Arabian Plate sequence stratigraphy: Potential implications for global chronostratigraphy

Michael D. Simmons, Peter R. Sharland, David M. Casey, Roger B. Davies and Owen E. Sutcliffe

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, Visean, 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.

ERA	PERIOD	EPOCH	STAGE	AGE (Ma)	GSSP	ARABIAN PLATE SEQUENCE STRATI- GRAPHY	ERA	PERIOD EPOCH	STAGE		AGE (Ma)	GSSP	ARABIAN PLATE SEQUENCE STRATI- GRAPHY	
			Gelasian Piacenzian	1.8 2.6					Tithoniar	1			J110 14 J110 SB 14	<u>7.0</u> 9.0
<u>0</u>	Щ		Zanclean Messinian	3.0 5.3 7.2 11.6 13.6 16.0 20.4 23.0				Ľ	Kimmeria	lgian	150.8		<u>J90</u> <u>J80</u> <u>151.8</u> <u>151.</u> J70 <u>J80</u> <u>151.8</u> <u>152.</u>	4
	GEN		Tortonian					2	Oxfordia	า	154.5		J60 SB 150	<u>25</u> 6.0
	NEO		Langhian			Ng40 14.5 Ng30 15.9 Ng20 17.5		-	Calloviar	<u> </u>	161.2		<u>J50 15</u> J40 16	<u>9.0</u> 2.5
			Burdigalian			Ng20 SB-19.0			Bathonia	n	164.7		J40 SB 16	<u>5.0</u>
			Aquitanian			Ng10 SB 23.0		SSIC	Bajocian		167.7		J20 17	<u>7.5</u>
		OLIGO- CENE	Chattian	-28.4		Pg50 24.5 Pg40 29.0		RA RA	Aalenian		171.6			
OZO			Rupelian			Pg30 33.0		= -	- .	175.6			J20 SB 17	<u>7.0</u>
EN I			Priabonian			Pg30 SB 33.5			loarcian		100.0		J10 18	1.0
	Ш Ц Ц		Bartonian	40.4				5	Pliensba	chian	163.0			
	OG	ENER ENER ENER	Lutetian				<u>ں</u>	EAR			189.6		J10 SB 18	<u>8.0</u>
	LAE	EOC		48.6		Pg20 50.0	OZO		Sinemuri	an				
	PA		Ypresian			Pg20 SB 51.0	ESC		Hettangian		196.5			
			L Thanetian				Σ		Rhaetian		199.6			
		AEA	Selandian	58.7 61.7		Pg10 59.0					203.6		Tr80 20	8.0
		Danian		65.5		Pg10 SB 63.0			Norian				1100 20	0.0
		Maastrichtian		05.5		K180 70.0		LATE					Tr80 SB 214	<u>4.0</u>
				70.6							216.5		Tr70 22	0.0
	IJ	Campanian Santonian				K170 78.0		SIC	Carnian				Tr70 SB 22	3.5
					K170 SB 80.0		IASS			000.0		Tr60 22	7.0	
	Ľ			83.5		K160 85.0		TR			228.0		Tr60 SB 22	<u>9.0</u>
	RLY CRETACEOUS	Coniacian		89.3		K150 88.0		щ	Ladinian				Tr50 23	<u>3.0</u>
		Turonian		93.5		K150 SB 92.0 K140 93.0		MIDDI			237.0			
		Cenomanian				K130 95.5			Anisian				Tr40 24: Tr40 SB 24	<u>2.0</u> 4.2
S				99.6		K120 99.0 K110 100.5		3LY	Olenekia	n	245.0		/Tr30-249.	7~
OZO		Albian						EAF	Induan		249.7 251.0		Tr20	0- <u>0.5</u> 1.0
MES						K100 108.0			Lopingian	Changhsingian	253.8		P40 25	3.0 6.0
		Aptian		112.0		K90 110.0 K90 SB 112.5				Wuchiapingian			<u>r 30 20</u>	0.0
					K80 119.0					260.4				
						11010	oic	z	Guada- Iupian	Wordian	265.8		P20 26	6.0
	EAF			125.0		K70 124.5 K60 125.5	ZOE	MIA.	Roadian	Roadian	270.6		P20 SB 27	1.0
		Barremian		130.0		K50 129.0		DER		Kungurian	275.6			
		Hauterivian				<u>K40 134.5</u>	PA		Artinski	Artinskian				
		Valanginian		136.4		K40 SB 139.5			Cisuralian		204.4			
		Berriasian		140.2		K30 140.0				Sakmarian	284.4		P10 28	<u>8.0</u>
		Derriasia		145.5		K20 142.0 K10 145.0								





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 stages names to choose from. Gradually in the second half of the 20th Century, these names have become synonimised 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; Zhamoida, 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 know 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 Cavelier 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 in 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 Simaeys (2004) and Van Simaeys 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 platformal 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 Simaeys, 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 Simaeys 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 2001and 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



111



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).



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).

section in Tunisia.

wichmann

137

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 eustacy; and/or (3) there are local sequences that do not match global patterns; and/or (4) there is no proven mechanism for third-order eustacy 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



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-Duaji, 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 z*one 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.

