the large continent of Antarctica stationed in polar position. Because ice sheets are very sensitive to altitude, it remains to be determined whether Antarctica displayed enough temporal variations in topography to cause substantial variability in water sequestration on land to influence third-order cyclicity. This will have to wait better geodynamic models of this continent. Currently, however, collective opinion is leaning toward accepting potentially enough accumulation on Antarctica to cause ice sheets at least in the Late Cretaceous (*38*, *39*). If this mechanism was indeed operative, the extent of such transient ice sheets would have to have been more pronounced in the earliest Cretaceous (Berriasian to Hauterivian) than in the Late Cretaceous (Santonian through Maastrichtian). Evidence for this, of course, remains to be obtained.

Periodic water sequestration in the mantle

By any measure, the Cretaceous was a period of high oceanic crustal production rates and recycling in the mantle. As alluded to earlier, this could mean high water expulsion rates from the mantle sources into the ocean as well as high water entrainment rates with subduction. For this mechanism to produce a net increase (or decrease) of free water, the duration of the time lag between expulsion and entrainment would be of crucial importance. Also, the total volume of water in this exchange would have to be considerable to cause observable deviations from the long-term steady state. The relevance of this mechanism for the shorter third-order cycles as well as long-term trends remains undetermined at this time and needs to be explored. For this mechanism to be wholly or partially applicable to the Cretaceous eustatic record, more mantle-sourced water would have to be flushed into the oceans during late early and late mid-Cretaceous intervals (Fig. 6).

Variations in the container capacity of the oceans

In the Cretaceous, a large component of the long-term eustatic trends can be explained by changes in the container capacity of the oceans. Higher sea floor spreading rates producing greater amounts of new oceanic crust and larger ridge lengths all contributed to elevated bathymetry. This, combined with emplacement of LIPs, goes

