



Arabian Plate sequence stratigraphy: Potential implications for global chronostratigraphy

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ABSTRACT

The ability to recognise and correlate third-order depositional sequences across Arabia and between Arabia and other plates indicates that these sequences are driven by synchronous eustatic sea-level change. This is of value in providing guidance for the definitions of stages, which are the fundamental units of chronostratigraphy. Each Phanerozoic stage requires a Global Stratotype Section and Point (GSSP), which is a location and specific bedding plane where the base of each stage is defined. This definition is tied to an event in the rock record useful for correlation. Progress in defining GSSPs has been delayed because of difficulties in choosing the most appropriate event and section to relate to a definition. It is recommended here that stage boundaries be related to correlative conformities of sequence boundaries. This closely links chronostratigraphy with sequence stratigraphy and honours the original concepts upon which many stages were first described in the 19th Century.

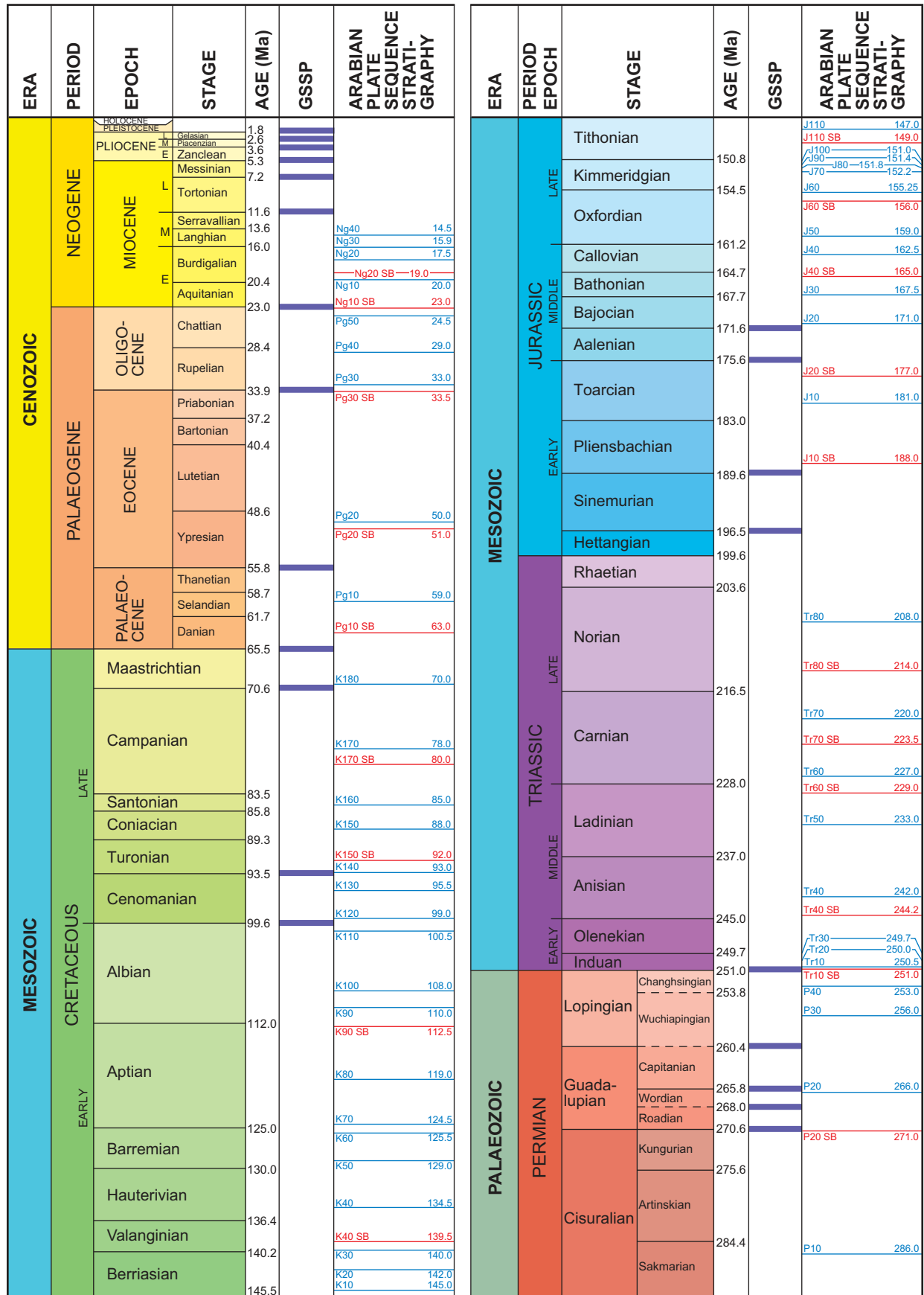
INTRODUCTION

Perhaps one of the most basic and often-asked questions in geoscience is “what age is it?” when referring to part of an outcrop or subsurface succession. To this end many geoscientists will have a geological timescale wallchart or reference card close to hand showing the relative positions of the familiar subdivisions of the geological timescale (Figure 1). Whilst most geologists will be aware that timescales evolve because of new radiometric dates or improvements in radiometric dating calibration and precision (for example, compare the latest timescale of Gradstein et al., 2004, with one of its predecessors such as Harland et al., 1990), many will be unaware that many of the units on the chart (Aptian, Viséan, etc) still lack a formal definition.

This is of concern because, for example, using the same set of fossils to derive an age, one geologist can call a given rock succession early Aptian, but another geologist may call the same succession late Barremian, all because each are using a different (usually palaeontological) event to define the base of the Aptian. Obviously this is very confusing for the non-specialist just wishing to understand the age and correlation of the rock succession. Unless chronostratigraphic terms are defined, one is reminded of the egocentric words of Humpty-Dumpty in the famous story by Lewis Carrol *Alice Through the Looking-Glass*: “when I use a word, it means just what I choose it to mean, neither more nor less”.

The purpose of this paper is to demonstrate that the evolving concepts of sequence stratigraphy, such as those published by Sharland et al. (2001, 2004) and Davies et al. (2002), may assist in defining the units of the geological timescale and, in turn, help harmonise the disciplines of sequence stratigraphy and chronostratigraphy. To do so, we:

- briefly review the historical background to key chronostratigraphic terminology;
- discuss the interplay between sequence stratigraphy and stage boundaries;
- argue that stratigraphic sequences are global and synchronous in nature; and
- present examples to demonstrate how sequence stratigraphy may assist in chronostratigraphic stage definition.



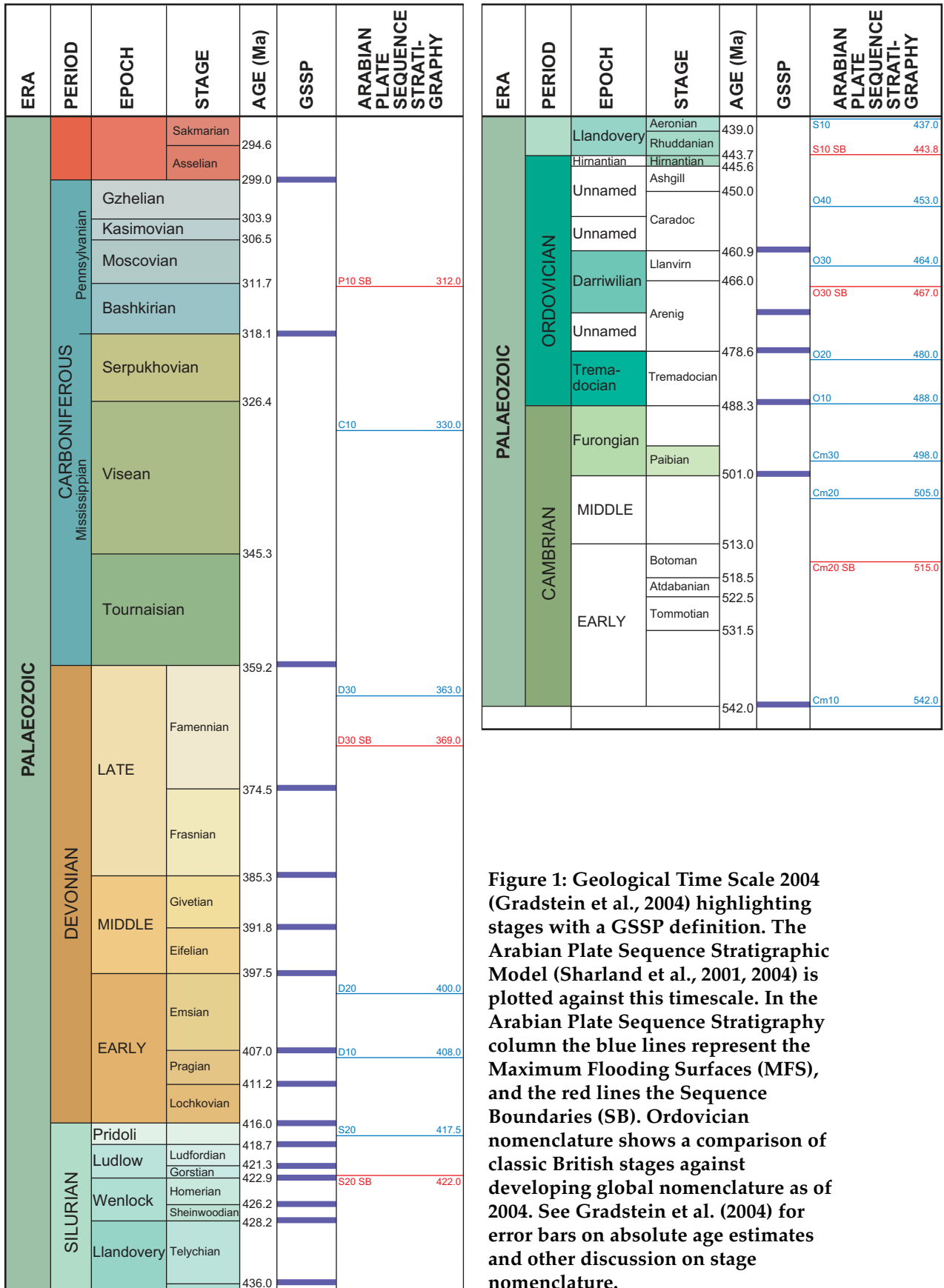


Figure 1: Geological Time Scale 2004 (Gradstein et al., 2004) highlighting stages with a GSSP definition. The Arabian Plate Sequence Stratigraphic Model (Sharland et al., 2001, 2004) is plotted against this timescale. In the Arabian Plate Sequence Stratigraphy column the blue lines represent the Maximum Flooding Surfaces (MFS), and the red lines the Sequence Boundaries (SB). Ordovician nomenclature shows a comparison of classic British stages against developing global nomenclature as of 2004. See Gradstein et al. (2004) for error bars on absolute age estimates and other discussion on stage nomenclature.

HISTORICAL BACKGROUND

The stage is the standard unit of chronostratigraphic subdivision. Although rooted in the fundamental concepts of William Smith, stages were first introduced by the great 19th Century French palaeontologist and stratigrapher Alcide d'Orbigny who recognised rock units in France (and elsewhere), which had distinctive fossil assemblages, such that those units could be correlated from location to location (d'Orbigny, 1842, 1849, 1852). Many of these units are still in use today, particularly many of the standard stages of the Jurassic and Cretaceous periods (Cavelier and Roger, 1980; Torrens, 2002).

In keeping with the prevailing view in the mid-19th Century that "cataclysmic events" controlled Earth history, d'Orbigny believed that each of his stages resulted from faunal turnovers in response to sudden events in Earth history (see reviews of Monty, 1968; Rioult, 1969; Torrens, 2002). Stages were described as "the expression of the boundaries which Nature has drawn with bold strokes across the whole globe" (d'Orbigny, 1842 as quoted in English translation by Rioult, 1969). Despite much debate in the geological literature over the last 150 years as to the definition of stages, it seems that we may be coming full circle and that sequence stratigraphy provides the vehicle to express d'Orbigny's original views within a modern geoscience framework. Because d'Orbigny was working mainly on outcrops in platform locations ("up-systems tract" in a sequence stratigraphic sense), many of his stages are bounded by unconformities (i.e. sequence boundaries). This is exactly why he observed faunal turnover at their boundaries, and is what sequence stratigraphy would predict (Holland, 1995).