					GRAPTOLITES (Ph. Legrand)	TRILOBITES (J.L. Henry)	CONODONTS (M. Weyant)
					armer (k)	as H-Khayal nd Romano) nan nan	nd Mehl) n udstrom) dstrom)
SYSTEM	STAGE	FORMATION	MEMBER	GENERALIZED LOG	Didymograptus gr. bifidus (Hall) Didymograptus gr. murchisoni (Didymograptus aff. D. clavulus Didymograptus ap. nu Cyptiograptus sp. ? Glyptograptus sp. Diplograptus sp. Diplograptus sp. Diplograptus sp.	N. (Neseuretus) tristani (I.s.) Plaesiacormia vacuvertis Thoma N. (neseuretus) sp. Ningvianolithus hanadirensis El Crozonaspis sp. Crozonaspis nov. sp. Dercooryphe cf. verneulit Hamr Phacopidina nov. sp. Annphidae Kerfornella sp. ? Calymenella sp. ? Calymenella sp.	Oistodus abondans (Branson al Boltonidius variabilis (Bergstror Drepanodus suberectus (Brans Drepanodus homocurvatus (Lin Saggitodontus sp. Corylodus sp. Keislognathus sp. Hibbardella sp.
z	adocian to ngillian		Quwarah Mbr		soni Zone		
ORDOVICIAN	Cara Ash	rmation	Ra'an Mbr		murchis		
	Llandeilian	Qasim Fo	Kahfah Mbr ₋ _		• • bidymograptus		
	Llanvirr ite-mid	dle Sag Sst	Hanadir Mbr Saiir Mbr		••••••••••••••••••••••••••••••••••••••		•••

Figure 11: Location of the 030 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





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 Cavelier 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 Gökdag, 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.

CHRONOS	TRATIGRAPHY	versus	SEQUENCE STRATIGRAPHY				
1815 - William Smith pub England, using fossils to	lishes 1st Geological Map of subdivide and correlate strata	l.	1888 - Suess introduces concept of eustacy.				
1850 - Alcide d'Orbigny in recognising fossil assemi unconformities.	htroduces the term "stage" blages separated by		1949 - Sloss et al. introduc	ce the concept of sequences.			
Late 19th Century - Nur	nerous Stages introduced.		1977 - Vail et al. link seque	ence stratigraphy to eustacy.			
1937 - Stratotype concep	t introduced.		1987 - Haq et al. eustatic	l sea-level curve published.			
1960 - GSSP concept int	roduced.		2001 - Arabian Plate Sequ	lence Stratigraphy published.			
1972 - First GSSP (base	Devonian).						
1986 - IUGS sets goal of	GSSP for every Stage.						
2006 - 50% of Stages ha	ve GSSP.						
Harmony of Sequence Stratigraphy and Chronostratigraphy?							

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 GSPP 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.

ACKNOWLEDGEMENTS

The authors are grateful to their colleagues at Neftex Petroleum Consultants Ltd for discussion of the ideas presented in this paper and comments on early drafts of the manuscript. We are also grateful to those geoscientists who have commented on our conference presentations at which we outlined the ideas within this paper. We would like to give special thanks to the anonymous GeoArabia reviewers whose comments helped improve this paper. We wish to thank Wendy Cawthorne and her colleagues at the library of the Geological Society of London for obtaining various published articles for us and to thank those geoscientists who kindly sent us reprints of their papers. Our thanks go to Heather Pattison and the GeoArabia team for greatly improving the presentation of this paper. All those figures based on previously published figures or data are redrawn or modified. We have made every effort to gain permission to do so from relevant copyright holders.

REFERENCES

Ager, D.V. 1993a. The Nature of the Stratigraphical Record (3rd Edition). Wiley, 151 p.

- Ager, D.V. 1993b. The New Catastrophism. Cambridge University Press, 231 p.
- Aguado, R., M. Company and J.M. Tavera 2000. The Berriasian/Valanginian boundary in the Mediterranean region: new data from the Caravaca and Cehegín sections, SE Spain. Cretaceous Research, v. 21, p. 1-21.
- Aguirre Urreta, M.B. and P.F. Rawson 1997. The ammonite sequence in the Agrio Formation (Lower Cretaceous), Neuquén Basin, Argentina. Geological Magazine, v. 134, p. 449-458.
- Al-Fares, A.A., M. Bouman and P. Jeans 1998. A new look at the Middle to Lower Cretaceous stratigraphy, offshore Kuwait. GeoArabia, v. 3, no. 4, p. 543-560.
- Al-Hajri, A. 1995. Biostratigraphy of the Ordovician chitinozoa of northwest Saudi Arabia. Review of Palaeobotany and Palynology, v. 89, p. 27-48.
- Al-Hajri, A. and B. Owens 2000. Sub-surface palynostratigraphy of the Palaeozoic of Saudi Arabia. In, A. Al-Hajri and B. Owens (Eds.), Stratigraphic Palynology of the Palaeozoic of Saudi Arabia. GeoArabia Special Publication 1, Gulf PetroLink, Bahrain, p. 10-17.
- Ali, A.J. and M.E. Nasser 1989. Facies analysis of the Lower Cretaceous oil-bearing Zubair Formation in southern Iraq. Modern Geology, v. 13, p. 225-242.

Alley, R.B., J. Marotzke, W.D. Nordhaus, J.T. Overpeck, D.M. Peteet, R.A. Piekle, R.T. Pierrehumbert, P.B. Rhines, T.F. Stocker, L.D. Talley and J.M. Wallace 2003. Abrupt climate change. Science, v. 299, p. 2005-2010.

Arkell, W.J. 1933. The Jurassic System in Great Britain. Oxford University Press, 681 p.

Arkell, W.J. 1956. Jurassic Geology of the World. Oliver and Boyd, 806 p.

