

Extended abstracts of the Induan-Olenekian Boundary Group Meeting

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Arriving at an Induan-Olenekian Boundary GSSP

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HISTORICAL CONSIDERATIONS

The modern International Geologic Time Scale recognizes two stages in the Lower Triassic (Ogg, 2012), the Induan and Olenekian, but many workers continue to use as substages, the informal stages Griesbachian, Dienerian, Smithian and Spathian as originally determined in Arctic Canada. Both sets of terminology are used here, with the Induan essentially equal to the Griesbachian and Dienerian, and the Olenekian more-or-less equal to the Smithian and Spathian. The base of the Smithian was originally defined in the Blind Fiord Formation at Smith Creek on Ellesmere Island at the Romunderi Zone above the Sverdrupi Zone (Tozer, 1967) and later at the base of the Hedenstroemi Zone on the basis of occurrences elsewhere (Tozer, 1994). ICS is not currently planning to formalize substages, so the task of the IOBWG should be simple – pick a point and a section to define the Induan–Olenekian boundary (=base-Olenekian GSSP).

GSSP CONSIDERATIONS

A majority of current GSSPs use biostratigraphic data as the primary marker, but it is critical that other physico-chemical markers should be referenced as secondary markers to facilitate the development of a high-precision time scale (Smith *et al.*, 2014). In so doing, we recognize that *correlation precedes definition* as a basic tenet of the process. The FAD of a species (if chosen as primary marker) defines a stage boundary only at the GSSP section, everywhere else we are trying to correlate. It is likely that the defining species will be missing in some sections (especially non-marine) and in other sections the FO will be (hopefully) younger than the FAD. Therefore correlatability is only achieved when as many secondary markers as possible, especially those that are recorded in both marine and terrestrial realms, are included in the definition. Demonstrating correlation of different geologic and bioevents in numerous widely distributed sections will show the event that is most useful for global correlation and ultimately point to the best section for definition. It is the goal of the IOBWG to reach a consensus (at least 60% majority) and submit a report to STS. If voting members vote 60% in favour it is passed on to ICS for a similar vote and ultimately to IUGS for formal acceptance. It is important to note that chronostratigraphic studies do not terminate with formal acceptance of a stage boundary, but rather continue within a defined temporal framework. These additional studies could continue to test the correlatability or focus on rates of evolution, migration, climate change, sea level and deposition between globally defined points. Furthermore, a formally accepted international stage does not replace regional stages or informal substages, but rather provides a formal chronostratigraphic framework for comparison.

SEQUENCE STRATIGRAPHY

Rocks deposited during the 4.8 million years of the Early Triassic (Ogg, 2012) are globally subdivided into 3 third-order depositional sequences (Embry, 1997). The first more or less equals the Induan (Griesbachian and Dienerian), the second approximates the lower Olenekian (Smithian) and the third approximates the upper Olenekian (Spathian). Original stage and system boundaries were often recognized at sequence boundaries because differences in biota and depositional setting were clear across the time gap. A GSSP must be defined in an interval of continuous deposition with little facies variation and therefore must occur below or above a sequence boundary or its correlative maximum regressive surface. The IOBWG has been focusing on a base-Olenekian definition within the transgressive part of the second Lower Triassic depositional sequence. It is possible that some people may object that part of what is currently called Smithian will be included in the Induan, but we should remember that this is the consequence of defining a point within a continuous succession and furthermore, the base of the Smithian has not been formally defined.

CONODONT EVOLUTION AND TAXONOMY

The early Olenekian (Smithian) is a time of evolutionary radiation in conodonts (Orchard, 2007; Orchard & Zonneveld, 2009) as well as ammonoids (begins in late Induan, i.e. Dienerian; see Ware *et al.*, 2015) in which there is a significant increase in diversity. The conodont diversity can be interpreted in different ways depending on taxonomic approaches, which can be classically subdivided into the ‘splitters’ and the ‘lumpers’. The result is either a large number of formal taxa or populations with high variability; it is possible to capture some of that variability with a number of morphotypes of a taxon. Regardless, during such times, the morphologic plasticity is high and this represents both a problem and an advantage. The problem is that others in the Triassic community might interpret that conodont work is still early in development and that specialists cannot decide. The advantage, however, is that conodonts offer a great deal of potential resolution during these intervals. My research suggests that this morphologic plasticity is greatest in the “centre of evolution” and that at the extreme ranges of distribution only certain morphotypes occur – it is as if evolution is complete when certain species or forms migrate away from the centre. This would suggest that picking a point within or near the end of the major radiation stage would have greater correlation potential compared to a point at the beginning of this radiation.

PERSONAL RECOMMENDATION

The IOBWG has made progress over 20 years and has essentially adopted the position of the FO of *Novispathodus waageni sensu lato*. In practice, this has already worked very well in many sections of the world including the proposed GSSP localities (Goudemand, 2014). I am open to other potential points, but my inclination is to pick a formal, perhaps arbitrary point within the broad sense of *Nv. waageni*. This level or point should be chosen as the one with the greatest potential for correlation by incorporating all other available tools including, but not necessarily limited to, magnetostratigraphy, chemostratigraphy (carbon isotopes), other fossils, geochronology, cyclostratigraphy (Li et al., 2016), and sequence stratigraphy. It is important that all of this work be fully integrated into our definition. Only then should we decide the section that best expresses this correlation, as well as being accessible; secondary reference sections are permissible. Currently, we have three sections on the table including 1) the Mud section (Spiti, Himachal Pradesh) M04 in northern India (Krystyn et al., 2007a, b), 2) West Pingdingshan section at Chaohu in Anhui Province, South China (Tong et al., 2003, 2004), and 3) the Nammal Gorge section in Pakistan (Romano et al., 2013). In the end, our recommendation to STS should read something like “we propose that the base-Olenekian GSSP is defined by the FAD of *Nv. decidedus* (i.e. we have decided) at 100x metres in a particular section, and a major carbon isotope shift, and/or certain magnetic reversal, and/or the appearance or disappearance of other fossils, which must at least include ammonoids, serve as secondary markers to correlate this point”.

ACRONYMS

IOBWG: Induan-Olenekian Boundary Working Group

STS: Subcommission on Triassic Stratigraphy

ICS: International Commission on Stratigraphy

IUGS: International Union of Geological Sciences

GSSP: Global Stratigraphic Section and Point is the material reference for the stage boundary definition, but it is useful only when it can be correlated widely by as many means as possible.

FO: the local first occurrence of a taxon in any given section, which collectively will likely be diachronous

FAD: the true first occurrence or evolution of a taxon representing its First Appearance Datum; usually determined, within resolution limits, only when compared to synchronous events like, for example, an isotopic shift or magnetic reversal. The definition of a stage boundary does not necessarily have to change if a FO is later shown to precede an identified FAD because the stage boundary is correlated with as many chronostratigraphic tools as possible.

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Correlating the Induan-Olenekian Boundary GSSP

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INTRODUCTION

A potential way to consider correlation of a base-Olenekian GSSP is to first consider the sequence stratigraphy in various sections. Assuming 1) the base-Olenekian GSSP should be located above a sequence boundary (SB) and at or above the equivalent correlative conformity or maximum regressive surface (MRS), and 2) that these surfaces can be reliably identified, then we have a reasonable way to compare the ranges of various taxa.

WESTERN AND ARCTIC CANADA

Baud et al. (2008) showed a co-planar SB and flooding surface in the Blind Fiord Formation with *Novispathodus waageni* above and *Euflemingites romunderi* just a little higher. The exact same occurrences are found above a SB at Opal Creek in SW Alberta. In west-central Alberta there is a SB within a coquina unit and a major flooding surface a little higher that includes *Novispathodus waageni*. In east-central British Columbia Orchard and Zonneveld (2009) showed a section which appears to be conformable with a turbidite unit (Meosin Mountain Mbr) a little higher. Immediately overlying this MRS the conodonts *Nv. waageni* and *Nv. latiformis* co-occur with *Discretella discreta* and *Euflemingites* is a little higher.

OTHER SECTIONS

The sequence stratigraphically significant surface discussed above is interpreted by me at the Mud (bed 13A), Chaohu (bed 25-18), and Nammal Gorge (near top of Ceratite Sandstone) sections that represent potential GSSPs. Using this surface as a datum suggests that above the surface some *Nv. waageni* morphotypes including *Nv. latiformis* occur with *Flemingites nanus* at Mud (Krystyn et al., 2007a, b). Similar taxa occur above this surface at Chaohu including *Eurygnathodus costatus* (Tong et al., 2004), but *Flemingites* and *Euflemingites* are just below. The latter may be a good secondary marker in tethyan faunas. The top of the Ceratite Sandstone was the original top of the Induan. According to Romano et al. (2013), *Fleminites nanus*, *F. bhargavai*, and *Nv. waageni* occur below the surface and *Euflemingites*, *Nv. waageni* and *Nv. spitiensis* occur above.

