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Supporting Online Material for

A Chronology of Paleozoic Sea-Level Changes

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Published 3 October 2008, *Science* **322**, 64 (2008)
DOI: 10.1126/science.1161648

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Sequence Stratigraphic Interpretations of Outcrop Sections

In addition to the normal criteria for sequence stratigraphic interpretations referred to in the main text of the paper, the following lithological and paleontological features have also aided us in interpreting system tracts and sequence boundaries in outcrop sections:

Condensed Section Deposits: These transgressive facies depict sediment starvation on the shelves as the depocenters move landward. Common condensed section facies include such authigenic components as glauconite and phosphorite, concentration of organic material and marine shell and bone beds, as well as oolitic ironstones. The preferential accumulation of pelagic and benthic fossil material due to sediment starvation also implies that condensed sections are often the best features for age dating within a sequence cycle.

Transgressive Coals: Transgressive coals occur as continuous sheet coals over a large area rather than being confined to a valley or a lake. They usually overlie rooted exposure surfaces (sequence boundaries) and are in turn overlain by marine deposits.

Evaporites: Relatively thick evaporites can be deposited both during the lowstands (generally confined to the basin) and during the late highstands (on shelves and interior seaways). Caution needs to be exercised in their interpretation and vertical and horizontal relationships need to be examined to ascertain their occurrence as lowstand or highstand features. Thus, depending on whether an evaporite is interpreted as a lowstand or a highstand feature, the sequence boundary is placed either below or above the evaporitic deposit.

Carbonate Megabreccias: These deposits occur on slopes and along basin margins as lowstand features in carbonate systems. Caution should also be taken in their interpretation, since they can also be produced by an advancing thrust sheet or regressive progradation of the platform. When abruptly emplaced on or at the foot of the slope with no relationship to progradation, they can be interpreted as lowstand equivalents (known megabreccias are listed in the last column of the cycle chart).

Exposure-Related Deposits: Surfaces with evidence of erosion and exposure are usually quite obvious but they can also be subtle, especially in early Paleozoic when soil formation processes were as yet less active. Incised valley fill deposits, autochthonous coals, eolian sandstones and karst in carbonates are some of the features related to exposure in the Paleozoic. In addition, laterite/bauxite deposits are indicative of extreme weathering of host rock during exposure in humid and warm climates.

Forced Regression: The phenomenon of forced regression (relative change of sea level without the benefit of normal progradation) was relatively common in the Paleozoic, where shorelines could migrate rapidly and over long distances as a consequence of low topographic relief in cratonic interiors. A forced regression of the shoreline is induced by stepwise base-level lowerings, setting off cannibalization of the coastal/near-shore sediments to form new coastal offlapping deposits.

Other Indicative Paleontological Features: Changes in evolutionary and biogeographic patterns such as radiations and extinctions and faunal migrations in response to changing sea level are well established. For example, extinctions of shallow-marine faunas are more likely to occur during lowstands while landward migration of offshore biofacies is preceded by a sea-level rise. Concentration of well-preserved fossil material is generally an indicator of a condensed section (see above). Sometimes, however, fossil deposits with exceptional preservation of soft body parts (such as the mid Cambrian Burgess Shale of Canada) may occur in a high sedimentation-rate environment (without subaerial exposure) during a late sea-level lowstand.

Selected Reference Districts for the Paleozoic

Reference Districts (RDs) designated for various time segments are listed below and principal references and background material used to reconstruct the sea-level history of these areas are listed in the numbered references *(1-82)* following their description. Age assignments for the sequence boundaries are based on the available biochronostratigraphic information.

Latest Proterozoic to Precambrian-Cambrian Boundary: Namibia, southern Africa is designated the RD for the latest Proterozoic through Precambrian-Cambrian (P/C) boundary interval. An integrated study of the sections in the area combines sequence-stratigraphic interpretations with carbon-isotopic measurements and U/Pb zircon dating to produce an accurate representation of the sea-level history for this interval *(1).* Upper three of the six sequence boundaries leading up to and the P/C boundary itself identified in the Swartkloofberg section of Namibia are included at the base of the cycle chart. The composite carbon-isotopic record at this section resembles the latest Proterozoic carbon-isotopic profile from Oman *(2)* with a distinct negative shift at the P/C boundary. This boundary shift had also been observed on the Siberian Platform *(3)*. The P/C boundary is characterized by an unconformity recognized in various parts of the world *(4)* suggesting a eustatic origin. The terminal Proterozoic leading up to the P/C boundary is also marked by the last pulses of an extensive glacial epoch with recurring incidence of ice expansion and retreat *(1)*. Thus, sea-level changes with amplitudes of 100-150m or more would not have been unusual in this interval of waning phase of glaciation. We assign estimated ages of ~549, ~548, ~545.5 and 544 m.y. before present (Ma) to the late Precambrian events leading to the P/C boundary and the boundary itself at 542 Ma.