- Aubry, M.-P. and W.A. Berggren 2000. The homeless GSSP: the dilemma of the Paleocene/Eocene boundary. Tertiary Research, v. 20, p. 107-112.
- Aubry, M.-P., W.A. Berggren, J.A. Van Couvering, R. Rio and D. Castradori 1998. The Pliocene Pleistocene boundary should remain at 1.81Ma. GSA Today, November 1998, p. 22.
- Aubry, M.P., W.A. Berggren, J.A. Van Couvering and F. Steininger 1999. Problems in chronostratigraphy: stages, series, unit and boundary stratotypes, global stratotype section and point and tarnished golden spikes. Earth-Science Reviews, v. 46, p. 99-148.
- Berry, W.B.N. 1987. The Ordovician-Silurian boundary: new data, new concerns. Lethaia, v. 20, p. 209.
- Beydoun, Z.R., M.A.L. As-Saruri, H. El-Nakhal, I.N. Al-Ganad, R.S. Baraba, A.S.O. Nani, A.S.O. and M.H. Al-Aawah 1998. Republic of Yemen, International Lexicon of Stratigraphy; Volume III. Fascicule 10b2, International Union of Geological Sciences, Publication no. 34, 245 p.
- Birkelund, T. 1983. Cretaceous stage boundaries. In, T. Birkelund, R.G. Bromley, W.K. Christensen, E. Hąkansson and F. Surlyk (Eds.), Abstracts. Cretaceous Stage Boundaries Symposium, Copenhagen, October 1983, p. 1-6.
- Birkelund, T., J.M. Hancock, M.B. Hart, P.F. Rawson, J. Remane, F. Robaszynski, F. Schmid and F. Surlyk 1984. Cretaceous stage boundaries: proposals. Bulletin of the Geological Society of Denmark, v. 33, p. 3-20.
- Blanc, E., L.G. Bulot and J.-C. Paicheler 1994. La coupe de référence de Montbrun-les-Bains (Drôme, SE France): un stratotype potentiel pour la limite Berriasien-Valanginien. Comptes Rendus de l'Académie des Sciences, Paris, v. 318, p. 101-108.