CONCLUSION

There are some issues with my seemingly simple initial correlation of a SB/MRS surface in terms of biotic occurrences on either side, but overall there is a close correspondence that sug-

gests correlation is likely, especially as new details emerge from the workshop. In addition, other physico-chemical markers need to be considered before a GSSP can be determined.

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The marine carbon isotope curve around the Induan-Olenekian Boundary (IOB): Potential and problems

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The Early Triassic is a very peculiar period in Earth history, as it represents the time after the worst mass extinction event and shows a delayed biotic recovery after the extinction event. Therefore it is of great interest and importance to correlate in time slices findings in various Early Triassic sections to combine the archived evidence of processes and evolutions in different geographical regions, facies, etc.. However, correlation often is hampered by absence or scarcity of time-diagnostic (macro-) fossils. The Early Triassic carbon isotope curve is a very valuable tool for stratigraphic correlation, but there are existing several problems/facts that need to be taken into account, as they result in variations of the curve. These problems/facts are:

- A** Regional variations
- B** Diagenesis
- C** (Mixing of) different sources of carbon with significantly different isotope values

There potentially exist two carbon isotope curves for marine sections, the I) carbonate carbon isotope and the II) organic carbon isotope curves.

I) Usually the carbonate carbon isotope curve is investigated in sedimentary sections, if sedimentary carbonate is available. For sections consisting of dominantly pure carbonates very detailed isotope profiles can be produced and often the influence of diagenesis is not very significant. Carbonate carbon isotope curves can (and do) vary with respect to the geographic region of the section location. This can be utilized to investigate regional influences on the carbonate carbon isotope evolution and thus the regional influences on the marine carbon cycle, but this also might be problematic with respect to chemostratigraphy. Even more problematic is the existence of different sources of carbonate and the mixing of these sources. When excluding diagenetic carbonate, there still might exist two different carbonate sources in deeper water sections: 1) authigenic carbonate formed close to the water-sediment interface with lower carbon isotope values and 2) shallow water carbonate formed either in the uppermost water column directly above (and thus sedimented by sinking to the seafloor), or in the uppermost water column in a shallow water environment and transported down the slope by currents and gravity flow, both having high carbon isotope values.

II) The bulk organic carbon isotope curve is usually investigated for sections lacking carbonates. As both carbon pools utilize the dissolved C in the water, also the organic carbon values vary regionally equivalent to the carbonate carbon values, but not identically, as different factors influence both commodities (which sometimes makes it interesting to compare both cur-

ves). Unless a significant thermal overprint or massive bacterial oxidation of organic matter, usually diagenesis is not a relevant issue with respect to the isotope curve. However, also for organic carbon two main reservoirs can exist: 1) marine organic matter having lower carbon isotope values (at pre-Cretaceous times) and 2) terrigenous organic matter having higher carbon isotope values (pre-Cretaceous times). With respect to the marine organic carbon pool, also deeper water and shallow water organic matter exists, however, usually less pronounced differences than between the two carbonate reservoirs. Compound-specific carbon isotope curves can circumvent this problem, but are more difficult to obtain.

LOWER TRIASSIC:

Ad I) Carbonate carbon isotope curve regional variations have been documented, some of them most probably related to regional variations in the marine carbon cycle, mainly variations in shallow water sections (e.g. Uomo/Italy, Zal/Iran, Guandao/China). Additionally, also profound variations have been identified that should be related to different carbonate sources (e.g. differences between shallow water and some deeper water sections (e.g. shallow water sections mentioned before and Mud/India, Chaohu/China). In both of the latter two sections (Mud, Chaohu) the influence of carbonate sources is documented as shallow water sediment rocks (from turbiditic flows) show higher carbon isotope values than the authigenic carbonate.

Ad II) Organic carbon isotope curve variations have been documented regionally as well (though there generally do exist less data on organic carbon up to now). Furthermore, also variations that most likely are related to different sources of the organic matter have been shown. These variations are found within individual sections whenever the influence of main organic pool changes (marine versus terrigenous, e.g. Suol, Pautovaya) sections) and between sections depending on the dominant organic matter pool (marine or terrigenous, e.g. Pakistan section (terrigenous dominated) versus Siberian sections (dominantly marine)).

CONCLUSIONS

Shallow water carbonate carbon isotope curves from well preserved rock samples most likely are the best commodity to study the (shallow water) marine carbon cycle and its variations, as carbonate only from one reservoir (shallow water) is present (when avoiding diagenetic carbonate). For deeper wa-

ter sections there has to be taken into account the presence of carbonate from two different reservoirs (shallow water and deeper water) and the mixing of carbonate from these reservoirs. When interpreting bulk organic carbon isotope curves the presence of organic matter from two different sources (organic and terrigenous) has to be taken into account, and the mixing of organic matter from both sources. Sedimentation of organic matter of different origin might produce a carbon isotope curve which shows a different pattern masking the primary marine carbon isotope variations.

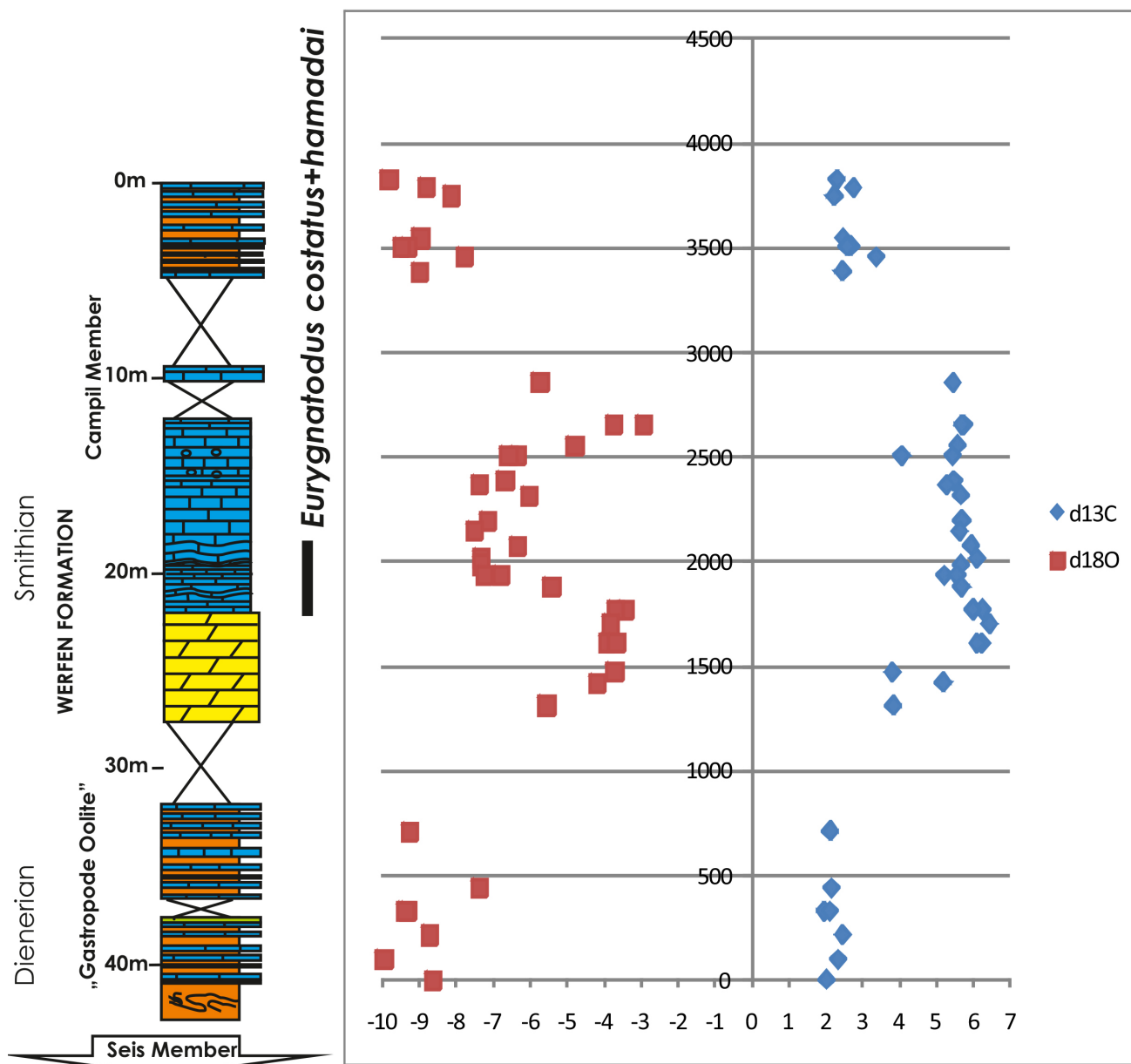
Significance of *Eurygnathodus costatus* and *Eurygnathodus hamadai* as indicators for the Dienerian-Smithian boundary (DSB): a study in the Dolomites (N-Italy)