Earliest Cambrian: The carbon-isotopic record in the Ara Group in Oman (designated the RD for the earliest Cambrian) also displays a short-lived but marked negative shift at the P/C boundary within the A4 carbonate-evaporite unit and an ash-bed dated at 542 Ma *(2)*. The Ara Group (which extends from latest Proterozoic into earliest Cambrian) represents six carbonate/evaporite cycles, where the extensive marine evaporites units are interpreted as occurring during the restricted conditions of the lowstands. Thrombolite reefs of the Ara formed buildups that were many 10s of m in thickness (indicating the minimum magnitude of sea-level rise during highstands). We interpret sequence boundaries at the top of evaporite units of A4, A5, and lower and upper evaporites of A6 with approximate estimated ages at ~540, ~538, ~536 and ~535 Ma.

Early-middle Cambrian: Outcrop sections in the White-Inyo Mountains of southern California have been selected as the RD for the mid Early through early Middle Cambrian (Tommotian to Toyonian) interval, where the succession has been studied by several authors *(5-9)*. In the composite succession of the RD the interval in question shows ten interpretable sequence boundaries that can be assigned the following ages: ~533, 528, 524, 521, 518.8, 517.8, 517, 515.5, 514 and 511.5 Ma.

Middle to Late Cambrian: The RD for the later Toyonian to mid Iverian interval is designated within the southern Canadian Rockies, where several outcrop sections span this interval *(10-15)*. Backstripping in the sections in this district yielded estimates of sea-level changes in excess of 200m for this time interval *(16)*. We interpret nine sequence boundaries, with estimated ages at 509, 507.5, 507, ~506, 504, 502, 501, 499 and 495 Ma within the RD.

Latest Cambrian to early Ordovician: In the latest Cambrian through Early Ordovician interval of the Lapintine Seaway (recorded in Georgina, Amadeus and Canning Basins of Australia) several prominent sea-level change events have been recognized *(17).* The Black Mountain succession of the Georgina Basin, where the conodont-control is especially good *(18)* forms the basis of the sequence-stratigraphic interpretations and is designated as the RD for this interval. For the most part this basin shows only minor to moderate deformation of the Ordovician strata. We place the sequence boundaries as slightly pre-dating the lowstands and assigned the twelve events identified here the following ages according to the new time scales: 492, 491.2, 489.8, 489, 488.3, 486.8, 483.8, ~481, 477, 476, 475 and 473 Ma.

Latest Early to early Middle Ordovician: For the short interval of late Arenigian to mid Llanvirnian we designate the sections in the State of Utah (including the upper type Ibexian and lower Whiterockian) as an appropriate RD. It represents a well-dated composite succession with multiple trilobite-brachiopod and conodont zonations *(19)* that provide good age control. Four sequence boundaries are interpreted at 471.8, 471, 467 and 464 Ma within the upper part of this RD.

Latest Middle to Late Ordovician: Succession in south central Oklahoma State is designated as the RD for the late Llanvirnian to Caradocian interval. Several authors have outlined the descriptive and paleontological aspects of these sections *(20-22)* and sequence stratigraphy has also been previously attempted *(23, 24).* We interpret seven sequence boundaries in this interval with estimated ages at 462.8, 461.8, 460.9, 458.2, 456.2, 455.5 and 452 Ma.

Latest Ordovician: The Upper Mississippi Valley in North America is selected as the RD for the Ashgillian (including Hirnantian) interval. The Galena Group is well studied and there are several *K*-bentonite dates *(25).* Sections in northeastern Iowa facilitate interpretation of sequence boundaries *(26-28)*. Six sequence boundaries are interpreted with estimated ages at ~450, 449, 448, 447.3, 446.3 and 445.7 Ma within the Iowan sections.