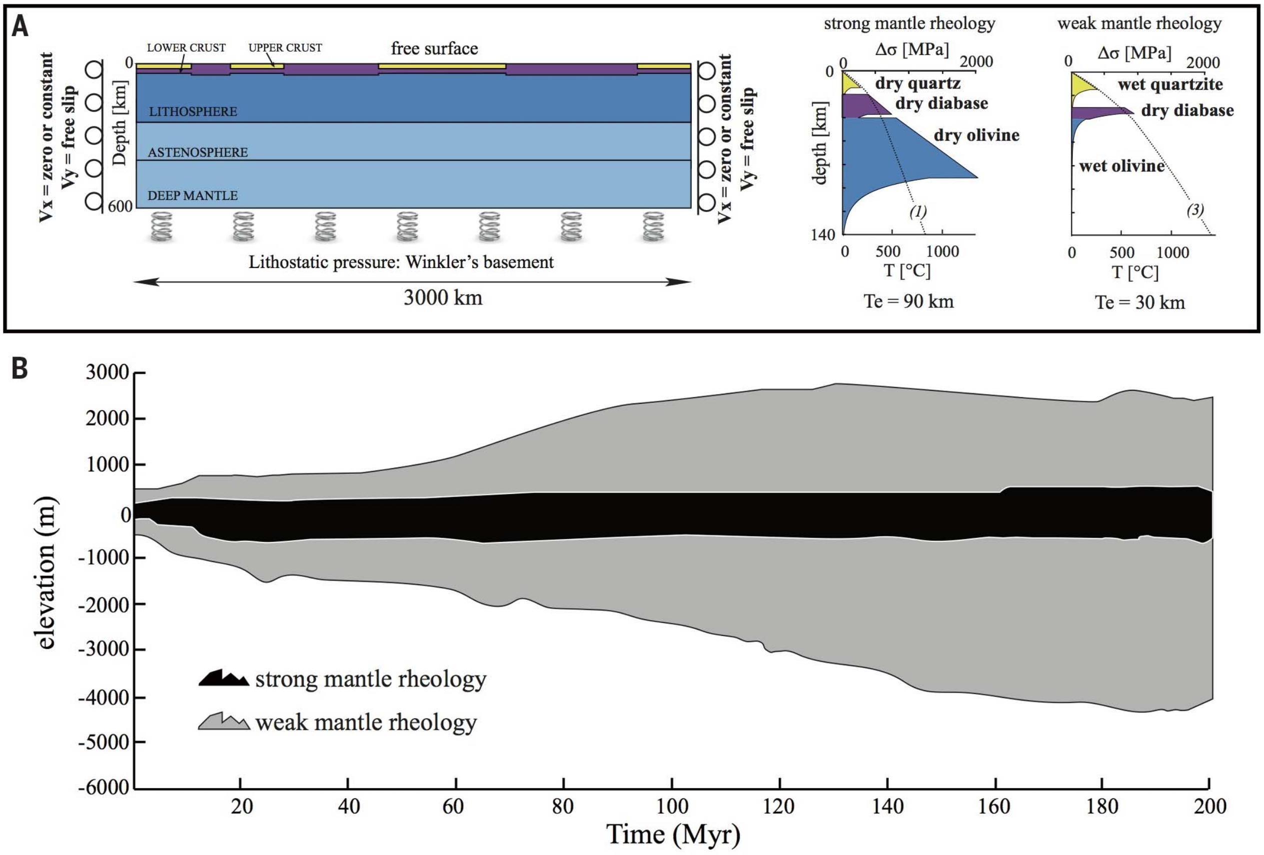


Fig. 4. Models showing capacity of continental lithosphere to support topographic and buried subsurface loads dependent on its strength. (**A**) Design of numerical model and two tested viscous-elasto-plastic yield strength rheological profiles with two end-member assumptions (strongest and weakest). (**B**) Predicted maximum amplitude of surface topography as a function of time [adapted from (*59*)]. During the Cretaceous, lithospheric strength has varied considerably, ranging from high production of ocean lithosphere to high plume activity. Strong surface amplitude variations in case of weak lithosphere with undepleted mantle result from Rayleigh-Taylor instabilities that develop in such lithosphere because of low viscosity of its negatively buoyant mantle part (the instabilities eventually initiate small-scale convection) and low flexural strength, which results in stronger surface response to the subsurface load variations associated with the R-T instabilities and mantle dynamics.

a long way toward explaining the overall high sea levels as well as variations in the long-term trends of this period. However, these could also contribute to some of the shorter-term variations, especially the rapid changes in container capacity such as those that occurred in the Late Cretaceous (e.g., rapid emplacement of the Deccan Traps, which were extruded within a few hundred thousand years, both on land and in the ocean) (*52*). Similarly, delivery of sediments to the ocean can overall enhance subsidence at the depocenters. This has not been systematically modeled, although available data (*32*) show that the effect of this factor was negative and did not vary much during the Cretaceous.

Mantle-lithosphere interaction and intraplate deformation

The Cretaceous was also a period of active plume emplacement in the oceanic settings that would have led to superswell development and rise of sea level to be later followed by subsidence. Plume emplacement is also often associated with continental breakup and the formation of volcanic rifted margins. A striking example of this is the emplacement of plumes at the end of the Cretaceous during the development of the Norwegian-Greenland Sea, while at the same time creating anomalous topography on the continental margins in the North Atlantic. The effects of the plumes on the surface are sensitive to inherited lithospheric structure and lead to spatial and temporal variations in vertical motions in continental interiors as well as along their margins. As shown by a recent study (*74*), intraplate stresses also have an impact on the long-wavelength surface response to mantle upwelling.