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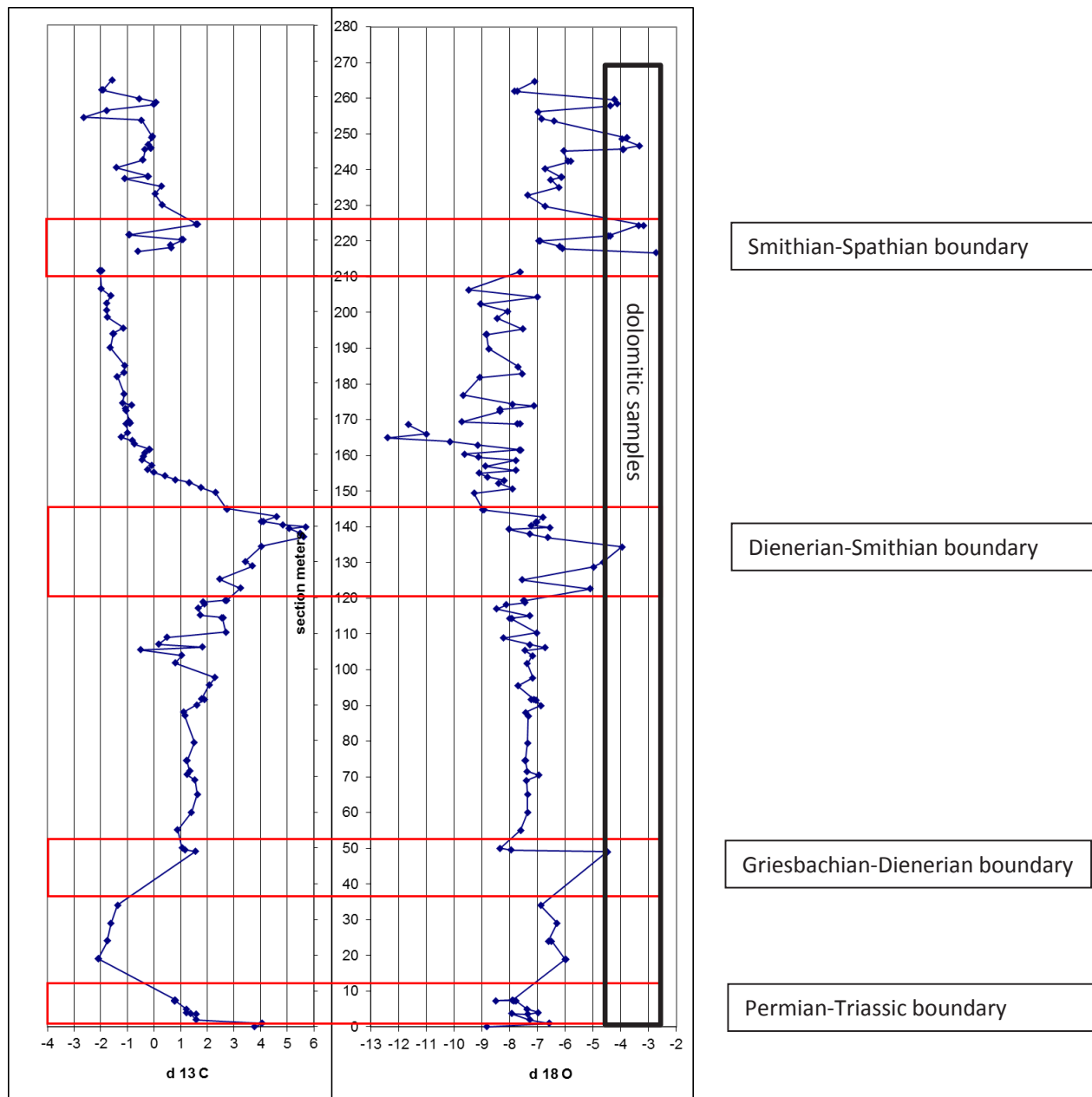


FIG. 2: Carbonate and oxygen isotope curves of the Uomo/L'Hom Picol section with approximate indication of boundaries.

The Early Triassic is a very peculiar period in Earth history, as it represents the time after the worst mass extinction event. Therefore it is of great interest and importance to correlate in time slices findings in various Early Triassic sections to combine the archived processes and evolutions in different regions. However, correlation often is hampered by absence or scarcity of time-diagnostic (macro-) fossils. The Early Triassic carbon isotope curve is a very valuable tool for stratigraphic correlation, but there are regionally significant variations in the curve shape for some Early Triassic intervals and thus additional markers are required. Conodonts have proven to be suitable, when available in the Early Triassic sediments, however for the Dolomites (and for many other shallow water sections as well) the fauna has been documented to be rather poor.

Now, sampling has been carried out in higher resolution and demonstrates that aside from the genera *Hadrodontina* and *Pachycladina* also *Eurygnathodus costatus* and *Eurygnathodus hamadai*

co-occur during a short period across the Dienerian-Smithian boundary (DSB), tightly embracing the boundary sensu maximum $\delta^{13}\text{C}$ values of the carbon isotope curve (Fig. 1 IOB interval of the Rio Salt section near St. Vigil, Dolomites, Northern Italy). As these forms are abundant and have been identified in many Tethyan and also in Panthalassan sections (at low to moderate latitudes), they are very important forms for the definition and identification of the DSB. Furthermore, in the Dolomites they mark short intervals of open-marine influence in this shallow water realm. Additionally, it also shows that certain lithofacies (e.g., occurrences of dolomitic rocks, identified in the diagrams in Fig. 1 and 2 by elevated $\delta^{18}\text{O}$ -isotopes around -4 to -2‰) in the Dolomites and also Dinarides (and perhaps even in other regions) can be correlated between different sections and regions and have been shown to occur more or less synchronously (Fig. 2: carbon and oxygen isotope values from the Uomo/L'Hom Picol section, Dolomites, Northern Italy).

Magnetostratigraphy at the Induan-Olenekian boundary in a global context: relationships with other correlation tools

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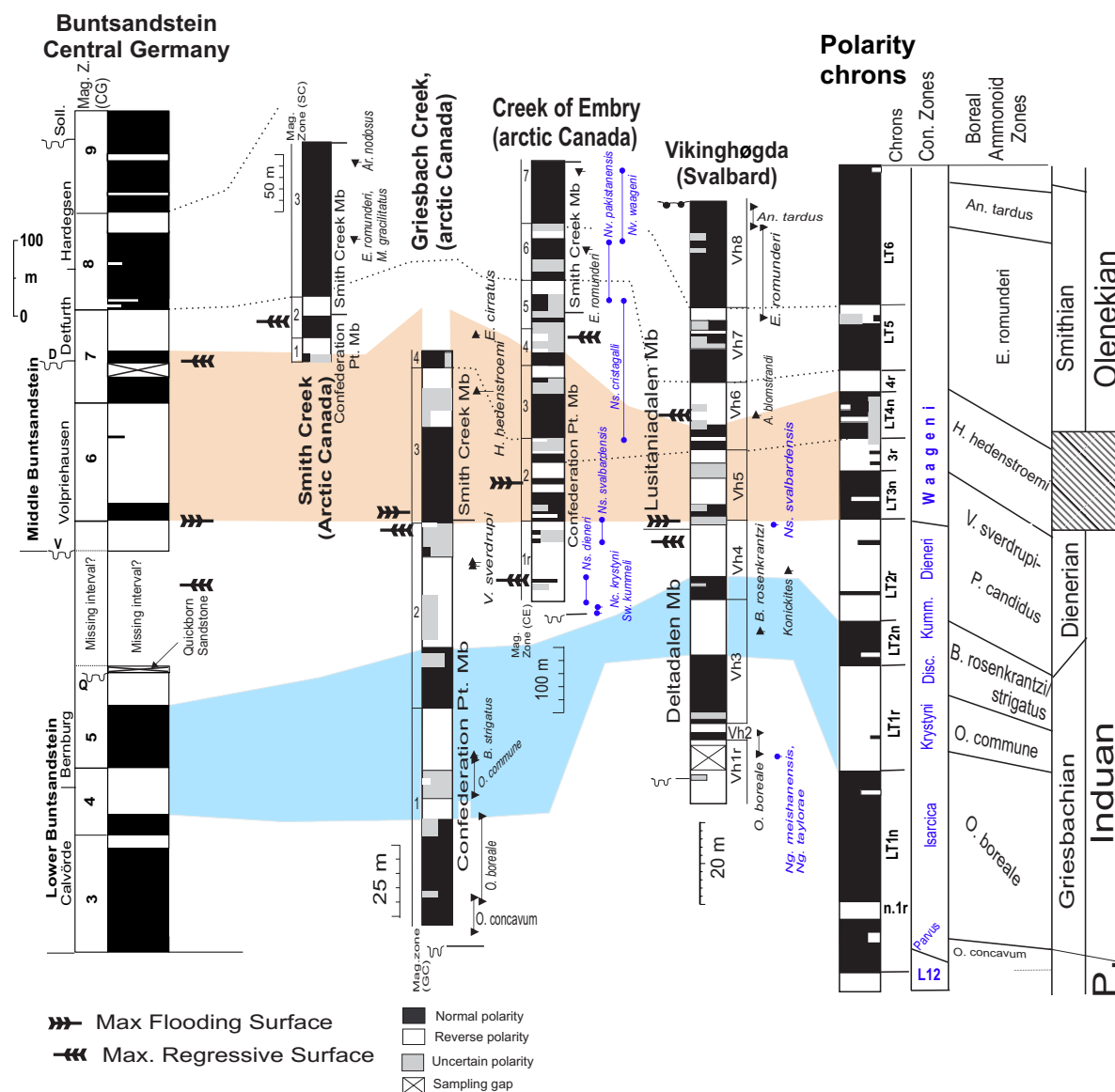


FIG. 1. Relationship between sequence stratigraphy and the magnetostratigraphy in Boreal sections and the German Buntsandstein. Data sources are indicated in Hounslow & Muttoni (2010).

