# A Chronology of Paleozoic Sea-Level Changes

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Sea levels have been determined for most of the Paleozoic Era (542 to 251 million years ago), but an integrated history of sea levels has remained unrealized. We reconstructed a history of sea-level fluctuations for the entire Paleozoic by using stratigraphic sections from pericratonic and cratonic basins. Evaluation of the timing and amplitude of individual sea-level events reveals that the magnitude of change is the most problematic to estimate accurately. The long-term sea level shows a gradual rise through the Cambrian, reaching a zenith in the Late Ordovician, then a short-lived but prominent withdrawal in response to Hirnantian glaciation. Subsequent but decreasingly substantial eustatic highs occurred in the mid-Silurian, near the Middle/Late Devonian boundary, and in the latest Carboniferous. Eustatic lows are recorded in the early Devonian, near the Mississippian/Pennsylvanian boundary, and in the Late Permian. One hundred and seventy-two eustatic events are documented for the Paleozoic, varying in magnitude from a few tens of meters to ~125 meters.

Although there has been substantial progress in recent years in integrating the record of Mesozoic and Cenozoic eustatic fluctuations (*1*, *2*), relatively little attention has been paid to reevaluating or synthesizing Paleozoic sea-level data, the coverage of which has been largely piecemeal. The Paleozoic Era encompasses more than half of the Phanerozoic Eon, featuring some of the most intriguing unanswered questions in Earth history. Unexplored Paleozoic strata also are believed to contain important unrecovered hydrocarbons. A reevaluation of the eustatic history of this Era therefore would not only serve as a tool for exploration geology but hopefully also revive interest in Paleozoic Earth science.

Sea-level curves provide utilitarian predictive models of sedimentation and thus are invaluable in geologic exploration. These curves offer a working representation of the long-term trends of the base level along continental margins and the individual inundations and drainings/desiccations of interior seaways, and thus the migration of hydrocarbon reservoirs and source facies. Where local tectonic influences are minimal and have not deformed the stratigraphic record (or where tectonics can be corrected for), these curves also can aid in first-order correlations. The relative magnitude and frequency of sea-level highs and lows, the extent and nature of the transgressive condensed intervals on the shelf (when organic-rich sediments accumulate), and the duration of subaerial exposure and incision of the shelf are also important exploration criteria (*3*). Here we present an integrated semiquantitative model of the Paleozoic sea-level history. It is based on widely distributed sequence-stratigraphic data within the biochronostratigraphic constraints of varying quality and reliability for various Paleozoic periods.

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Although previous reconstructions of regional sea-level histories have been limited to discrete slices of time, they provide a wealth of information on the long- and short-term trends and have been an invaluable resource for this synthesis [see the supporting online material (SOM) text]. Particularly, the studies from relatively stable pericratonic and cratonic basins of North American and Australian cratons have been indispensable. As discussed later, we have designated reference districts (RDs) for various time segments (largely from North America and Australia, but also from northern and southern Africa, northwestern Europe, and China). We interpret the sedimentary record in these districts as representing the modal mean of change in sea level during intervals of relative tectonic quiescence. The RDs were also compared with sections elsewhere around the world to ascertain the broad transgressive/regressive trends and individual variations of sea levels and provide corroborative data. Because of spatial constraints, in this article we only report a brief account of our main findings (see also SOM text).

**Timing and magnitude of sea-level events in the Paleozoic.** Obstacles encountered in resolving the timing and magnitude of individual sea level events based on a synthesis of worldwide data of varying quality and utility are not specific to the Paleozoic; they are also applicable to the younger eras. The Paleozoic, however, has a special suite of constraints that sets it apart. For example, most Paleozoic oceanic crust has been subducted (with the exception of a few obducted ophiolite mélanges), making it unfeasible to directly estimate the mean age of the oceanic crust for deciphering long-term eustatic trends. Paleozoic stratigraphy is also strongly biased toward epi- and pericratonic basins, characterized by their plentiful unconformities and endemic faunas. Nevertheless, these attributes make these basins natural places for the study of "unconformity-bounded" units (depositional sequences). The unconformity-bounded subdivision also makes the existing Paleozoic literature, spanning over a century of research, relevant and useful.