Silurian: An almost complete succession is exposed in western New York State which is designated as the RD for the Silurian in its entirety. Several workers have presented the descriptive aspects of these sections *(29-33).* Several Silurian eustatic curves have also been proposed based on these and other sections in North America and elsewhere (*34-37)*. We assign the following ages to the fifteen third-order sequence boundaries in the Silurian succession of the New York RD: 443.7, 439, 436.8, 435, 432, 430.5, 429, 427.5, 426, 425, 423, 421, 420.5, 419 and 417.5 Ma.

Early Devonian: For the Lochkovian to Emsian interval we return to Australia and designate the sections at Broken River and Waratah Bay (eastern and southeastern Australia, respectively) as the RD. This succession and a regional sea-level curve have been summarized by Australian stratigraphers *(38, 39).* We assign the following ages to ten sequence boundaries identified in the RD area: 415.5, 414.5, 413.5, 411.5, 410, 407, and 406, ~ 404, 401.2 and 399.5 Ma.

Late Early to Late Devonian: For the remainder of the Devonian (younger Emsian through Famennian interval) we designate a succession in western New York as the RD. The physical/paleontological aspects of these sections have been discussed by a number of stratigraphers *(40-43).* Based on these and other sections in North America and Europe, Johnson *et al. (44, 45)* presented a composite sea-level curve for the Devonian. In this interval our reinterpretations led us to the place 30 sequence boundaries with estimated ages at 397.5, 395.4, 395, 393.3, 392.8, 392.3, 391.6, 391, 390, 388.4, 387.5, 386.2, 385.9, 385.5, 384, 382, 380.8, 379, 377.6, 376, 375.2, 374.5, 372, 370, 367.5, 366.4, 365.7, 363.4, 361 and 359.2 Ma.

Mississippian: The succession in the British Dinantian and Namurian (*proparte*) sections (Avon Gorge in southwestern England for the lower section and Askrigg Block and Craven Basin in the Midlands for the upper section) is designated as the RD for the Early Carboniferous (Mississippian in North America). These sections are well-known through the work of several authors, especially that of Ramsbottom *(46-51).* Ramsbottom also presented a model of regional sedimentary cycles (termed Mesothems by him) for the Dinantian through Westphalian interval, tracing these sedimentary cycles over northwestern Europe. Our reconsideration of these sections place the 21 third-order sequence boundaries at 353.5, 351, 348.5, 345.7, 344.5, 343, 339, 336, 332.8, 331, 330.2, 329, 327.4, 326.6, 325, 324, 323, 321.7, 320.5, 319.2 and 317.5 Ma.

Pennsylvanian: A composite succession in the mid-continent of North America (sections mostly in Oklahoma and Kansas) form the RD for the Late Carboniferous (Pennsylvanian in North America). These sections have been the subject of many investigations going back to the first synthesis of Moore *et al. (52)* and subsequent descriptions and paleontological studies *(53-58)*, cyclostratigraphy (*59)* and sequence stratigraphy *(60-64).* Much of the Pennsylvanian is characterized by higher-frequency (4^{th}-order) cycles, most likely related to the periodicity of the waxing and waning of glacial ice. We assign the following ages to the sixteen third-order sequence boundaries of the Pennsylvanian: 316.7, 316, 315.6, 314.3, 313.3, 312.3, 311.3, 309, 308.3, 306.7, 305.5, 304.7, 303.5, 301.8, 300.5, and 299 Ma.