The magnetic polarity stratigraphy for the Lower Triassic is fairly well established with some direct calibration against conodonts, boreal ammonoids, cyclostratigraphy and carbon isotopes (Hounslow & Muttoni, 2010; Li et al., 2016; Hounslow, 2016). Most proposals for the position of the Induan–Olenekian boundary (IOB) place it near the base of magnetochron LT3n

(Sun et al., 2009; Zhao et al., 2013). This work reviews how the correlation afforded by using LT3n could provide a means for global correlation of the IOB into all sedimentary regimes, not just richly fossiliferous ones. Withstanding revision of the conodonts, various possible proposals for using a primary conodont datum place the IOB either in the upper-most part of

Tool type	Sections also with magnetostratigraphy	Nearest proxy for base of LT3n [Section]
Conodonts	Daxiakou, West Pingdingshan, Creek of Embry, Vikinghøgda	FO <i>Nv. w. waageni</i> [Dax,WP], LO <i>Ns. Svalbardensis</i> [CofE, Vik]
Ammonoids	Creek of Embry, Vikinghøgda, Greisbach Creek, Chaohu	<i>H. hedenstroemia</i> ~ 45 m above [at GC] in mid LT3r; <i>Euflemingites</i> and <i>Flemingites</i> within 1 m [Ch]
Conchostracans	Volpriehausen (Buntsandstein)	Common <i>Magnietheria mangaliensis</i> in LT2r-LT3?
Palynology	Vikinghøgda, Volpriehausen (Buntsandstein)	Acme of <i>Densoisporites neiburgii</i> [Volp.] in top LT2r; base of <i>Naumovaspera striata</i> assemblage zone in top LT2r [Vik]
Tetrapods	Volpriehausen (Buntsandstein)	Approx. base of Parotosuchus assemblage
Carbon isotopes	Daxiakou, West Pingdingshan	Initial part of $\delta^{13}C_{carb}$ peak [Dax, WP]
Geochronology	None near IOB	251.2 \pm 0.2 Ma from <i>K. densistriatus</i> beds [Jinya/Wailli]
Cyclostratigraphy	Daxiakou, West Pingdingshan, Buntsandstein	249.92 Ma [Dax, WP], 251.14 [Dax], 250.0 [Bunts.]
Sequence stratigraphy	Creek of Embry, Vikinghøgda, Greisbach Creek, Volpriehausen (Buntsandstein)	MFS near base LT3n [Volp., GC, Vik.]

TABLE 1. Comparison of possible proxies for the Induan-Olenekian boundary based on published magnetostratigraphic studies which cover the IOB interval. The relationship of the IOB proxy to the magnetochrons is indicated using physical and biostratigraphic tools which can be directly related to those sections. Section details in Hounslow & Muttoni (2010); Daxiakou details in Hounslow et al. (this volume).

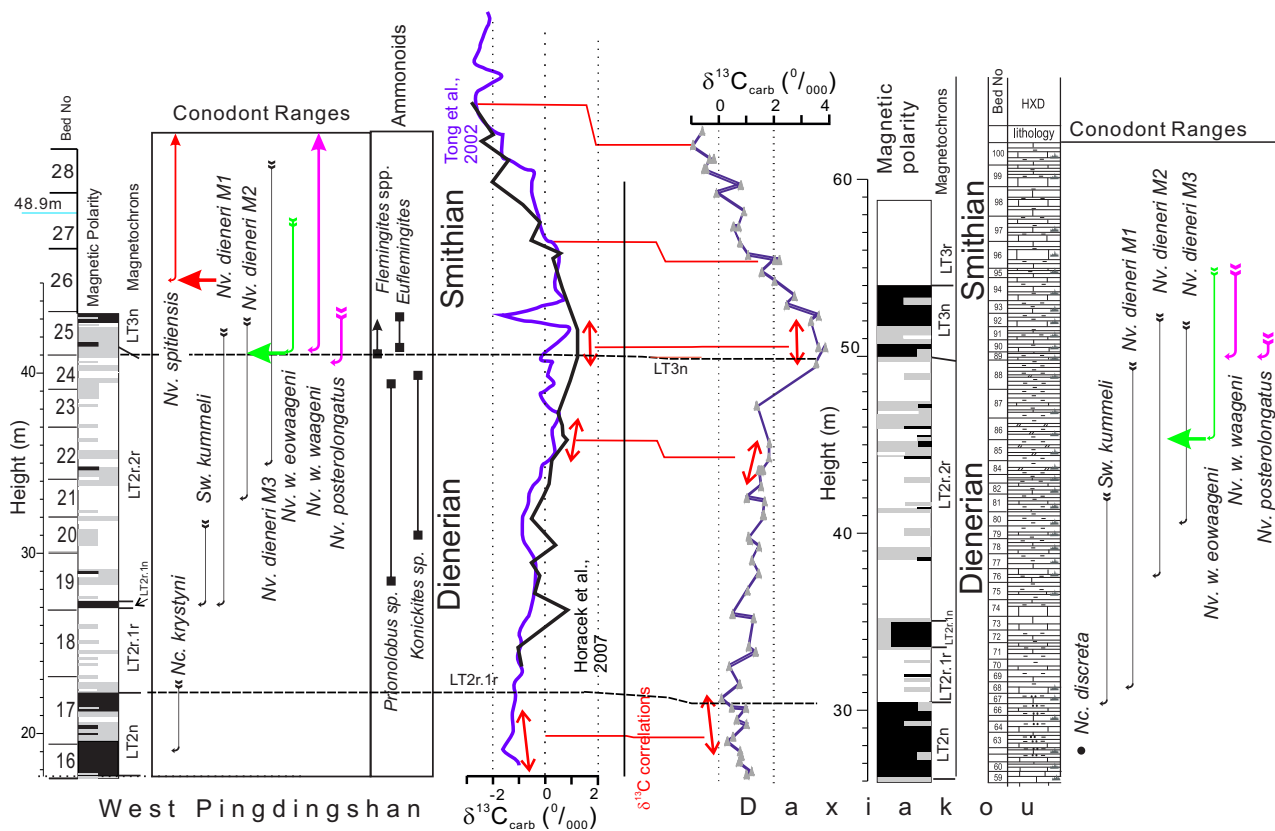


FIG. 2. Correlation relationships using the magnetostratigraphy and carbon isotope stratigraphy in the West Pingdingshan and Daxiakou sections. The large green and red arrows show possible definitions of the IOB in the two sections, using conodont datums. Data from Sun et al. (2009), Hounslow et al. (this vol.), Tong et al. (2007), Zhao et al. (2013) and Horacek et al. (2007).