An accurate time scale is of crucial first-order importance for any global synthesis. Geological time scales have been improving and becoming better integrated in recent years. The Paleozoic time scale in particular has been in a considerable state of flux, with major recent changes to the ages of period and stage boundaries. The most up-to-date published time scale is that compiled by Gradstein *et al.* (*4*). Some parts of this chronostratigraphy have been updated recently (*5*), which we have adopted here. Ongoing attempts at astronomical tuning and recalibration of $^{40}Ar/^{39}Ar$ ages will probably lead to further refinements of the boundary ages (*6*). However, with the exception of a few radiometrically determined boundaries, all of the Paleozoic correlations are actually based on fossil biozonations. Thus, the duration of a biozone in question provides a minimum measure of uncertainty in the correlations of sequence boundaries.

The degree of precision of correlations from one basin to another depends on the biostratigraphic fossil assemblage used for such purposes. For the Paleozoic, biochronostratigraphy is traditionally based on several groups of commonly occurring fossils, the majority of which tend to be endemic and/or facies-controlled (*7*). This underscores the need to use multiple overlapping criteria (biozonal assignments based on several groups) where possible, to enhance the chronostratigraphic signal-to-noise ratio.

The second issue of importance for a reconstruction such as this concerns the uncertainty in estimating the magnitude of rises and falls in sea level. In the Paleozoic, the general lack of data on ice-volume proxies, such as oxygen isotopes (because of severe diagenetic alterations), limits us to relying on physical measures of sea-level changes from stratigraphic data. A fundamental limitation for accurate physical estimates stems from the lack of a universal reference point against which sea level changes can be computed. For convenience, we often compare past eustatic fluctuations with present-day (PD) shorelines, but over the longer periods this comparative reference point becomes less meaningful because continents have changed both by horizontal accretion/destruction and vertical motions. It is often possible to determine when the sea withdrew below the extant shelf edge, but it is challenging to accurately gauge the amount of sea-level fall from stratigraphic data because of the unknown amount of erosion on the shelf. A rise in sea level is even more difficult to measure meaningfully because of the potentially less-than-complete filling of the accommodation space during the highstand or because of a subsequent fall in sea level that may erode part or much of the highstand systems tract. Thus, for practical purposes, all amplitude assessments from physical data must be considered relative rather than absolute.

Backstripping can potentially refine such estimates through corrections for sediment loading and compaction and basin-floor subsidence (*8*, *9*). Nevertheless, considerable uncertainties remain in this approach because of long-ranging paleobathymetric indicators and the potential for differential subsidence. Corrections for the flexural response of a margin to the loading and unloading of water/ice and sediments are also not straightforward or precise and can bias the measurements in either direction. During this synthesis, the only meaningful approach we could adopt was to reproduce the magnitude estimates of rises and falls in sea level as gleaned from the RDs and ancillary sections (based variously on stratigraphic measures such as thickness of system tracts, bio- and lithofacies depth assessments, the depth of incision on shelves, and partial backstripping). We classified each event semi-quantitatively (measured as a magnitude of fall from the previous highstand) as minor (<25 m), medium (25 to 75 m), or major (>75 m). From the worldwide data, it is apparent that although the overall long-term (cumulative) rise in sea level could be as much as 250 m, the individual third-order changes in sea level [that is, those occurring over ~0.5 to 6 million years (My)] rarely exceeded 150 m. Many of the higher-frequency (<0.5 My) variations are within the minor to medium range. These estimates will be subject to refinement in the future once various basins (in the RDs and elsewhere) have been effectively backstripped and when better paleobathymetric assessments are available.

**Reconstruction of the Paleozoic sea-level history.** Though Earth scientists have been interpreting changes in sea level based on stratigraphic data for over a century, the first attempt at an integrated history of the Paleozoic sea level was embedded in the broader presentation of seismic-stratigraphic methodology by Vail *et al.* (*10*). Hallam (*11*) also reviewed much of the Paleozoic sea level data accumulated up to the 1980s. More recently, Haq and Al-Qahtani (*12*) presented a regional history of the sea level in the Phanerozoic Arabian Platform and compared it with an updated eustatic sea level curve based on previous syntheses. However, the Paleozoic portions of those curves largely depicted second-order events, mostly cycles of >5 My duration.