The ideas of d'Orbigny were soon enthusiastically embraced by many other European palaeontologists and stratigraphers, and soon a plethora of stage nomenclature spread across the globe. By the middle of the 20th Century there were probably easily in excess of 1,000 stage names to choose from. Gradually in the second half of the 20th Century, these names have become synonymised to the 90 or so that we commonly use today (see, for example, reviews of Jurassic nomenclature in Arkell, 1933, 1956).

To facilitate this necessary rationalisation, it became apparent to many stratigraphers that a formal definition of each of the stages in common use was required. As might be expected, the procedure for definition became a matter of considerable debate and argument. The history of this debate is ably reviewed by Torrens (2002), Castradori (2002), Walsh (2004) and Walsh et al. (2004). We need only concern ourselves with the modern view that each stage requires a Global Stratotype Section and Point (GSSP) to be defined (Remane, 2003; Walsh et al., 2004).

A GSSP is effectively a single bedding plane in a given outcropping sedimentary section that acts as the standard against which the lower boundary of a stage is defined. Historically the placement of the GSSP is typically related to a palaeontological event (i.e. the extinction or inception of a fossil species or group of species), which is thought to have great value in international and interbasinal correlation. However, it is not always a palaeontological event that is used – palaeomagnetic shifts and stable-isotope excursions have also been chosen. Perhaps somewhat perversely, the base Maastrichtian Stage is defined at the mid-point between several palaeontological events (Odin, 2001).

Notwithstanding criticism of the GSSP concept from some quarters (e.g. Naidin, 1998; Aubry et al., 1999; Zhamoïda, 2004 – these authors urging attention to classical unit stratotypes and regional correlations), the International Commission on Stratigraphy (ICS) has embraced the concept and is agreed that all stages of the Phanerozoic should have a GSSP by the International Geological Congress in 2008 (Gradstein et al., 2004; Gradstein and Ogg, 2004). At the time of writing this seems to be an ambitious aim. No more than 60% of stages have a GSSP formally defined and ratified by the ICS. Even some of those stages that have been given a formal definition in the early stages of GSSP research are now undergoing revision as stratigraphers have found fault with the original GSSP. It is worth exploring the problems in GSSP definition further so as to appreciate how sequence stratigraphy may contribute to the discussion.

PROBLEMS WITH THE APPLICATION OF THE GSSP CONCEPT

As noted above, GSSPs are related to an event, usually palaeontological, that facilitates correlation. The primary problem then is which event to choose? As can be imagined, considerable arguments reign as to:

CRETACEOUS STAGE BOUNDARIES
COPENHAGEN 1983

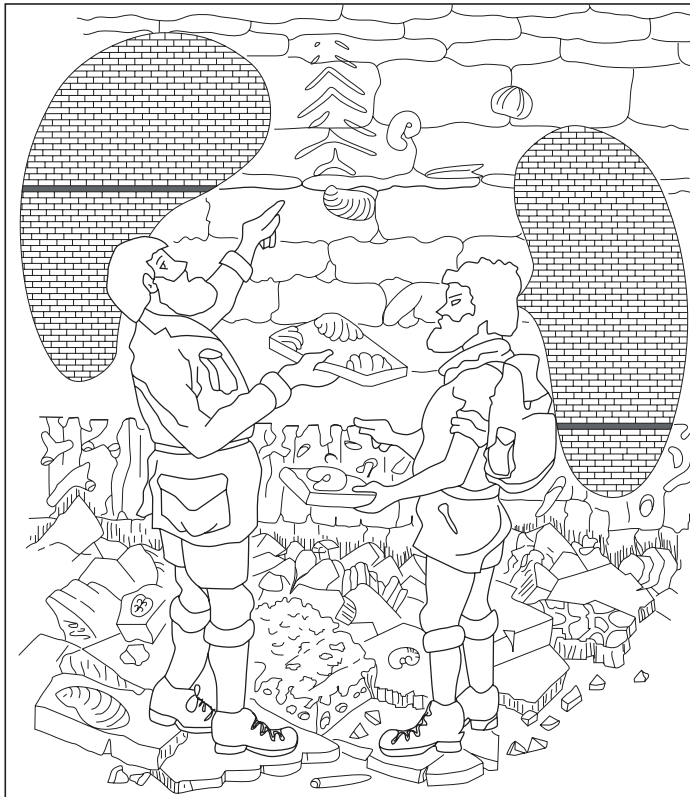


Figure 2: Cartoon by Tove Birklund, showing two geoscientists arguing about the different merits of two fossil groups for defining a Cretaceous stage boundary. Arguments such as these have greatly hindered the selection of GSSPs. Sequence stratigraphy may help guide which fossil event to choose.

- (1) the synchronicity or diachroneity of a given event;
- (2) the ease with which the event can be recognised (often this involves taxonomic concepts of the species involved);
- (3) its relation to the original description and concept of the stage; and
- (4) its relation to stage usage as in common practice today.

Doubtlessly too, all the above are coloured by what can be termed personal preferences, prejudices and geopolitics. All these considerations have led to extensive delays and debates in choosing a GSSP as shown in the cartoon of Figure 2. It should also be borne in mind that GSSP research is carried out through volunteer academic effort, rather than as a commercially driven enterprise.

It is essential of course that care be taken over the selection of a GSSP least subsequent problems be found with its suitability. For example, the base Pragian (early Devonian) GSSP in the Czech Republic has recently been reviewed (Slavik & Hladil, 2004) and it has been shown the bioevent chosen for the GSSP guide event (inception of the conodont *Eognathodus sulcatus* “*eosulcatus*”) occurs some distance below the designated GSSP level in the GSSP section. There is thus a disconnect between the GSSP and its associated marker event! It is argued that many Silurian GSSPs have similar problems or are in unsuitable locations (e.g. Berry, 1987, see also discussion in Holland et al., 2003).

A more philosophical, but nonetheless important, argument in GSSP selection has been relating the selection of a GSSP to what has been called a (synchronous) “natural event” in the rock record. Such natural events include unconformities resulting from sea-level changes and changes in palaeoceanography or palaeoclimate. Events like these often have important historical significance for recognition of stage boundaries. We will return to this point later. We are conscious that some geologists will question what the duration of events such as those listed above is. There is increasing evidence that sea-level change and climate change can be very rapid – measured in thousands rather

than millions of years (e.g. Alley et al., 2003; Kemp et al., 2005). This matches the limits of biostratigraphic resolution so sea-level and climate change events can often be regarded as “geologically instantaneous”, although clearly not instantaneous in the strict sense of this word.

THE SEQUENCE STRATIGRAPHIC SETTING OF STAGE BOUNDARIES

As noted above, stage boundaries were, in most cases, originally defined by d’Orbigny and others at points of faunal turnover in the rock record. In sequence stratigraphic terms, these are mostly sequence boundaries in a platform setting. These, of course, are not ideal locations to choose for defining stages. This is because if such locations are stacked upon each other there will be gaps of “missing time” between them, representing non-deposition and erosion at the sequence boundary (Figure 3).

A good example of such a stage definition is the Toarcian stage of the early Jurassic (Figure 3). The stage was originally described from Thouars in France by d’Orbigny (1852). The base of the section here is of erosive based sands (sequence boundary at their base) and it is now known that there are ammonite zones that are not represented in this section (Gabilly *in* Cavelier and Roger, 1980; Remane, 2003).

To rectify these deficiencies in original stage descriptions, GSSPs are now sought in basinal positions where there is effectively continuous sedimentation (Gradstein et al., 2004; Ogg, 2004). Such locations will enable stages to form a continuum of Phanerozoic time with no gaps between them. In the case of the Toarcian, a GSSP is being considered at Peniche in the basinal succession of the Lusitanian Basin, Portugal (Durante et al., 2004; Morton, 2006).

Straightaway it can be seen that an obvious place to locate a GSSP in such a setting is the correlative conformity to the sequence boundary relating to the original stage definition on a coeval platform. That is to say, at the base of the lowstand system tract. This would mean that a stage defined at a correlative conformity would honour the event that related to the original stage definition.

Objections may be raised to the placement of a GSSP at a correlative conformity. One of these is that in so doing the new stage boundary no longer represents the same point in time as the original definition (see Aubry and Berggren, 2000; and review of Castradori, 2002). Advocates of such a viewpoint may also argue that the time interval between the correlative conformity and the onlap point representing the original stage boundary should be allocated to an entirely new-named unit. To do so however misses the point of the original definition. The stage was being related to an event in Earth history – by choosing the correlative conformity one chooses the only point in a rock succession where the climax of that event is preserved.

Hollis Hedberg (who was one of the driving forces behind the GSSP concept) remarked in 1970 that “the worst possible boundary for a chronostratigraphic unit is an unconformity”. We would agree, and suggest that the best possible boundary is the correlative conformity to that unconformity.

In practice, GSSPs have so far rarely been defined at correlative conformities. Instead, they have been located at palaeontological (or other) events that do not relate to any sequence stratigraphic surface. Indeed the sequence stratigraphic setting is rarely considered when choosing a GSSP, arguments instead typically centring on the relative merits of various palaeontological (or magnetic, or isotopic) events as a tool for practical correlation. We feel that this is “missing the wood for the trees”.

The Jurassic Period contains good examples of such GSSPs (see Morton, 2006 for a review of Jurassic GSSPs). For example, the GSSP for the base Pliensbachian has recently been defined (Meister et al., 2006) at the base of the *jamesoni* Zone in Yorkshire. Here, as stated by the authors, the GSSP lies within a TST (there is a prominent correlative conformity to a sequence boundary further down in the section). This is not surprising in that for the Jurassic Period at least, stages have long been regarded as groupings of ammonite zones (Arkell, 1956). Thus in the Jurassic, at least conceptually, biostratigraphy rules absolutely and often the only question is to find a GSSP locality with a good ammonite succession, other events in the rock record being considered of secondary or no importance. Hancock (1977) has also expressed the view that stages are nothing more than groupings of biozones. Even if this were correct, one would be tempted to ask which biozones and how are they in turn defined?