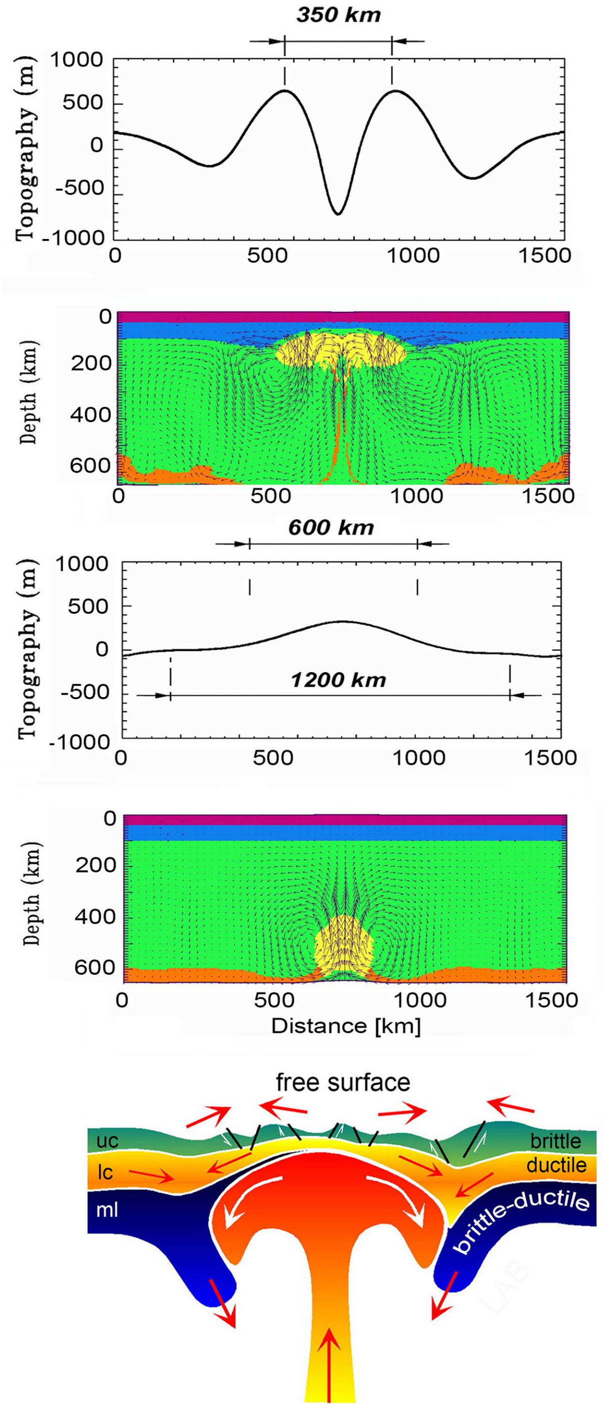


Fig. 5. The surface signature of mantle-lithosphere interactions is strongly dependent on the rheological stratification of the lithosphere. In contrast to the effect of ascending plume in oceanic domain leading to a topographic swell with a wavelength of several hundred kilometers, the interaction of a plume with the stratified continental lithosphere leads to differential uplift and subsidence becoming more pronouncedly differentiated with time [adapted from (*56*)]. uc, upper crust; lc, lower crust; ml, mantle lithosphere. A large part of the mantle impact on topography is dampened in the ductile lower crust and modulated by mechanical instabilities in the rheological layers.

During the Cretaceous, much of the lithosphere was thermally rejuvenated at the onset of the period, and it subsequently aged and cooled. As a result, there was an overall long-term increase in plate rigidity. This increase in strength has in turn increased the capacity of the lithosphere to sustain greater topographic loads. At the same time, it led to flexural widening of the post-rift phase, resulting in apparent onlap in the longer term. As we have already observed, the Cretaceous was a time of major plate reorganizations with strong impact on stress fields in the lithosphere and resulting in intraplate deformation that affected differential vertical motions over wide areas. A characteristic feature of these stress-induced vertical motions is their short-term nature that might affect regional changes on the third-order time scales. For the Cretaceous record, it has been found that rift basins on the African plate underwent simultaneous anomalous differential motions, coinciding with the timing of plate reorganization in the adjacent Atlantic and Indian oceans (*75*).

Dynamic topography

Dynamic topographic predictions are very sensitive to assumptions about crustal thickness and rheological strength and the presumed characteristics of mantle upwelling and mode and geometry of subducting plates. The results of dynamic topographic models are thus prone to intrinsic uncertainties, requiring high-resolution tomographic imaging. Commonly, dynamic topographic models assume rigid plates, and for the Cretaceous most models focus on the effects of down-going slabs leading to overall downwarping and tilting of overlying continents. Dynamic topographic hindcasting rarely goes all the way back to the Early Cretaceous.