Permian: Sections in West Texas comprise the RD for much of the Permian Period. For the Late Permian (Lopingian), however, the West Texas succession is incomplete. Thus, for the Late Permian and the transition from Permian to Triassic we have selected the Yangtze Platform of South China as the RD. Descriptive aspects of the West Texas sections have been presented by several authors *(65-70),* as are the paleontological aspects *(71),* cyclostratigraphy *(72-76)* and sequence stratigraphy *(63, 77)*. Descriptive aspects of the Late Permian (Wujiapingian and Changxingian) of South China have been summarized by Chinese scientists (*78-82*). Although the Yangtze Platform was affected by the early Permian and mid Triassic Dongwu-Indosinian movements, the Late Permian sequences are well preserved in this region and sequences are interpretable. The 29 third-order sequence boundaries identified in the composite Permian succession with following estimated ages: 297.5, 296.7, 295.8, 294.6, 293.2, 292, 291, 289.6, 288, 286.5, 284.4, 281.5, 278, 275.6, 273.5, 272, 270.5, 268.4, 267.5, 267, 266.5, 265.8, 263, 262, 260.4, 256, 253.8, 252.5 and 251.5 Ma. Much of Permian is also characterized by higher-frequency (4^{th}-order) cyclicity. The Permian-Triassic boundary fall at a transgressive surface dated at 251 Ma *(4, 5).* The next younger 3^{rd}-order cycle boundary occurs within the earliest Triassic at 249.5 Ma.

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Ancillary Sections:

In this section we list our choice of Ancillary Sections from around the world where the sequence boundaries identified in the RDs have been ascertained. Majority of the sequence boundaries identified in RDs are duplicated in the ancillary sections.

However, in some cases some boundaries are either unidentifiable due to lack of discernible hiatuses, or conversely, a few additional boundaries may be present in the ancillary sections that are not clearly identifiable in RDs. The relevant references that provide the background descriptions and biostratigraphic and paleoenviornmental data for these sections are listed in the numbered citations (*83-275*). Like the RDs, the age assignments are estimated based on the available biochronostratigraphic information.

Latest Proterozoic-Cambrian:

For the latest Proterozoic ancillary sections can be found in Oman *(83-85)* and on the Siberian Platform *(86-89)*. These sections show trends that are similar to the RD of Namibia, including the marked negative carbon isotopic shift at the P/C boundary. For the early Cambrian interval ancillary sections are identified on the Siberian Platform *(90-91)* where sequence boundaries are estimated at ~533, 528, 521, 518.8, 515.5, 514 and 511.5 Ma. In Estonia *(92-96)* we estimated the following ages for sequence boundaries exposed here: 533, 528, 521, and 518.8 Ma. In Scania, Sweden *(97, 98)* sequence boundaries can be placed at 533, 52, 518.8, 517.8 and 517 Ma. In Flinders Range of southern Australia *(99-102)* we can assign the identified sequence boundaries the following ages: 528, ~524, 521, 517, 515.5, 514 and 511.5 Ma. Yunnan Province in China *(103-106)* reveals sequence boundaries at 528, ~524, 521, 518.8 and ~517.8 Ma. The boundaries at 528, 524, 518.8 and 515.5 Ma can also be carried into northwestern Mongolia by shelly macro and microfossil correlations *(107).*

For the Middle and Late Cambrian interval the ancillary sections are located in western Utah *(108-111)*, with sequence boundaries estimated at 509, 507.5, 507, 506, ~504, 502, ~501, 499, 496, 494.2 , 491.2 and 489.4 Ma; in western Virginia and eastern Tennessee *(112-115)* with sequence boundaries identified at 507.5, ~507, 506, 504, 502, 501, 499 and 496 Ma; in southern California and southern Nevada *(116-118)* with sequence boundaries at 509, 508, 507.5, 499, 496, 495, 494.2, 491.2 and ~489.8 Ma); western Newfoundland *(119-120)* with sequence boundaries at 501, 499, 496 and 495 Ma); and Burke River, Australia *(121-125),* with sequence boundaries at 507.5, 506, 504, ~502, ~501, ~499, ~496, 491.2, and 489.8 Ma).

Ordovician:

Ancillary sections that document Early Ordovician sequence boundaries can be seen in Oklahoma *(126-131),* with sequence boundaries estimated at 488.3, 483.8, ~481, 477, 475, 473, ~471.8, ~471, 467, 464 Ma; in western Newfoundland *(132-140),* with sequence boundaries at 483.8, 477, 473 ~471, 467, and 464 Ma; in Estonia *(141-143),* with sequence boundaries at 483.8, 477, ~473, ~471, 467, 464 and 462.8 Ma); in Amadeus Basin in Australia *(144-146)* with sequence boundaries at 486.8, 483.8, 477, 473, 471.8, ~471, 467 and 464 Ma); and in West Texas *(147-150),* with sequence boundaries at 488.3, 483.8, 481, 477, 475, 473, and ~471 Ma. Goldhammer *et al. (150)* also described higher-frequency cycles within the Early Ordovician El Paso Group of West Texas.