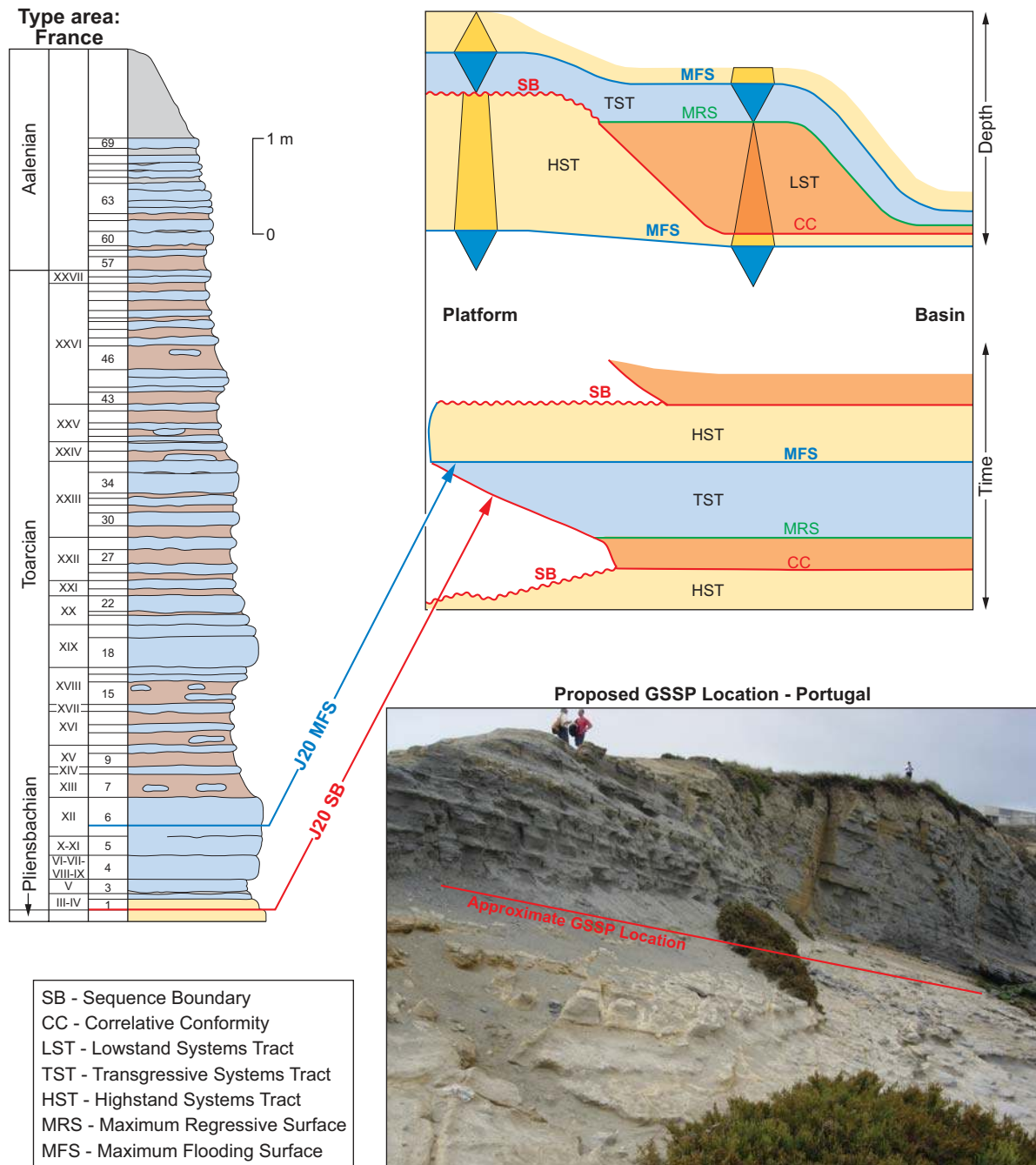


Figure 3: The sequence stratigraphic location of the type area of the Toarcian Stage compared with the proposed GSSP location. The type area in Thouars, France (illustration after Cavalier and Roger, 1980) is in a platform, up-system tract, position with a sequence boundary (missing time) at its base. The proposed GSSP, at Peniche in Portugal, is in a basinal setting with continuous deposition and the GSSP relates to a change in an *Eodactylites* ammonite fauna. Its precise systems tract setting is uncertain, but may be TST. Peniche outcrop photograph courtesy of Dr. Stephen Hesselbo, University of Oxford.

Perhaps somewhat understandably, stratigraphers have been wary about applying the concepts of sequence stratigraphy to the definition of chronostratigraphic units. Concerns have been raised about the true synchronicity of sequences and the development of a global eustatic sea-level curve (discussed further below), with further concerns about how one might physically recognise sequence stratigraphic surfaces, especially in basinal settings. Birkelund (1983) summarised the state of thinking in the 1980s: “Knowledge of sea-level oscillations, however, is still far beneath the precision needed for serious

discussions of stage boundaries". Contrast this with the view expressed by Gradstein et al. (2004): "The major global oscillations (of sea level) have probably been identified".

In a series of papers seemingly ignored by the stratigraphic community, or of which the community have been unaware of, Chinese geoscientists (e.g. Mei Shilong, 1996; Wang Xulian and Su Wenbo, 2000; Wang Xulian, 1999, 2002; Wang Hongzhen, 2000) have been quietly advocating the application of sequence stratigraphic concepts to stage definition. Whilst the arguments of Wang Xulian and his co-workers are a little different to ours (they contend that the transgressive surface, rather than the sequence boundary / correlative conformity, is of prime importance). Mei Shilong concurs with our view that it is the correlative conformity of the major sequence boundaries that provide a guide for GSSPs (in his terms, the "Best Natural Boundary" in the rock record). Both views support the contention that with sequence stratigraphy now coming of age it has its role to play in the definition of chronostratigraphic units.

Elsewhere, Knox (1994) has briefly reviewed how sequence stratigraphic settings might define some of the problematic stages of the Palaeogene, pointing out, as we do here, that stages were typically originally described from platform settings and that it is only by analysis of the complete basinal succession that the true extent of a stage can be assessed (Figure 4). For example, the Ypresian stage is bound by an unconformity in its historical stratotype of the Ieper Clay (see also Steurbaut, 2006), but in the continuous sedimentation of the Central North Sea its base could be extended to the base of the lowstand Forties Sandstones in the lowermost Sele Formation. It should be pointed out that in connection to this example, a base Ypresian GSSP has recently been selected relating to the pronounced negative carbon-isotope excursion associated with the so-called Palaeocene – Eocene Thermal Maximum (PETM) (Dupuis et al., 2003).

Recently, sequence stratigraphy has entered the debate on the placement of the base of the Hettangian stage and hence the Triassic-Jurassic boundary (Hesselbo et al., 2004a, b; Hallam and Wignall, 2004). In southwest England, the succession representing the transition from the Triassic to Jurassic can be interpreted in terms of changing sea-level and Hesselbo et al. (2004a, b) suggest that the sequence boundary within the upper Cotham Member of the Lilstock Formation may form a useful guide to placement of the base Hettangian. This is significantly lower than placement of the boundary on the

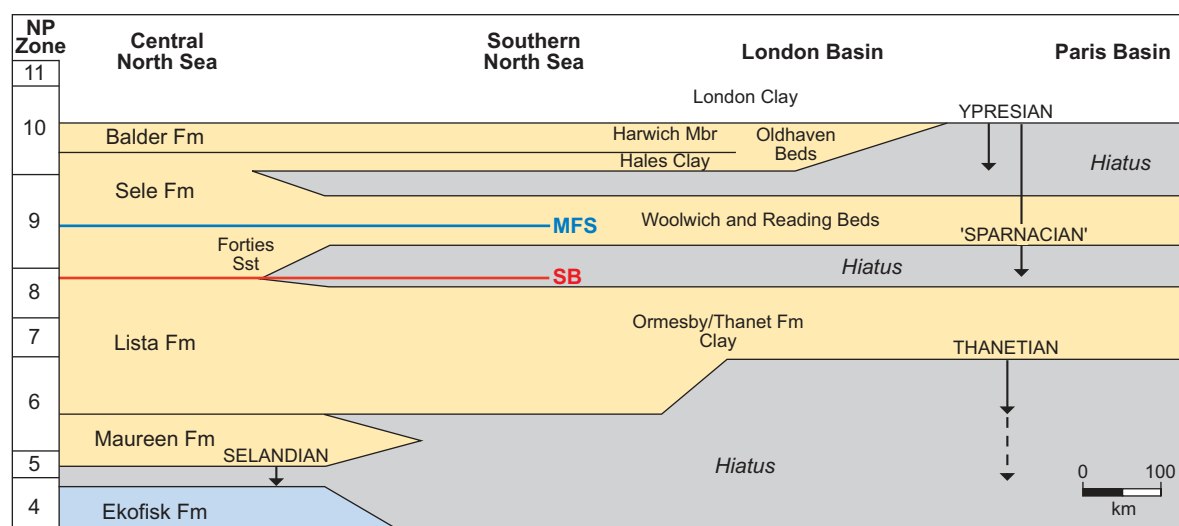


Figure 4: Chronostratigraphic chart modified after Knox (1994) for the Palaeogene of the North Sea-Paris Basin region showing that in their type areas of the Paris Basin, the Ypresian and Thanetian stages are bounded by unconformities. To capture the missing time represented by these unconformities, the stages could be extended downward to incorporate the time represented by the basinal sediments of the North Sea Basin where there is continuous deposition.

basis of a purely palaeontological event (e.g. inception of *Psiloceras planorbis*). There are, however, contrasting views (e.g. Hallam, 1990; Hallam and Wignall, 2004) of the interpretation of the succession in terms of changing sea-level, but the crucial point is that sequence stratigraphy is considered as relevant to the discussion on the correct level for the GSSP.

We would not argue that it is entirely erroneous to ignore the sequence stratigraphic setting of a stage boundary, but we would suggest that considering sequence stratigraphy will provide a guide to the best palaeontological (or other) guide event. Furthermore, by selecting an event associated with the correlative conformity location a link with the original description of a stage is maintained by relating the GSSP to the event that drove the original definition. Hopefully this will facilitate a more rapid conclusion to the debates on GSSP location and/or revision. Peter Vail and his colleagues foresaw such an eventuality when in 1977 they wrote “Using global cycles with their natural and significant boundaries, an international system of geochronology can be developed on a rational basis. If geologists combine their efforts to prepare more accurate charts of regional cycles, and use them to improve the global chart, it can become a more accurate and meaningful standard for Phanerozoic time”. We would not go so far as to suggest that sequence stratigraphy should replace classical chronostratigraphy, but that the new disciplines can be harmonised.

It is not surprising to find a link between sequence stratigraphy and the sorts of faunal turnover which were originally used to recognise stages. The global changes in sea-level that lead to the occurrence of sequences will also lead to extinction and inception of species because of the destruction and creation of ecological niches associated with sea-level change. Holland (1995) has, for example, demonstrated that a major peak in inception events is associated with the correlative conformity of a sequence boundary in a basinal setting and there is also a significant increase in extinction events at this point (Figure 5). The genetic stress resulting from the reduction in marine habitats associated with sea-level fall obviously results in new species out-competing their forebears (as stated in “Origin of Species”, Darwin, 1859). Conceptually therefore, sequence boundaries/correlative conformities should be the location of significant bioevents that can be used for GSSP definition and description.

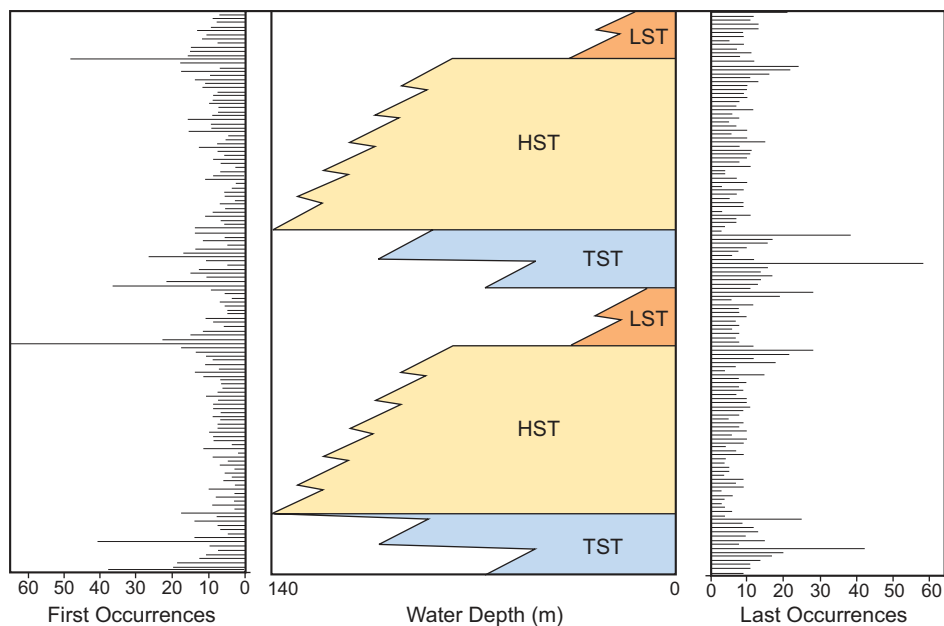


Figure 5: Relationship of palaeontological inception and extinction events to sequence stratigraphy (after Holland, 1995). Note the large number of inceptions associated with the correlative conformity at the base of the LST (there is also a simultaneous peak in extinction events). Therefore, correlative conformities offer a variety of bioevents to help define a GSSP.

The harmonisation of sequence stratigraphy and chronostratigraphy that we advocate in this paper can be further illustrated by an example. Below we use the base Chattian as an example to show how sequence stratigraphy can be related to original stage definition and hence provide guidance on GSSP location.

Base Chattian Example

The late Oligocene Chattian Stage was first introduced by Fuchs (1894) and described from sandstones in northern Germany. Van Simaeyns (2004) and Van Simaeyns et al. (2004) have now shown that this area of original description lies in a platform location where the base of the stage is an unconformity representing non-deposition (Figure 6). This unconformity is related to a significant glacial episode and associated eustatic sea-level fall. Close to the base of the stage is an MFS associated with post-glacial warming and associated eustatic sea-level rise.

Given the platform nature of the stratotypical Chattian region in the southern North Sea Basin (i.e. a setting with discontinuous deposition), a GSSP is currently being sought in a basinal succession associated with continuous deposition. Such locations are thought to exist in central Italy, for example the Monte Cagnero section (Van Simaeyns, 2004). At this location the extinction of the planktonic foraminifera genus *Chiloguembelina* is considered to be a useful guide event. However, whilst *Chiloguembelina* is a distinctive planktonic foraminifera and its last appearance datum therefore relatively easy to recognise, it is debatable whether its extinction is a synchronous event (Van Simaeyns et al., 2004). Furthermore, in the basinal settings of central Italy, the extinction of *Chiloguembelina* does not appear to be related to any palaeoclimate or sea-level change event. There is, therefore, a disconnect between the event originally defining the base of the Chattian Stage (glacially induced lowstand) and the event currently chosen to guide the GSSP location.