LT2r or within the early part of LT3n. The data from Daxiakou and West Pingdingshan demonstrate that the FO of *Nv. waageni* (Zhao et al., 2013) and the base of LT3n likely coincide in both sections, and so provide two strong combined markers for definition of the base Olenekian. In these two sections the age difference between these may be up to 10ka (based on the cyclostratigraphy). At Chaohu the first *Euflemingites* and *Flemingites* also occur with one meter of the base of LT3n. Using the base of LT3n as a means of high resolution correlation, Table 1 outlines how this boundary may be related to other kinds of correlation and dating tools, and which sections provide this information. Magnetostratigraphy across the IOB has only been calibrated so

far against good ammonoid faunas in the Sverdrup Basin and Svalbard sections, where LT3n falls in the 60 m barren interval between *V. sverdrupi* and *H. hedenstroemi*, some 15 m above *V. sverdrupi* in the Griesbach Creek section. The Buntsandstein successions and associated magnetostratigraphy (Szurlies, 2007) are important for constructing relationships with non-marine faunas. Magnetochron LT3n is probably the equivalent of magnetozone CG6n in the German Buntsandstein (Szurlies, 2007; Li et al., 2016), placing the IOB in the lower part of the Volpriehausen Fm. This relationship suggests that the common presence of the conchostracan *Magnietheria mangaliensis* (Scholze et al., 2016) and the acme of miospore *Densoisporites neiburgii* (Heunisch, 1999) both occur in the top LT2r perhaps some 100-200

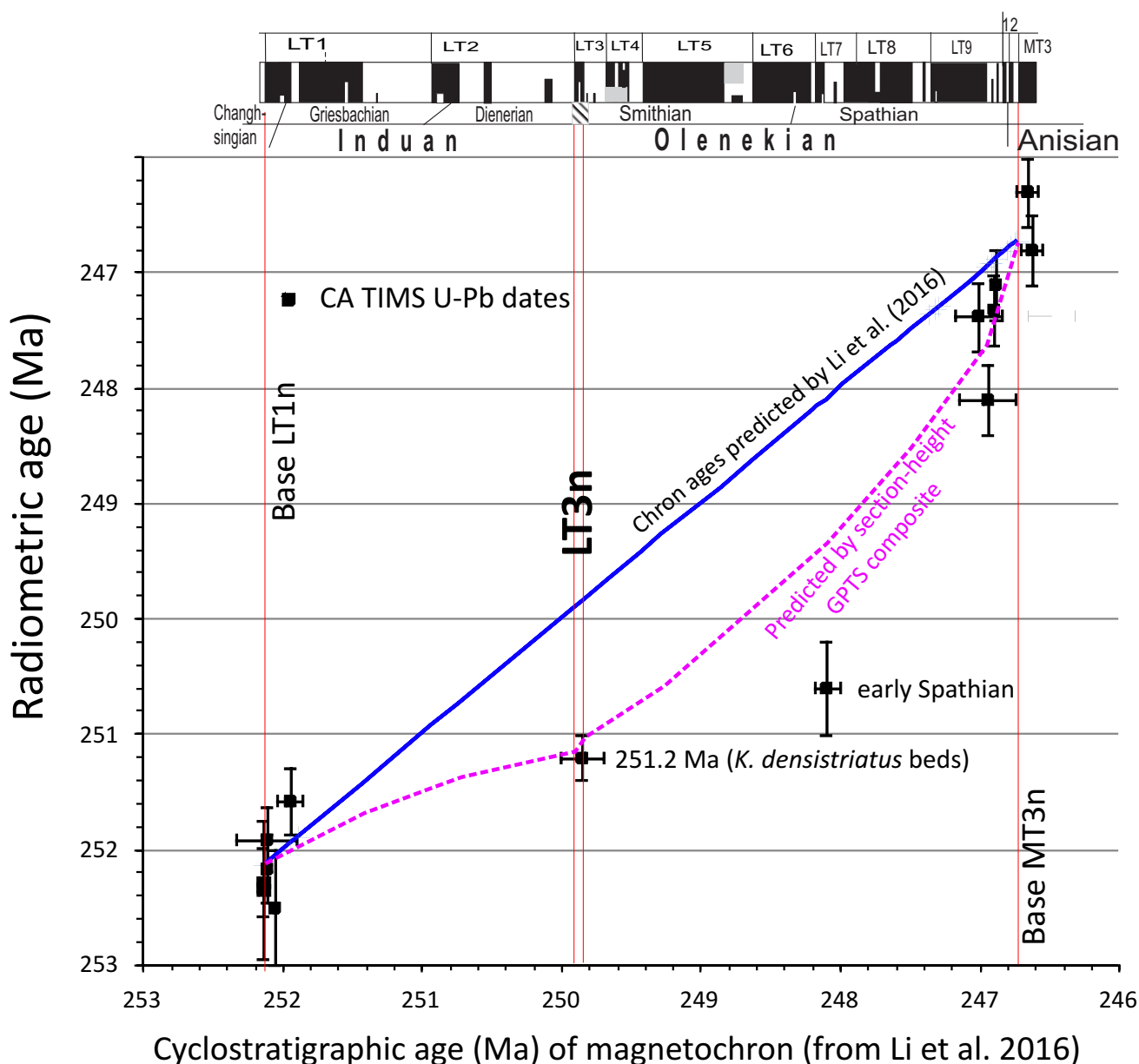


FIG. 3: Relationship between magnetostratigraphy and ages based on cyclostratigraphy and radiometric dates in the Lower Triassic. Blue line is the ages predicted by Li et al. (2016) for the magnetostratigraphy in the upper part of the panel. Radiometric dates for the Lower Triassic are plotted with respect to the magnetostratigraphy, with the error bars in the y-axis the 2 σ age uncertainty, and error bars on the x-axis, the uncertainty in placing the TIMS date onto the magnetostratigraphy. Dates listed in Galfetti et al. (2007) and Hounslow (2016). Dotted line is the relationship between the magnetostratigraphy of Li et al. (2016) and the section-height composite in Hounslow & Muttoni (2010) approximately attached through the TIMS dates near the PTB and the Olenekian-Anisian boundary.

ka older than the base of LT3n. The base of the *Parotosuchus* tetrapod assemblage may relate approximately to the same point, since it occurs also in the Volpriehausen Fm (Lucas & Schoch, 2002). In the Barents Sea and Svalbard successions the *Naumovasporea striata* miospore assemblage zone also begins in the topmost part of LT2r (Vigran et al., 2014). These faunal turnovers in the late part of LT2r may relate to a maximum regressive surface seen in both the Boreal Triassic and the Buntsandstein at about the same position in the magnetostratigraphy (Fig. 1).

At Daxiakou and West Pingdingshan $\delta^{13}\text{C}_{\text{carb}}$ (Tong et al., 2007) be directly related to the magnetostratigraphy across the IOB. At both West Pingdingshan and Daxiakou the base of LT3n relates to the initial part of the main peak in $\delta^{13}\text{C}$. In both sections the isotope excursion continues throughout LT3n and

into the overlying LT3r (Fig. 2). However, the magnetostratigraphy at West Pingdingshan needs re-sampling in bed 25 to more confidently locate the base of LT3n with respect to the carbon isotope variations.

The German Buntsandstein, Daxiakou and West Pingdingshan section have a cyclostratigraphy which can be related to LT3n (Li et al., 2016). Cycles from the Buntsandstein, Daxiakou and West Pingdingshan are based on gamma-counts, with the cycles for the Buntsandstein assumed to be 100 ka cycles. Their synthesis of the cyclostratigraphy has produced an age for the base of LT3n of 249.92 ± 0.1 Ma, based on an anchor to the base Induan at Meishan of 251.902 Ma. Wu et al. (2012) also generated a cyclostratigraphy at Daxiakou using two magnetic datasets which relate to the magnetite (i.e. detrital) content, in which they derived a duration of 1.16 Ma for the Induan, 0.82

Ma shorter than Li et al. (2016). Radiometric dates from the Lower Triassic suggest that the base of LT3n is around 251.2 Ma (Galfetti et al., 2007), approximately consistent with both the cyclostratigraphic duration of the Induan of Wu et al. (2012), and predicted duration, if the polarity timescale in composite section-height is stretched between base LT1n and base MT3n, and anchored through the existing radiometric dates near the base Induan and latest Spathian (Fig. 3).

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Lower Triassic bio-magnetostratigraphy from the late Permian to the early Olenekian from the Daxiakou Section (Hubei Province, China)

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The great advantage of using a supporting magnetostratigraphic marker for GSSP's is it allows correlation into non-marine, biostratigraphically ambiguous successions—advantages which have been clearly identified in Cenozoic GSSP's (Miller & Wright, 2017). The magnetic polarity stratigraphy for the Lower Triassic is fair well established in outline (Li et al., 2016), but it will probably grow in fine-detail over coming decades. Successions in China provide key data for this, but magnetostratigraphic data from South and central China for the Upper Permian and Lower Triassic is often compromised by partial remagnetisations which can hide the original Triassic magnetisation. In spite of many studies on Chinese Lower Triassic sections, there are few if any sections which combines high resolution biostratigraphy, magnetostratigraphy and carbon isotope geochemistry across the Permian-Triassic boundary and through the entire Induan. The Daxiakou section (near Xiakou town, Hubei province) from the northern carbonate-marl basin, is one of few sections in China in containing a conodont defined Permian-Triassic boundary (PTB) and Induan-Olenekian boundary (Zhao et al., 2013; Lyu et al., 2017). The section also displays the dual peaked $\delta^{13}\text{C}_{\text{carb}}$ isotopic excursion at the PTB (Shen et al., 2012; Zhao et al., 2013). The FO of *Hindeodus parvus* is in bed 11c. Bed 86 posses the first occurrence of *Novispathodus waageni eowaageni* (Zhao et al., 2013) and bed 89 *Nv. waageni waageni* (and *N. posterolongatus*) both levels possible markers for the base of the Olenekian; although these taxa probably need a better definition (Goudemand, 2014; Lyu et al., 2017). The early Olenekian $\delta^{13}\text{C}_{\text{carb}}$ excursion ranges across bed 88 to 96 peaking in bed 90 (Fig. 1).