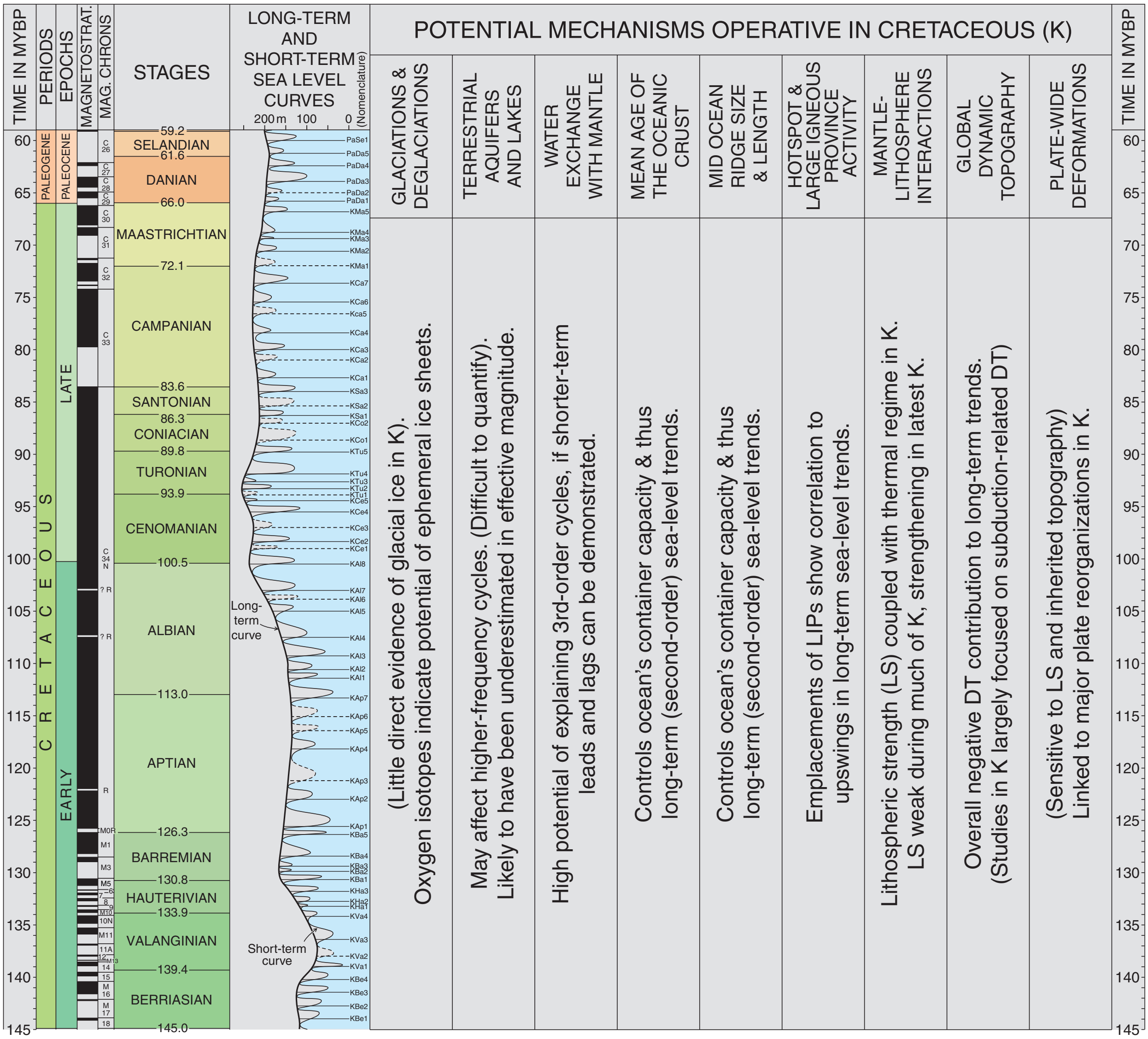
One such reconstruction is from Australia, where regional topography inferred is thought to have been influenced by an ancient subducting slab (*76*). In the Early Cretaceous, the eastern margin of Australia deflected downward in response to active subduction to its east. After subduction ceased in the Late Cretaceous and remnants of the subducted slab moved downward and westward relative to the eastward-drifting Australian Plate, the eastern half of Australia may have sunk as much as a kilometer, inverting only after the slab descended deeper into the mantle in the latest Cretaceous (*76*). These vertical motions would strongly influence all stratigraphic estimates of sea level variations along this and other margins from Cretaceous strata in Australia.

