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Eustasy and Chrono-correlations: Facts and Theories with Examples from the Ordovician

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Article abstract

During the past 15 years a very rapidly increasing general interest in eustasy and its causes and, in particular, highly detailed chrono-correlations utilizing the Phanerozoic sea-level curves compiled by Peter Vail and coworkers at Exxon have resulted in a large number of publications, including several using presumed Ordovician eustatic events for chrono-correlations. However, facts and theory argue against the possibility of recognizing synchronous sea-level fluctuations in a set of widely separated stratigraphie sections (see also Paleoscene 16: Miall, 1994). There are simply too many factors influencing the shape of the ocean geoid, the recording of sea-level changes on the margins of continents, and fossil and/or radiometrically based time constraints. These factors make it impossible to identify and discriminate individual eustatic events with the precision necessary for detailed high-resolution chrono-correlations in pre-Tertiary successions. Instead, fossils and radiometric data remain the decisive tools for detailed regional and worldwide chrono-correlations.

Eustasy and Chrono-correlations: Facts and Theories with Examples from the Ordovician

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SUMMARY

During the past 15 years a very rapidly increasing general interest in eustasy and its causes and, in particular, highly detailed chrono-correlations utilizing the Phanerozoic sea-level curves compiled by Peter Vail and coworkers at Exxon have resulted in a large number of publications, including several using presumed Ordovician eustatic events for chrono-correlations. However, facts and theory argue against the possibility of recognizing synchronous sea-level fluctuations in a set of widely separated stratigraphic sections (see also Paleoscene 16: Miall, 1994). There are simply too many factors influencing the shape of the ocean geoid, the recording of sea-level changes on the margins of continents, and fossil and/or radiometrically based time constraints. These factors make it impossible to identify and discriminate individual eustatic events with the precision necessary for detailed high-resolution chrono-correlations in pre-Tertiary successions. Instead, fossils and radiometric data remain the decisive tools for detailed regional and worldwide chrono-correlations.

RÉSUMÉ

Au cours des 15 dernières années, un intérêt croissant s'est manifesté pour les questions touchant l'eustasie et ses causes, et en particulier pour des corrélations chronologiques très détaillées basées sur les courbes des niveaux océaniques phanérozoïques compilées par Peter Vail et ses collègues de la société Exxon. De nombreuses publications sont parues sur ce sujet, dont plusieurs se basent sur de présumés événements eustatiques ordoviciens pour établir des corrélations chronologiques. Cependant, faits et principes permettent pas de reconnaître l'existence de fluctuations océaniques synchrones au sein de séquences stratigraphiques très distantes (voir aussi Paleoscene 16: Miall, 1994). Il existe simplement beaucoup trop de facteurs qui agissent sur la forme du géoïde océanique, sur la préservation des marques de changements du niveau des mers sur les marges des continents, ainsi que sur la préservation des marqueurs chronologiques que sont les fossiles biologiques ou radiométriques. Ces facteurs rendent impossible l'identification et l'isolement d'événements eustatiques particuliers, avec la précision nécessaire permettant d'établir des corrélations chronostratigraphiques détaillées dans des séquences pré-tertiaires. Les données des fossiles biologiques et radiométriques demeurent plutôt les outiles fondamentaux dans l'établissement de corrélations chronologiques mondiales et régionales détaillées.

INTRODUCTION

Bandwagons of science can be dangerous vehicles of scientific pursuit, proof, and promotion; too often they tend to gather an ever-increasing momentum of their own. Two such bandwagons are presently making tracks on the charts of Ordovician chrono-stratigraphy and worldwide chrono-correlations. One, which is just beginning to gather momentum, is the method of graphic correlation (*e.g.*, Sweet, 1984; Cooper, 1992). Cooper (1992, p. 15) resolves the duration of the Australasian graptolite zones of the Bendigonian and the Yapeenian to about 250,000 years (250 k.y.) each, solely on the basis of net rock thicknesses. I have, elsewhere, discussed the virtual impossibility of accurately identifying and correlating zones of such duration in Ordovician strata; the margins of error are wider than the correlated interval of time (Fåhræus, 1986; see also below).

The second bandwagon is the attempt to capitalize on presumed synchronous, worldwide, (glacio-)eustatic sea-level events in the Ordovician for high-resolution chrono-correlations. From a cautious start by Fortey (1984), Barnes (1984) and Erdtmann (1986), who recognized four to five apparently eustatic events for the interval Tremadocian through Llanvirnian, Nielsen (1992b, p. 368, fig. 1) has recognized 25 such events taking place at times of surmised high or low (and everything in between) sea-level stands for the Arenigian alone. Nielsen (1992a, b) recognized these variations in sea-level stand and eustatic events on a worldwide basis and submitted highly detailed and precise correlations between his proposed sea-level curve and Arenigian graptolite, conodont and trilobite zonations from Scandinavia (particularly Skåne in Sweden and Bornholm in Denmark) through Australia (Amadeus Basin and Victoria), Spitsbergen, western Newfoundland, Utah (Ibex area), and Wales. In Nielsen's correlation chart (1992b, p. 368), some of the zonal correlations have a resolution finer than 50 k.y., while the resolution of the interval from one eustatic event to another in some cases is finer than 250 k.y. These proposed resolutions exceed biostratigraphically identifiable events in the Ordovician by one to two orders of magnitude.