Further, within the basinal succession in which the GSSP ought to be located there is evidence for a major lowstand event - for example, an influx of the cold-water dinoflagellate *Svalbardella*. This event, perhaps coupled with oxygen isotope evidence to demonstrate sea-water cooling, can act as a guide to GSSP location in a correlative-conformity setting relating to the original stage definition.

In summary, selection of a base Chattian GSSP could be improved by reference to sequence stratigraphy rather than simple use of an easily identifiable, but potentially diachronous bioevent.

THE SYNCHRONICITY OF SEQUENCE STRATIGRAPHIC SURFACES

Since the publication of the first eustatic sea-level curve of Vail et al. (1977) and their seminal description of sequence stratigraphic methodology, the veracity and recognition of eustatically-controlled stratal surfaces and their global synchronicity has been much debated in the literature (see Schlager, 1991; Miall, 1997; and Miall and Miall, 2001 for good reviews of doubts and opposition; Hardenbol et al., 1998 provides a defence). Since the Vail et al. publication, other eustatic curves have been published for various parts of the geological column, notably Haq et al. (1987) and Hardenbol et al. (1998). However, because the data supporting the construction of these curves is not fully available, we prefer to use our own sequence stratigraphic model, independently developed (initially in Arabia) "from the rocks up" and internally consistent. This was published as Arabian Plate Sequence Stratigraphy by Sharland et al. (2001) with minor updates by Sharland et al. (2004) (Figure 1).

Since the publication of our sequence stratigraphic model in 2001 we have continued to research and refine it (e.g. Davies et al., 2002; Sharland et al., 2004). Of particular relevance to this article is that the third-order sequences recognised across the Arabian Plate in 2001 and 2004 (specifically their MFS and SBs) can now be demonstrated to occur in many other parts of the globe, correlated at the biozone level (so to within a resolution typically in the order of 500,000 years, although this is variable).

We concur that stratigraphic sequences are developed by interplay of eustacy, sediment supply and tectonic subsidence, but it is our observation that in the majority of sedimentary basins, eustacy will be the dominant

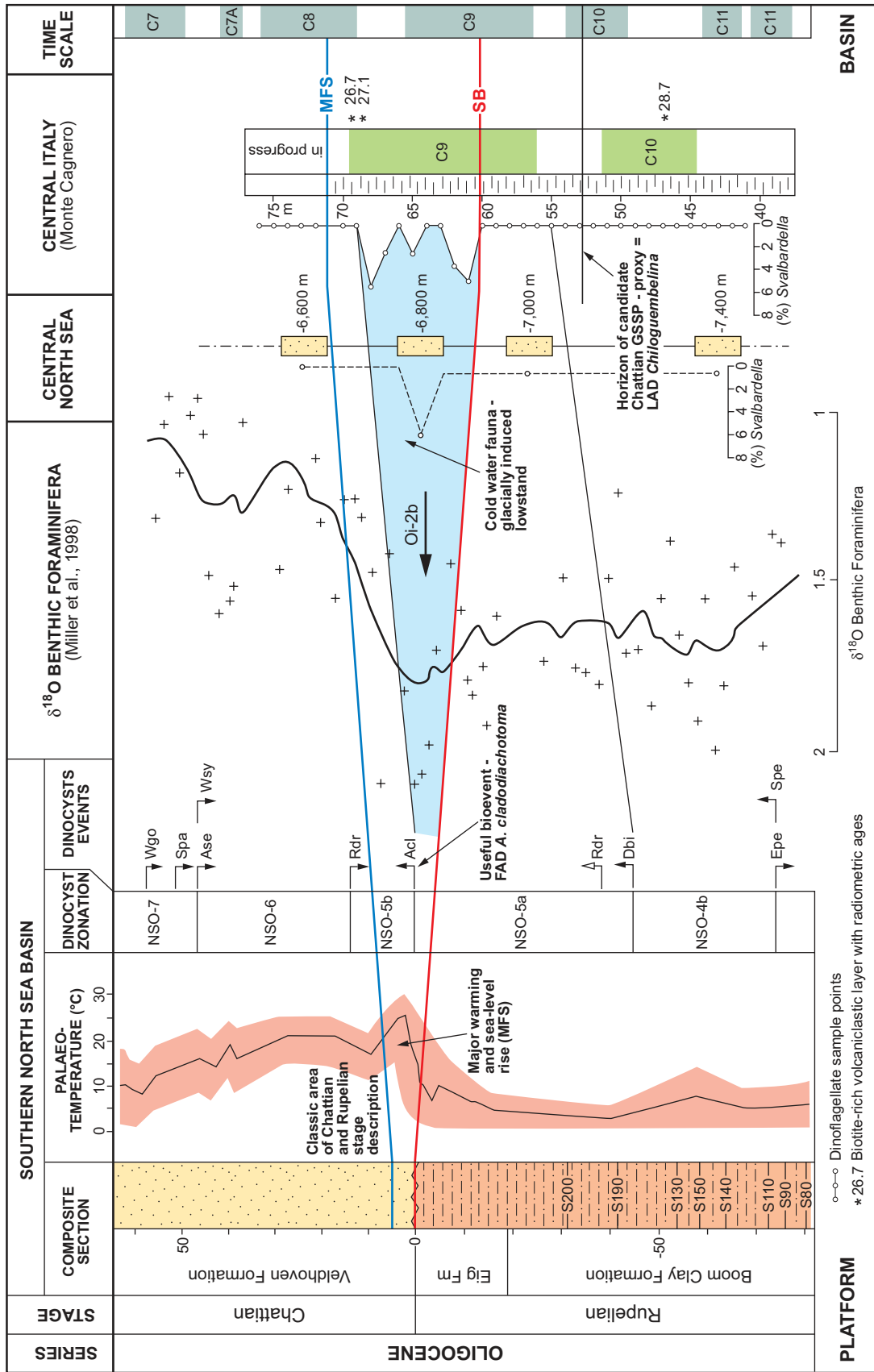


Figure 6: Sequence stratigraphy of the base Chattian (primary data after Van Simaey, 2004). See text for explanation (redrawn with the permission of Stichting Netherlands Journal of Geosciences).

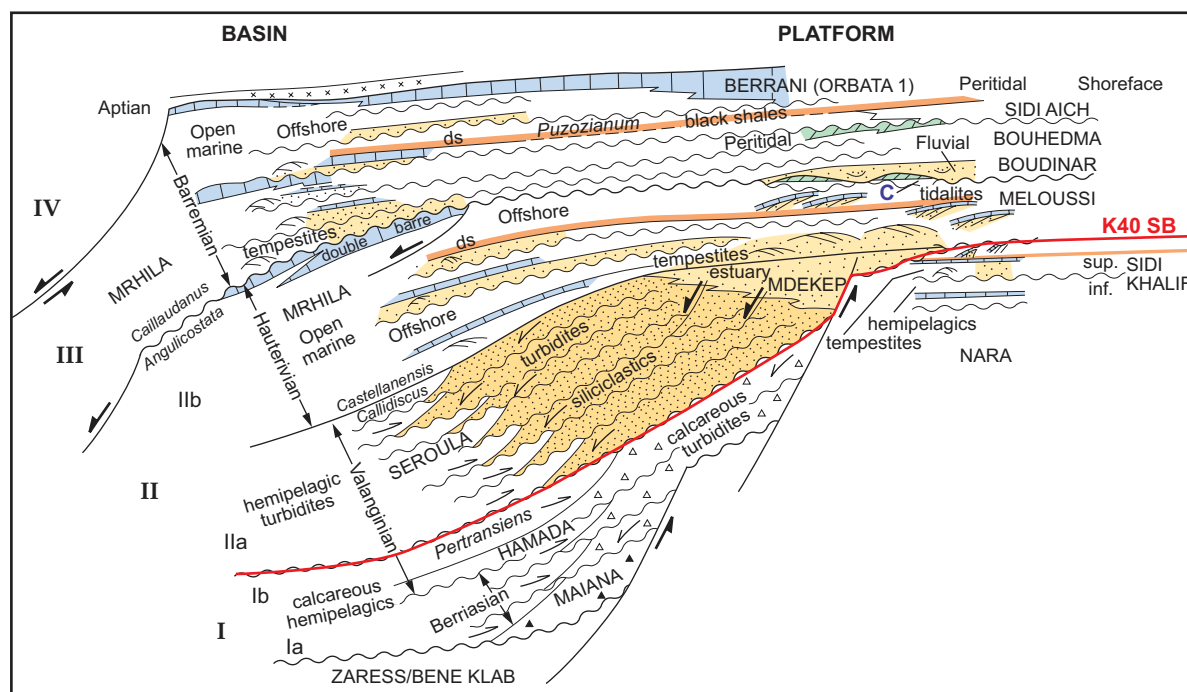


Figure 7: Reference section for K40SB in the Tunisian Dorsale (basinal correlative conformity setting) where it is represented by an erosive surface and forward-stepping of the Seroula clastics into the basin (Souquet et al., 1997; Peybernes et al., 1994) (redrawn with the permission of Société Géologique de France).

factor, such that the eustatic signal will always be visible. This is because the relative speeds of these three controls is not equal – eustatic sea-level change typically being much faster (Miller et al., 2003).

Space prevents us from reviewing many Phanerozoic sequences from our model, but we hope that the reader will accept the premise presented here using examples that serve to demonstrate our belief that our sequence stratigraphic model can be applied globally.

In our publications (Sharland et al., 2001, 2004; Davies et al., 2002) we have concentrated on demonstrating the presence and correlation (at the biozone level) of MFS across the northern Gondwana/southern Tethys margin. This is because in comparison to sequence boundaries, MFS can be identified and biostratigraphically calibrated in both platform and basin settings. Of course, intervening sequence boundaries can be biostratigraphically calibrated and correlated, but only in their expression as correlative conformities in basins. It is however important for us to demonstrate that sequence boundaries/correlative conformities can be correlated, as it is these surfaces that we are proposing as being useful adjuncts to stage definitions.

Sequence boundary K40 SB lies between the K30 and K40 MFS of Sharland et al. (2001, 2004). A reference section for this SB would be in the Tunisian Dorsale outcrop (basinal correlative conformity setting) where it is represented by an erosive surface and forward-stepping of the Seroula clastics into the basin (Souquet et al., 1997; Peybernes et al., 1994) (Figure 7). At this locality it is reliably dated as lying within the *campylotoxus* zone of the early Valanginian.

In Morocco, K40 SB occurs at the base of the Sidi Lhousseine Formation in the western High Atlas (Canerot et al., 1986; Rey et al., 1988) and is a disconformity above which marls and sandstones are present (lowstand deposits). This disconformity (probably a correlative conformity because of basinal setting) lies within the *campylotoxus* ammonite zone (Wippich, 2003).