For the Middle and Late Ordovician interval ancillary sections are located in the New York State *(151-153)*. Sequence boundaries are identified at 462.8, 461.8, 460.9, 458.2, 456.2, 455.5, 452 and 450 Ma. Additional ancillary sections are located in southern Sweden *(152-158),* with sequence boundaries picked at 462.8, 460.9, 456.2, 452, 450, 449, 445.7, 443.7 Ma; and Siberian Platform *(159-161),* with sequence boundaries at: 462.8, 460.9, 458.2, ~456.2, ~455.5, 452, ~450, 449, 445.7 Ma. Bohemia provides another area with ancillary sections and a nearly complete coverage of the Middle to Late Ordovician *(162-165).* Sequences are ascribed the following ages: 462.8, 461.8, 460.9, 458.2, 456.2, 455.5, 452, 450, 449, 445.7, and 443.7 Ma.

Silurian:

For the Silurian ancillary sections can be found in the Michigan Basin where a nearly complete Silurian is exposed *(166-172)*. The sequence boundaries are assigned the following ages: 443.7, 439, 436.8, 435, 432, ~430.5, 425, 423, 421, 420.5, 419, 417.5 and 415.5 Ma. Additional ancillary sections are found at the Welsh Borderlands and in Wales *(173-179).* Here sequence boundaries can be assigned the following estimated ages: 443.7, 439, 436.8, ~435, 432, ~429, ~427.5, 425, 423, 421, 420.5, 419, 417.5, and 415.5 Ma). In Yangtze Platform of China and southern China *(180-183)* Early to Middle Silurian sections are exposed and sequence boundaries can be placed at 443.7, 439, 436.8, 432, 429, 425 and ~423 Ma. The Mursuk and Ghadames Basins in Libya *(184, 185)* document deltaic sequences (bracketed by graptolite zones). Following sequence boundaries can be identified: 443.7, 439, 429, 423, 421, 420.5, 419, 417.5, and 415.5 Ma. On the island of Gotland, Sweden *(186-190)* mid to Late Ordovician sequence boundaries can be recognized at 429, 425, 423, 421, 420.5 and ~419 Ma.

Devonian:

Ancillary sections for the Devonian are located in eastern Iowa, Alberta and Williston Basins of North America, the Dinant Basin of Belgium, in the Czech Republic and in Ghadames Basin in Libya and Algeria. Descriptive and paleontological aspects of the sections in eastern Iowa have been presented by several stratigraphers *(191-199)*. The sequence boundaries in this area can be assigned the following ages: ~395, 393.3, 392.8, 390, 387.5, 386.2, 382, 377.6, 374.5, 367.5 and 365.7 Ma. In the Alberta Basin *(200-207)* the following sequence boundaries can be documented: 407, ~399.5, ~397.5, 395, 393.3, 392.8, 392.3, 391.6, 390, 387.5, 386.2, 384, 382, 380.8, 379, 376, 374.5, 372, 370, 365.7 and 361 Ma.

The Williston Basin *(208-211)* reveals sequence boundaries of the late Devonian at 393.3, 392.8, 390, 388.4, 386.2, 384, 382, 376, 374.5, 372, 370, 365.7 and 361 Ma.

The Dinant Basin *(212-216)* of Belgium reveals following sequence boundaries: 399.5, 397.5, ~395, ~392.8, 390, 386.2, 384, 382, 377.6, 376, 374.5, 372, 367.5, 365.7 and 361 Ma. In the Czech Republic a nearly complete Devonian is present, though all the sequence boundaries seen in the RD are not discernible *(217-221)*. Following boundaries are recorded: 415.5, ~410, 407, 406, 397.5, 392.8, 390, 386.2, 382, 380.8, 379, 377.6, 376, 374.5 and 372 Ma. Ghadames Basin sections exposed in Libya and Algeria *(222, 223)* show sequence boundaries at: 397.5, 392.8, 390, 387.5, 386.2, 382, 377.6, 374.5, 372, 367.5, 365.7 and 361 Ma.

