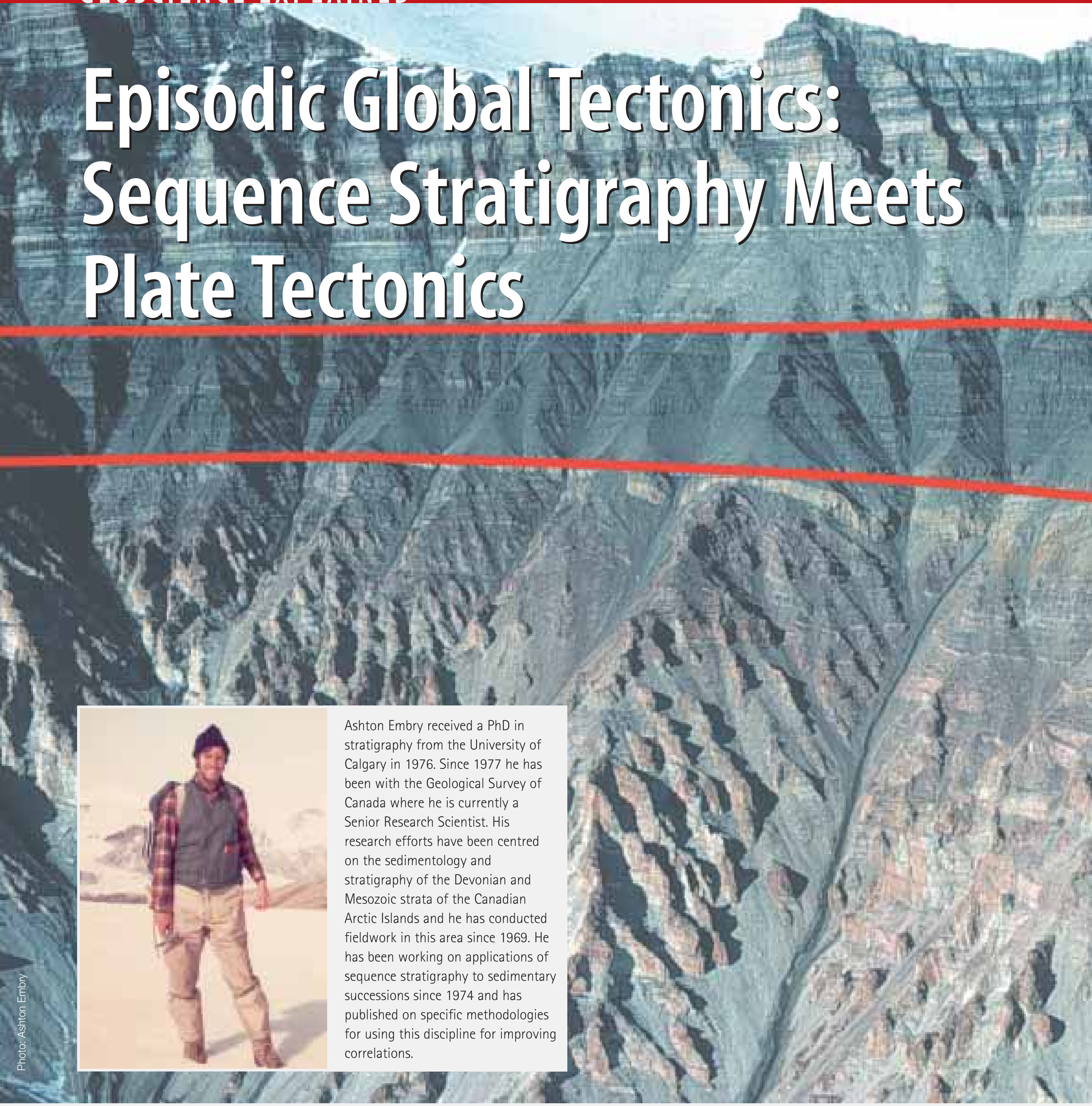