In the Middle East, this surface is very clear in platform settings where in southern Iraq and Kuwait the base of the Zubair Formation is associated with a forward stepping delta system (van Bellen et al.,

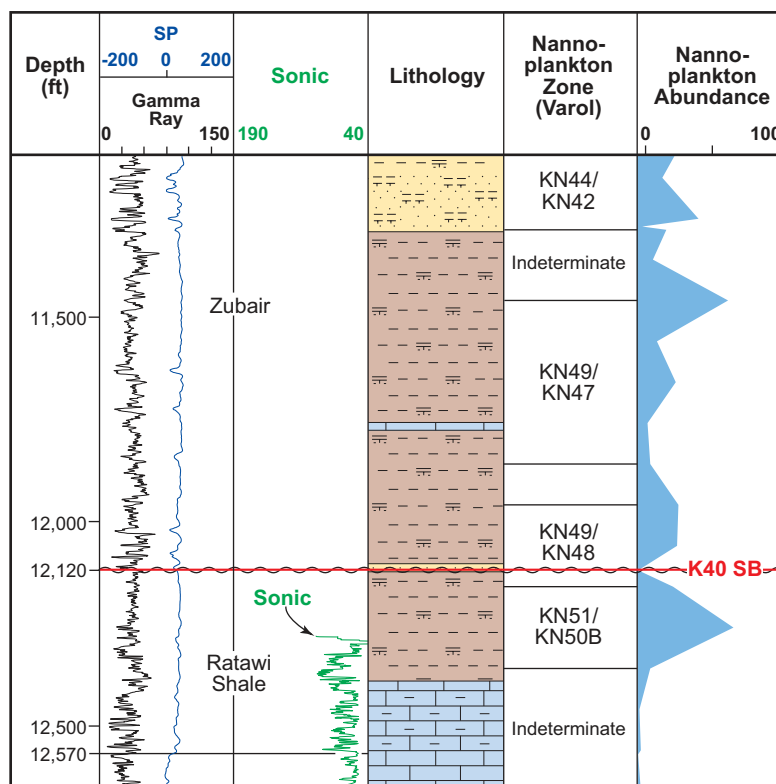
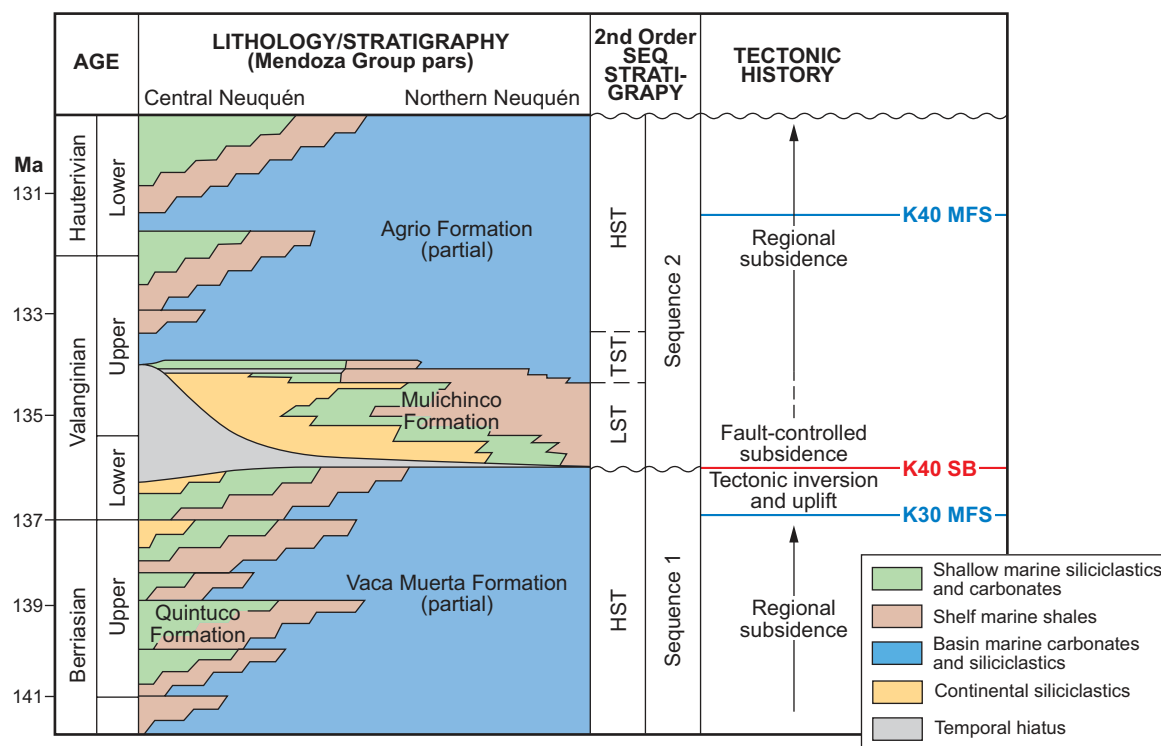


Figure 8: K40 SB as expressed at the base of the Zubair clastics in Kuwait (data after Al-Fares et al., 1998). Nannofossil zone KN49/48 is partly coincident with the *campylotoxus* ammonite zone, suggesting that this SB may occur in the same ammonite zone as the reference section in Tunisia. Note that our age interpretation of the nannofossil zonation differs from that given by Al Fares et al.

1959; Ali and Nasser, 1989; Al Fares et al., 1998; Nemsock et al., 1998; Davies et al., 2002) (Figure 8). In Yemen the boundary between the Sa'ar and overlying Furt Formation (= Sa'af Member) is a widely recognised disconformity omitting sediments of late Valanginian age (Beydoun et al., 1998; Holden and Kerr, 1997). Of course, in these platformal settings biostratigraphic calibration of this sequence boundary is less precise, although, for example, in Kuwait K40 SB lies within nannofossil zone KN49/48 (Al Fares et al., 1998), which is partly coincident with the *campylotoxus* ammonite zone.

Outside of the Middle East and North Africa, K40 SB can be recognised in a number of locations worldwide. In the basinal succession of the Carpathians of Romania, Melinte and Mutterlose (2001) have documented an influx of clastic sediments (lowstand, K40 SB correlative conformity at base) biostratigraphically calibrated by ammonites and nannofossils to the *campylotoxus* ammonite zone. Amongst the nannofossils an influx of boreal taxa occurs (and a reduction of Tethyan nannoconids) coincident with K40 SB. The topic of what drives the eustatic sea-level changes we observe is too complex to discuss in detail here, but this sequence boundary does appear to be coincident with what a number of authors have suggested is an expansion of polar ice-caps (Stoll and Schrag, 1996; Price, 1999). It is also coincident with a sea-level low suggested by Hardenbol et al. (1998), although it is slightly younger than the eustatic low suggested by Haq et al. (1987).

In the Neuquén Basin of Argentina, the Mulichinco Formation represents a lowstand (Schwarz and Howell, 2005) with K40 SB at its base. Ammonites provide biostratigraphic calibration suggesting the SB is close to the boundary of the local *riveroi* and *atherstoni* zones, equivalent to the *campylotoxus* zone of the global standard (Aguirre Urreta and Rawson, 1997) (Figure 9). Globally, other examples of K40 SB include the base of the Hosston sands in the Texas Gulf Coast (Scott et al., 1988) or the La Caja of NE Mexico (Goldhammer and Johnson, 2001). In the Colville River delta area of Alaska, K40 SB probably underlies the Alpine C sands, an important reservoir in the Alpine Field (Houseknecht and Bird, 2004).



Ma	AGE	AMMONITE ZONES	AMMONITE SUBZONES	LITHOSTRATIGRAPHIC UNITS
132	Valanginian	<i>Pseudofavrella angulatiformis</i>	<i>Neocomites</i> sp.	Agrio Formation
133			<i>Chacantuceras ornatum</i>	
134			<i>Pseudofavrella angulatiformis</i>	
135	Early	<i>Olcostephanus (O.) alherstoni</i>	<i>O. (Viluceras) permotestus</i>	Mulichinco Formation
136			<i>Karakaschiceras attenuatus</i>	
137	Early	<i>Lissonia riveroi</i>	<i>O. (Olcostephanus) alherstoni</i>	Quintuco/Vaca Muerta Formations
			<i>Neocomites wichmanni</i>	

Figure 9: Occurrence of K40 SB in the Neuquén Basin of Argentina, at the base of the Mulichinco Formation. Data from Schwarz and Howell (2005) redrawn with the permission of the Geological Society of London and Dr. Ernesto Schwarz. Ammonites provide biostratigraphic calibration suggesting the SB is close to the boundary of the local *riveroi* and *alherstoni* zones, equivalent to the *campylotoxus* zone of the global standard (Aguirre Urreta and Rawson, 1997), as in the reference section in Tunisia.

At present, there is no GSSP for the base Valanginian (Aguado et al., 2000; Gradstein et al., 2004) and usage includes the base of the *otopeta* ammonite zone (Birkelund et al., 1984), the inception of the calpionellid *Calpionellites darderi* (Hoedemaker et al., 2003) and the base of the *pertransiens* ammonite zone (Blanc et al., 1994). We recommend that the correlative conformity of K40 SB be the guide event for the base of the Valanginian, correlative to the unconformity on adjacent platforms around the world. Although this is stratigraphically higher than the events currently under consideration, it is an event that can be recognised globally (see above and Figure 10).

There are of course a number of authors who doubt the synchronicity of global sequences (e.g. Schlager, 1991; Miall, 1997), suggesting that (1) biostratigraphic resolution is inadequate to determine synchronicity; and/or (2) local tectonics overprints eustasy; and/or (3) there are local sequences that do not match global patterns; and/or (4) there is no proven mechanism for third-order eustasy on a global scale. These criticisms have encouraged us to define sequences only when we have biostratigraphic confidence in correlation at the highest resolution possible and where we are able to carry-out a sequence-stratigraphic interpretation in an internally consistent manner. If we observe

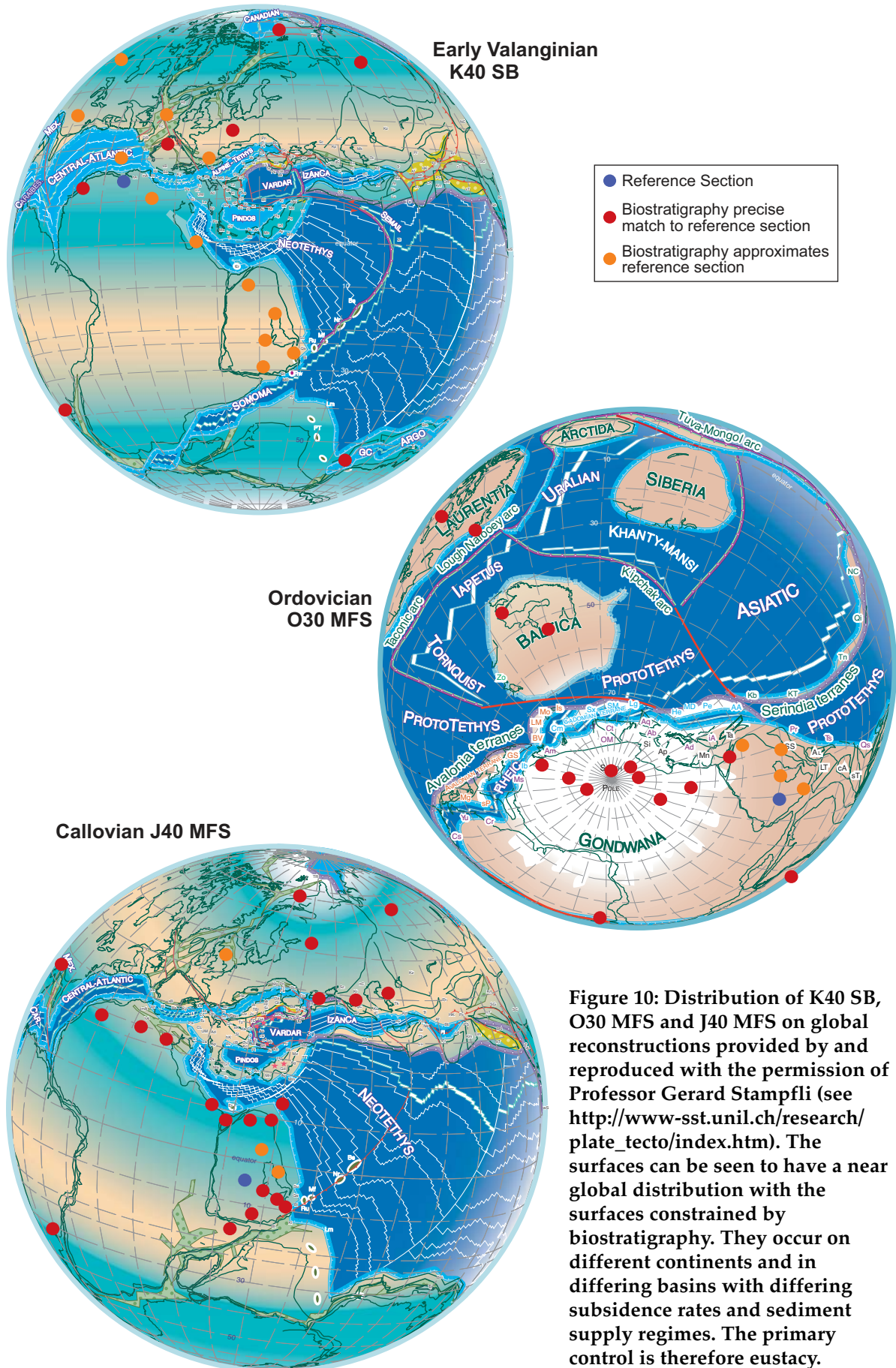


Figure 10: Distribution of K40 SB, O30 MFS and J40 MFS on global reconstructions provided by and reproduced with the permission of Professor Gerard Stampfli (see http://www-sst.unil.ch/research/plate_tecto/index.htm). The surfaces can be seen to have a near global distribution with the surfaces constrained by biostratigraphy. They occur on different continents and in differing basins with differing subsidence rates and sediment supply regimes. The primary control is therefore eustasy.

the same sequence-stratigraphic surface in multiple basins, each with differing tectonics and sedimentation rates, then the surface must be eustatic in origin. The causality and rates of such eustatic change are the subject of another paper we have in preparation, but like Miller et al. (2003, 2005) we can envisage rapid glacio-eustatic sea-level changes in what are traditionally seen as “greenhouse” periods of Earth history.