Nielsen's papers (1992a, b) are published in proceedings of the *6th International Symposium on the Ordovician System* (Webby and Laurie, 1992), which also includes nine other contributions explicitly dealing with Ordovician eustatic events and chrono-correlations. Is it possible to subdivide Ordovician time as finely as Nielsen (1992a, b) proposed based on chrono-correlations of eustatic events? To answer this question, it is necessary to consider in some detail those factors that control sea level, the sedimentary record of sea-level change, and the ability of stratigraphers to precisely date these changes. These topics are treated briefly in the next sections of this paper (see Miall, 1994, for a perceptive and more extended analysis of this topic). I return to the particular problem of Ordovician chrono-correlations later in the paper.

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EUSTATIC *VERSUS* RELATIVE SEA-LEVEL CHANGE

Definitions, Quaternary Data, and Controlling Factors

The concept of eustatic or worldwide synchronous sea-level changes was first introduced by Suess (1906). This idea provided kindling for some classic works (*e.g.*, Stille, 1924; Umbgrove, 1942), but was not widely applied until Vail *et al.* (1977) caused a "...revolution in stratigraphic thinking" (Miall, 1986). This "revolution" has resulted in literally thousands of publications; during the year 1990, for example, approximately 1200 contributions dealing with sea-level changes were published (Osleger, 1993).

Eustatic and relative sea-level change are two related but often confused concepts. Eustatic sea-level change refers to change in the vertical position of the sea surface, measured with respect to some fixed datum. Relative sea-level change refers to change in the vertical separation between the sea surface and the seabed. All measurements of sea-level change, whether by direct observation of tide gauges, indirect inferences from the sedimentary record, or any other means, are measurements of relative sea-level change. Inference of eustatic change from such measurements implicitly assumes a knowledge of how the seabed has moved vertically as a consequence of tectonic and/or isostatic processes. Pirazzoli (1993, p. 137) concluded that there now exist enough data to conclude that "...no coastal region of the Earth can be considered as having been stable during the past 10,000 years, or even during the last century." Certainly the range of relative sea-level values shown in Figure 1 supports this argument (see Pirazzoli *et al.*, 1989). If valid, this conclusion argues against being able to isolate a eustatic sea-level curve from observational data of relative sea-level change. The main cause of the inconsistent sea-level histories shown in Figure 1 is the fact that the tide gauges on continents and ocean islands are not static, but are involved in their own vertical movements. The combined effect of these movements, which are induced by some combination of continental-margin subsidence, tectonism, epeirogeny and glacio-isostatic re-adjustments, is unpredictable in detail and cannot be filtered from any underlying global signal of truly eustatic sea-level change.

Setting aside this practical problem, there are significant theoretical objections to the concept of world-wide, globally uniform, and synchronous eustatic sea-level changes. This concept is, nevertheless, implicit in the sequence stratigraphic approach of Vail *et al.* (1977) and, by extension, in the use of sequence stratigraphy for chrono-stratigraphic correlations. The fundamental reason that eustatic sea-level variations cannot be globally uniform lies in the definition of the geoid and the factors that affect it.

The shape of the sea surface, with short-term effects such as winds and tides averaged out, defines the geoid, a surface on which all points have the same gravitational potential energy. This potential energy is produced by the combined effects of centrifugal acceleration due to the Earth's rotation, and gravitational attraction between sea water and other mass on and within the Earth. Any factors that redistribute mass on or within the Earth will modify the Earth's gravitational field and so change the sea-surface geoid. Unless this mass redistribution is spatially uniform over the Earth, the sea-surface geoid cannot rise or fall by the same amount at all points throughout the world's oceans.

Formation and ablation of continental ice sheets involves transfer of water mass between the ocean basins and the surface of continents, and transfer of mantle material as a consequence of isostatic adjustment to these changing surface loads. This mass redistribution is non-uniform because the spatial distribution of ice sheets is non-uniform. Farrell and Clark (1976) and Clark *et al.* (1978) have discussed geoid change expected from melting of Wisconsinan ice sheets, and have shown that post-glacial eustatic sea-level change differs in both magnitude and algebraic sign for different locations around the globe. The physical principles controlling these variations are, of course, equally valid for all glaciations throughout Earth history. Thus, it would seem that continental glaciations (*e.g.*, the Ordovician glaciations) produce conditions incompatible with world-wide, globally uniform, and synchronous eustatic sea-level changes.