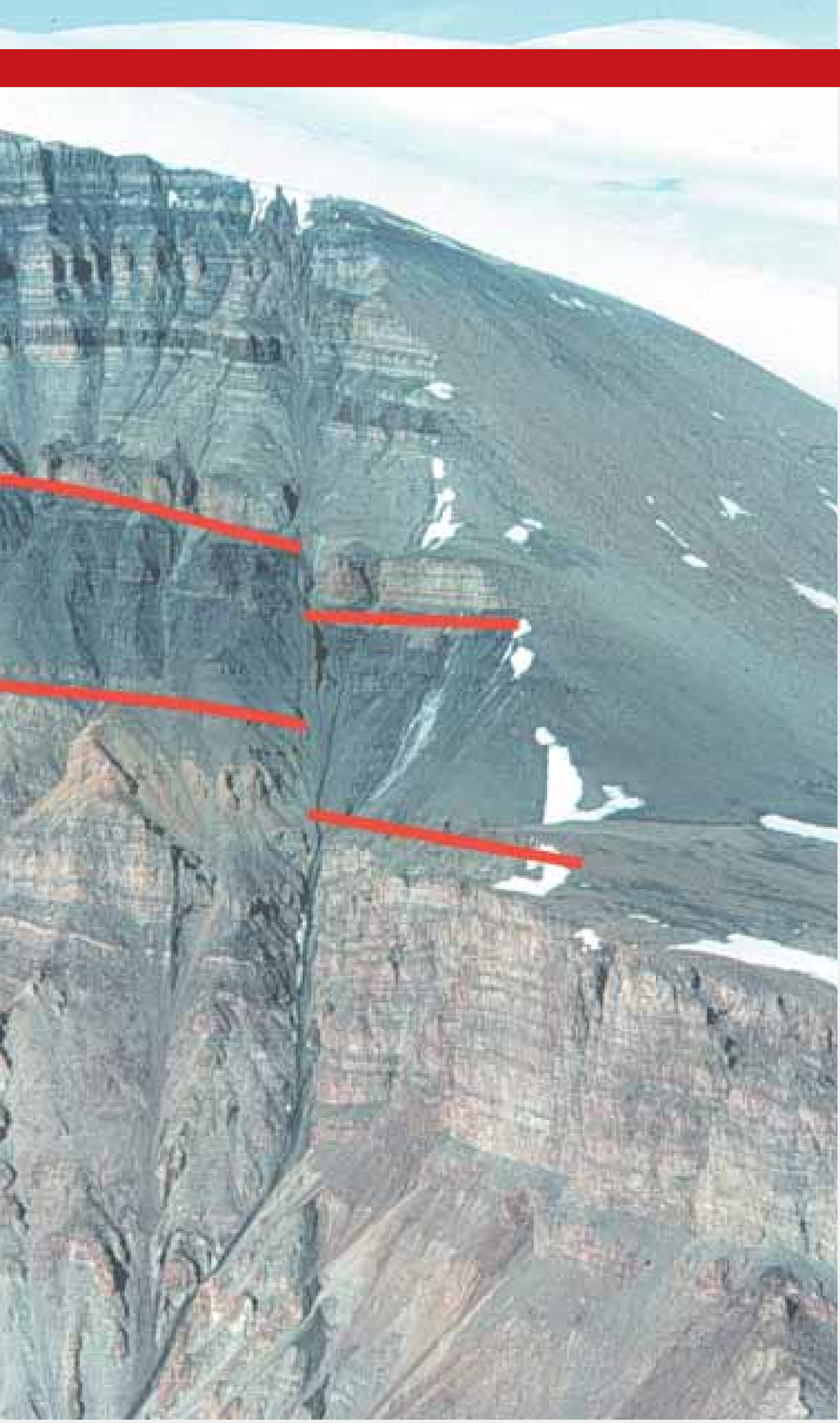