The stratigraphic record is a composite of several orders of superimposed sedimentary cycles, depending on their causal mechanisms. They range from the high-frequency Milankovitch-scale climatic cycles (often 1 m to a few meters in thickness) to third-order (mostly 1 to 2 My in duration) and fourth-order (<0.5 My in duration)

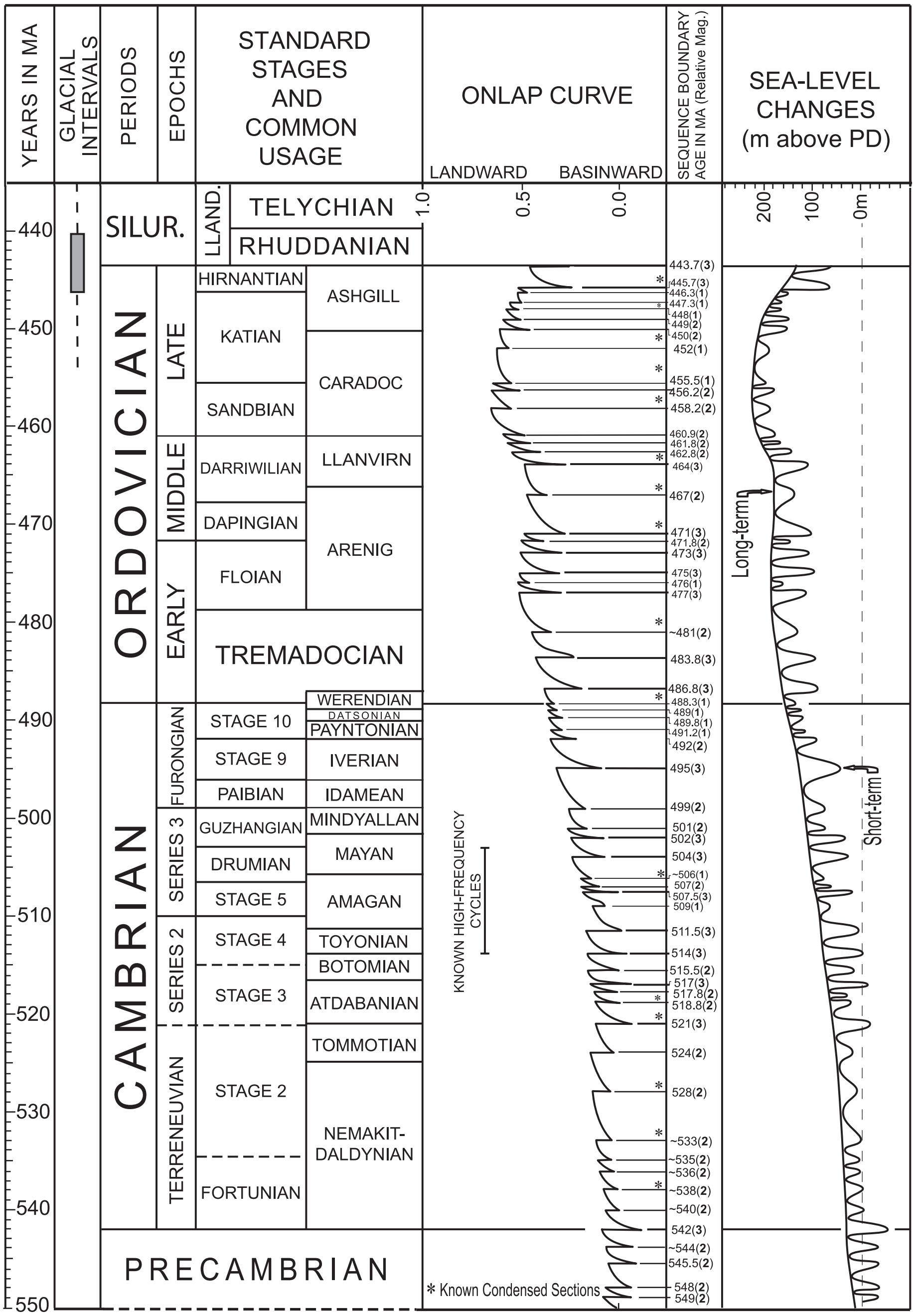


**Fig. 1.** Cambrian-Ordovician sea-level changes. The time scale and standard and regional stages are modeled after Gradstein *et al*. and Ogg *et al*. (*4*, *5*). The left half of Figs. 1 to 3 shows the stratigraphic subdivisions calibrated to the absolute time scale. Known intervals of continental glaciation (*26*–*28*) are indicated alongside the numerical time scale. The right half of each figure starts with an onlap curve, which is a measure of relative landward or basinward movement of the regional baseline as estimated in the RD sections. Sequences that are associated with known prominent condensed sections (indicated by asterisks) are also shown in this column. The biochronological ages of the sequence boundaries (estimated in the RDs and ancillary sections) are indicated in the next column. A semiquantitative measure of the relative magnitude of each short-term event is shown in parentheses [minor, **1** (<25 m); medium, **2** (25 to 75 m); and major, **3** (>75 m)]. Periods with known higher-frequency eustatic cycles and documented condensed sections are also indicated in this column, by vertical bars. This is followed to the right by the sea level curves, both the long-term envelope and the short-term curve of (third-order) fluctuations in the sea level (those suspected to be of fourth order are shown by dashed lines). The dashed vertical line in this column represents an approximation of the PD sea level. Long-term and short-term sea-level curves are calibrated to the PD sea level.

eustatic cycles, and larger (several million years in duration) tectonic cycles. In practice, it is difficult to consistently separate third- and fourth-order cycles. Our ability to resolve the record chronostratigraphically in any given section depends on the thickness of the preserved section, the quality of the outcrop, the position of the section along the shelf-slope-basin profile, and the quality of biochronostratigraphic data. Here we have attempted to identify sequences at third-order resolution; however, a few fourth-order sedimentary cycles inevitably were also incorporated. Although the existence of higher-frequency cycles may be more widespread in the Paleozoic, some intervals more visibly preserve fourth-order (~400,000 years) cycles, such as the mid-Cambrian, mid-Devonian, mid- to late Carboniferous, and Permian (Figs. 1 to 3).