The present-day geoid, as determined by satellite measurements, varies significantly over the globe, with more than 180 m of vertical separation between the lowest point south of India

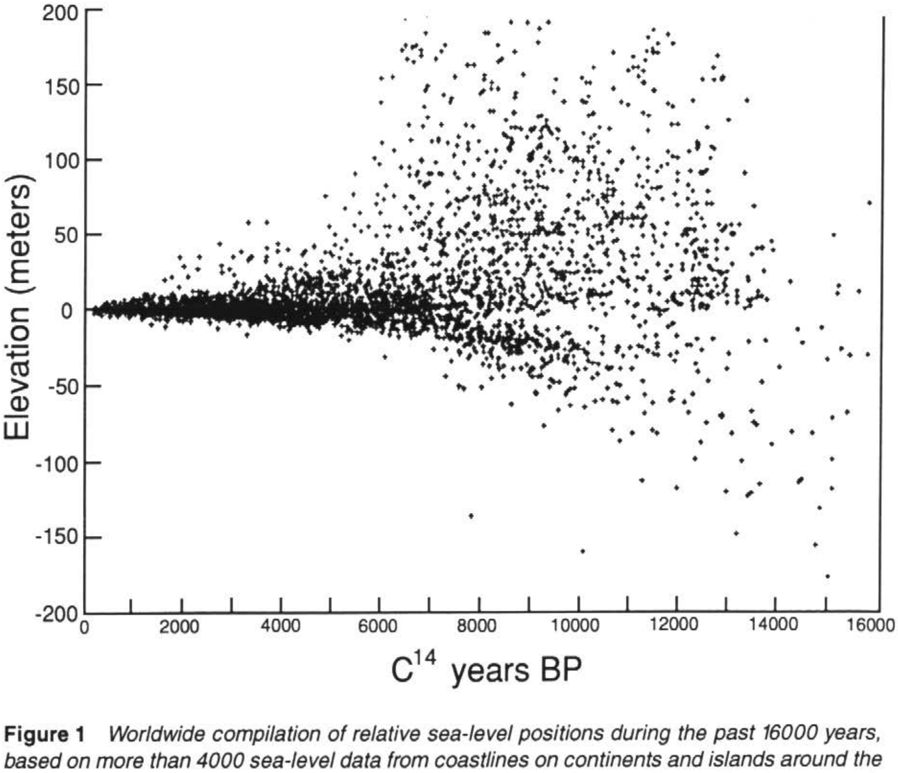

Figure 1 *Worldwide compilation of relative sea-level positions during the past 16000 years, based on more than 4000 sea-level data from coastlines on continents and islands around the world, compiled by W.S. Newman (presented in Pirazzoli* et al., *1989, fig. 3). Sea-level records rapidly fan out over time to reach a high of 235 m above, and a low of 180 m below, present-day local sea levels.*

and the highest point north of Australia (Fowler, 1990). This variation is due largely to non-uniformity in the Earth's internal mass distribution, a condition likely associated with mantle convection and motions of lithospheric plates (Mitrovica and Peltier, 1989). It is reasonable to assume that past plate configurations were accompanied by different patterns of mantle convection and plate boundaries, by different distributions of mass within the planet, and so by different geoid topography. For this reason, global tectonic processes are also incompatible with world-wide, globally uniform, and synchronous eustatic sea-level changes. The following sections discuss situations in which non-uniform sea-level change is even associated with what are generally believed to be "stable" tectonic settings.