Episodic Global Tectonics: Sequence Stratigraphy Meets Plate Tectonics

Photo: Ashton Embry

Ashton Embry received a PhD in stratigraphy from the University of Calgary in 1976. Since 1977 he has been with the Geological Survey of Canada where he is currently a Senior Research Scientist. His research efforts have been centred on the sedimentology and stratigraphy of the Devonian and Mesozoic strata of the Canadian Arctic Islands and he has conducted fieldwork in this area since 1969. He has been working on applications of sequence stratigraphy to sedimentary successions since 1974 and has published on specific methodologies for using this discipline for improving correlations.

Based on recent advances in plate tectonics, sedimentology and sequence stratigraphy, I suggest that the Earth is affected by relatively short-lived episodes of increased tectonic activity separated by longer intervals of relative quiescence. If true, this may have important implications for how we interpret the history of the earth and exploit its resources.



Two prominent unconformities are marked by the red lines. The lower one is an angular unconformity that places Upper Triassic shale (dark) on Carboniferous clastics and carbonates (light). Yelverton Pass, northern Ellesmere Island.

Ashton Embry, Geological Survey of Canada, Calgary aembry@nrcn.gc.ca

From the early 1960s to the mid 1990s sedimentary geology enjoyed many exciting new developments which included the formulation of plate tectonic theory and consequent insights into the origin and development of sedimentary basins, major advances in sedimentology that allowed detailed facies analysis and paleogeographic reconstructions, and the development of sequence stratigraphy that provided insights into allogenic controls of sedimentary successions and the generation of predictive stratigraphic models.

It seems we have reached a bit of a plateau regarding big, new concepts and methods in sedimentary geology. However, cyclostratigraphy appears to one field that promises to bring new understanding and improved time control for sedimentary and tectonic processes. We may also be on the verge of another major shift in thinking, and this comes from a combination of the aforementioned three advances achieved in the latter half of the 20th century – plate tectonics, sedimentology and sequence stratigraphy.

Episodic Diastrophism

The methodologies, interpretations and insights from these three pillars of sedimentary geology have led to a concept that I call "Episodic Global Tectonics". Its main thesis is that the Earth is affected by relatively short-lived episodes of increased tectonic activity separated by longer intervals of relative quiescence. The widespread episodes of increased tectonism seem to occur with a frequency of 1-2 million years and vary substantially in magnitude. Currently they are best expressed within sedimentary successions but igneous and metamorphic terrains potentially also harbour indicators of such episodic crustal instability.

A similar concept was debated in geological circles during the 1800s and the first half of the 20th century. However, after 1950 the concept has been essentially ignored although it can be found in a few papers. In this article I will provide a summary of early thinking on this concept, the evidence that has indicated to me it is worth considering, a theoretical model that might account for such a phenomenon, and some of the implications for geology if episodic global tectonics actually did occur throughout earth history.

In the 19th century episodic global tectonics was widely accepted and each geological period was seen as being bounded by unconformities that represented global "revolutions". By the end of the century the concept was under considerable debate, and it was questioned if unconformities indicated "great earth movements affecting all quarters of the globe" or were due to "an aggregation of local events dependent on local conditions uncontrolled by overmastering agencies of universal dominance". The author of these quotes was the influential American geologist, Thomas Crowder Chamberlin, known best for his method of multiple working hypotheses. He favoured the former explanation and in 1909 proclaimed "diastrophism as the ultimate basis of correlation".

The Rise of Sea Level

During the first half of the 20th century natural, worldwide divisions of earth history were generally accepted but many interpreted them due mainly to tectonically driven rises and fall of sea level rather than to widespread epeirogenic uplift. In 1949 James Gilluly, in his presidential address to the Geological Society of America, declared that "worldwide orogenic revolutions do not appear to have been demonstrated" and few have dared to raise the concept of episodic global tectonics since that time.

One individual who gently kept the concept alive was Larry Sloss who, in the same year as Gilluly declared that global tectonics was a non-starter, gave birth to sequence stratigraphy by coining the term sequence for a stratigraphic unit bounded by unconformities. Sloss' sequences were bound by major Phanerozoic unconformities that extended over much of North America, and by the early 1970s he was claiming that the same unconformities were present on the cratonic portions of other continents. Furthermore he had no doubt as to the tectonic origin of such unconformities and thus Larry Sloss became the "keeper of the faith" for episodic global tectonics until his death in 1996.

Ironically, when Sloss was proposing tectonic mechanisms to explain his observations, his former student, Peter Vail, along with his Exxon colleagues, revolutionized sequence stratigraphy with seismic sections and a eustasy-driven, deductive model of sequences and their bounding unconformities. The Exxon eustatic model was accompanied by incredibly detailed and precisely dated sea level charts and it washed away any thoughts of global tectonism. The geological community, with the proviso that local tectonics "enhanced" unconformities in some cases, ecstatically embraced eustasy as the long sought key to global correlation.