- Boote, D.R.D. and D. Mou 2003. Safah field, Oman: retrospective of a new-concept exploration play, 1980 to 2000. GeoArabia, v. 8, no. 3, p. 367-430.
- BouDagher-Fadel, M.K., F.T. Banner, J.E. Whittaker and M.D. Simmons 1997. The Early Evolutionary History of Planktonic Foraminifera. Chapman Hall, 269 p.
- Canerot, J., P. Cugny, B. Peybernes, I. Rahhali, J. Rey and J.P. Thieuloy 1986. Comparative study of the Lower and mid-Cretaceous sequences on different Maghrebian shelves and basins - their place in the evolution of the North African Atlantic and Neotethysian Margins. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 55, p. 213-232.
- Caron, M. 1985. Cretaceous planktonic foraminifera. In, H.M. Bolli, J.B. Sauders and K. Perch-Nielsen (Eds.), Plankton Stratigraphy. Cambridge University Press, p. 17-86.
- Castradori, D. 2002. A complete standard chronostratigraphic scale: how to turn a dream into reality? Episodes, v. 25, p. 107-110.
- Cavelier, C. and J. Roger 1980. Les Etages Français et Leurs Stratotypes. Mémoire du Bureau de Recherches Géologiques et Minières, no. 109, 295 p.
- Coccioni, R., R. Franchi, O. Nesci, N. Perilli, F.-C. Wezel and F. Battistini 1990. Stratigrafia, micropaleontologia e mineralogia delle Marne a Fucoidi (Aptiano inferiore Albiano superiore) delle sezioni de Poggio le Guaine e del Fiume Bosso (Appennino umbro-marchigiano). In, G. Pallini, F. Cecca, S. Cresta and M. Santantonio (Eds.), Proceedings Fossili, Evoluzione, Ambiente. Pergola, 25-30 Ottobre, 1987, Comitato Centenario Raffaele Piccinini, p. 163-201.
- Darwin, C. 1859. Origin of Species by Means of Natural Selection or the Preservation of Favoured Races in the Struggle for Life. John Murray, 512 p.
- Davies, R.B., D.M. Casey, A.D. Horbury, P.R. Sharland and M.D. Simmons 2002. Early to mid-Cretaceous mixed carbonate-clastic shelfal systems: examples, issues and models from the Arabian Plate. GeoArabia, v. 7, no. 3, p. 541-598.
- Destombes, J. 1963. Donnees stratigraphiques sur l'Ordovicien de l'Anti-Atlas (Maroc). Revue De l'Institut Français du Pétrole, 1963, p. 150-157.
- Destombes, J., H. Holland and S. Willefert 1985. Lower Palaeozoic rocks of Morocco. In, C.H. Holland (Ed.), Lower Palaeozoic of North-Western and West-Central Africa. Wiley, p. 91-336.
- Deunff, J. 1977. Un microplancton á acritarches dans les schistes Llanvirniens de l'Anti-Atlas (Zagora-Maroc). Notes du Service Geologique de Maroc, v. 38, p. 141-151.
- Dromart, G., J.-P. Garcia, S. Picard, F. Atrops, C. Lecuyer and S.M.F. Sheppard 2003. Ice age at the Middle-Late Jurassic transition? Earth and Planetary Science Letters, v. 213, p. 205-220.
- Dunbar, R. 2004. The Human Story. Faber & Faber, 216 p.
- Dupuis, C., M. Aubry, E. Steurbaut, W.A. Berggren, K. Ouda, R. Magioncalda, B.S. Cramer, D.V. Kent, R.P. Speijer and C. Heilmann-Clausen 2003. The Dababiya Quarry Section: lithostratigraphy, clay mineralogy, geochemistry and paleontology. Micropaleontology, v. 49, p. 41-59.
- Durante, L.V., V.P. Wright, S. Fernández-López, S. Elmi, M. Krautter, A. Azerêdo, M.H. Henriques, R. Rodrigues and N. Perilli 2004. Early Jurassic carbonate evolution in the Lusitanian Basin (Portugal): facies, sequence stratigraphy and cyclicity. In, L.V. Durante and M.H. Henriques (Eds.), Carboniferous and Jurassic Carbonate Platforms of Iberia. 23rd IAS Meeting of Sedimentology, Coimbra, 2004, Field Trip Guidebook, v. 1, p. 47-71.
- Ekren, E.B., D. Vaslet, A. Berthiaux, P. Le Strat and J. Fourniguet 1986. Geologic map of the Ha'il quadrangle, sheet 27E, Kingdom of Saudi Arabia (scale 1:250,000). Explanatory notes and map GM-115C. Deputy Ministry for Mineral Resources, Jeddah, Saudi Arabia, 46 p.
- Elaouad-Debbaj, Z. 1984. Acritarches et chitinozoaires de l'Arenig-Llanvirn de l'Anti-Atlas (Maroc). Review of Palaeobotany and Palynology, v. 43, p. 67-89.
- El-Khayal, A.A. and M. Romano 1988. A revision of the upper Saq Formation and Hanadir Shale (Lower Ordovician) of Saudi Arabia. Geological Magazine, v. 125, p. 161-174.
- Fuchs, T. 1894. Tertiärfossilien aus den kohleführenden Miozänablagerungen der Umgebung von Krapina und Radoboj und über die Stellung der sogenannten "Aquitanischen Stufe". Mitteilungen aus dem Jahrbuche der königlich Ungarischen Geologischen Anstalt, v. 10, p. 161-175.
- Gibbard, P.L., A.G. Smith, J.A. Zalasiewicz, T.L. Barry, D. Cantrill, A.L. Coe, J.C.W. Cope, A.S. Gale, F.J. Gregory, J.H. Powell, P.R. Rawson, P. Stone and C.N. Waters 2005. What status for the Quaternary? Boreas, v. 34, p. 1-6.
- Goldhammer, R.K. and C.A. Johnson 2001. Middle Jurassic-Upper Cretaceous Paleogeographic Evolution and Sequence-stratigraphic Framework of the Northwest Gulf of Mexico Rim. American Association of Petroleum Geologists, Memoir 75, p. 45-81.
- Gradstein, F.M. and J.G. Ogg 2004. Geologic Time Scale 2004 why, how, and where next! Lethaia, v. 37, p. 175-181.
- Gradstein, F.M., J.G. Ogg and A.G. Smith (Eds.) 2004. Geologic Time Scale 2004. Cambridge University Press, 500 p.
- Gutierrez-Marco, J.-C., J. Destombes, I. Rabano, G.F. Acenolaza, G.N. Sarmiento and M.A. San José 2003. El Ordovicio Medio del Anti-Atlas Marroqui: paleobiodiversidad, actualizacion bioestratigrafica y correlacion. Geobios, v. 36, p. 151-177.
- Hallam, A. 1990. Correlation of the Triassic Jurassic boundary in England and Austria. Journal of the Geological Society of London, v. 147, p. 421-424.
- Hallam, A. and P. Wignall 2004. Discussion on sea-level change and facies development across potential Triassic-Jurassic boundary horizons, SW Britain. Journal of the Geological Society of London, v. 161, p. 1053-1054.

Hancock, J.M. 1977. The historic development of concepts of biostratigraphic correlation. In, E.G. Kauffman and J.E. Hazel (Eds.), Concepts and Methods of Biostratigraphy. Dowden, Hutchinson & Ross, p. 3-22.

Hancock, J.M. 2001. A proposal for a new position for the Aptian/Albian boundary. Cretaceous Research, v. 22, p. 677-683.

