The magnetostratigraphy of the Olenekian-Anisian boundary and a proposal to define the base of the Anisian using a magnetozone datum

Mark W. Hounslow[1], Michael Szurlies[2], Giovanni Muttoni[3], and Jerzy Nawrocki[4]

[1]*CEMP, Geography Dept., Lancaster University, Bailrigg, Lancaster, UK. LA1 4YB (m.hounslow@lancs.ac.uk).*

[2]*GeoForschungsZentrum Potsdam, Telegrafenberg Haus C, D-14473 Potsdam, Germany (szur@gfz-potsdam.de).*

[3]*Department of Earth Sciences, University of Milan, Via Mangiagalli 34, 20133 Milan, Italy (giovanni.muttoni1@unimi.it).*

[4]*Paleomagnetic Laboratory, Polish Geological Institute, Rakowiecka 4, 00-975 Warsaw, Poland (jerzy.nawrocki@pgi.gov.pl).*

Introduction

There exist many magnetostratigraphic studies across the boundary of the Lower and Middle Triassic, from both low and high-palaeolatitude marine sections (Muttoni et al., 1995, 1996, 2000; Lehrmann et al., 2006; Hounslow et al., 2007, inpress-b), and non-marine sections (Steiner et al., 1993; Nawrocki & Szulc, 2000; Huang & Opdyke, 2000; Hounslow & McIntosh, 2003; Dinarès-Turell et al., 2005; Steiner, 2006; Szurlies, 2007). These many studies now supply excellent independent assessment of the sequence of polarity reversals across the Olenekian-Anisian boundary (OAB), providing a potentially high-detail of correlation using magnetostratigraphy. This is supplemented by well-established magnetostratigraphies through the remainder of the Lower and Middle Triassic (Muttoni et al., 2000, 2004; Steiner, 2006; Szurlies, 2007; Hounslow et al., inpress-a).

Correlation using magnetostratigraphic normal/reverse polarity 'bar-code' patterns relies on a reasonable, within-section consistency of sedimentation rate. Comparison between sections with large sedimentation rate differences is best accommodated by stretching or shrinking the entire magnetostratigraphic scale, using other correlation constraints (biostratigraphic, radiometric etc) as a guide. Similarly, hiatus can distort the magnetostratigraphic pattern unless properly identified using biostratigraphic, or sedimentological data. For the most part use of these 'sedimentation rate principles' have provided sound solutions for magnetostratigraphic correlation in most marine and terrestrial settings, except perhaps where sedimentation rates are very low (e.g. some pelagic settings). These principles provide the basis of the correlations in Figures 1 and 2, constrained by the biostratigraphy, which is sometimes conflicting, perhaps in part due to the 'first-occurrence versus first presence problem'.