Mississippian:

Ancillary sections for the Mississippian include the Dinant Basin *(224-226)* where a substantial part of the Early Carboniferous is exposed. Here sequence boundaries can be interpreted at 353.3, 351, 348.5, 345.7, 343, 339.2, ~332.8, 329.4, ~327.4 and ~326.4 Ma. In the Moscow Basin in Russia *(227-231)* a nearly complete Early Carboniferous is exposed with sequence boundaries that can be assigned estimated ages at 353.3, 351, 348.5, 343, 339.2, 332.8, 329.4, ~327.4, 326.6, 323, and 321.7 Ma. The Upper Mississippi Valley sections *(231-237)* also record the earlier part of the Mississippian. Here sequence boundaries at 353.3, 351, 348.5, 343, 339.2, 332.8, ~331, 329.4 Ma can be picked on the southwestern Iowan shelf. Ancillary sections in southern West Virginia *(238-241)* reveal sequence boundaries of the earlier Mississippian at: 359.2, 353.3, 351, ~345.7, 339.2, 332.8, 329.4, ~327.4, 326.6, ~323 and 321.7 Ma.

Pennsylvanian:

The Donetz Basin on the Russian Platform *(242-244)* reveals sections that form appropriate ancillary sections for the Pennsylvanian. Here numerous higher-frequency cycles are represented in mixed carbonate-clastic sections. All of the Pennsylvanian third-order sequences seen in the RD (from 313.3 through 299 Ma) may be represented, but it is difficult to distinguish them from the fourth-order higher frequency sequences. The Arkoma and Anadarko Basins of mid continental North America *(245-253)* reveal higher-frequency sequences ranging in age from 311.3 through 299 Ma. The late Pennsylvanian sections in North Central Texas *(254-261)* also reveal higher-frequency cycles. Third-order sequence boundaries can be placed at 306.7, 303.5, 300.5 and 299 Ma. This record *(64, 262)* reveals ~ 25 higher frequency cycles within a period of 10 m.y., pointing to an average of 400 k.y. periodicity within this interval.

Permian:

Sections in North Central Texas cover lower three-quarters of the Permian record *(263-266)* and most of the third-order sequence boundaries identified in the RD of West Texas (up to the 265.8 Ma) can also picked here, though dating is less precise. The ancillary section in southern Urals in Russia *(231, 267-272)* reveal the third-order sequence boundaries at 299, 294.6, ~289.6, 284.4, 273.5, 270.6 and 268.4 Ma. Some of the higher frequency cycles may also be present here. Western European ancillary sections in the Netherlands, North Sea and northeastern England *(231, 273-275)* reveal many of the sequence boundaries of the younger Permian (between 267 and 260.4 Ma) that can be correlated with the RD.