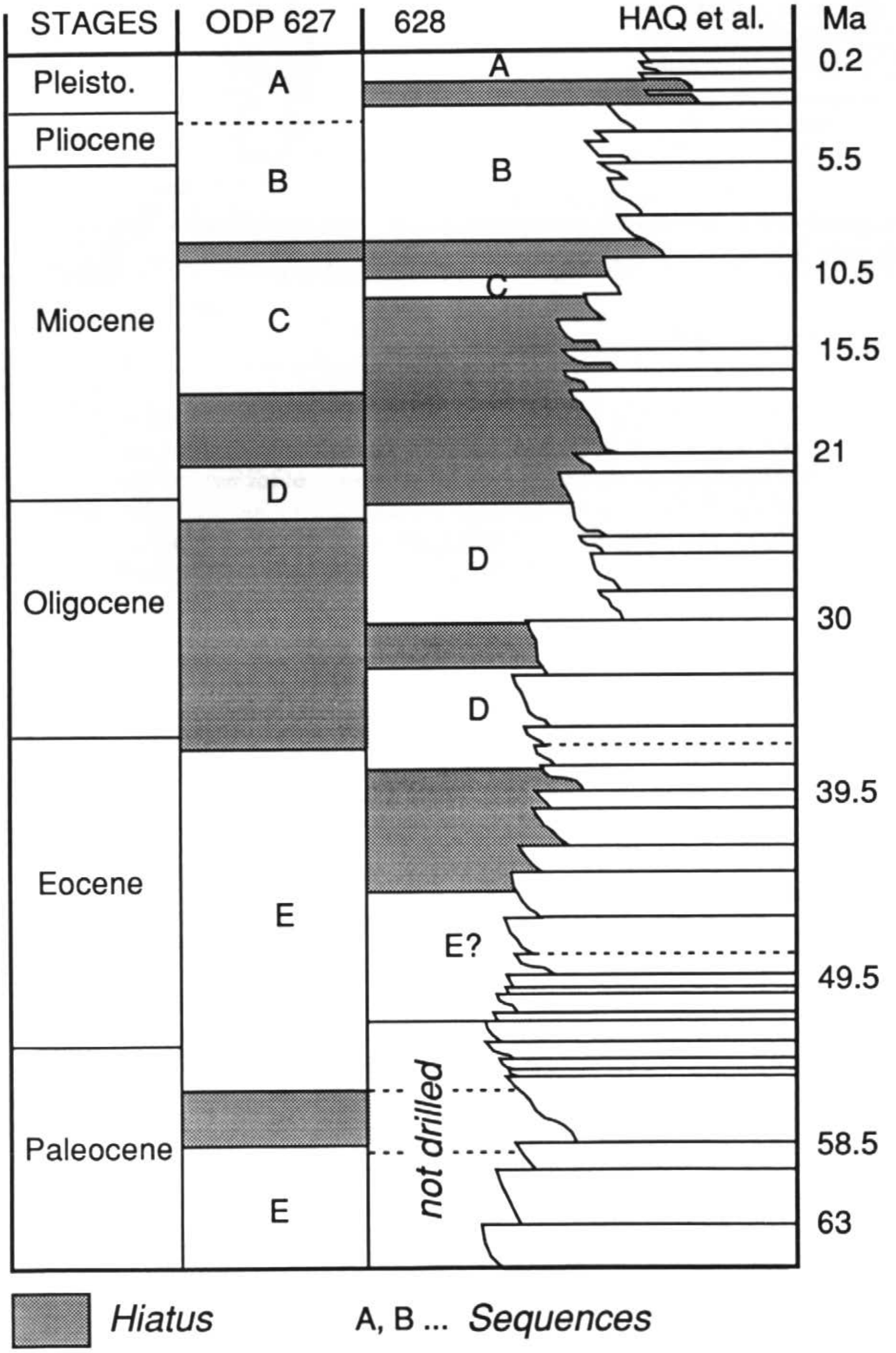

Figure 2 *Correlation of drill-cores from DSDP Sites 627 and 628 on the Blake Plateau with the onlap curve of Haq* et al. *(1987). After Schlager (1993).*

Epeirogeny

Epeirogeny refers to widespread elevation changes of a large part or all of a continent. It has recently been convincingly argued by Galer (1991) that the most effective mechanism driving epeirogeny is the potential temperature of the asthenospheric mantle, with a temperature increase raising the continent(s), and a temperature decrease allowing the continent(s) to sink to a deeper equilibrium level. Assuming that the temperature variation of the asthenosphere is not uniform, continents may rise, sink and tilt independently of each other. As a result, different continents have different hypsography (Harrison *et al.*, 1981) and, therefore, different relative sea-level histories.

Widespread elevation changes that extend well into plate interiors may also result from changing intraplate stresses, with areas under compression experiencing uplift and areas under extension experiencing subsidence (Cloetingh, 1986). The frequency of these stress changes can mimic the frequency of high-order sea-level changes.

Passive Margins

The margin of a continent registers transgressions and regressions as shifts in sedimentary facies, with periods of subaerial exposure resulting in erosion and down-cutting. On a tectonically stable margin, such sedimentary features would give a true record of eustatic sea-level changes. However, there are no truly stable margins. For example, the "passive" margin of North America between Florida and Maine has, during the past 18,000 years, tilted down to the north by 140 metres, opposite to the expected result for glacio-isostatic rebound (Officer and Drake, 1981).

The sedimentary sequences of passive margins often display recurrent patterns and geometries, a circumstance that has given rise to the popular approach to stratigraphy called "sequence stratigraphy." "A depositional sequence is a stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities" (Vail *et al.*, 1977, p. 53) and "sequence stratigraphic analysis divides the stratigraphic sequences into physical *chronostratigraphic units* in which the lithofacies are genetically related" (Vail *et al.*, 1991, p. 619, my emphasis).