Three unconformities are marked by the red lines. The lower one puts Middle Triassic shales on Lower Triassic fluvial sandstones. The middle unconformity has Upper Triassic limestone on Middle Triassic shale. The upper one is within the Upper Triassic and at this locality about 200 m of strata have been removed at the unconformity. Greely Fiord, northern Ellesmere Island.

The red lines mark prominent maximum regressive surfaces within the Lower Triassic succession. These conformable surfaces form readily recognizable sequence boundaries well within the basin and correlate to unconformities on the basin flank. Otto Fiord, northern Ellesmere Island

Mesozoic Sequence Boundaries, Sverdrup Basin

At the same time as the Vail eustasy-based sequence model was sweeping over the geological community, I was studying the 9 km thick Mesozoic succession in the Sverdrup Basin of Arctic Canada. Numerous major unconformities punctuated the strata and I employed sequence stratigraphy for subdividing the succession into pragmatic units for facies analysis and paleogeographic reconstructions. One of the major improvements that Exxon scientists made to sequence stratigraphy was to extend the definition of a sequence boundary from "only an unconformity" as used by Sloss to one which included a "correlative conformity". This allowed sequence boundaries and the sequences they enclosed to be correlated over much, if not all, of a basin.

I discovered that the sequence bounding unconformities that occurred on the flanks of the Sverdrup Basin joined basinward with conspicuous stratigraphic surfaces that marked the initiation of major transgressions. I referred to such readily recognizable surfaces as "maximum regressive surfaces" and they were ideal for the use as the conformable portion of the sequence boundary. These surfaces, which could be dated by paleontology, provided a convenient age designation for the sequence boundary. These observations differed from what was portrayed on the Exxon deductive sequence model which placed the maximum regressive surface (their transgressive surface) stratigraphically well above the unconformity. Such a difference is likely due to their use of a non-actualistic sinusoidal base level curve as a primary input parameter in their model. When a reasonably actualistic base level curve (e.g. one based on eustasy or episodic tectonics) is used for sequence modeling, the start of transgression coincides with the initiation of base level rise. This in turn results in the unconformity and the maximum regressive surface forming a single unbroken boundary from basin edge to basin center as is observed in most cases.

Tectonics and Sequences

Now that I had my sequence boundaries clearly defined and well dated, the question of whether they were of eustatic or tectonic origin arose. I first went with a eustatic origin because they matched events on the Exxon sea level curve. However, I was not comfortable with this because various features of the boundaries strongly favoured a tectonic origin.

The characteristics which had tectonics written all over them included:

- The strata below the unconformities were often tilted and in some cases faulted
- There were major changes in depositional regime across the boundaries
- There were major changes in sediment composition and direction of source areas across the boundaries
- There were significant changes in tectonic regime and subsidence rates across the boundaries

Almost exactly 20 years ago I let the data rather than the prevailing theory guide my interpretations and postulated that the Mesozoic sequence boundaries of the Sverdrup basin were mainly of tectonic origin. Further work over the past two decades has only solidified this position.

The top of the Lower Triassic sequence is marked by a prominent maximum regressive surface (red line) near the basin centre. The strata consist mainly of slope and outer shelf shale and siltstone with some thin outer shelf sandstone just below the boundary. Nansen Sound, northern Ellesmere Island

Global Comparisons

It was somewhat disturbing to me that tectonically driven sequence boundaries of the Sverdrup Basin matched very well with events on the Exxon global sea level chart. I decided to review the literature for the occurrence of major sequence boundaries in the Triassic in other basins throughout the world to see if my Triassic boundaries were due to a local tectonic phenomenon or were expressions of something larger.

The literature descriptions plus observations made on field excursions to the Triassic of the southwestern USA, Svalbard and northeastern British Columbia left no doubt in my mind that the major Triassic sequence boundaries I had recognized in my corner of the world dominated the Triassic stratigraphy in basins on at least four continents. The available evidence also indicated that the Triassic sequence boundaries in a number of basins had characteristics supportive of a tectonic origin. Thus I was faced with the hard-to-escape interpretation that significant tectonic episodes affected large areas of the Triassic world and that they were separated by long intervals of relative quiescence. Derek Ager's oft quoted quip that "the stratigraphic record is like a soldier's life; long intervals of boredom separated by short intervals of terror" took on new meaning.