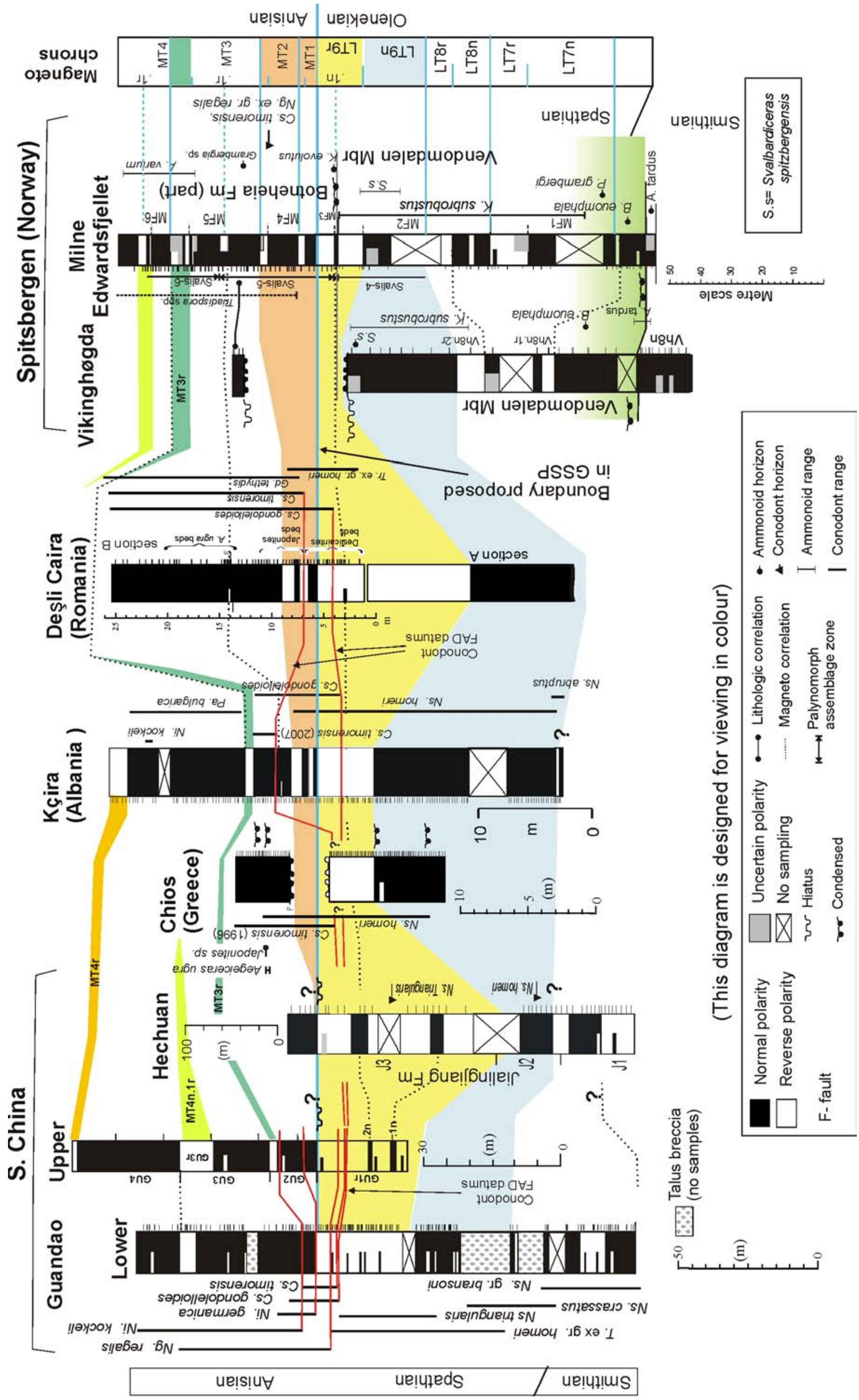
Magnetostratigraphy across the Olenekian-Anisian boundary

The main features of the polarity pattern across the Olenekian- Anisian boundary (OAB) interval can be summarised thus:

a) Magnetozone LT9r (i.e. reverse polarity upper part of LT9) can be confidently detected in marine sections at Kçira, Chios, Deşli Caira, Guandao, Milne Edwardsfjellet (Fig. 1) and in the upper part of the Middle Buntsandstein (Fig. 2). With less confidence (in part due to the limited biostratigraphic constraints), it can be detected in the Hechuan section and in some other non-marine sections (Figs.1,2). The reverse magnetozone has at least one normal submagnetozone (LT9r.1n), found at Milne Edwardsfjellet, Deşli Caira, upper Guandao and probably in the Solling Fm as well (Szurlies 2007: Karlshafen and Bockenem A100 sections; Figs. 1 & 2). There is some evidence of a second normal polarity submagnetozone within LT9r, at the upper Guandao (i.e. GU1r.1n) and Hechuan sections, although the magnetostratigraphic data from both Guandao sections is 'noisy' due to many 'half-bar' putative submagnetozones (i.e. intervals identified by only a single specimen; Fig. 1).

b) Magnetozone chrons (i.e. a normal-reverse couplet) MT1 and MT2 characterise the base of the relatively-long normal polarity interval which occurs in the Lower Anisian, probably extending into the early Pelsonian (Muttoni et al., 2000; Nawrocki & Szulc, 2000; Fig. 2). The reverse and