The palaeomagnetic data from the Daxiakou section, covers the Changhsingian into the early Olenekian. The palaeomagnetic data define 3 magnetisation components, 1) a post-folding late Mesozoic remagnetisation, 2) a composite component comprising the post folding and pre-folding components, and 3) a dual polarity pre-folding magnetisation (passing the fold test) interpreted to represent the Triassic geomagnetic field. The mean virtual geomagnetic pole (VGP) is close to the expected Triassic VGP, based on other studies from S. China, indicating no tectonic rotation of the site. These indicate the reliability of the palaeomagnetic and magnetostratigraphic data at Daxiakou. Uncertainty in the magnetostratigraphy relate to the sampling resolution, and in some intervals (gray intervals in Fig. 1) the rocks preserve no evidence of the Triassic magnetic field.

The Lower Triassic magnetostratigraphy at Daxiakou is consistent with many other sections in the Tethyan and Boreal realms particularly Hechuan to the west and the West Pingdingshan section to the east. Like other sections in the argillaceous basin in the northern part of the South China Block, the Permian-Triassic boundary interval at Daxiakou is condensed, particularly the equivalent of magnetozone LT1n. The base of LT1n is within the *C. taylorae* conodont zone some 0.4 m above the apparent extinction event shown by the low in the $\delta^{13}\text{C}_{\text{carb}}$ isotopic excursion in the lower part of bed 9.

At Daxiakou the FO of *Nv. waageni waageni* (Zhao et al., 2013) and *Nv. posterolongatus* occur near the base of LT3n in bed 89. The uncertainty in the position (~0.25 m) of the base of LT3n is about ½ of a precessional cycle (~10 ka) using the cyclostratigraphy of Wu et al. (2012) or Li et al. (2016). The earlier subspecies has a FO of *Nv. waageni eowaageni* within the underlying magnetozone LT2r some 4.5 m lower (~1.5 eccentricity cycles; ~150 ka older using scale in Wu et al., 2012; Li et al., 2016).

The relative position of the first occurrences of *Nv. w. waageni* and *Nv. posterolongatus* and the base of magnetozone LT3n is similar to that seen at West Pingdingshan (Sun et al., 2009; Fig. 2). There the FO of subspecies *N. w. waageni* is about 0.5 m above the top the reverse polarity LT2r magnetochron, some 0.8 m above the base of bed 25 (an age difference of ~20 ka according to cyclostratigraphy; Guo et al., 2008; Li et al., 2016). At West Pingdingshan the position of the base of LT3n is less clear due to remagnetisation in the specimens at this level (Fig. 2). However the base of LT3n is most probably ~0.5 m from the base of bed 25 (~0.7 m of uncertainty on its position) or with less likelihood it maybe 1.8 m above the base of bed 25. The lower position is most similar to that seen at Daxiakou (Zhao et al., 2013), and more consistent with the carbon isotope stratigraphy. According to the magnetostratigraphy the FO of *Nv. waageni eowaageni* (and some other species) are diachronous between these two sections (Fig. 2).

Together these data demonstrate that the FO of *Nv. waageni waageni* and the base of LT3n provide a strong set of closely-tie markers for defining the base of the Olenekian. At Daxiakou the age difference between these two markers may range up to about 10 ka, with a similar scale of uncertainty at West Pingdingshan. Using the base of LT3n would therefore provide a level of uncertainty in any correlation comparable to many Cenozoic GSSPs. In their assessment of Cenozoic GSSPs Miller and

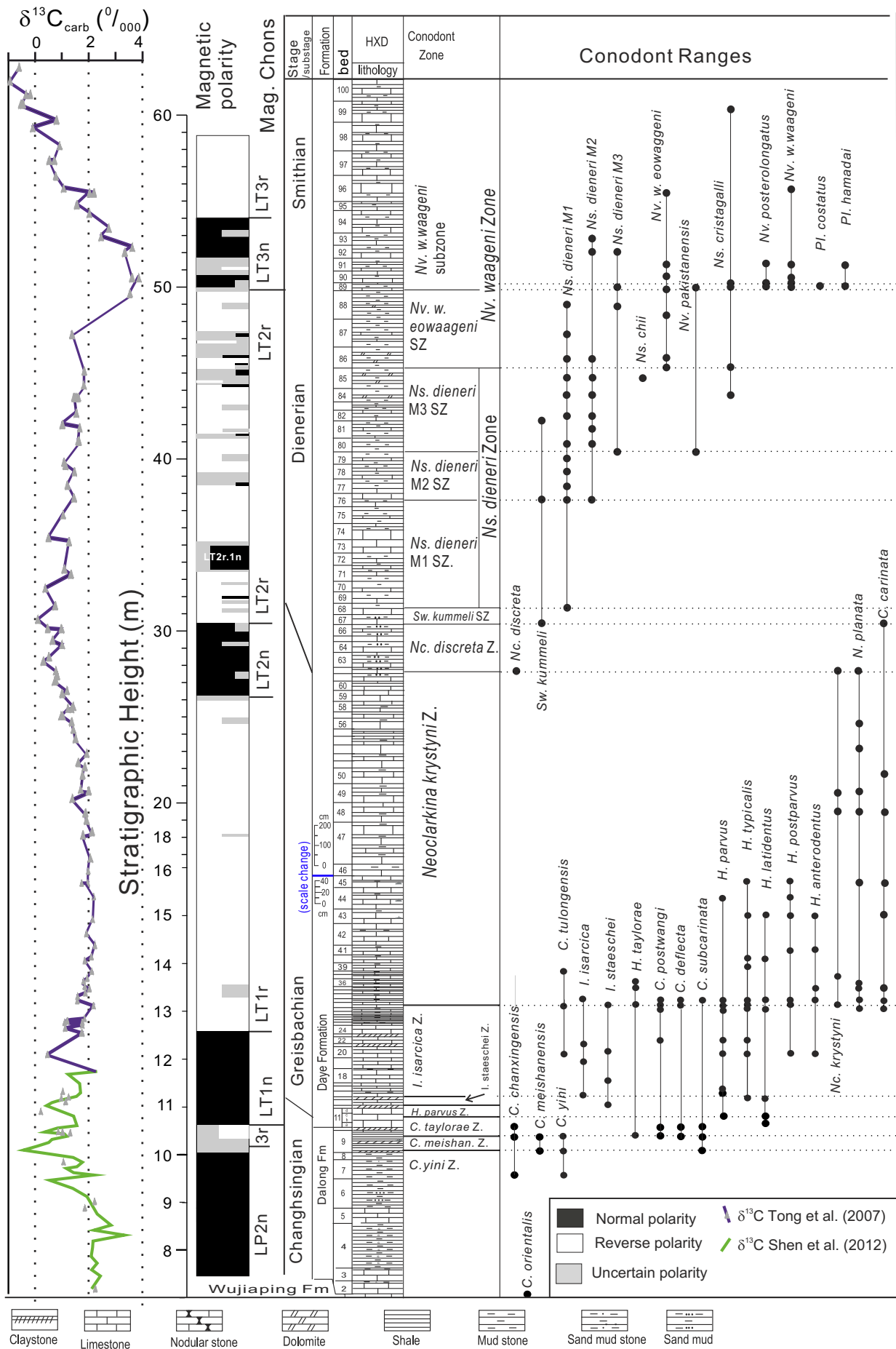


FIG. 1. Summary of the magnetostratigraphy, carbon isotope stratigraphy and key conodont biostratigraphy in the Daxiakou section. Conodont biostratigraphy from Zhao et al. (2013) and carbon isotope stratigraphy from Tong et al. (2007) and Shen et al. (2012).