- Hancock, J.M. 2004. The mid-Cenomanian eustatic low. Acta Geologica Polonica, v. 54, p. 611-627.
- Haq, B.U., J. Hardenbol and P.R. Vail 1987. Chronology of fluctuating sea levels since the Triassic (250 million years ago to present). Science, v. 235, p. 1156-1167.
- Hardenbol, J., J. Thierry, M.B. Farley, T. Jacquin, P.-C. de Graciansky and P.R. Vail 1998. Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. In, P.-C. de Graciansky, J. Hardenbol, T. Jacquin and P.R. Vail (Eds.), Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. Society for Sedimentary Geology, Special Publication, v. 60, p. 3-13.
- Harland, W.B., R.L. Armstrong, A.V. Cox, L.E. Craig, A.G. Smith and D.G. Smith 1990. A Geologic Time Scale 1989. Cambridge University Press, 263 p.
- Hart, M., F. Amédro and H. Owen 1996. The Albian Stage and substage boundaries. Bulletin de l'Institut Royal des Sciences Naturelles de Belgique, Sciences de la Terre, 66 (Supplement), p. 45-56.
- Hedberg, H.D. (Ed.) 1970. Preliminary Report on Stratotypes. 24th International Geological Congress Montreal, International Subcommission on Stratigraphic Classification, Report 6, p. 1-39.
- Hedberg, H.D. 1976. International Stratigraphic Guide. Wiley, New York, 200 p.
- Hesselbo, S.P., S.A. Robinson and F. Surlyk 2004a. Sea-level change and facies development across potential Triassic – Jurassic boundary horizons, SW Britain. Journal of the Geological Society of London, v. 161, p. 365-379.
- Hesselbo, S.P., S.A. Robinson and F. Surlyk 2004b. Discussion on sea-level change and facies development across potential Triassic Jurassic boundary horizons, SW Britain. Journal of the Geological Society of London, v. 161, p. 1054-1056.
- Hoedemaeker, P.J., S. Reboulet, M.B. Aguirre-Urreta, P. Alsen, M. Aoutern, F. Atrops, R. Barragan, M. Company, C.G. Arreola, J. Klein, A. Lukeneder, I. Ploch, N. Raisossadat, P.F. Rawson, P. Ropolo, Z. Vasicek and J. Vermeul 2003. Meeting Report: report on the 1st International Workshop of the IUGS Lower Cretaceous Ammonite Working Group, the 'Kilian Group' (Lyon, 11 July, 2002). Cretaceous Research, v. 24, p. 89-94.
- Holden, A. and H.M. Kerr 1997. A subsurface lithostratigraphic division of the Hauterivian to Aptian, Furt (informal) and Qishn Formations, Yemen. Marine and Petroleum Geology, v. 14, p. 631-642.
- Holland, C.H., M.G. Bassett and R.B. Rickards 2003. Stability in stratigraphy. Lethaia, v. 36, p. 69-70.
- Holland, S.M. 1995. Depositional sequences, facies control and the distribution of fossils. In, B.U. Haq (Ed.), Sequence Stratigraphy and Depositional Response to Eustatic, Tectonic and Climatic Forcing. Kluwer, p. 1-24.
- Houseknecht, D.W. and K.J. Bird 2004. Sequence stratigraphy of the Kingak Shale (Jurassic Lower Cretaceous), National Petroleum Reserve in Alaska. American Association of Petroleum Geologists Bulletin, v. 88, p. 279-302.
- Kemp, D.B., A.L. Coe, A.S. Cohen and L. Schwark 2005. Astronomical pacing of methane release in the Early Jurassic period. Nature, v. 437, p. 396-399
- Kennedy, W.J., A.S. Gale, P.R. Bown, M. Caron, R.J. Davey, D. Grocke and D.S. Wray 2000. Integrated stratigraphy of the Aptian-Albian boundary in the Marnes Bleues, at the Col de Pré-Guittard, Arnayon (Drôme), and at Tartonne (alpes-de-Haute-Provence), France: a candidate Global Boundary Stratotype Section and Boundary Point for the base of the Albian. Cretaceous Research, v. 21, p. 591-720.
- Knox, R.W.O'B. 1994. From regional stage to standard stage: implications for the historical Paleogene stratotypes of NW Europe. GFF, v. 116, p. 56-57.
- MacLaren, D.J. 1978. Dating and correlating, a review. In, G.V. Cohee, M.F. Glaessner and H.D. Hedberg (Eds.), Contributions to the Geologic Time Scale. American Association of Petroleum Geologists, Studies in Geology 6, p. 1-9.
- McClure, H.A. 1988. Chitinozoan and acritarch assemblages, stratigraphy and biogeography of the Early Palaeozoic of Northwest Arabia. Review of Palaeobotany and Palynology, v. 56, p. 41-60.
- Mei Shilong, M. 1996. The Best Natural Boundary: a new concept developed by combining the sequence boundary with the GSSP. Acta Geologica Sinica, v. 9, p. 98-106.
- Meister, C., M. Aberhan, J. Blau, J.L. Dommergues, S. Feist-Burkhardt, E.A. Hailwood, M. Hart, S.P. Hesselbo, M.W. Hounslow, M. Hylton, N. Morton, K. Page and G.D. Price 2006. The Global Boundary Stratotype Section and Point (GSSP) for the base of the Pliensbachian Stage (Lower Jurassic), Wine Haven, Yorkshire, UK. Episodes, v. 29, p. 93-106.
- Melinte, M. and J. Mutterlose 2001. A Valanginian (Early Cretaceous) 'boreal nannoplankton excursion' in sections from Romania. Marine Micropalaeontology, v. 43, p. 1-25.
- Menegatti, A.P., H. Weissert and R.S. Brown 1998. High-resolution δ¹³C-Stratigraphy through the early Aptian "Livello Selli" of the Alpine Tethys. Palaeoceanography, v. 13, p. 530-545.
- Miall, A.D. 1997. The Geology of Stratigraphic Sequences. Springer, 433 p.
- Miall, A.D. and C.E. Miall 2001. Sequence stratigraphy as a scientific enterprise: the evolution and persistence of conflicting paradigms. Earth-Science Reviews, v. 54, p. 321-348.

- Miller, K.G., P.J. Sugarman, J.V. Browning, M.A. Kominz, J.C. Hernández, R.K. Olsson, J.D. Wright, M.D. Feigenson and W. Van Sickel 2003. Late Cretaceous chronology of large, rapid sea-level changes: glacioeustasy during the greenhouse world. Geology, v. 31, p. 585-588.
- Miller, K.G., J.D. Wright and J.V. Browning 2005. Visions of ice sheets in a greenhouse world. Marine Geology, v. 217, p. 215-231.
- Monty, C.L. 1968. d'Orbigny's concepts of stage and zone. Journal of Palaeontology, v. 42, p. 689-701.