The Triassic was of course the time when Pangea was in full bloom and one way of rationalizing such widespread tectonics was that I was actually looking at only one continent, albeit a super one. I then looked at my Jurassic unconformities that also had all the indicators of a tectonic origin. And like the Triassic ones they were also represented on the Exxon sea level curve, especially the early version that only included the major Jurassic events. A literature search revealed that these too were common in many basins around the world seemingly confirming the Exxon interpretation. However, in many cases the Jurassic unconformities also bore the telltale signs of tectonics being a major factor in their generation. This convinced me that very widespread, perhaps global, sequence boundaries were not necessarily proof of a eustatic origin and that tectonics could also produce such a phenomenon.

In Search of a Mechanism

The occurrence of widespread, synchronous, tectonically generated sequence

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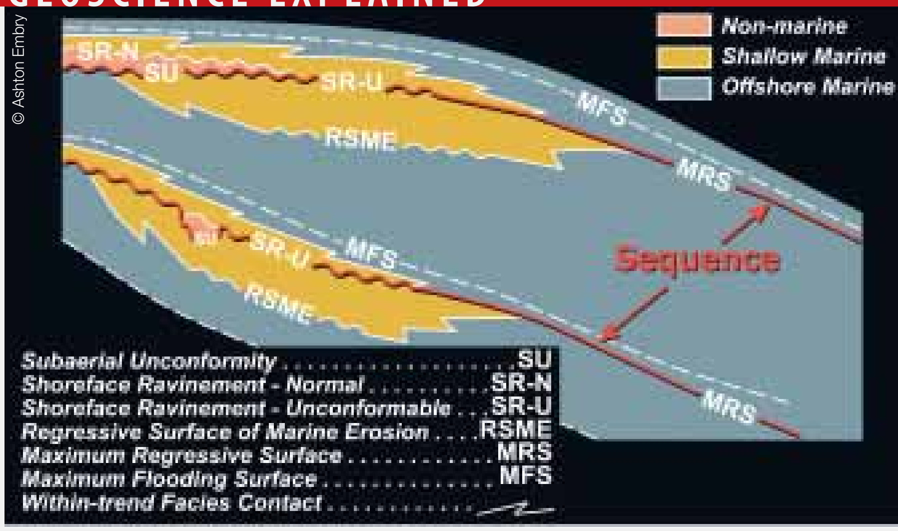

Sequence stratigraphic model with the sequence boundaries coinciding with unconformities on the basin flank and maximum regressive surfaces farther basinward.

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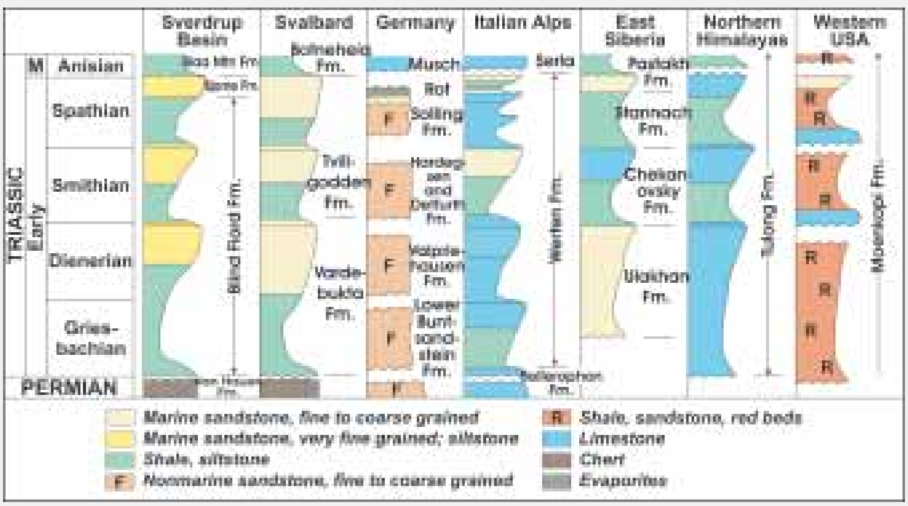

Early Triassic sequence boundaries from various basins in North America, Europe and Asia. The same boundaries are in all the basins and they are of tectonic origin.