A further example to demonstrate the global synchronicity of our sequence-stratigraphic model is afforded by the Middle Ordovician O30 MFS of Sharland et al. (2001), which lies within the *murchisoni* graptolite biozone.

The reference section for this MFS lies in shales near the base of Hanadir Member, Qasim Formation, Saudi Arabia (Figure 11) (El-Khayal and Romano, 1988; Vaslet, 1989; Al-Hajri, 1995; Ekren et al., 1986; Senalp and Al-Duajji, 2001; Al-Hajri and Owens, 2000) with graptolites of the *Didymograptus murchisoni* Zone supported by trilobites and chitinozoa (McClure, 1988; Paris et al., 2000) and acritarchs (Strother et al., 1996) of the *clavata* – *pissotensis* chitinozoan zones (e.g. *Laufeldochitina clavata*, *Linochitina pissotensis*).

In the Anti-Atlas of Morocco, an MFS can be demonstrated in the upper part of the open-marine Tachilla Shales, which lie between the Zini and First Bani sandstones (Figure 12). This MFS is associated with *murchisoni* zone graptolites (Destombes, 1963; Destombes et al., 1985; Elaouad-Debbaj, 1984; Gutierrez-Marco et al., 2003) and acritarchs including *Frankea sartbernardense* (Deunff, 1977), demonstrating that it is an expression of the O30 MFS as defined in Saudi Arabia.

The well-exposed Ordovician succession of Baltica has been described by Nielsen (2004). A late Llanvirn sea-level rise (= *murchisoni* Zone) is recognisable across the region, in for example, the Taurupe Formation of Estonia and Latvia.

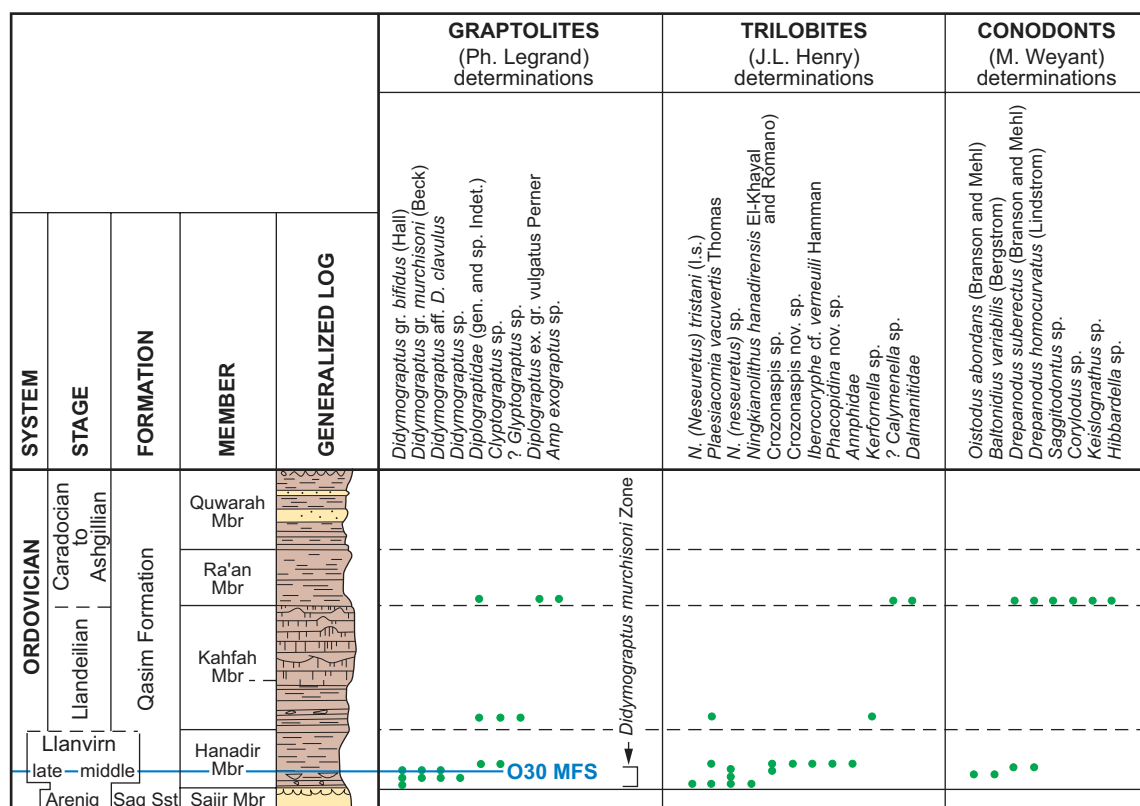


Figure 11: Location of the O30 MFS reference section in the Hanadir Shale of Saudi Arabia. Graptolites place this MFS in the *murchisoni* zone. Data after Vaslet (1990) (redrawn with the permission of the Bureau de Recherches Géologiques et Minières).

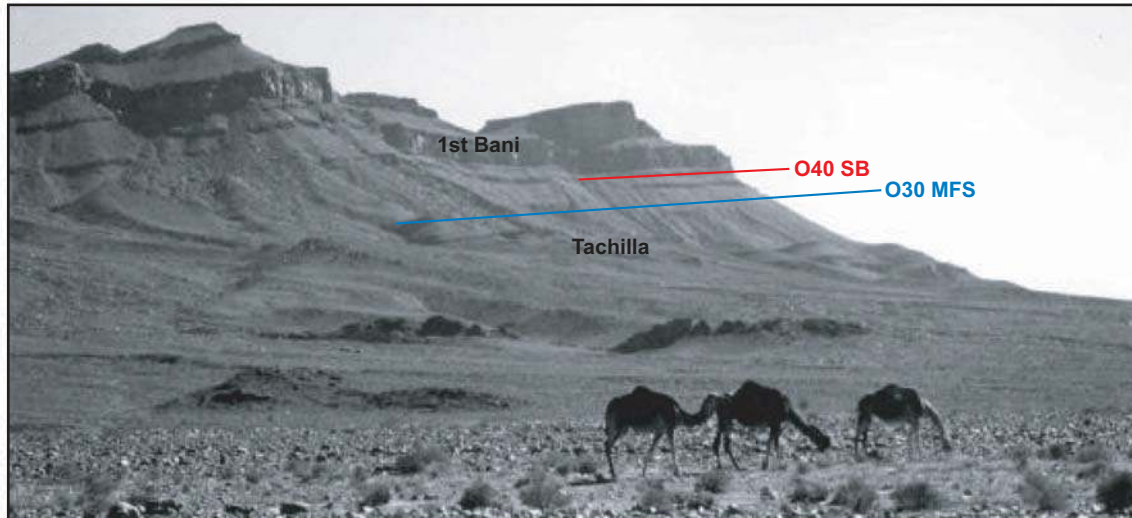


Figure 12: O30 MFS can be picked in the open-marine Tachilla Shale of the Anti-Atlas, Morocco. Graptolites and palynomorphs described from this interval confirm attribution to the *murchisoni* graptolite zone, as in the reference section in Saudi Arabia. Photograph reproduced with the permission from Gutierrez-Marco et al. (2003).

These, and other examples, allow us to demonstrate that the O30 MFS can be recognised in *murchisoni* Zone sediments (or equivalent) right across northern Gondwana, and in the separate continents of Baltica and Laurentia as shown on Figure 10. There is no doubt that O30 is a global phenomenon.

Another way of testing the global applicability of the Arabian Plate sequence stratigraphic model is to compare the position of our surfaces with those defined in the sea-level curves of other authors, where we can clearly see how their curve has been constructed.

One such curve would be that of Sahagian et al. (1996) for the Jurassic and Cretaceous of the Russian Platform and Western Siberia. Here, a detailed relative sea-level curve has been constructed using the excellent outcrops and seismic and borehole expression of the progradation and retrogradation of clastics systems into the Russian Platform. The ages of progradation and retrogradation are calibrated by various palaeontological data, including ammonites. This allows attribution of sea-level falls and rises to the Boreal ammonite standard for the Jurassic and Cretaceous, which in turn can be compared with the Tethyan standard.

As can be seen from Figure 13, there is excellent biostratigraphic correspondence of our Arabian Plate MFS from Sharland et al. (2001) with sea-level maxima as identified by Sahagian et al. (1996). There are additional maxima (= MFS) recognised by Sahagian et al. and some of these correspond to MFS that we have subsequently recognised in Arabia and elsewhere in the world in unpublished work. However, the most important point is that MFS recognised in Arabia can be recognised in West Siberia and confirmed to be of precisely the same age (within the resolution of biostratigraphy – in this case less than 0.5 My).

Dromart et al. (2003) have reviewed global sea-level change in the Callovian period. They note a major sea-level rise occurred in the mid-Callovian (*anceps* – *coronatum* zones) and tabulated its occurrence, usually in the form of organic-rich deposits, with data points as far afield as the Philippines and the Falkland Plateau in the South Atlantic. This is our J40 MFS (Sharland et al., 2001), with its reference section in the Tuwaiq Mountain Limestone of Saudi Arabia, another surface with global distribution (see Figure 10).

Interestingly, Dromart et al. (2003) have also tabulated the global synchronicity of a major sea-level fall and hence sequence boundary in the late Callovian (*lamberti* zone) – this is our J50 SB (Sharland et al., 2001). They provide convincing oxygen isotope data to suggest that an ice cap with a total ice