The example of regional topographic anomalies related to the fragments of Farallon slab traversing underneath North America and its influence on the East Coast stratigraphic sea level estimates has already been mentioned (*20*) (Fig. 3). These reconstructions, which go back to the mid-Cretaceous, modeled regional subsidence and ensuing flooding, which shows sensitivity to changes in the assumed mantle viscosity structures through time. The authors used an inverse mantle convection model that simulates seismic structure and plate motion to reconstruct Farallon plate subduction back to the mid-Cretaceous with the objective to constrain depth dependence of mantle viscosity and buoyancy by comparing model prediction and stratigraphy. Another, younger than Cretaceous (Neogene), example is provided by a modeling study of African topographic anomalies that are interpreted to have been influenced by buoyant forces in the mantle for the past 30 million years (*77*).

Nevertheless, existing dynamic topography models indicate an overall negative global contribution by crustal topographic variations to the long-term sea level change (*32*, *72*). Models for present-day dynamic topography for the Mediterranean (*78*) show that mantle flow can produce strong differentiation in zones of positive and negative topography, linked to assumptions about crustal structure. Thus, there is considerable challenge involved in reconstructing detailed crustal structure in the geologic past (Fig. 7). It is also noteworthy that in the continents, dynamic topography can be substantially modulated as the result of a dampening effect of lithosphere-asthenosphere boundary undulations in the lower crust and short-wavelength modulation of the associated signal due to mechanical response of competent crustal and mantle layers (*56*).

Relative contribution of various mechanisms and their feedbacks and interconnections

Qualitative measures of contribution of various factors on the long-term sea level trends are relatively easy to envision. In contrast, quantitative assessments are fraught with difficulties. Most workers nevertheless agree that mean age of the oceanic crust and ocean floor productivity are the largest contributors to long-term sea level trends in the Cretaceous. Sea floor productivity contributes highest positive contribution, varying between 250 and 225 m of sea level in the Cretaceous (*32*). Volcanic activity becomes a relatively major positive contributor



GLACIATIONS & DEGLACIATIONS	TERRESTRIAL AQUIFERS AND LAKES	WATER EXCHANGE WITH MANTLE	MEAN AGE OF THE OCEANIC CRUST	MID OCEAN RIDGE SIZE & LENGTH	HOTSPOT & LARGE IGNEOUS PROVINCE ACTIVITY	MANTLE-LITHOSPHERE INTERACTIONS	GLOBAL DYNAMIC TOPOGRAPHY	PLATE-WIDE DEFORMATIONS
(Little direct evidence of glacial ice in K). Oxygen isotopes indicate potential of ephemeral ice sheets.	May affect higher-frequency cycles. (Difficult to quantify). Likely to have been underestimated in effective magnitude.	High potential of explaining 3rd-order cycles, if shorter-term leads and lags can be demonstrated.	Controls ocean's container capacity & thus long-term (second-order) sea-level trends.	Controls ocean's container capacity & thus long-term (second-order) sea-level trends.	Emplacements of LIPs show correlation to upswings in long-term sea-level trends.	Lithospheric strength (LS) coupled with thermal regime in K. LS weak during much of K, strengthening in latest K.	Overall negative DT contribution to long-term trends. (Studies in K largely focused on subduction-related DT)	(Sensitive to LS and inherited topography) Linked to major plate reorganizations in K.

Fig. 6. An updated eustatic curve for the Cretaceous Period plotted against various potential mechanisms that could have been operative collectively in this period to produce the resulting long-term (and possibly also contribute toward the short-term) sea level trends [adapted from (*10*)]. Whereas the long-term trends can be explained by a number of these processes, individually or in combination, the reasons for shorter-term (third-order) cyclicity remain elusive. MYBP, millions of years before the present.

in the Late Cretaceous (~50 m). Sediments provide a relatively constant negative contribution overall of ~50 m through the same period.