Vail *et al.* (1977, 1991) and many others (*e.g.*, Posamentier and Vail, 1988; van Wagoner *et al.*, 1990; Posamentier and Allen, 1993) consider cyclic sea-level changes to be the most important factor causing the transgression and regression patterns observed in these depositional sequences; sediment supply, basin subsidence and tectonism are considered to be of secondary importance.

The central thesis of Vail and coworkers is that superimposed cycles of variable length, presumably caused by worldwide sea-level changes, can be recognized in seismic profiles. Vail *et al.* (1991) defined these cycles to have the following durations: first-order cycles= 50+ million years (m.y.); second-order cycles=3-50 m.y.; third-order cycles= 0.5-3 m.y.; fourth-order cycles=0.080.5 m.y.; fifth-order cycles=0.03-0.08 m.y., and sixth-order cycles=0.01-0.03 m.y. The sea-level curve of Vail *et al.* (1977) was based on recognition of coastal onlap (transgression) and downlap (regression) cycles from seismic records obtained from different regions, *i.e.*, it is a composite with compromises (Summerhayes, 1986).

There are two serious problems with unreservedly equating transgressive and regressive sedimentary sequences with sea-level changes. First, it assumes that basin subsidence keeps pace with increase or decrease in sediment load, and second, that the shifts in facies and intermittent subaerial exposure are solely a function of changes in sea level. Neither of these assumptions is necessarily true. For example, if basin subsidence exceeds sediment input, the record will show a transgressive sequence, whereas it will show a regressive sequence if the reverse is true. More fundamentally, transgression and regression patterns in the sedimentary record are the result of an interplay between 1) sea-level changes, local and eustatic; 2) sediment supply, dispersal and removal; and 3) the tectonic history of the basin and its hinterland (*e.g.*, Grabau 1924; Miall, 1991; Swift and Thorne, 1991; Schlager, 1991, 1993).

Pitman (1978) has shown that the strand-line position on a "passive" margin may shift following alterations in the rates of sea-level fall or rise such that if the rate of sea-level fall slows down, the shoreline will actually move landward (*i.e.*, transgression); if the rate of sea-level fall increases, it will move seaward. Conversely, if the rate of sea-level rise increases, the shoreline will move landward, but if it is slowed down, the shoreline will migrate seaward (*i.e.*, a regression). This is so because the shoreline position "...tends to stabilize at that point on a margin where the rate of rise (or fall) of sealevel is equal to the difference between the rate of subsidence of the platform and the rate of sediment infill" (Pitman, 1978, p. 1389). The caveat in Pitman's argument is that sea-level rise or fall does not exceed rate of platform subsidence, hence changes in shoreline position caused by sea-level changes associated with major glaciations and deglaciations or major local tectonism are excluded from his shoreline displacement argument.

BIOSTRATIGRAPHIC RESOLUTION AND CORRELATION OF GLOBAL STRATIGRAPHIC EVENTS

The Hiatus Problem

All sedimentary sequences include hiatuses that are due to non-deposition and erosion (including dissolution) caused by variations in sediment supply, currents and wave activity, sea-level oscillations, and sea-water chemistry. Nearshore deposits contain more hiatuses than pelagic strata owing to higher sensitivity in shallow water to local and eustatic sea-level changes, climatic influence, variations in sediment supply, storms and current activity (especially long-shore and tidal currents). Even pelagic sediments, however, contain many hiatuses. Moore *et al.* (1978) have summarized and statistically treated Deep Sea Drilling Project (DSDP) data for Cenozoic hiatuses in pelagic sediments. Their data show that: 1) there is a general increase in hiatus frequency with increasing age of the sediments, and 2) the worldwide continental configuration (governing the routes of major bottom currents) is highly correlated with hiatus frequency. Maxima in numbers of hiatuses coincide with major global tectonic events related to continental separation and opening of major water passages (Moore *et al.*, 1978, p. 132-133).

Figure 2 shows the hemipelagic sedimentary record from two DSDP localities 11 km apart (Sites 627 and 628) on the Blake Plateau off the southeast United States. It shows the irregular distribution and duration of the hiatuses in the individual drill core records and the poor correlation of the preserved sediments with the sea-level curve of Haq *et al.* (1987). The variations are thought to have been caused by local variations in the Gulf Stream that sweeps the Blake Plateau (Austin *et al.*, 1988; Schlager, 1993).

Hiatuses generally increase in duration and abundance the greater the geologic age of the deposit (*e.g.*, Barrell, 1917; Sadler, 1981; Fåhræus, 1986). "The older the sediments are, the thinner is the accumulated rock sequence for any given interval of time" and "...the longer the interval of time is, the thinner (relatively) is the sequence" (Fåhræus, 1986, p. 153). This observation has obvious consequences for the resolution and precision of dating and correlating events, zones and boundaries in old rocks (see below).