The Paleozoic sequence-stratigraphic data are derived entirely from public-domain outcrop sections (seismic data are generally lacking or spotty except for the late Paleozoic). The criteria for interpreting regional rises and falls in sea level from sequence-stratigraphic data and seismic data have been summarized elsewhere (*3*, *10*, *13*) and are not repeated here. In addition, several lithological features (condensed section deposits, transgressive coals, evaporites, carbonate megabreccias, and exposure-related and forced-regressive deposits) and paleontological attributes have also aided our interpretations in placing outcrop features within sequence-stratigraphic framework (see the description in the SOM text).

Reconstruction of the long-term envelope and the short-term history of changes in sea level requires differing approaches. The long-term changes are believed to be mostly driven by the slow tectonic processes that change the volumetric capacity of the ocean basins. Individually, each data set on which the long-term envelope can be based must be considered relative rather than absolute measures of eustatic trends. However, a long-term curve based on global continental flooding estimates (*14*–*17*), stacked regional sea-level data (evaluated by us), and modeling results for the mean age of the oceanic crust yields consistent results. Algeo and Seslavinsky (*17*) have presented an analysis of the flooding history and hypsometry of 13 Paleozoic landmasses and estimate that the long-term eustatic highs were 100 to 225 m above PD sea level. They also conclude that Paleozoic continents experienced an additional change of ±100 m in vertical movements because of epeirogeny. The upper limits of our estimates of long-term highs are influenced by this analysis.

More-recent modeling results of the Mesozoic-Cenozoic sea floor (*18*–*20*), although based on differing assumptions, consistently point to the mean age of the oceanic crust, rather than sea-floor spreading rates or ridge volume, as potential forcing for the long-term eustatic change. Cogné and Humler (*20*) have extrapolated their modeling results back to the Paleozoic, for which direct measurements of sea-floor isochrons are not possible because of subduction. Instead, they estimate land-ocean distributions from measurements of areas of continental landmasses based on paleomagnetic reconstructions. Their results show a credible agreement between periods of high fragmentation of the continents and high global sea levels through much of the Paleozoic. One recent aspect of the modeling efforts is the conclusion that continental margins could be subjected to a substantial degree of mantle flow–related vertical motions over relatively short geological intervals. This process causes changes in local dynamic topography, which may have led to an underestimation of changes in sea level from physical data in the past (*21*).