Fig.ure1 (next page): Summary bio-magnetostratigraphy of important marine Olenekian-Anisian boundary sections. Guandao sections from Lehrmann et al. (2006) and Orchard et al. (2007a); conodont ranges apply to Lower Guandao. Hechuan section from Steiner et al. (1989). Chios section is a composite from Muttoni et al. (1995, 1996). Kçira from Muttoni et al. (1996; 2000). Deşli Caira from Gallet in Grădinaru (2003); Grădinaru (pers. comm., 2007) and Orchard et al. (2007b). Vikinghogda and Milne Edwardsfjellet sections from Hounslow et al (2007, inpress-a, inpress-b). Magnetochrons are coded LT for the Lower Triassic (from Hounslow et al., inpress-a) and MT for the Middle Triassic. Ticks adjacent to polarity columns indicate the magnetostratigraphic sampling levels. Concurrent range zones of Vigran et al. (1998)-Svalis$_4$= *J. punctispinosa - C. pustulatus - C. ologogranifer - V. jenensis- D. nejburgii*; Svalis$_5$=*S. seebergensis- A. circumdatus- A. spiniger- Pretricolpipollenites* spp.; Svalis$_6$= *A. macrocavatus - T. plicata – J .punctispinosa- K. punctatus*.


S. China
Guandao
Lower
Upper
Hechuan
Chios (Greece)
Kçira (Albania)
Deşli Caira (Romania)
Spitsbergen (Norway)
Vikinghøgda
Milne Edwardsfjellet
Magneto chrons
Anisian
Spathian
Smithian
Olenekian
Botneheia Fm (part)
Vendomdalen Mbr
Jialingjiang Fm
Conodont FAD datums
Boundary proposed in GSSP
section A
section B
Talus breccia (no samples)
Normal polarity
Reverse polarity
F- fault
Uncertain polarity
No sampling
Hiatus
Condensed
Lithologic correlation
Magneto correlation
Palynomorph assemblage zone
Ammonoid horizon
Conodont horizon
Ammonoid range
Conodont range
Metre scale
S.s= Svalbardiceras spitzbergensis
(This diagram is designed for viewing in colour)

normal parts of the magnetochrons MT1 and MT2 appear to vary somewhat in relative thickness, probably due to sedimentation rate changes in the different sections near the OAB. Nonetheless, magnetozone chrons MT1 and MT2 can be confidently correlated between Kçira, Deşli Caira, and Milne Edwardsfjellet. Magnetochrons MT1 and MT2 are also clearly present in the Riera de Sant Jaume section in the Spanish Buntsandstein, and the Middle-Upper Buntsandstein boundary interval from the German Basin (Fig. 2). In some other European sections, part of MT2n (and MT1) is probably missing, due to a minor unconformity (at about the level of the so-called S-unconformity of the German nomenclature; Fig. 2). MT1 and MT2 were not detected at Chios due to faulting and hiatus at the top of LT9r (Muttoni et al., 1996, 2000). This situation may also be similar at Guandao (and Hechuan?) where MT3n (of Bithynian age) appears to rest directly on LT9r (Fig.1).

These suggest that the Deşli Caira proposed GSSP and the Kçira section contain a relatively complete magnetostratigraphic record across the OAB, with Kçira being more condensed than Deşli Caira, probably accounting for the undetected submagnetozone(s) in LT9r. The Guandao sections appears to have magnetochrons MT1 and MT2 missing, but appear have a considerably expanded latest Spathian LT9r, compared to any other marine sections.

A 2nd correlation possibility of the Guandao sections could place GU2 being equivalent to MT3, which would make the 'full-bar' normal submagnetozones in GU1r (i.e. GU1r.1n and GU1r.2n; Fig. 1) the equivalent of MT1n and MT2n. This is the original correlation proposed by Lerhmann et al. (2006), in which GU2n is the equivalent of MT4n, a correlation which is driven by with the conodont biostratigraphy, but largely ignores the magnetostratigraphy. This 2nd correlation possibility for the Guandao sections would suggest submagnetozones GU1r.1n and GU1r.2n are the equivalent of MT1n and MT2n, a possibility which is only valid if there are order of magnitude fluctuations (on a metre to 10 m scale) in the sedimentation rate in this part of the section. There is not evidence in the lithology of these sections that such sedimentation rate changes have occurred (*cf.* Lehrmann et al. 2006; Orchard et al., 2007).