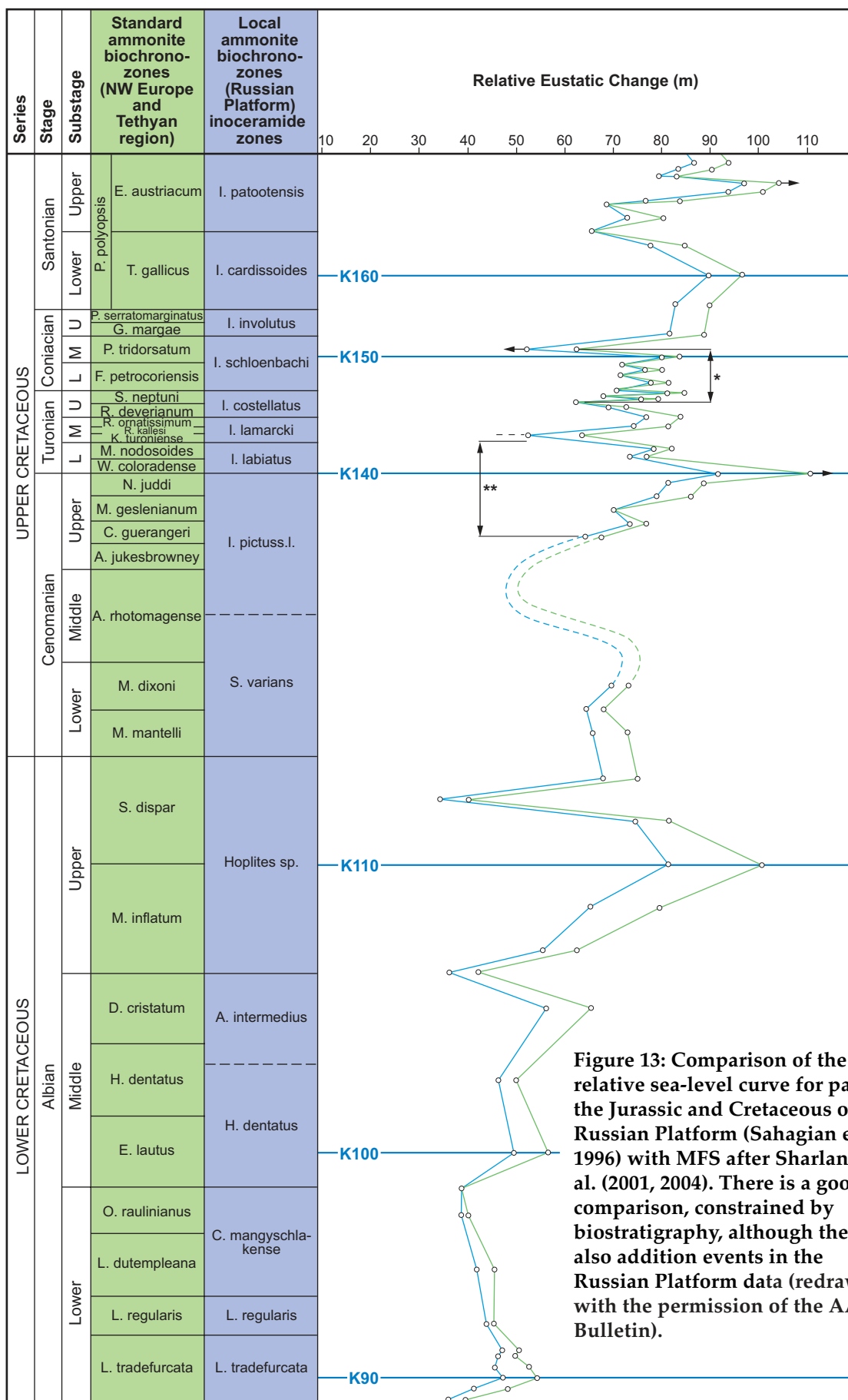
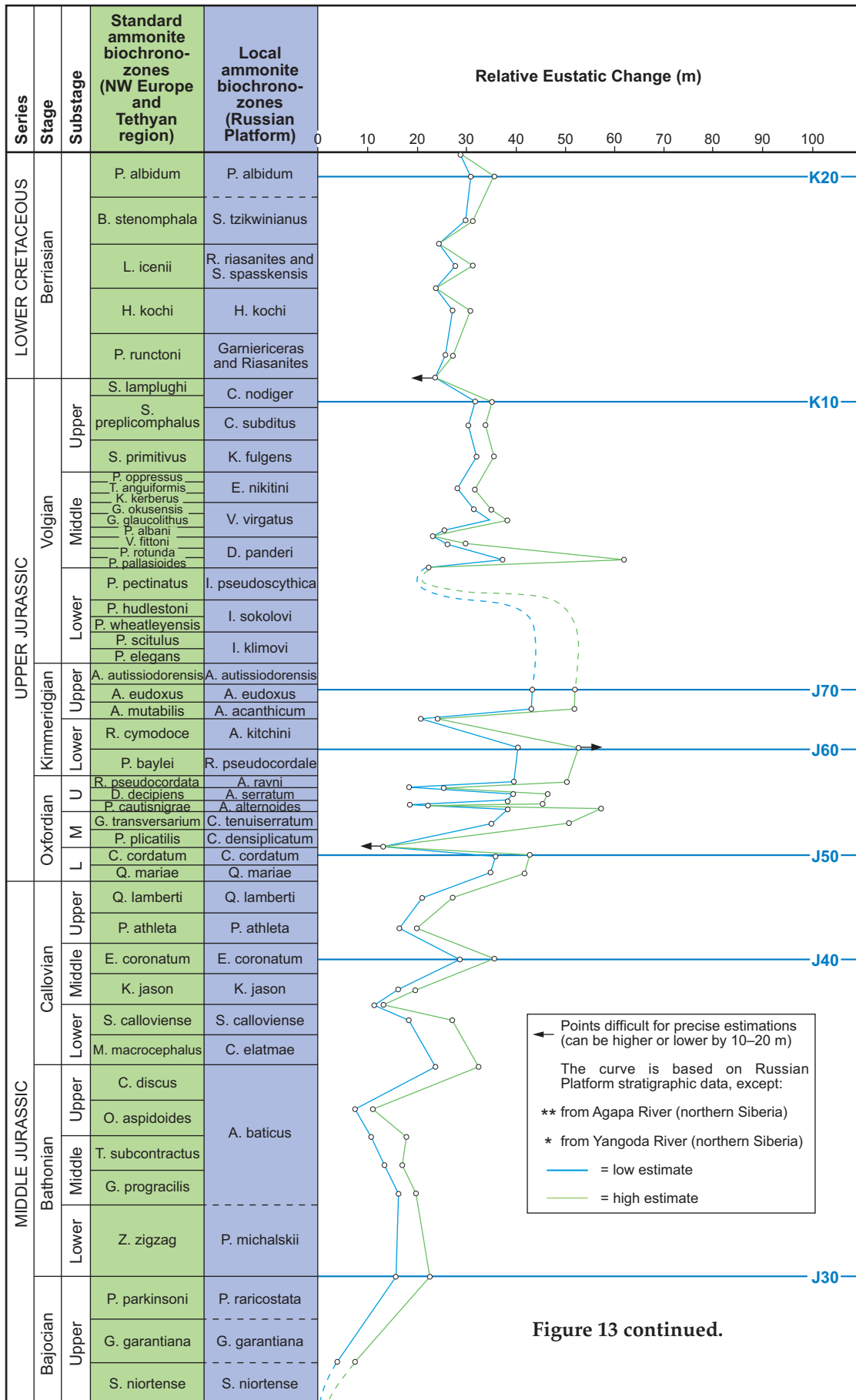


Figure 13: Comparison of the relative sea-level curve for parts of the Jurassic and Cretaceous of the Russian Platform (Sahagian et al., 1996) with MFS after Sharland et al. (2001, 2004). There is a good comparison, constrained by biostratigraphy, although there are also addition events in the Russian Platform data (redrawn with the permission of the AAPG Bulletin).



volume of 6–9 million km³ had developed over present-day East Siberia, the formation and melting of which would be sufficient to change sea-level in the order of 40-80 m.

Other examples of demonstrating the global synchronicity include Hancock (2004) who demonstrated the widespread and synchronous occurrence of what we would term K130 SB in the middle Cenomanian.

We feel confident that a detailed global model of eustatic sea-level change and sequence stratigraphy tied precisely to huge volumes of outcrop and subsurface data is emerging, and that with this in mind, we can propose that such global sequences form a useful adjunct to chronostratigraphic (i.e. stage) definition.

Base Albian (K90 SB) Example

At present there is no agreed definition for the base of the Albian (Gradstein et al., 2004). Can sequence stratigraphy offer a guide to choosing a viable definition?

The Albian stage, as with other examples we have mentioned, was originally described in a platform setting, with an unconformity (sequence boundary) at its base. It was originally described from the Alb region of France by d’Orbigny (1842) and at its type locality there are erosive based sands in its lower part (Figure 14). Consequently a GSSP is currently being sought in a basinal location with continuous deposition. Several contrasting guide events have been suggested for the base Albian

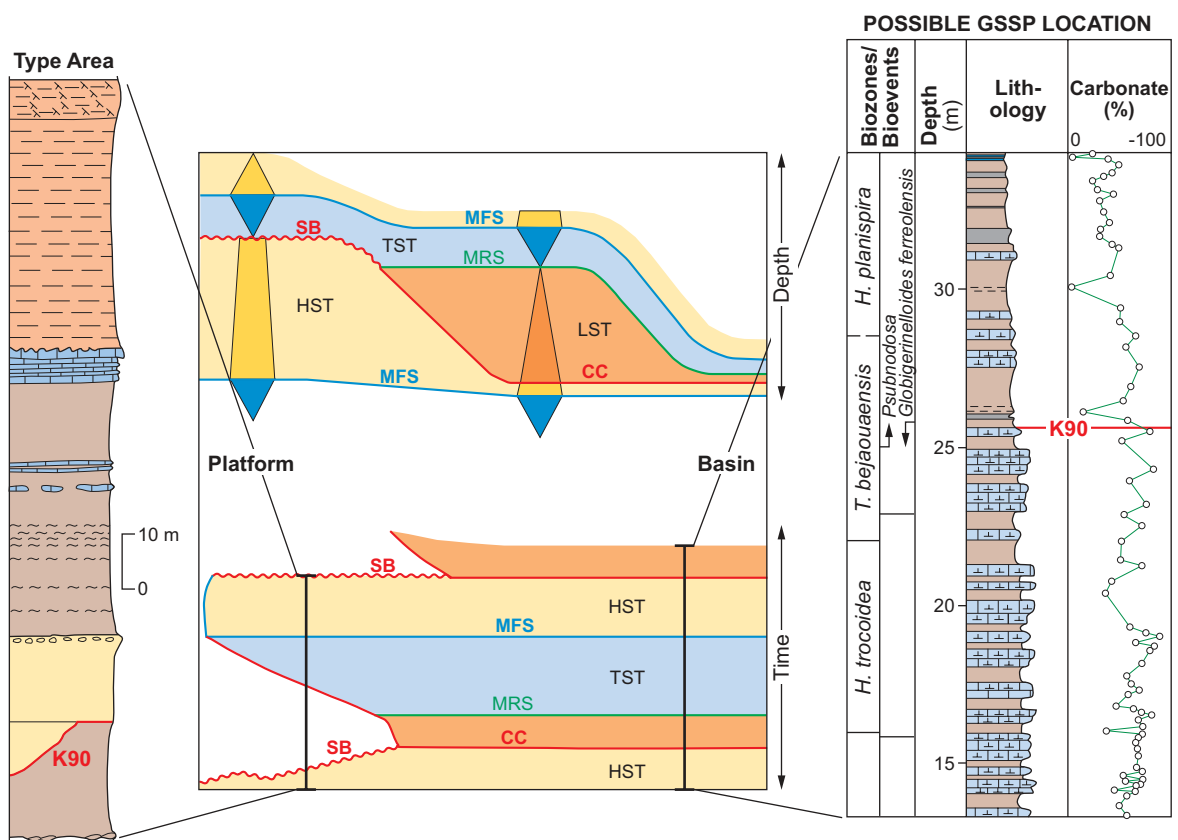


Figure 14: The sequence stratigraphic location of the type area of the Albian stage compared with a possible GSSP location in Umbria, Italy. The type area in Alb, France (illustration after Cavalier and Roger, 1980) is in a platform, up-system tract, position with a sequence boundary (K90 SB) (missing time) at its base. In the basinal setting in Italy (Coccioni et al., 1990) there is continuous deposition, although K90 CC can be detected by the influx of clays into the basin synchronous with the extinction of the planktonic foraminifera *Globigerinelloides ferreolensis*. This may provide a guide to GSSP selection.

GSSP, and there is much debate amongst the Albian community as to the value of each and the best location for a GSSP (Hart et al., 1996; Kennedy et al., 2000; Hancock, 2001; Owen, 2002).

K90 SB is the sequence boundary to the K90 MFS as defined by Sharland et al. (2001) and is an important and easily recognisable sequence boundary across Arabia. We have also recognised it in North Africa, the Mediterranean region, South America, and throughout the former Soviet Union, as far north as the Barents Sea.

In Arabia, K90 SB is typically associated with the replacement of carbonate deposition (e.g. Shu'aiba Formation, Dariyan Formation) with clastic deposition (e.g. Burgan Formation, Nahr Umr Formation) (Figure 15). In Arabia this dramatic change is the sedimentary response to the uplift of the Arabia-Nubian Shield, in turn responding to accelerated opening of the South Atlantic Ocean and the onset of increased subduction in the Neo-Tethys Ocean. In response to these events major deltas sourced by rivers flowing from the Arabian Shield prograded eastwards and caused the cessation of carbonate deposition. Facies transitions across this sequence boundary are spectacular and are of no small economic importance. The karstification of the underlying platform carbonates at this sequence boundary helps create, for example, many Shu'aiba reservoirs (Witt and Gökdog, 1994; Boote and Mou, 2003), whilst the onset of clastic deposition at the sequence boundary is also the onset of deposition of the important Burgan and Nahr Umr reservoirs.