The shorter-term changes in sea level (third- and higher-order events) were more likely mostly driven by changes in the volume of water in the world ocean through glacial (and as yet unknown) processes. The short-term Paleozoic curve as portrayed here (Figs. 1 to 3) is based on the best of several sections in an area designated the RD, in which, according to our interpretations, tectonic influences were minimal and the eustatic signal is more likely to have been preserved. Sea level–change events identified in the RDs were then sought elsewhere worldwide (in the existing stratigraphic data) and documented in designated ancillary sections (SOM text).

The previous physically estimated magnitude of the shorter-term (third- and fourth-order) sea-

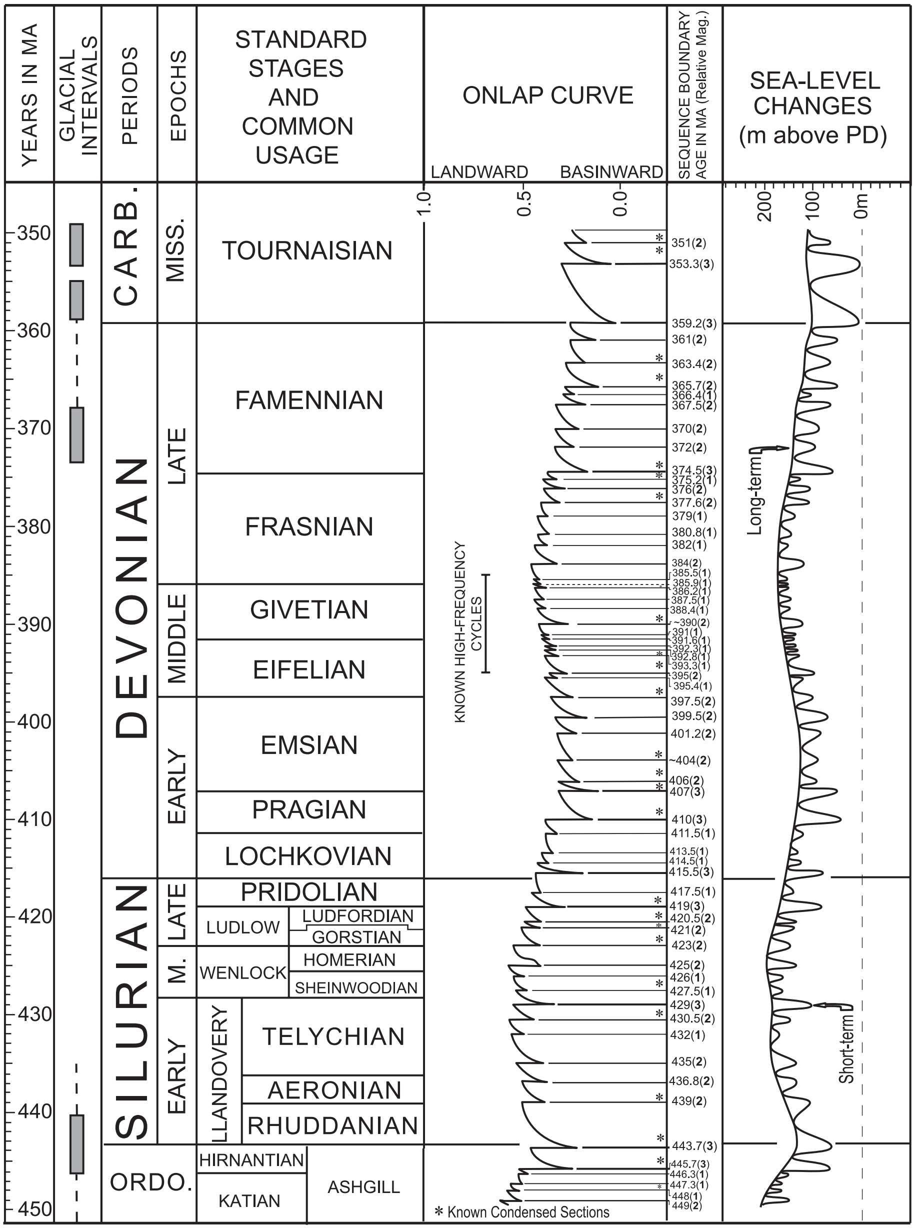


**Fig. 2.** Silurian-Devonian sea-level changes. See the caption of Fig. 1 for details.

level events in the Paleozoic range from a few tens of meters to ~250 m (*22*). A recent synthesis of the Carboniferous-Permian yielded fluctuations of a few tens of meters in the nonglacial intervals and changes of up to 120 m in the glacially dominated periods (*23*). Many of these regional estimates will be subject to refinement in the future, once the sections in question are rigorously backstripped.