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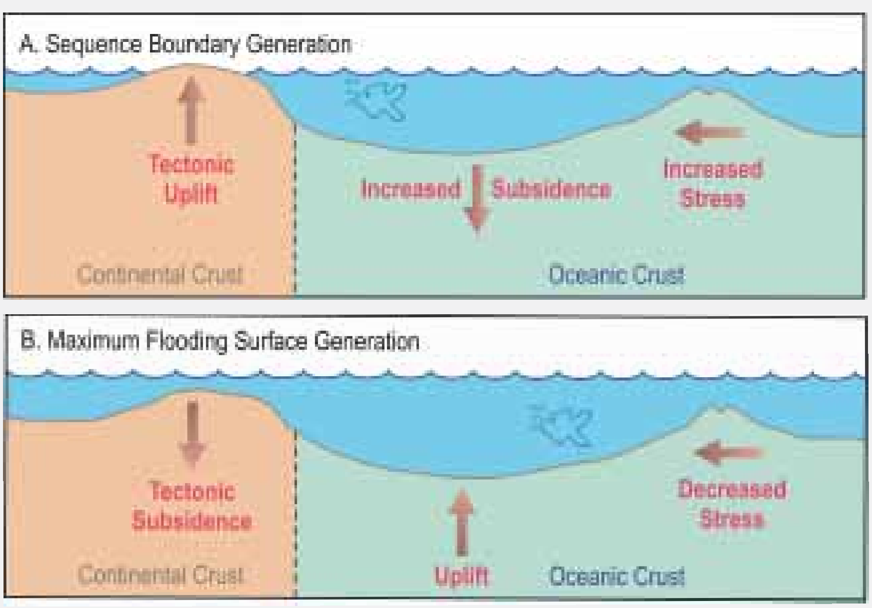

A schematic model illustrating the roles of tectonics and eustasy in the generation of episodic global sequence boundaries. Changes in horizontal stress regimes due to changes in spreading rates and/or directions result in both eustatic and tectonic effects. These tectonically-driven effects result in global sequence boundaries that show the effects of tectonism.

boundaries is a clear expression of episodic global tectonics and it begs for a reasonable theoretical model to explain such a phenomenon.

Larry Sloss over 30 years ago appealed to "episodic changes in the proportion of melt in the asthenosphere below the continents" as a driving mechanism (*Sloss and Speed, 1974*). I offered up the hypothesis of episodic changes in the spreading rates and/or directions of the interlocking plates affecting the horizontal stress field that in turn would drive tectonic movements on the margins of sedimentary basins (*Embry, 1997*). This model also included a eustatic component related to tectonic deformation of the oceanic crust.

Recently I stumbled on a wonderful paper that postulated that perturbations in mantle convection and consequent effects on crustal processes drive the generation of global, large scale sequence boundaries (*Collins and Bon, 1996*). Overall I think this hypothesis of mantle-driven crustal dynamics may be the best explanation so far for episodic global tectonics and I recommend this paper to anyone interested in some mind-expanding hypothesizing.

Implications

I certainly shy away from the cliché of paradigm shift for the concept of episodic global tectonics but it does have some implications for how we interpret the history of the earth and exploit its resources.

It provides the elusive "natural order" to earth history and the sequence boundaries would contribute to global correlations and the refinement of the global time scale especially for the Precambrian. The occurrence of predictable episodes of tectonism would help to focus resource exploration because the consequences of such relatively short-lived events might well include petroleum trap formation and mineralizing fluid migration.

I am hopeful the academic and industrial geoscientific communities will take this hypothesis seriously and will begin testing its validity. Right now there is some tantalizing evidence that supports it and its implications are too profound to let it lie dormant in the shadow of the over-extended and poorly supported eustasy model. Anyways, we owe it to Larry Sloss to see if he was right on this one as he was on so many other things.