Morrison, R. and G. Kukla 1998. The Pliocene – Pleistocene (Tertiary – Quaternary) boundary should be placed at about 2.6 Ma not at 1.8 Ma! GSA Today, August 1998, p. 9.

- Morton, N. 2006. Chronostratigraphic units in the Jurassic and their boundaries: definition, recognition and correlation, causal mechanisms. Progress in Natural Science, v. 16, p. 1-11.
- Murphy, M.A. 1994. Fossils as a basis for chronostratigraphic interpretation. Neues Jahrbuch für Geologie und Paläontologie Abhandlungen, v. 192, p. 255-271.
- Naidin, D.P. 1998. Global and regional standards in stratigraphy (on the 60th anniversary of the term stratotype). Russian Geology and Geophysics, v. 39, p. 1023-1032.
- Nemsock, S., N.H. Morrison, A. Carruthers and S. Abdullah 1998. Sedimentary interpretation of a multilayered clastic oil reservoir: impact on development plans for the Zubair reservoir, Raudhatain field. Society of Petroleum Engineers, Paper no. 48972, p. 177-187.
- Nielsen, A.T. 2004. Ordovician sea level changes: a Baltoscandian perspective. In, B.D. Webby, F. Paris, M.L. Droser and L.G. Percival (Eds.), The Great Ordovician Biodiversification Event. Columbia University Press, p. 84-93.
- Odin, G.S. (Ed.) 2001. The Campanian Maastrichtian Boundary: Characterisation at Tercis les Bains (France) and Correlation with Europe and other Continents. International Union of Geological Sciences, Special Publication (Monograph) Series 36, Elsevier, 910 p.
- Ogg, J.G. 2004. Status of divisions of the International Geologic Time Scale. Lethaia, v. 37, 183-199.

Orbigny, A.d'. 1840-2. Paleontologie Francaise. Terrains cretaces. Cephalopodes. Masson, 662 p.

- Orbigny, A.d'. 1842-51. Paleontologie Francaise. Terrains jurassiques. Cephalopodes. Masson, 642 p.
- Orbigny, A.d'. 1849-52. Cours elementaire de Paleontologie et de Geologie stratigraphiques. Masson, 847 p.
- Owen, H.G. 2002. The base of the Albian Stage; comments on recent proposals. Cretaceous Research, v. 23, p. 1-13.
- Paris, F., J. Verniers and A. Al-Hajri 2000. Ordovician chitinozoans from central Saudi Arabia. In, A. Al-Hajri and B. Owens (Eds.), Stratigraphic Palynology of the Palaeozoic of Saudi Arabia. GeoArabia Special Publication 1, Gulf PetroLink, Bahrain, p. 42-56.
- Peybernes, B., P. Souquet, J.M. Vila, M. Benyoussef, M. Duranddelga, F. Kamoun, J.J. Delvolve, A. Charrier, M. Ghanmi, M. Zarbout and J. Saadi 1994. Les series turbiditiques du Tithonien Superieur et du Cretace basal (Formations Maiana, Hamada et Seroula) de la zone Nord-Atlasique á Schistosite (NE de la Tunisie). Comptes Rendus de l'Academie des Sciences Serie II Fascicule A, v. 319, p. 1535-1543.
- Price, G.D. 1999. The evidence and implications of polar ice during the Mesozoic. Earth-Science Reviews, v. 48, p. 183-210.
- Remane, J. 2003. Chronostratigraphic correlations: their importance for the definition of geochronologic units. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 196, p. 7-18.
- Remane, J., M.G. Bassett, J.W. Cowie, K.H. Gohrbandt, H.R. Lane, O. Michelsen and N. Wang 1996. Revised guidelines for the establishment of global chronostratigraphic standards by the International Commission on Stratigraphy (ICS). Episodes, v. 19, p. 77-81.
- Rey, J., J. Canerot, B. Peybernes, K. Taj-Eddine and J.P. Thieuloy 1988. Lithostratigraphy, biostratigraphy and sedimentary dynamics of the Lower Cretaceous deposits on the northern side of the western High Atlas (Morocco). Cretaceous Research, v. 9, p. 141-158.
- Rioult, M. 1969. Alcide d'Orbigny and the stages of the Jurassic. The Mercian Geologist, 3, p. 1-30.
- Sahagian, D., O. Pinous, A. Olferiev and V. Zakharov 1996. Eustatic curve for the Middle Jurassic Cretaceous based on Russian Platform and Siberian stratigraphy zonal resolution. American Association of Petroleum Geologists Bulletin, v. 80, p. 1433-1458.
- Schlager, W. 1991. Depositional bias and environmental change important factors in sequence stratigraphy. Sedimentary Geology, v. 70, p. 109-130.
- Schwarz, E. and J.A. Howell 2005. Sedimentary evolution and depositional architecture of a lowstand sequence set: the Lower Cretaceous Mulichinco Formation, Neuquén Basin, Argentina. In, G.D. Veiga, L.A. Spalletti, J.A. Howell and E. Schwarz (Eds.), The Neuquén Basin, Argentina: A Case Study in Sequence Stratigraphy and Basin Dynamics. Geological Society of London, Special Publication no. 252, p. 109-138.
- Scott, R.W., S.H. Frost and B.L. Shaffer 1988. Early Cretaceous sea-level curves, Gulf Coast and southeastern Arabia. Society for Sedimentary Geology, Special Publication 42, p. 272-284.
- Senalp, M. and A. Al-Duaiji 2001. Qasim Formation: Ordovician storm- and tide-dominated shallow marine siliciclastic sequences, Central Saudi Arabia. GeoArabia, v. 6, no. 2, p. 233-268.
- Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.H. Hall, A.P. Heward, A.D. Horbury and M.D. Simmons 2001. Arabian Plate Sequence Stratigraphy. GeoArabia Special Publication 2, Gulf PetroLink, Bahrain, 371 p.
- Sharland, P.R., D.M. Casey, R.B. Davies, M.D. Simmons and O.E. Sutcliffe 2004. Arabian Plate Sequence Stratigraphy revisions to SP2. GeoArabia, v. 9, no. 1, p. 199-214.