In addition, the correlation problems of relating Guandao to other sections relates to the fact that *Ni. kockeli* and *Ni. germanica* appear very low in the section compared to the magnetostratigraphy in other comparable sections. Both these conodont forms appear to start high up in MT4n at Kçira and in the Polish and German Muschelkalk (Figs. 1, 2). The upper range of *Cs. timorensis* and *Cs. gondolelloides* terminates at or below the level of MT3r at Kçira, but within GU3n (equivalent of MT4n) in the Upper Guandao section. For these reasons it is not clear if GU2r or GU3r in the Upper Gaundao section is the equivalent of MT3r. However, it is more probable that GU2r is the equivalent of MT3r, and GU3r is MT4n.1r, seen at Milne Edwardsfjellet and in the Polish Muschelkalk (Figs. 1 & 2). This suggests that the equivalent of MT1 and MT2 are either missing or highly condensed in the Guandao sections. Perhaps some evidence for this is that the FAD of *Ni. kockeli* and *Ni. germanica* step higher into magnetozone GU2n, at the Upper Guandao section compared to the Lower Guandao section- evidence of a missing or condensed interval at Lower Guandao?

The position of magnetochrons MT1 and MT2 in the non-marine sections of the Central European Basin (i.e. Poland, Obernsees core, Central Germany composite) around the OAB is largely constrained by the excellent and vast amount of well-log coverage across this basin from the UK in the west to Poland in the east (e.g., Geluk, 2005; Fig. 2). Hitherto, conchostracan zonations, vertebrates and palynostratigraphy from these successions do no allow such basin-wide unambiguous detailed correlation at this level. However, based on a palynological study, Brugman (1986) already placed the OAB within the uppermost Middle Buntsandstein. Magnetochron MT2 also appears to have been detected by Huang & Opdyke (2000) in the Badong Fm in South China. One of the features at this level, which supports the magnetostratigraphic construction in Figure 2, is the appearance of *Triadispora* sp., which in the Milne Edwardsfjellet section are consistently present from magnetochron MT2 (Hounslow et al., In press-b), the correlated approximate level at which they become common to abundant in the Upper Buntsandstein sections.

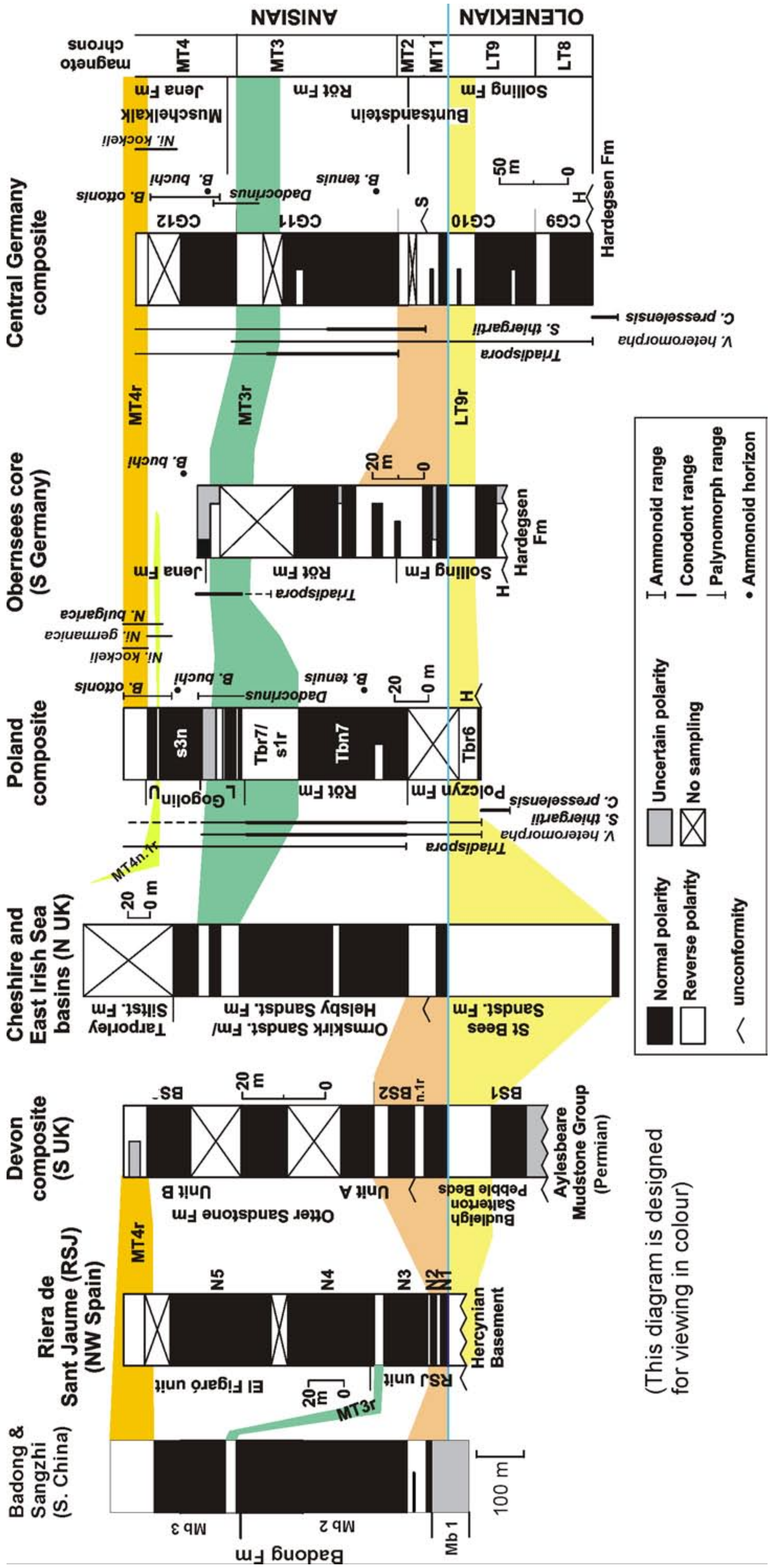
Correlation of biostratigraphic datums at the Olenekian-Anisian boundary