Although we deem the long-term trends to be real, the difficulties in estimating meaningful measures of the magnitude of eustatic changes discussed above imply that the absolute global amplitude of both the long-term envelope and the short-term changes remain elusive. All such measures must be currently considered as approximate. These observations also caution us about the futility of generalizing the magnitude of individual sea-level events from one continental margin to represent worldwide eustatic values.

The concept of RDs [first proposed by M. E. Johnson (*24*)] implies that we consider the sections therein to be currently the best available representation of the modal mean for the time segment under consideration. Our criteria for inclusion of an area as a RD are as follows: (i) the time segment in question is represented by a period of tectonic quiescence locally (or is correctable for tectonic influences) and has suffered relatively little postdepositional deformation and is thus interpretable with sequence-stratigraphic methodologies; (ii) sections are relatively well-dated, preferably with multiple biostratigraphies (to enhance the chronostratigraphic signal-to-noise ratio); (iii) outcrops in the area have open public access; and (iv) the area will easily lend itself to geohistory analysis so that the relevant sections can be eventually backstripped (as well as corrected for local dynamic topographic changes over time) for more-refined estimates of the magnitude of changes in sea level. We list the selected RDs and ancillary sections in the SOM, along with background literature and ages assigned by us to the interpreted sequence boundaries.

**Results and conclusions.** Here we offer (in our view) a robust working model of the history of the Paleozoic sea level that is, nevertheless, subject to refinement with better chonostratigraphies and when the sections are subjected to backstripping analyses. Our results show a long-term sea level curve, including a rising sea level during the Cambrian–through–Early Ordovician interval [see fig. S1 and explanation in (*25*)], a marked dip during the Middle Ordovician (the Dapingian to early Darriwilian) preceding a substantial rise entering the early Late Ordovician, and the highest sea levels of the Paleozoic during the early Katian (when the sea level is estimated to be ~225 m higher than at the PD). This was followed by a sharp fall during the latest Ordovician (late Katian to the Hirnantian) that continued into the earliest Silurian. The remainder of the Early Silurian saw the beginning of another long-term rise that culminated in a mid-Silurian (mid-Wenlock) high, followed by a decline that lasted from Late Silurian (Ludlow) through Early Devonian (Emsian). The Middle Devonian saw the beginning of yet another long-term rise, which reached its acme in the early Late Devonian (Frasnian). After a slight dip at the Frasnian/Famennian boundary and a recovery in the early Famennian, the long-term curve shows a gradual sea-level decline in the later Devonian (late Famennian) with a punctuated fall near the Devonian/Carboniferous boundary. After a short recovery, subsequent long-term decline began in the mid-Mississippian (mid Visean), reaching a low in the late Mississippian (near the Mississippian/Pennsylvanian boundary). The next long-term rise (though less pronounced than all previous rises) began in the mid-Pennsylvanian (Moscovian) and lasted only until the end of the Pennsylvanian (Gzhelian), followed by a slight fall thereafter in the earliest Permian (Asselian). The sea level stabilized at that level for the remainder