- Slavik, L. and J. Hladil 2004. Lochkovian/Praghian GSSP revisited: evidence about conodont taxa and their stratigraphic distribution. Newsletters in Stratigraphy, v. 40, p. 137-153.
- Souquet, P., B. Peybernes, J. Saadi, M. BenYoussef, M. Ghanmi, M. Zarbout, M. Chikhaoui and F. Kamoun 1997. Séquences et cycles d'ordre 2 en régime extensif et transtensif: exemple du Crétacé inférieur de l'Atlas tunisien. Bulletin de la Sociéte Géologique de France, v. 168, p. 373-386.
- Stampfli, G.M. and G.D. Borel 2004. The TRANSMED transects in space and time: constraints on the paleotectonic evolution of the Mediterranean Domain. In, W. Cavazza et al. (Eds.), The TRANSMED Atlas, Springer, p. 53-80.
- Steurbaut, E. 2006. Ypresian. In, L. Dejonghe (Ed.), Current Status of Chronostratigraphic Units Named from Belgium and Adjacent Areas. Geologica Belgica, v. 9, p. 73-93.
- Stoll, H.M. and D.P. Schrag 1996. Evidence for glacial control of rapid sea level changes in the Early Cretaceous. Science, v. 272, p. 1771-1774.
- Strother, P.K., A. Al-Hajri and A. Traverse 1996. New evidence for land plants from the lower Middle Ordovician of Saudi Arabia. Geology, v. 24, p. 55-58.
- Taher, A.A. 1997. Delineation of organic richness and thermal history of the Lower Thamama Group, East Abu Dhabi: a modeling approach for oil exploration. GeoArabia, v. 2, no. 1, p. 65-88.
- Tornaghi, M.E., I. Primoli Siva and M. Ripepe 1989. Lithostratigraphy and planktonic foraminiferal biostratigraphy of the Aptian-Albian "Scisti a Fucoidi" in the Piobbico Core, Marche, Italy: background for cyclostratigraphy. Rivista Italiana Palaontologia e Stratirafia, v. 95, p. 223-264.
- Torrens, H.S. 2002. From d'Orbigny to the Devonian: some thoughts on the history of the stratotype concept. Comptes Rendus Paleovol, v. 1, p. 335-345.
- Vahrenkamp, V.C. 1996. Carbonate isotope stratigraphy of the upper Kharaib and Shuaiba Formations: implications for the Early Cretaceous evolution of the Arabian Gulf region. American Association of Petroleum Geologists Bulletin, v. 80, p. 647-662.
- Vai, G.B. 1997. Twisting or stable Quaternary boundary? A perspective on the glacial late Pliocene concept. Quaternary International, v. 40, p. 11-22.
- Vail, P.R., R.M. Mitchum Jr., R.G. Todd, J.M. Widmier, S. Thompson III, J.B. Sangree, J.N. Bubb, and W.G. Hatlelid 1977. Seismic stratigraphy and global changes of sea-level. In, C.E. Payton (Ed.), Seismic Stratigraphy – Applications to Hydrocarbon Exploration. American Association of Petroleum Geologists, Memoir 26, p. 49-212.
- Van Bellen, R.C., H.V. Dunnington, R. Wetzel and D.M. Morton 1959. Iraq. Lexique Stratigraphique Internationale. III, Asie, 10a, 333 p.
- Van Simaeys, S. 2004. The Rupelian-Chattian boundary in the North Sea Basin and its calibration to the international timescale. Geologie en Mijnbouw, v. 83, p. 241-248.
- Van Simaeys, S., E. De Man, N. Vandenberghe, H. Brinkhaus and E. Steurbaut 2004. Stratigraphic and palaeoenvironmental analysis of the Rupelian – Chattian transition in the type region: evidence from dinoflagellate cysts, foraminifera and calcareous nannofossil. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 208, p. 31-58.
- Vaslet, D. 1990. Histoire géologique de la bordure occidentale de la plate-forme arabe, vol. 1 : Le Paléozoïque (Anté-Permien supérieur) d'Arabie Saoudite. Bureau de Recherches Géologiques et Minières, Document no. 191, 210 p. (Table A1, p. 60).
- Walliser, O.H. 1984. Pleading for a natural D/C boundary. Courier Forschungsinstitut Senckenberg, v. 67, p. 241-246.
- Walliser, O.H. 1985. Natural boundaries and commission boundaries in the Devonian. Courier Forschungsinstitut Senckenberg, v. 75, p. 401-408.
- Walsh, S.L. 2004. Solutions in chronostratigraphy: the Paleocene / Eocene boundary debate, and Aubry vs Hedberg on chronostratigraphic principles. Earth Science Reviews, v. 64, p. 119-115.
- Walsh, S.L., F.M. Gradstein and J.G. Ogg 2004. History, philosophy and application of the Global Stratotype Section and Point (GSSP). Lethaia, 37, p. 201-218.
- Wang Hongzhen 2000. Problems of sequence stratigraphy in China. Journal of China University of Geosciences, 11, p. 204-214.
- Wang Xulian and Su Wenbo 2000. An important reference criterion for the selection of GSSP. Chinese Science Bulletin, 45, p. 472-479.
- Wang Xulian 1999. Some fundamental problems in outcrop sequence stratigraphy. Science in China (Series D), 42, p. 636-645.
- Wang Xunlian 2002. On steps and methods for the establishment of global boundary stratotype section and point (GSSP) from the viewpoint of integrated stratigraphy. Science in China (Series D), v. 45, p. 1027-1041.
- Wippich, M.G. 2003. Valanginian (Early Cretaceous) ammonite faunas from the western High Atlas, Morocco, and the recognition of western Mediterranean 'standard' zones. Cretaceous Research, v. 24, p. 357-374.
- Witt, W. and H. Gökdag 1994. Orbitolinid biostratigraphy of the Shu'aiba Formation (Aptian), Omanimplications for reservoir development. In, M.D. Simmons (Ed.), Micropalaeontology and Hydrocarbon Exploration in the Middle East. Chapman and Hall, p. 221-234.
- Zhamoida, A.I. 2004. Problems related to the International (Standard) Stratigraphic Scale and its perfection. Stratigraphy and Geological Correlation, v. 12, p. 321-330.