Following publication of the magnetostratigraphic and biostratigraphic results from Chios and Kçira, in 1995, 1996 the acceptance of a solid taxonomic definition of *Chiosella timorensis* has taken place (Grădinaru et al., 2006; Orchard et al., 2007b). Examination of photos of the conodont collections from the Kçira section has revised the FAD of *Cs. timorensis* some 4.4 m higher in the section (at 26.5±0.2 m) than its 1996 level (A. Nicora pers. comm. to M.J. Orchard, 2007), to be located within Kç2n (equivalent to MT3n (Fig. 1). A similar up-wards revision is presumably needed for Chios, but in the absence of a detailed re-study, we have used that level originally published in Fig. 1.

The magnetostratigraphic correlations outlined above, along with the revisions pertinent to *Cs. timorensis* suggest a number of important points about the actual distribution of age diagnostic fossils across the OAB:

The appearance of *Cs. timorensis* appears to be diachronous relative to the magnetostratigraphy between the Guandao, Chios, Kçira and Deşli Caira sections. At Guandao and

Fig.ure 2 (next page): Summary of bio-magnetostratigraphies of important mainly non-marine sections from the Central European Basin across the Olenekian-Anisian boundary. Badong Fm (S. China) fom Huang and Opdyke (2000); Riera de Sant Jaume from Dinarès-Turell et al. (2005), Devon from Hounslow & McIntosh (2003), Irish Sea from Mange et al. (1999). Central Germany from Szurlies (2007), Obernsees core from Soffel & Wippern (1998) re-interpreted by Szurlies (2007), Poland composite modified from Nawrocki (1997) and Nawrocki & Szulc (2000) according to Szurlies (2007). Unconformities: H=Hardegsen, S=Solling.