Spasojevic and Gurnis (72) suggest that with the exception of Southeast Asia (and possibly Australia), in the Late Cretaceous time dynamic topography provides an overall negative contribution to sea level up to the order of 1 km, primarily due to slab subduction, creating broad topographic depressions at the surface of the overlying lithosphere. These models, however, could be effectively refined once the effects of internal deformation of the plates and their obvious dependence on rheology are incorporated. These deformations can lead to vertical motions on the time scale of third-order events, with a wide range of magnitudes that vary from a few tens of meters for strong plates to several hundreds of meters (up to 1 km) for weaker ones. As discussed earlier, the contribution of this factor was most likely higher in the Early Cretaceous than in the Late Cretaceous, depending on the rheological strength as well as level of tectonic activity.

We should once again underscore that most of the factors discussed above are interrelated and have feedbacks. Changes in mantle convection not only influence dynamic topography but could also have a direct effect on the stress field within the plate, leading to differential vertical motions at different spatial scales. Resultant topographies also generate stresses and deformation, whereas rigidity of the lithosphere is a key to sustained topography (75). During the Cretaceous, with relatively high and variable mantle activity and a peak in the crust generation in the Early Cretaceous and volcanism in the Late Cretaceous, the nature of feedbacks would have also changed. In all of these, inherited spatial variability in the lithosphere structure is the key to surface topography and its influence on sea level change.

Conclusions and future perspectives

Substantial progress has been made in our understanding of the connection between deep-Earth processes and their surface expression, which has brought about a desirable convergence of views between solid-Earth geophysics and sedimentary geology concerning eustasy. It is becoming obvious that knowledge of inherited topography is crucial to the disentangling of sea level changes at all spatial and temporal time scales and perhaps in the understanding of their causal mechanisms. Solid-Earth mechanisms that modify inherited landscapes and our measure of sea level are many and often interrelated. These include glacial isostatic adjustment, dynamic topography, mantle-lithosphere interactions, oceanic crustal production rate variations, and plate reorganizations and deformations, among others. Superimposed on these are the broad climatic influences, of which glaciations and deglaciations are most relevant to sea level change. We are now at a stage where we have begun to understand many of these causal mechanisms and their complex feedbacks for the long-term trends in eustatic changes, and estimates for the amplitude of these changes are also converging based on different data sets. Likewise, considerable headway has been made in deciphering the causes for short-term eurybatic changes on regional scales that are also influenced by lithospheric memory and its responses to coupled deep-Earth processes (79, 80). We have also become aware that the role of volcanism in rifting can be an important determinant of the long-term sea level change, which can produce punctuated although not cyclic changes with a frequency of 5 to 10 million years. Alternatively, the record of sea level change can provide an important constraint on upper mantle processes.