ABOUT THE AUTHORS

Mike Simmons is Director of Geoscience at Neftex Petroleum Consultants Ltd., a leading consultancy company specializing in global sequence stratigraphy and its applications to hydrocarbon exploration and production. He has responsibilities for the development of the Neftex Sequence Stratigraphic Model. Mike oversees the application of the model in Neftex's regional studies and carries out bespoke sequence stratigraphic studies for clients. Previously he was Director and Chief Geologist of CASP at Cambridge University and the Head of the Department of Geology and Petroleum Geology



at the University of Aberdeen in Scotland. Mike spent 11 years with BP Exploration working as a Senior Geologist/Biostratigrapher, specializing in the Middle East and Former Soviet Union regions. He holds BSc and PhD degrees from Plymouth University.

mike.simmons@neftex.com

Peter Sharland is Managing Director of Neftex Petroleum Consultants Ltd based in the UK (www.neftex.com). Neftex is completing the development of a global sequence stratigraphic database and model based on the vast public domain and provides these data to subscribing oil companies via the web. In this work Neftex identifies, correlates and maps key stratal surfaces around the World and presents the resulting interpretations in complex 2D and 3D models. During his career Peter has worked on global geoscience projects as well as projects in the Middle East, North Africa and the Former



Soviet Union. Prior to Neftex Peter worked for LASMO, BP and LL&E. Peter received his BSc in Geology from London University in 1983 and has 24 years of industry experience.

peter.sharland@neftex.com

David (Dave) Casey is Technical Director and co-founder of Neftex Petroleum Consultants Ltd and has over 20 years of oil industry experience. His responsibilities within the company include IT and information management and mentoring of structural geoscience. Prior to co-founding the company in 2001, he was an independent geoscience consultant specialising in the petroleum geology of the Middle East and Greater Caspian regions. He is also a co-author of Arabian Plate Sequence Stratigraphy. Dave began his career as a petroleum geologist with BP in 1983, where he spent 11 years



gaining experience on the United Kingdom and the Middle East and Caspian. Dave holds a BSc in Geology and an MSc in Hydrogeology from Reading University, as well as a PhD in Sedimentary Geology and Tectonics from Oxford University. dave.casey@neftex.com **Roger Davies** is Projects Director and co-founder of Neftex Petroleum Consultants Ltd. Roger has over 25 years of oil industry experience starting with a Major oil company (BP) and working as an independent geoscience consultant before cofounding Neftex in 2001. Within Neftex, Roger leads bespoke projects for clients and has a fundamental role in the development and application of the Neftex Sequence Stratigraphic Model. He has a PhD in Carbonate Sedimentology and Micropalaeontology from Southampton University, and a BSc in Geology from Bristol University. His early career was spent as a Sedimentologist working worldwide on carbonate and clastic reservoirs for BP.



roger.davies@neftex.com

Owen Sutcliffe is Senior Geoscientist with Neftex Petroleum Consultants Ltd whom he joined in 2003. He leads the application of the Neftex sequence stratigraphic model to successions in a variety of basins globally. He graduated from the University of Leeds in 1993 with a BSc (Honours) in Geological Science and was subsequently awarded a PhD from the University of Bristol in 1997. Owen's main geological interests focus on the stratigraphic and sedimentological evolution of Palaeozoic petroleum systems of the World and the application of glacial sedimentological models to appropriate reservoirs. He acts as an



adviser to a PhD student from the University of Leeds. After 2 years post-doctoral research on the architectural character of the upper Ordovician in North Africa (University of Wales, Aberystwyth and LASMO), Owen started a 3-year career with Badley Ashton & Associates.

owen.sutcliffe@neftex.com

Manuscript received 24 January, 2007

Revised May 8, 2007

Accepted May 20, 2007

Press version proofread by authors July 12, 2007