ANISIAN
OLENEKIAN
magneto chrons
MT4
MT3
MT2
MT1
LT9
LT8
Central Germany composite
Muschelkalk
Jena Fm
Röt Fm
Buntsandstein
Solling Fm
Hardegsen Fm
CG12
CG11
CG10
CG9
Ni. kockeli
B. ottonis
B. buchi
Dadocrinus
B. tenuis
C. presselensis
S. thiergartii
V. heteromorpha
Triadispora
MT4r
MT3r
LT9r
Obernsees core (S Germany)
Poland composite
Gogolin
Polczyn Fm
s3n
Tbr7/ s1r
Tbn7
Tbr6
N. bulgarica
Ni. germanica
MT4n-1r
Cheshire and East Irish Sea basins (N UK)
Tarporley Siltst. Fm
Ormskirk Sandst. Fm/ Helsby Sandst. Fm
St Bees Sandst. Fm
Devon composite (S UK)
Otter Sandstone Fm
Unit B
Unit A
Budleigh Salterton Pebble Beds
Aylesbeare Mudstone Group (Permian)
BS1
BS2
n.1r
Riera de Sant Jaume (RSJ) (NW Spain)
El Figaró unit
RSJ unit
Hercynian Basement
N5
N4
N3
N2
N1
Badong & Sangzhi (S. China)
Badong Fm
Mb 3
Mb 2
Mb 1
100 m
Normal polarity
Reverse polarity
unconformity
Uncertain polarity
No sampling
Ammonoid range
Conodont range
Palynomorph range
Ammonoid horizon
(This diagram is designed for viewing in colour)

Chios (1996 definition) this datum occurs within the upper part of LT9r, at Deşli Caira within MT1r, and at Kçira within MT3n (Fig. 1). At Kçira, the original (i.e. 1996) definition of *Cs. timorensis* placed the first occurrence within the uppermost part of LT9r. The magnetostratigraphic sampling at the lower and upper Guandao sections, is particularly closely-spaced in the upper part of correlated LT9r (Lehrmann et al., 2006; Orchard et al., 2007a; Fig. 1), which indicates no evidence of magnetochrons MT1 and MT2 at about the level of *Cs. timorensis*. Similarly, magnetostratigraphic sampling density is high at the Chios, Kçira and Deşli Caira sections. What is the origin of this apparent diachroneity- is it caused by multi-regional evolution of *Cs. timorensis*? Is the magnetostratigraphy compromised in one or more of these sections? Are there problems of adequate sampling of the conodont faunas in some of these sections to solidly recognise a FAD? We can see no substantiated argument to nullify any of these possibilities, and as such choosing the *Cs. timorensis* datum to define the base of the Anisian could turn out to be a poor decision.

A much more consistent datum, relative to the magnetostratigraphy is the appearance of *Chiosella* (*Neospathodus*) *gondolelloides*, which at Kçira, Deşli Caira and Guandao occurs in the upper part of LT9r. This 'datum-1' of Orchard et al. (2007b) is also closer to the traditional Boreal ammonoid-based Spathian-Anisian boundary (i.e. between the latest Spathian *Svalbardiceras spitzbergensis* Subzone and the *Grambergia taimyrensis* Zone; Dagys & Weitschat, 1993; Dagys & Sobolev, 1995), which is located between LT9r.1n and the mid parts of the immediately underlying reverse magnetozone LT9r.1r (Fig. 1). In the Milne Edwardsfjellet section this transition is bracketed by the occurrence of *Karangatites evolutus* (index form for 2nd subzone of Siberian *G. taimyrensis* Zone) close to the top of LT9r.1n, overlying the ammonoid *S. spitzbergensis* in LT9r.1r. This relationship is to some extent confirmed by the occurrence of ?*Svalbardiceras* and *Karangatites* from Deşli Caira (Grădinaru & Sobolev, 2006). Hence, 'datum-1' provides better low to high-latitude correlation potential than that of the (diachronous) FAD of *Cs. timorensis*. Datum-1 is also close to the boundary between the $Svalis_4$ and $Svalis_5$ palynomorph assemblages of Vigran et al. (1998), which occurs in the 1st metre of the Botneheia Fm (i.e. base of MF3r; Fig. 1) in the Milne Edwardsfjellet section (Fig. 1; Hounslow et al. In press-b). In the Central European Basin, the correlated datum-1 level probably falls within the upperpart of the Solling Fm (i.e. the uppermost Middle Buntsandstein, Fig. 2).

If either of these conodont datums should become the 'golden-spike' level in the Deşli Caira proposed GSSP, some of the Boreal ammonoids traditionally considered Anisian, will have first appearances in the latest Olenekian.