The Problem of Biostratigraphic Dating and Resolution

Simple probability tells us that first and last occurrence of a fossil in a sedimentary sequence is a matter of chance determined by paleoecology, taphonomy and net rock accumulation (not to mention the good luck of the interested paleontologist!) (Fåhræus, 1986). Remembering the observed decrease in rock accumulation rate with increasing age, it should be clear that the older the strata, the more pronounced is the "...inverse relationship between biostratigraphic resolution and precision of (fossil-based) chrono-correlations" (Fåhræus, 1986, p. 151). Consequently, there is a pragmatic limit to the fineness of the biostratigraphic resolution that can be obtained in a study proposing chrono-correlations. This limit is principally determined by the age of the sediment and the thickness of the recognized biostratigraphic units, *e.g.*, conodont or graptolite zones and their boundaries. I have elsewhere discussed this problem at some length (Fåhræus, 1986; see also Fåhræus, 1982, 1994, and Fåhræus and Hunter, 1981). In this paper, I will only stress the paleoecological constraints on chrono-correlations.

The fact that the time range of a fossil organism, as represented in the rock record, always represents a range that is less than the actual lifespan of the particular fossil species is not always appreciated in chrono-correlations based on fossil organisms. A fossil species found in a sedimentary section is there because of a number of factors, but the primary determinants are ecological parameters, *e.g.*, water salinity, temperature, turbulence and depth, grain size and lithology of bottom sediment, and food supply. A species will inhabit a particular area as long as the ecology is suitable. In addition to the ecological parameters, the worldwide distribution of a species depends upon its dispersal possibilities (*i.e.*, method of reproduction, physiology, mobility and availability of migration routes). When the ecological parameters change beyond the adaptive capacity of the species it will either migrate or become extinct. If the changes are temporally as well as spatially gradual, the species will follow the "migration" of its habitat, *e.g.*, in connection with transgressions and regressions, climatic changes, *etc.*

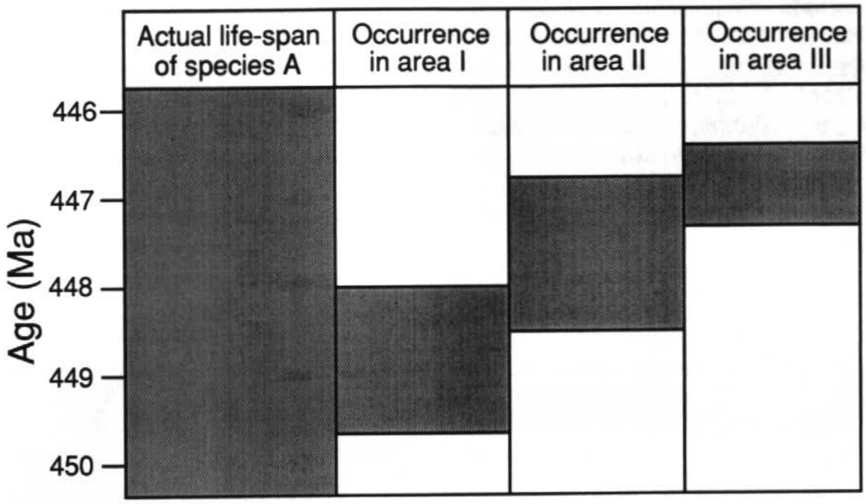

Figure 3 *Actual lifespan and local stratigraphic distribution of a fossil species. See text for further explanation.*