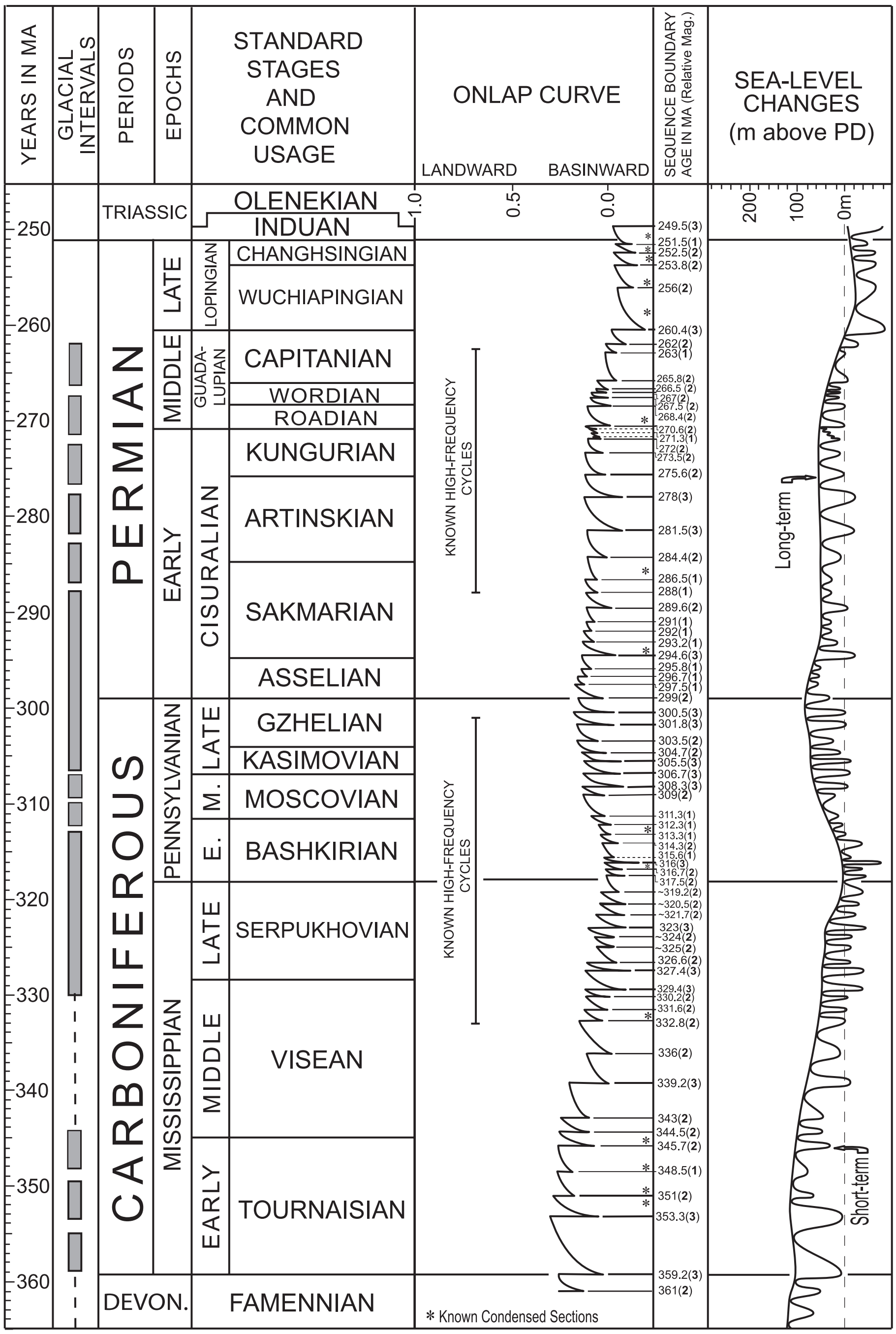


**Fig. 3.** Carboniferous-Permian sea-level changes. See the caption of Fig. 1 for details.

of the Early Permian. A sharp trend toward a declining sea level started in the mid-Permian (Roadian), culminating in the nadir of the sea level for the Paleozoic in the early Late Permian (Wuchiapingian). It began to recover in the latest Permian (Changhsingian), but the general low extended into the Early Triassic.

The shorter-term (third-order) base-level changes generally vary in duration from ~0.5 to 3.0 My (with the exception of Early-to-Middle Mississippian). One hundred seventy-two discrete third-order events (cycles) have been identified, with an average duration of ~1.7 My per cycle. In some intervals, the sections preferentially preserve fourth-order cycles, indicating a possible long-period orbital eccentricity control. Four such intervals have been identified so far: in the middle Cambrian (Toyonian to Mayan), middle Devonian (late Eifelian to Givetian), middle to late Carboniferous (late Visean to Kasimovian), and early to Middle Permian (Artinskian to Capitanian); however, fourth-order cycles may exist more widely. Whether this higher frequency is entirely due to higher sedimentation (a preservational effect) or the underlying signal (that is, long-term orbital forcing) is not always clear. The two younger intervals of higher-frequency cycles (in the Carboniferous and Permian) also coincide with periods of known glaciation, but for the two older intervals (the middle Cambrian and middle Devonian) no glaciation has been documented (*26–28*).