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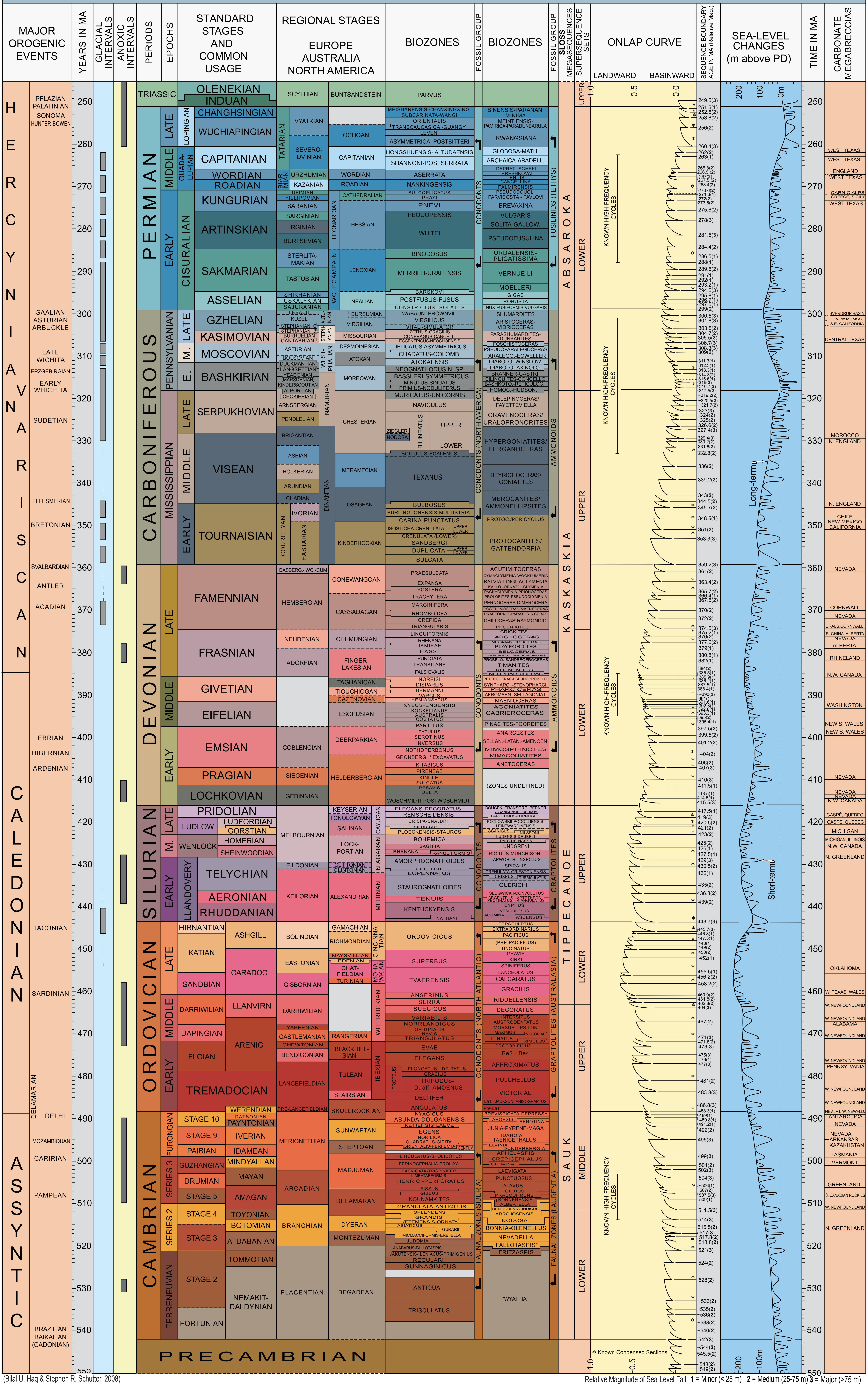
Figure Caption:

A Chronology of Paleozoic Sea-Level Changes: A complete colored version of the Cycle Chart is included here. The left half of cycle chart shows the stratigraphic subdivisions (Periods, Epochs, Standard Stages) calibrated to the absolute time scale, which has been adopted from GTS2004 (together with the 2008 updates, text references *4, 5*). Major orogenic events and known intervals of continental glaciation and oceanic anoxia are indicated in columns to the left of the numerical time scale. Regional stratigraphic subdivisions from Europe, North America and Australia are included as space allows alongside the standard nomenclature. The regional stratigraphic subdivisions are followed by the biozonations that are most relevant for the particular time interval. The right half of cycle chart starts with the sequence nomenclature (Megasequences and Supersequence sets after Sloss, text ref. *36)* followed by an onlap curve which is a measure of relative landward or basinward movement of regional baseline. Asterisks in this column indicate sequences associated with known prominent condensed sections. The biochronological ages of the sequence boundaries, as estimated in the RDs are indicated in the next column. The relative magnitude of each short-term event (or group of events) is also indicated in parentheses following the ages of the sequence boundaries [Minor = **1** (> 25 m); Medium= **2** (25-75 m); Major = **3** (< 75 m)]. This is followed to the right by the sea-level curves, showing both the long-term envelope and the short-term curve of (third-order) sea-level fluctuations (those suspected to be of fourth-order are shown as dashed lines). The vertical dashed line in this column represents an approximation of the present day sea level. The last column of the chart contains the known Megabreccia events as they have been synthesized from the worldwide data. These tend to occur in the carbonate systems at major draw downs of sea level.

A CHRONOLOGY OF PALEOZOIC SEA-LEVEL CHANGES



(Bilal U. Haq & Stephen R. Schutter, 2008)

Relative Magnitude of Sea-Level Fall: **1** = Minor (< 25 m) **2** = Medium (25-75 m) **3** = Major (>75 m)