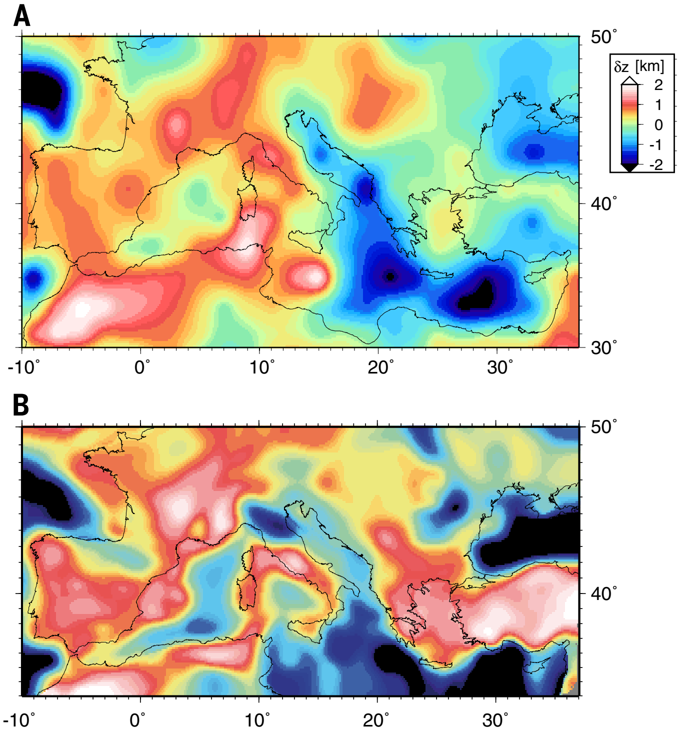


Fig. 7. Modeled prediction for dynamic topography for the Mediterranean area based on mantle flow patterns inferred from seismic tomography [adapted from (78)]. These models are also dependent on availability of constraints on crustal thickness. (**A**) Prediction adopting global crustal thickness model. (**B**) Vertical motions calculated adopting a higher resolution regional model the Mediterranean area based on available geophysical data in the region. This model predicts uplift in Anatolian plateau and Iberia, areas with elevated topography and subsidence in the eastern Mediterranean.

Despite this progress in understanding long-term eustasy, causes for third-order cyclicity remain enigmatic, although there are avenues that should be investigated further, such as periodic imbalance between water entrainment and expulsion within the mantle, and potentially longer-term residence of substantial amount of water on land during dry intervals (lowstands). The latter is especially relevant to sea level changes related to higher-frequency Milankovitch-scale oscillations. It is quite possible that we are misjudging both the time scales and magnitude of both these effects in influencing the stratigraphic record. Dynamic topography has come to the rescue in explaining away the disparities in the amplitudes of sea level measured stratigraphically at different places in spite of the underlying eustatic signal. But it does not shed light on the causal mechanisms for these changes or the occurrence of quasi-cyclic third-order changes on global scale. In addition, we have also learned that the role of volcanism in rifting can be a significant determinant of the long-term sea level change, which can produce punctuated although not cyclic changes with frequency of 5 to 10 million years.

As regards the causal mechanisms of quasi-cyclic third-order fluctuations, if we hold water sequestration on land as a major contributor, it would require ice volume to fluctuate with amplitudes that are large enough to drive several tens of meters of sea level change. Thus, it is imperative that we find direct evidence of significant glaciation in the Cretaceous. The most likely source of such glaciation would probably be located at high altitudes on Antarctica. This again necessitates inherited elevated topography on a scale requiring the involvement of large-scale mantle processes underneath Antarctica. The period was also characterized by large-scale volcanic activity associated with plate reorganizations and continental breakup events. However, the temporal evolution of Cretaceous volcanic activity associated with plate reorganizations and breakup events needs to be constrained in more detail if credible links must be established between tectonics and regional and global sea level changes in this period. Inherited land and sea floor topographies also set the stage for understanding the events to follow in the Cenozoic.

Lateral variations in upper mantle viscosity and lithosphere rheology that have implications for both glacial isostatic adjustment and dynamic topography must be further investigated. Glacial isostatic adjustment models have only recently begun to take into account mantle heterogeneity and associated lateral variation in lithospheric strength (81), but these need to incorporated into longer-term dynamic topographic models as well. Recent model studies in the Mediterranean area have shown strong dependence of dynamic topography on lateral variations in crustal structure and rheology (*77*). Likewise, such coverage is needed on a global scale for crustal and lithosphere structure for the present day as well as the geologic past. A first-order global strength model for present-day oceanic and continental lithosphere has recently become available (*23*). We need to build on this initial effort to construct higher-resolution maps as well as past rheological models on a global scale.

It is evident that modern sea level–related research, through its intimate connection with inherited landscapes, is not only an integrative force between solid-Earth geophysics and sedimentary geology, but could also play a role in integrating continental and marine studies. In this connection, deep-drilling programs, both on land and at sea, will be of crucial importance for achieving the integrative goals. Finally, we note that a review by Schlanger (*82*) had already predicted in 1986 that higher-frequency eustatic variations will not be understood by a single discipline (stratigraphy) alone and may ultimately involve a geophysical solution.

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