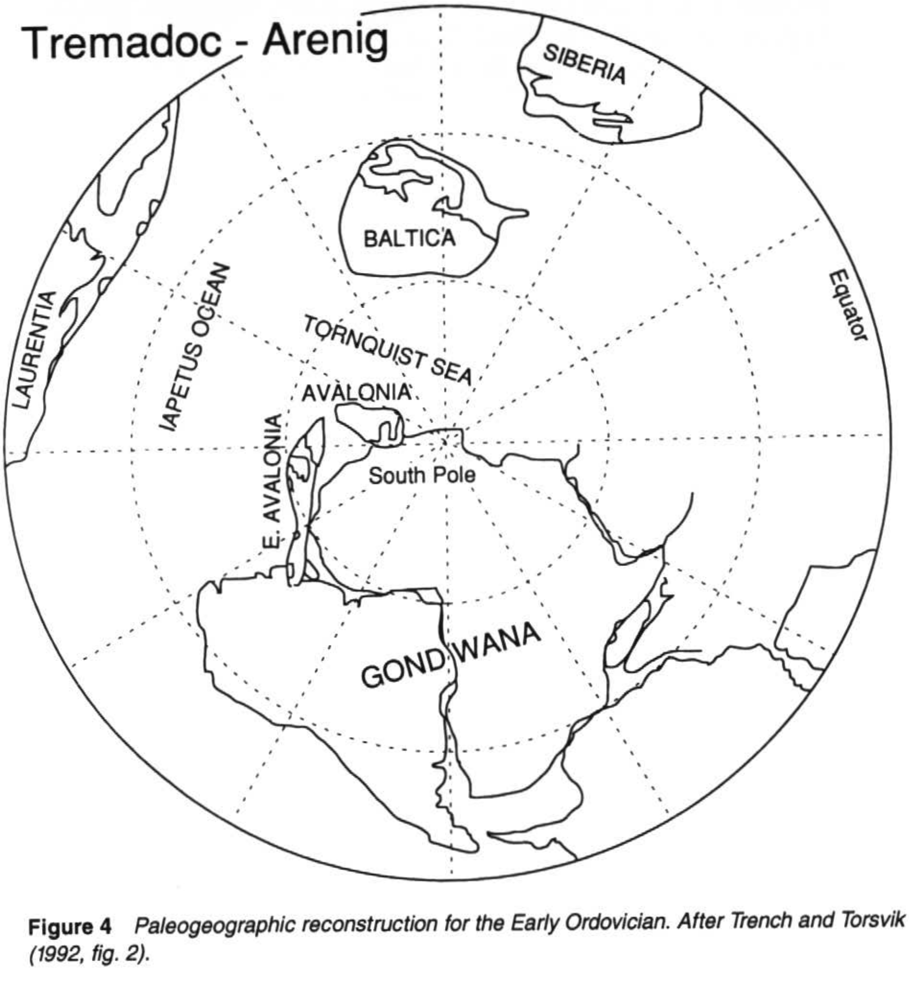

Figure 4 *Paleogeographic reconstruction for the Early Ordovician. After Trench and Torsvik (1992, fig. 2).*

The limiting factor in all chrono-correlations based on fossils — particularly when using range zones — is the actual life span of the fossil taxa employed. The consequences of this simple fact are illustrated in Figure 3, which shows the actual life span of species A and its immigration and emigration into and from areas I, II and III (for a more complicated and detailed investigation of this problem see Fåhræus, 1986). From this figure we can conclude that: 1) the actual resolution of the range zone of species A approaches 4 m.y.; 2) occurrences in areas I and III do not even overlap in time, but are separated by 0.5 m.y.; 3) the occurrence in area II is the longest, but is negatively diachronous with the upper range in area III by 0.5 m.y. and is 1 m.y. positively diachronous with the first occurrence of species A in area I; and 4) in area III, which is the type area for the species, the range is the shortest, only 1 m.y., and includes the youngest occurrence. A particularly significant rule of thumb can be extracted from this example concerning the biostratigraphic resolution of chronocorrelations between sections that contain only a partial record of the full range of critical fossils: if the resolution claimed for a correlation is finer than the likely life span(s) of the critical fossil species, and particularly if the character (or age) of the sediment suggests the possibility of a high frequency of hiatuses, then such a fine resolution is probably unjustified.

PROBLEMS WITH ORDOVICIAN CHRONO-CORRELATIONS THAT RELY ON ANALOGY WITH QUATERNARY GLACIO-EUSTATIC CYCLES

As for the Quaternary, Ordovician sea-level fluctuations (and associated steep climatic gradients) have most commonly been ascribed to glaciations and deglaciations (*e.g.*, Spjeldnæs, 1961, 1981; Erdtmann, 1986; Fortey, 1984, Jaanusson, 1984). Direct physical evidence only exists for the Ashgillian and earliest Llandoverian glaciation of Gondwana. There are corroborating paleontologic, sedimentologic and isotopic indicators of a pronounced climatic gradient, with a cold south paleopole (Fig. 4) from at least the Arenigian (*e.g.*, Jaanusson, 1979; Spjeldnæs, 1981). The time from initiation to maximum extent for the Cenozoic Antarctic ice cap (38 m.y., Flohn, 1984, p. 610, with pertinent references) is similar to the combined duration of the Tremadocian and Arenigian (using the 34 m.y. estimate of Harland *et al.*, 1990), whereas the Cenozoic northern hemisphere ice cap has waxed and waned through four very major glaciations in a time period spanning less than two Arenigian graptolite zones.

A major difference between the preserved Ordovician record and the Quaternary marine record is greater completeness of the Quaternary successions. For example, the Ordovician of Sweden is represented by a maximum of about 200 m of mainly carbonate strata, and less at many localities. Parts of this succession are considered to be "complete" (*e.g.*, Jaanusson, 1972). However, given a duration for the Ordovician of 70 m.y. (Harland *et al.*, 1990) , the average rate of rock accumulation is about 3 mm·1000a^{-1}. When compared to the high rates of carbonate sedimentation on modern shelves (*e.g.*, Milliman, 1974), an unavoidable conclusion is that the Swedish Ordovician succession must be full of hiatuses. Nevertheless, given that the successions of Swedish conodont and graptolite zones can be recognized and correlated on a worldwide basis, it has been assumed that the time involved in any of the hiatuses is shorter than the duration of any of the biozones.