It should be noted that for the Early to middle Mississippian, the duration of most of the third-order cycles seem inordinately long (up to ~6.0 My). Although occasional long cycles (3 to 5 My) also occur at other times (for example, in the Cambrian through early Silurian), the consistent occurrence of long cycles in the Early to middle Mississippian may point to time-scale problems for this interval (the Tournaisian and Visean stages are also inordinately long, probably for the same reason).

We are unable to comment on all of the causes for shorter-term (third-order and fourth-order) eustatic changes in the Paleozoic. Although glaciation has been attributed to ~28% of the Paleozoic time (and suspected for another 10%), it has not been documented for the remainder of this era (*26–28*). Thus, waxing and waning ice sheets cannot be considered to be the only underlying cause for fluctuations in the Paleozoic sea level. Nevertheless, because the Paleozoic glacial record remains fragmentary, the question remains open. Conversely, there may be other, nonclimatic, causal mechanisms for short-term changes in sea level that still remain to be discovered.

**References and Notes**


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7. Common Paleozoic biostratigraphic indicators include brachiopods, graptolites, chitinozoans, ammonoids, fusulinids, and conodonts. Brachiopods appear in the Early Cambrian and are common throughout the Paleozoic but tend to be provincial and facies-dependent, preferring shallow-water environments. Planktonic graptolites appear in the late Cambrian and persist through the early Devonian. They are particularly useful as index fossils in the Ordovician and Silurian, but they are more likely to occur in the basinal facies. Chitinozoa occur from Ordovician through Devonian and have been used successfully for the subdivision of this interval. Paleozoic ammonoids in general are common from the Devonian through the Permian and, although relatively widespread, they also show a considerable degree of provincialism or facies-dependence for some intervals. For example, the ammonoid *Goniatites,* preserved in Devonian-to-Permian strata, are strongly facies-controlled, preferring mostly the basinal environments of inland seas. Fusulinids have been used for biochronologic subdivision with varying degrees of success from the Late Mississippian through the Permian. Conodonts first appeared in the Cambrian and range through the Triassic. Their shallowest-water biofacies tend to be eurytopic, opportunistic, and long-ranging and thus only marginally useful for biostratigraphic resolution. But toward deeper waters they become more cosmopolitan and biostratigraphically meaningful. When deeper-water biofacies are present, conodonts are well suited for higher-resolution correlations from the Ordovician through the Permian interval.
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22. For example, in the Middle and Late Cambrian, backstripped estimates from the Canadian Rockies yielded values of up to 250 m of change, whereas in Utah for strata of the same age, only ~100 m of change was estimated (*29*). In Iowa, nonbackstripped measurements from the Ordovician through Mississippian sequences provided estimates of a few tens of meters to ~100 m of change (*30*). Estimates from topographic relief of incised valleys in the Silurian yielded values of ~30 to >70 m of change worldwide (*24, 31, 32*). In the British Isles, a cumulative rise of 227 m in the Early Carboniferous and ~200 m in the mid-Carboniferous was indicated after partial backstripping, with the magnitude of individual third-order events ranging between 5 and 56 m (*33*). Estimates from the Late Mississippian yield magnitudes of 30 to 100 m of change in the Illinois Basin (*34*). Other estimates from North America in this glacially dominated interval imply minimum amplitudes of 80 m, reaching >100 m of change from preserved relief on subaerial exposure surfaces of large algal bioherms (*35*).
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25. Because of scalar limitations, the Paleozoic cycle chart of sea level fluctuations is presented in three separate figures, each comprising two of the periods of the Paleozoic Era (Figs. 1 to 3). The SOM also includes a complete downloadable color PDF version (fig. S1) of the cycle chart with more details [for example, major orogenic and anoxic events, regional stratigraphic subdivisions and biozonations, and sequence nomenclature (*36*) and known carbonate megabreccias as they have been synthesized from the worldwide data. The latter tend to occur in the carbonate systems at major drawdowns of sea level].
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**Supporting Online Material**

www.sciencemag.org/cgi/content/full/322/5898/64/DC1
SOM Text
Fig. S1
References

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