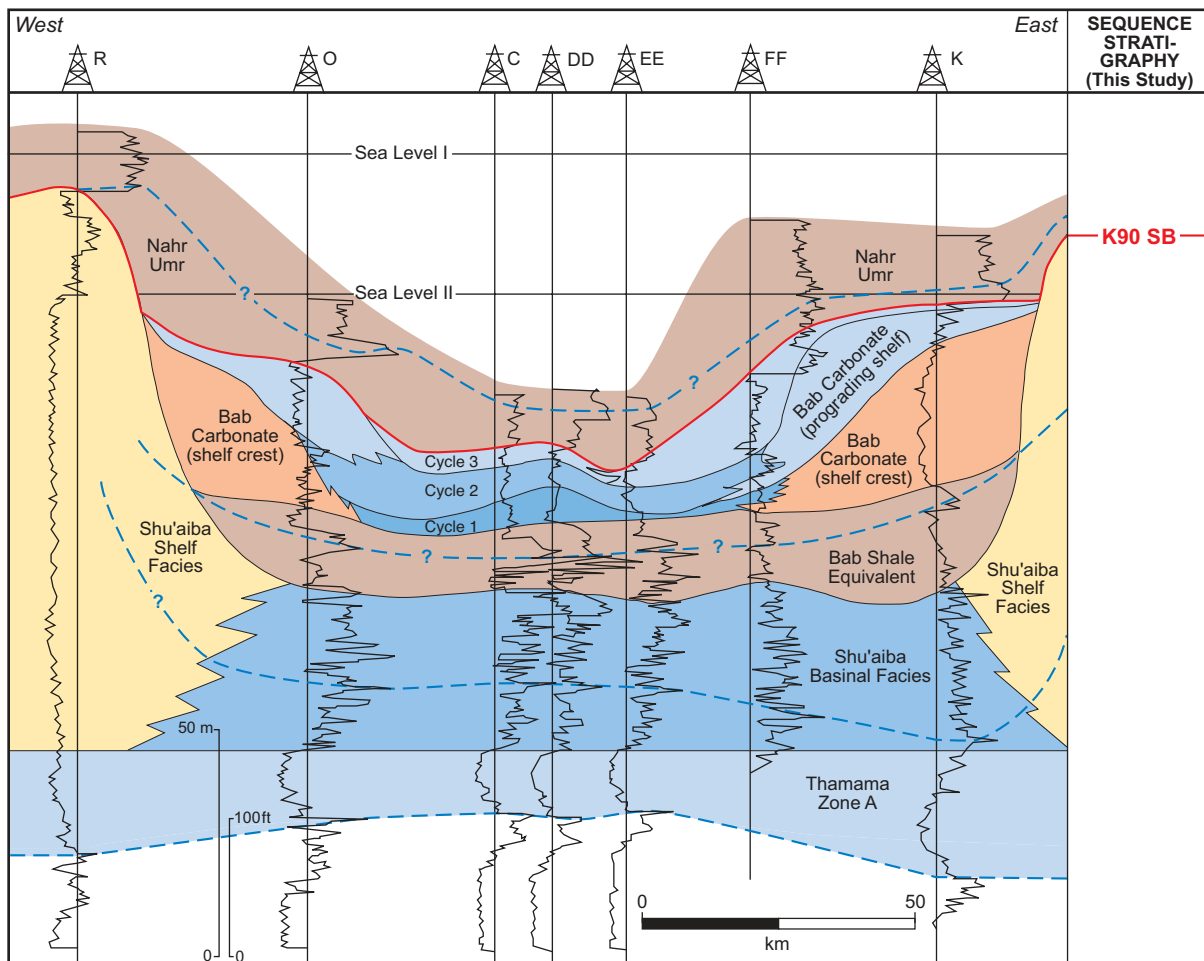


Figure 15: Occurrence of K90 SB in the Shu'aiba Platform – Bab Basin area of the UAE (data after Taher, 1997, redrafted in Sharland et al., 2001). Clastic input characterises this SB/CC and biostratigraphic and isotope data (Vahrenkamp, 1996) places this boundary in the *jacobi* Zone of the ammonite standard.

In a platform location, K90 SB can encompass a long period of non-deposition and erosion. However, in basinal settings, where carbonates are replaced by clastics it can be tied to the later part of the *jacobi* ammonite biozone (e.g. Bab Basin, United Arab Emirates data, Vahrenkamp, 1996; Tunisia Dorsale data, Souquet et al., 1997). This ammonite zone traditionally lies in the uppermost part of the Aptian.

As noted above, K90 SB is readily identifiable outside of Arabia and indeed it is expressed in the basinal areas of the Mediterranean region under consideration for GSSP definition. For example, at Poggio le Guaine, Umbria, Italy (Coccioni et al., 1990), K90 SB (in correlative conformity) can be located by the sudden onset of clay-rich deposition at the base of the K90 lowstand (Figure 14). This onset of clastic deposition (and hence SB/CC) is associated with the extinction of the planktonic foraminifera *Globigerinelloides ferreolensis*. A similar feature is seen in the Piobbico core taken nearby (Tornaghi et al., 1989). The extinction of *Globigerinelloides ferreolensis* has long been considered by micropalaeontologists (Caron, 1985; BouDagher-Fadel et al., 1997) as an approximate proxy for the Aptian/Albian boundary. Given that this event is associated with the globally important K90 SB we would strongly recommend that it is this K90 SB event that is given priority as a base Albian GSSP guide. This would harmonise the base of the Albian with an important sequence boundary and honour the original concepts on which the Albian was first described.

DISCUSSION AND CONCLUSIONS

We hope that through the examples described above we have been able to demonstrate that there is a natural link between chronostratigraphy and sequence stratigraphy (Figure 16), a culmination of almost 200 years of scientific endeavour beginning with William Smith's first geological mapping exercise published in 1815.

When stages, the basic units of chronostratigraphy, were first introduced by d'Orbigny, many were unconformity-bounded units, relating to marked events (we would say sea-level change) in Earth history. Whilst many stages were originally described from platform settings, GSSPs for stages are currently being sought in basinal locations where there is continuous deposition. In such settings it may be practical to recognise the correlative conformity to the sequence boundary relating to the original description. This in turn can be related to a palaeontological event (fossil species evolutionary inception or extinction) which can be used as a guide in GSSP definition. In such a way the two disciplines of chronostratigraphy and sequence stratigraphy can be reconciled and harmonised.

Harmonising stage boundaries and correlative conformities of sequence boundaries are one way in which a "natural boundary" may be selected for a stage boundary. The concept of "natural boundaries" has been much debated in the literature during the history of GSSPs and both Ager (1993a) and, more recently, Remane (2003) and Walsh et al. (2004) have been critical of such a concept. Nonetheless, many would argue that stratigraphers who have looked at a given period of geological time long enough know instinctively that there are "events" in the rock record during that time period that can be recognised at many localities (Wang Xulian, 2002) (termed the "Best Natural Boundary" by Mei Shilong (1996)). These range from events relating to impacts of extra-terrestrial bodies and mass volcanism, to climate and sea-level change. This echoes the original concepts of d'Orbigny who believed that his stages were "a natural chronological division of earth history" (Monty, 1968). Hedberg (1976) in the original version of the *International Stratigraphic Guide* recognised that "if major natural changes ("natural breaks") in the historical development of the Earth can be identified at specific points in sequences of continuous deposition, these may constitute desirable points for the boundary-stratotypes of stages".

In a series of well-argued polemics Walliser (1984, 1985) noted that there are what he termed "natural" boundaries and "commission" boundaries in the Devonian Period. By this he meant that many Devonian workers would instinctively recognise say the base of the Famennian Stage from Australia to Canada on the basis of a change in the rock record relating to climate/sea-level change – this may not be the same location as an artificially introduced boundary based on the extinction or inception of a particular species, no matter how useful that event in correlation.

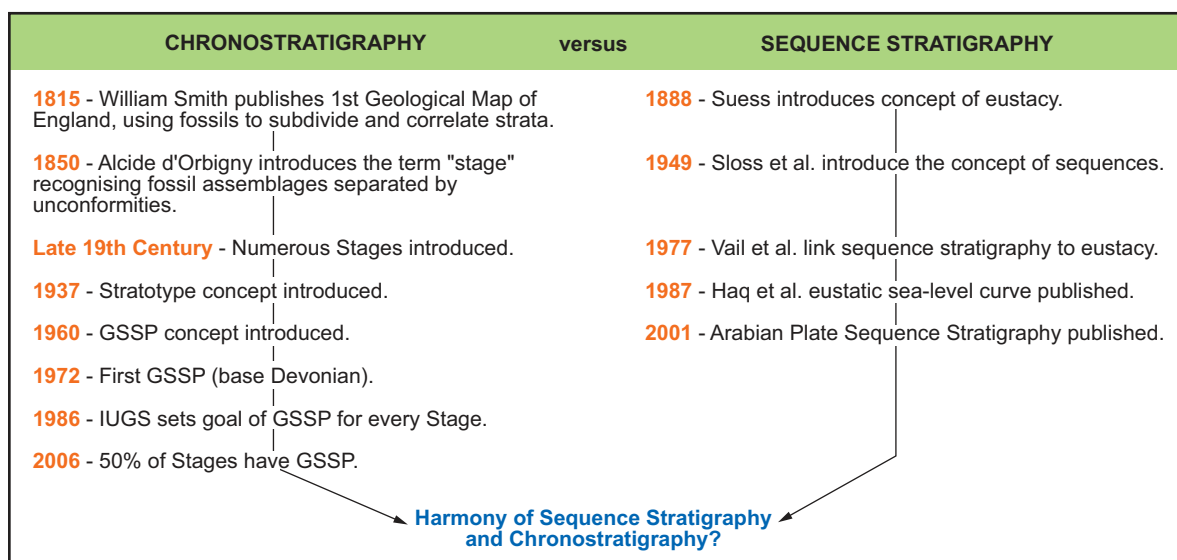


Figure 16: In the course of geological research, chronostratigraphy and sequence stratigraphy have undergone separate, parallel, lines of research. The integration of sequence stratigraphic concepts into GSSP definitions will provide a means of harmonising these two related disciplines.

We have much sympathy for Walliser's views – there are events in the rock record that are important in correlation, and these should be taken into account. Derek Ager (1993a) in his splendid book "the Nature of the Stratigraphical Record" argued that stratigraphers should cease their quest for the golden horizon of the "true" beginning of chronostratigraphic subdivisions via "natural boundaries", but, conversely, in his last book (Ager, 1993b) stressed the importance of the event in geological history. The late Jürgen Remane, *doyen* of the ICS and a major protagonist for the creation of GSSPs, stated, in an often-quoted and much debated remark that "correlation should precede definition" (Remane et al., 1996; Remane, 2003) (see also Murphy, 1994, for a similar view). And, as the late D.J. MacLaren (another pioneer in the GSSP movement) once wrote: "Without correlation, successions of time derived in one area are unique, and contribute nothing to understanding Earth history elsewhere" (MacLaren, 1978). We would agree – what is the eustatic event (and hence associated bioevent) in the rock record that can be correlated and recognised around the world? This should form the basis for GSSP definition.

The stratigraphers defining GSSPs represent a small fraction of practising geoscientists. If they do not choose boundaries that geoscientists can readily recognise in the rock record and relate to events in Earth history, they will not find favour and the geoscience community will be no further forward in its quest to obtain definition and stability in chronostratigraphy.

As a final example, the definition of the base of the Pleistocene has recently come under review as part of the hot debate on the status and definition of the Quaternary. Gibbard et al. (2005) indicate that they would like to see the base Pleistocene revised from association with an event around 1.8 Ma to association with an event at 2.6 Ma (the base of the Gelasian stage). They are not the first to suggest this – the base Pleistocene was formally defined and ratified with a GSSP over 20 years ago and an attempt to revise this definition in 1998 met without success (see for example, Morrison and Kukla, 1998, versus Vai, 1997, and Aubry et al., 1998). The gist of the Gibbard et al. argument is that the onset of the expansion of Northern Hemisphere ice sheets occurs around 2.6 Ma and it is this event that forms the "natural" base to the Pleistocene Stage, which is commonly used as a synonym for ice-age conditions (the reduction in African forests and the coeval increase in savannah led our human ancestors to leave the canopy at this time (Dunbar, 2004)). The GSSP event at 1.8 Ma is, in the opinion of Gibbard et al., and other workers, a minor climatic event (it was nonetheless coincident with the onset of the rapid expansion in human brain size (Dunbar, 2004)). So we now have two usages of

Pleistocene – one that is defined by its GSSP and sanctioned by the ICS and another that is being used by a large group of scientists active in Pleistocene research!

To recall the phrase of Humpty-Dumpty we used at the beginning of this article “when I use a word it means exactly what I want it to mean, neither more, nor less”. We must avoid such a situation in chronostratigraphy by defining chronostratigraphic units using events in the rock record that the whole Earth Science community can recognise as significant. Sequence stratigraphy is an essential tool in the recognition of such events.

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