Base of magnetozone MT1n as the datum for the Olenekian-Anisian boundary

The Deşli Caira provides a well-defined and continuous magnetostratigraphy tied to a range of relevant biostratigraphic markers. We propose that the base of magnetozone MT1n in the Deşli Caira section can provide a robust and globally correlatable datum for defining the base of the Anisian. If choosing a magnetostratigraphic datum, in place of a succession of validated sequential faunal evolutionary changes, our case has to demonstrate a consistent pattern of polarity reversals (Remane et al., 1996). We have done this above, using data from marine and non-marine successions, which is also constrained and related to faunal-ranges and FAD events. Use of a magnetic polarity boundary as the primary GSSP correlation datum has parallels in the Quaternary, Neogene, Palaeogene and Lower Cretaceous, as both proposed and actual datums (http://www.stratigraphy.org/gssp.htm), a reflection of the high correlation potential using magnetozone boundaries. Whilst magnetostratigraphy in Triassic successions has not such a historical pedigree as in earlier systems, its potential is clear for high resolution sub-division of geological time in future studies.

Selecting the base of MT1n for defining the base of the Anisian has a number of advantages.

- The global correlation potential of a magnetostratigraphic datum is far greater than any biostratigraphic datum, since it is not restricted by facies or climate, having the potential to be recognised at low and high-palaeolatitude and in marine and non-marine successions. Magnetozone boundaries probably provide the closest to a true chronostratigraphic datum available in stratigraphy (Remane et al., 1996).
- The documentation and correlation potential of the base of MT1n has been clearly demonstrated in multiple studies, in multiple sections, with multiple lithofacies. These studies document a clear pattern of repeatable magnetozones and submagnetozones across the OAB (Figs. 1 and 2)
- Magnetozone MT1n marks the base of the predominantly normal polarity interval which characterises the Lower Anisian, and as such is a distinctive part of the Triassic magnetic polarity pattern. The magnetozone hierarchy of MT1r and MT2r overlain by the remainder of the Lower Anisian, dominantly normal polarity MT3n (Figs. 1 & 2), provides a distinctive 'bar-code' for recognition. This extends to recognition of hiatus and erosional loss of sediment at the OAB, if the MT1r and MT2r magnetozones are missing in correlated sections (Figs 1 and 2).
- The underlying reverse magnetozone LT9r has a demonstrable pattern of finer-scale submagnetozones with at least one (i.e. LT9r.1n) and possible two short duration submagnetozones, for finer scale subdivision of underlying boundary strata. These illustrate, through correlation, how it is possible to map the proposed OAB in the Deşli Caira section (with its Tethyan fauna) into the Boreal ammonoid zonation.
- The base of MT1n at Deşli Caira falls between

two of the other strongest proposed datums for defining the base of the Anisian, namely FAD of *Cs. timorensis*, and FAD of *Cs. gondolelloides*. Both of these could act as secondary markers for the base of the Anisian.
- With the magnetostratigraphy it is possible to demonstrate, through correlation, that palynological proxies could also be utilised near to the boundary, in the absence of other information. The $Svalis_4$-$Svalis_5$ boundary, occurring just prior to MT1n, is a useful and clearly documented marker in Boreal regions (Vigran et al., 1998). The incoming of consistently present *Triadispora* sp. appears to characterise a level within magnetochron MT2, and may be a useful additional marker above the proposed OAB in low latitude sections containing a palynological record (Figs. 1, 2).

Conclusions

The OAB interval is characterised by a well-documented pattern of magnetic polarity reversals that has been observed in different sections at varying levels of detail. We propose to place the base of the Anisian in the Deşli Caira proposed GSSP section at meter level 5.7 m (Section B) at the base of normal polarity magnetozone MT1n. We believe that such a magnetostratigraphic datum, provides better than any single conodont datum, the requirements of global exportability that are fundamental to a GSSP definition. Secondary correlative markers would be the FAD of *Cs. timorensis*, just above the boundary and the FAD of *Cs. gondolelloides*, just below the boundary. This choice would provide a key means for linkage of marine and nonmarine strata, and provide for other sections, that for climatic or paleogeographic reasons, do not share the same paleontological content. The magnetostratigraphic correlation herein illustrated, supports the existence of a number of other palynostratigraphic and ammonoid proxies that could be utilised to help define the base of the Anisian in both low and high latitude sections, in the absence of magnetostratigraphy.

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