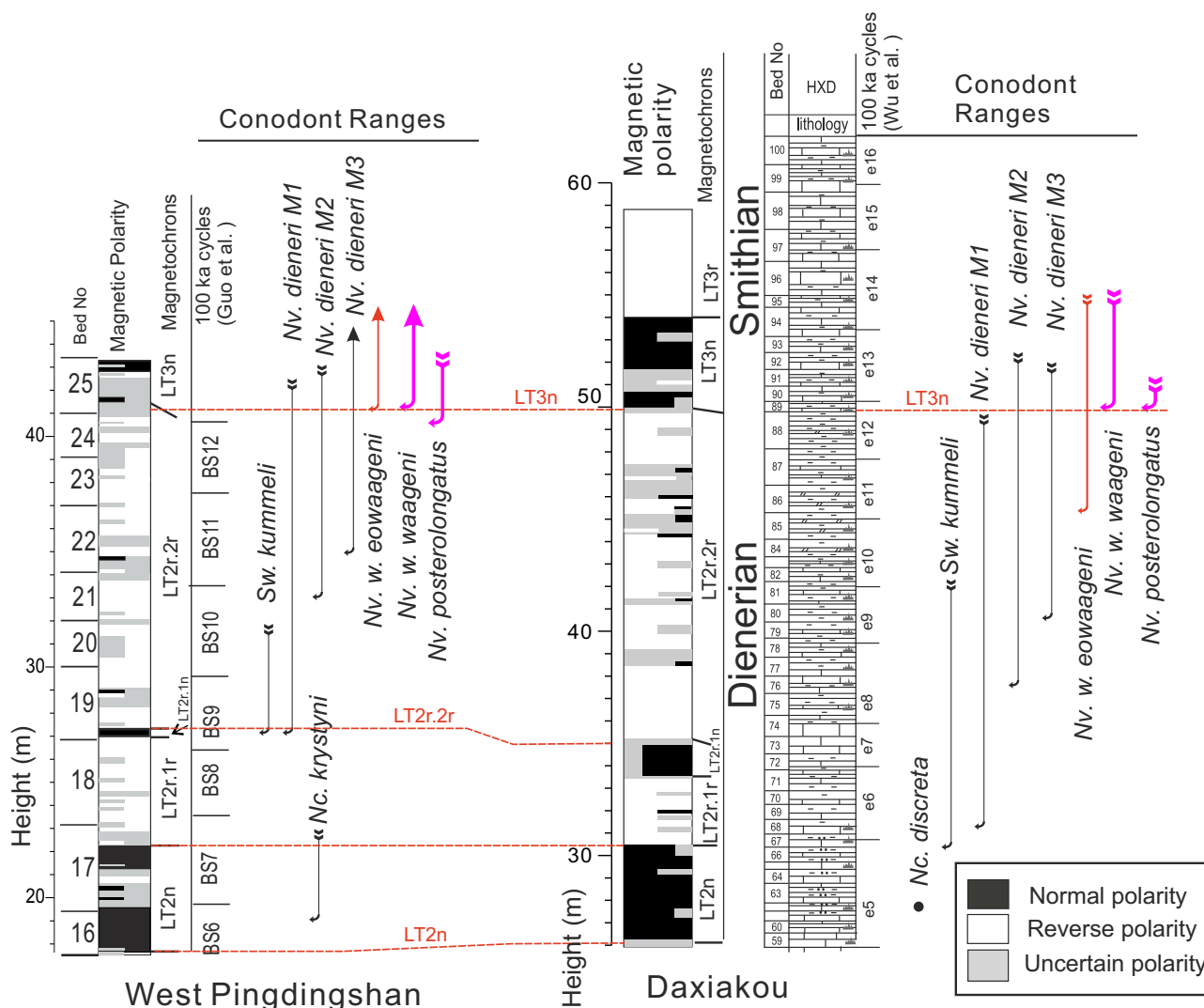


FIG. 2. Correlation of the stratigraphy across the IOB between Daxiakou and West Pingdingshan. Data from Sun et al. (2009), Guo et al. (2008), Wu et al. (2012) and Zhao et al. (2013).

Write (2017) conclude that “Biostratigraphy remains essential for placing magnetostratigraphy and isotopic stratigraphy into a correct time frame, but [biostratigraphy] lacks the temporal precision and global dimension” a hard reality which Triassic workers may wish to consider.

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A species of the *Eurygnathodus costatus* morphocline as important auxiliary conodont marker for the waageni-date definition of the IOB in low palaeolatitudes

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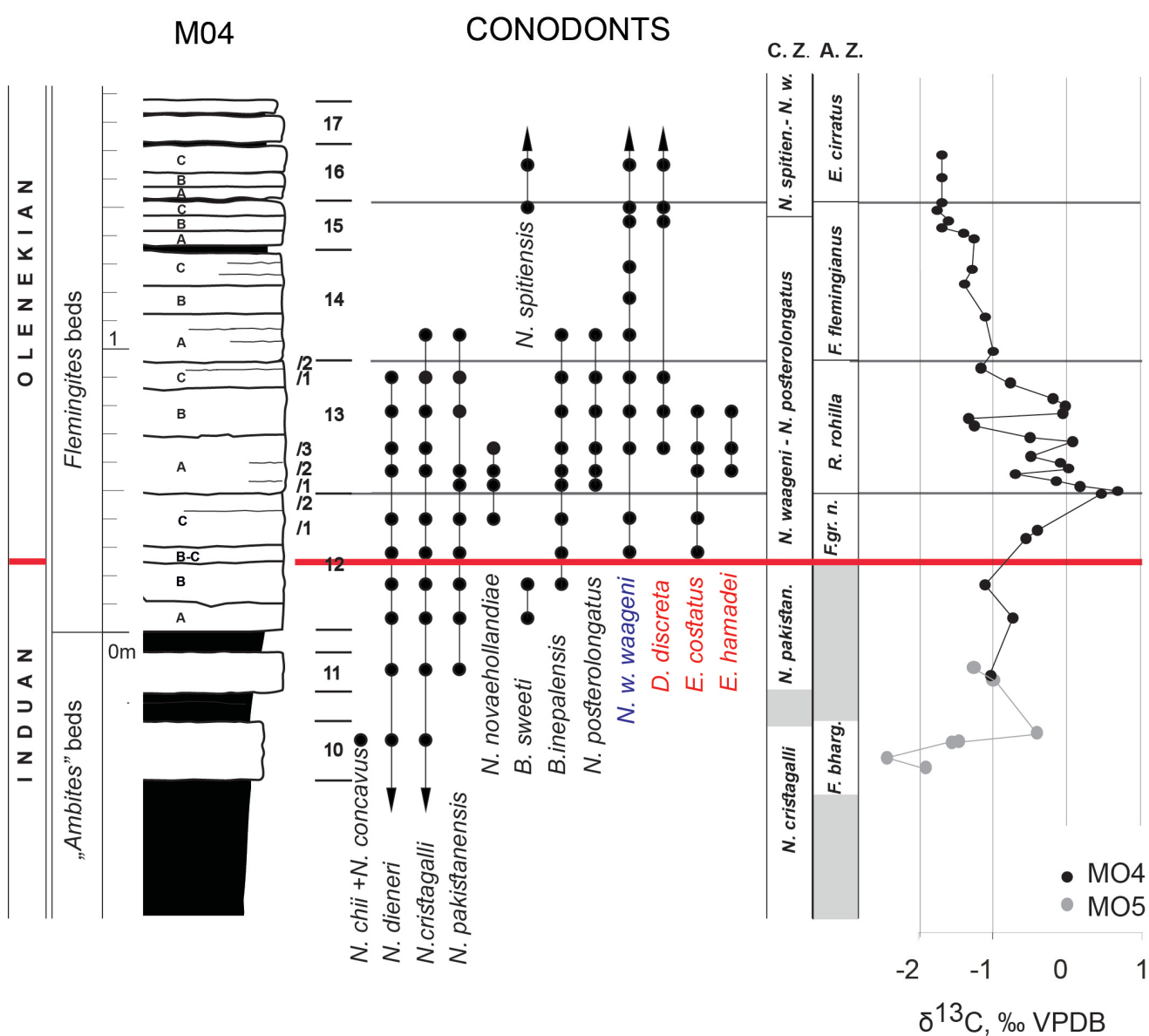


FIG. 1: Conodont biostratigraphy vs. carbonatic delta 13C isotopic curve in the IOB GSSP candidate section of Mud (Spiti, Himalaya).

Extended research in Spiti (Indian Himalaya) and published data from sections in other Tethys regions demonstrate a convincing timely correspondence between the FOs of *Nv. w. waageni* and *Eurygnathodus costatus*. In Spiti (Mud GSSP candidate section) their occurrences can be cross-correlated with a rich ammonoid fauna and a well-individualized carbonatic delta ^{13}C isotopic curve which shows a steep positive increase right after the appearance of *E. costatus* (Fig. 1). The latter species is followed by *Eurygnathodus hamadei* still within the positive excursion, and both species co-occur through the peak excursion. The very thin record of Spiti is well mirrored in the much expanded 25 m thick Golob 44 section of Ziri (Slovenia). A successive appearance of the two *Eurygnathodus* species has also been documented from Chaohu (China) and Chanakchi or former Sovetachen (Armenia). In the latter locality *E. costatus* starts again closely below the main positive excursion. As the latter species is there preceded by *E. paracostatus* – which is interpreted as forerunner of *E. costatus* – it may be argued

that the Chanakchi record can be seen as FAD proof of the species. Additional occurrences of *E. costatus* and/or *E. hamadei* are known from various other places in Far-eastern Russia (Primorye), Japan, China (e.g. Daxiakou, Guandao), Malaysia, Vietnam, Oman, Serbia, Croatia and Italy (Southern Alps).