The probable glacial control on Ordovician sea level has induced many authors to advocate very detailed chrono-correlations like those that have been applied to Quaternary successions. For example, evidence for *Milankovitch* forcing of sedimentary periodicity in the Ordovician has recently been claimed by Read and Goldhammer (1988) for Lower Ordovician peritidal cyclic carbonates in the Appalachians where they recognized fourth- and fifth-order cycles with durations of approximately 20 k.y. and 100 k.y., respectively (see Arthur and Garrison, 1986, for background on *Milankovitch cyclicity*). Ross and Ross (1992) have proposed Ordovician chrono-correlations, based on sequence stratigraphy, across the North American continent, from north to south and east to west. They also extended these correlations to the Welsh Basin and Estonia. In addition to the fourth- and fifth-order cycles, Ross and Ross (1992) also claim to recognize third-order cycles with durations of 1-8 m.y. and second-order patterns (their term) with durations of 5-8 m.y.

Lindström (1986) has argued that the average time resolution of stratigraphic dating in the Ordovician (whether radiometric or fossil-based interpolations) probably is not much better than 3.5 m.y. (see also Fåhræus, 1986). Many Ordovician fossil zones have a resolution much better than 3.5 m.y, but because of ecological factors this is of no advantage when determining the age of an horizon in two or more sections (Fig. 3).

The longest *Milankovitch* frequency generally recognized is 800 k.y. (Read and Goldhammer, 1988), much shorter than the best biostratigraphic resolution in the Ordovician of approximately 3.5 m.y. Hence, the recognition of *Milankovitch* cycles in two or more sedimentary sequences of Ordovician age is of no aid when attempting long distance correlations because visually acceptable matches can be made between cycle sets that actually have different age, because such small age differences cannot be distinguished using fossils. Undetected hiatuses would make chrono-correlation based on perceived matches of inferred *Milankovitch* cycles even more dangerous.

DISCUSSION

W.S. Newman's graph (Fig. 1) and Pirazzoli's disheartening conclusion (1993, p. 137) that "...no coastal region of the Earth can be considered as having been vertically stable during the past 10,000 years, or even during the last century" decisively illustrate the difficulties involved when trying to decipher the Holocene sea-level record on the basis of the geologic record. Most of the differences between local sea-level records stem from the fact that the geoid is represented by an equipotential surface with a topography governed by changing gravity relationships, some induced by ice loading. For stratigraphers, this means that a eustatic "event" resulting in a transgressive sequence in one area can coincide with a regressive sequence in another area and no discernable sequence change in a third area. With regard to Galer's (1991) convincing argument for the cause of epeirogenic movements, and assuming that the heat distribution and its variations in the asthenosphere are not uniform (distribution of hot spots alone argues against such a possibility), it follows that continents *must* rise, sink, and tilt independently of each other, *i.e.*, "eustatic" markers should not be expected to correlate from one continent to another. Similar conclusions have been reached by Summerhayes (1986), Miall (1986, 1991, 1992, 1994), Christie-Blick *et al.*, (1990), Emery and Aubrey (1991), Schlager (1993), and Pirazzoli (1993).

Certainly the Ordovician geoid shape is unknown. Further, in such old successions there is the added complication that coarse biostratigraphic resolution makes it essentially impossible to correlate inferred sea-level events across and between continents without recourse to circular reasoning. Without reliable chrono-correlation, there is no firm basis for deciding that local (and therefore relative) sea-level events record global changes rather than a local interplay of subsidence, sediment supply and tectonics (including intra-plate stress changes).

The cycles recognized by Nielsen (1992a, b) and others, on a worldwide basis, are believed to be nothing more than clusters, in time, of local and eustatic sea-level events that cannot be dated at a finer resolution than 3.5 m.y. at best. What these authors claim to be able to resolve is impossible in terms of worldwide sea-level oscillations, general passive-margin sedimentation and tectonism, intra- and inter-plate tectonism, completeness of the Ordovician successions, and fossil and radiometrically based time constraints, irrespective of whether it is done with Ordovician or Holocene strata.

In conclusion, recognition of presumed eustatic transgressive-regressive events, and their clustering in time, during the course of the Ordovician Period certainly has its own scientific interest and merit, particularly when clarifying the geologic histories of specific areas. However, for purposes of detailed regional and worldwide high-resolution chrono-correlations, fossils and radiometric data are the decisive tools. To involve assumed eustatic events in such correlations only lends a spurious cloak of precision to the fossil and/or radiometric data, leading to a high probability of erroneous conclusions and the possibility of perpetuation of error.

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