The common occurrence of the two *Eurygnathodus* species around the IOB – and their FO restriction to the boundary interval – makes them potential candidates as index fossils or at least as primary proxies for a still to be internationally defined IOB in low to middle palaeolatitudes. Especially, since they are present in both deeper and shallow marine sections of which the latter are generally poor in time diagnostic (offshore) conodonts. Furthermore, and adverse to the *Nv. waageni* group, both species are very easily recognizable. Disadvantageous is the absence of *Eurygnathodus* in the Boreal region. Though *E. costatus* is known from the Chache Creek terrane of western North America, missing of *Eurygnathodus* in its cratonic shelf areas still remains an open question.

Land plant fossils and the Induan–Olenekian boundary

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INTRODUCTION

Macrofossils of land plants from the Lower Triassic are comparatively rare and mostly represent impoverished floras dominated by pleuromeiacean lycopsids (e.g., Rees, 2002; Grauvogel-Stamm & Ash, 2005; Cascales-Miñana & Cleal, 2014). Despite this, there is no shortage of spores and pollen grains from this interval, and biostratigraphic schemes based on mainly terrestrial palynomorphs have been established for various regions (Fig. 1). To date, palynomorphs have not been described from the main two proposed GSSP sections – at Mud (Spiti Valley, India) and Chaohu (Anhui Province, China) – for the Induan–Olenekian boundary (IOB).

PALYNOSTRATIGRAPHY

In Pakistan, associated ammonoids show that the IOB approximately coincides with the boundary between palynological assemblage zones PTr 1 (*Densoisporites* spp.–*Lundbladispota* spp.) and PTr 2 (*Lundbladispota* spp.–*Densoisporites* spp.), as described by Hermann et al. (2012). This includes the proposed GSSP candidate section at the Nammal Gorge. PTr 2 also marks the local FAD of *Aratrisporites*. In palynozonations for other parts of Gondwana, the position of the IOB is less well constrained. In India, Tiwari & Kumar (2002) assigned the *Krempipollenites indicus* assemblage zone (corresponding to the *Klausipollenites schaubbergeri* assemblage zone of Tiwari & Tripathi, 1992) to the Induan, and the *Playfordiaspora cancellosa* assemblage zone to the Olenekian, but without a clear age control for the boundary. In Australia, the IOB would be located within the long-ranging *Protohaploxyppinus samoilovichii* zone in Eastern and Western Australia (Helby et al., 1987; Metcalfe et al., 2015), or the *Kraeuselisporites septatus* zone in Western Australia (Dolby & Balme, 1978).

In North China, the *Lundbladispota* (= *Densoisporites*) *nejburgii* assemblage from the upper Liujiaguo Formation and the *Voltziaceasporites heteromorpha* assemblage from the upper Heshangguo Formation were dated as Induan and Olenekian, respectively, based on plant remains and ammonoids (Ouyang & Norris, 1988), but the IOB is not documented. Due to similarities, the *Limatulasporites–Cycadopites–Tubermonocolpites–Micrhystridium* assemblage and the *Lundbladispota–Cycadopites–Veryhachium* assemblage from Qinghai Province were also correlated to the Induan and Olenekian, respectively (Ji & Ouyang, 2006).

Vigran et al. (2014) assigned a common zonation to the palynological findings from many outcrops and wells on Svalbard and in the Barents Sea area, wherein the IOB approximately falls

together with the boundary between the *Maculatasporites* spp. and the *Naumovaspota striata* assemblage zones. The local LADs of *Propriosporites pocockii* and *Densoisporites playfordii*, as well as the FAD of *Punctatisporites fungosus* lie close to the IOB.

In the German Basin, the IOB presumably occurs in the lower part of the Volpriehausen Formation (Middle Buntsandstein; Ogg et al., 2014), which falls into the *Densoisporites nejburgii*-acritarch acme subzone of the *D. nejburgii* zone (Kürschner & Hergreen, 2010). The FAD of *D. nejburgii* is at the base of this zone, shortly below the boundary. In the Transdanubian (Mid-) Mountains of Hungary, Góczán et al. (1986) defined 12 palynozones for the Induan and 5 for the Olenekian. They proposed the mass occurrence of *D. nejburgii* as a marker for the IOB, which they located at the boundary between the *reductum–ultraverrucata* and *nejburgii–reductum* dominance zones, or the *Scythiana–Veryhachium* and *nejburgii–bisaccate* Opper zones. It should be noted that the Induan assemblages are dominated by acritarchs.

A biozonation based on megaspores exists for Poland (Marcinkiewicz et al., 2014, and references therein). Here, the uppermost Permian to Induan *Otymisporites triassicus* zone is succeeded by the lower Olenekian *Trileites polonicus* zone, but the boundary is unclear.

3. MACROFLORA

The Induan is mostly considered to lack plant macrofossils due to the effect of the end-Permian mass extinction, making a comparison with the earliest recovery floras of the Olenekian very difficult. This is especially true for Euramerican successions, which did so far not yield any Induan plant assemblages, although the Olenekian ones are locally sometimes surprisingly diverse (Kustatscher et al., 2014; Grauvogel-Stamm & Kustatscher, in press), suggesting that the dearth of Induan plant remains might also be due to taphonomic bias. Likewise, very few plant assemblages are known from the Southern Hemisphere, where the lowermost Triassic floras are general poorly diversified, whereas the upper Lower Triassic successions are generally dominated by seed ferns (mostly *Corystospermales* and *Peltaspermales*; e.g., Silvestro et al., 2015). Plant assemblages from China and Russia, on the other hand, are more diverse and generally dominated by sphenophytes, lycophytes, ferns and Gigantopteridales for the Induan, followed by a more diverse flora with abundant lycophytes, sphenophytes, ferns, seed ferns and conifers during the Olenekian (Yu et al., 2010a, b; Xiong & Wang, 2011). However, in a general overview it appears that most of the taxa that survived the end-Permian mass extinction

event also survive the IOB. The taxa that survive the end-Permian mass extinction (according to some of the above-cited papers) but get extinct at the end of the Induan are typical Paleozoic forms (e.g., *Annularia*, *Lepidodendron*, *Gigantopteris*). On the other hand, typical Triassic elements such as e.g., *Albertia*, *Anomopteris*, and *Isoetites* seem to first appear after the IOB. The lack of a transition between the late extinction of Paleozoic taxa and the appearance of new forms, as well as spores and pollen from this time indicating more diverse floras would suggest that the taphonomic and sampling bias concerning plant macroremains is still too high to determine a reliable stratigraphic marker for the IOB.

CONCLUSIONS

While macroremains from the Lower Triassic are still poorly studied and probably subject to strong taphonomic bias, spores and pollen grains might be useful for biostratigraphy in the Induan and Olenekian and can also be used as (approximate) indicators of the IOB in several regions. However, the comparability of palynozones between regions is limited, and palynostratigraphic data from the main GSSP candidate sections is not currently available. A major advantage of spores and pollen is their presence in both terrestrial and marine sediments, giving them the potential to correlate between the two realms, yet in many cases independent age control is still needed for calibration.

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A proposal for a multiproxy definition of the Induan-Olenekian Boundary and its corresponding GSSP candidate at Nammal Nala (Salt Range, Pakistan)

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DEFINITION OF THE IOB

A stage boundary is usually placed at a biological event linked with environmental perturbations such as an extinction or an important faunal turnover. In the case of the Induan/Olenekian boundary (IOB), one of the potential event is the diversification of ammonoids, with the appearance of several new families. However, until recently, the timing of this event was only imprecisely known, as no high resolution study had been done on sections spanning this boundary.

Recently, re-investigations of sections in some classical localities in the Salt Range and in Spiti, with detailed bed-by-bed sampling and ammonoid taxonomic revision, provided an unprecedented high-resolution ammonoid-based biostratigraphic scheme for this interval, with 12 zones in the Late Induan (i.e. Dienerian; Ware et al., 2015), and 15 in the Early Olenekian (i.e. Smithian; Brühwiler et al. 2010, 2011). These recent studies also showed that the recovery of ammonoids during the Early Olenekian was progressive, starting already in the late Dienerian and peaking at the end of the early Smithian. However, two families generally considered as typically Smithian, Flemingitidae and Kashmiritidae, appeared in the same zone, so this event was chosen as a proxy for the IOB. The IOB is thus here defined as situated at the base of the *Flemingites barghavai* zone (zone S1 in Brühwiler et al., 2010). This definition of the boundary is situated lower than the definition as proposed by Krystyn et al., (2007), at the base of the *Rohilites rohila* zone (zone S5 in Brühwiler et al. 2010). Besides ammonoids, several events coinciding with the boundary as defined here can be used as proxies (Fig. 1), such as the first appearance of the conodont genus *Novispathodus*, a $\delta^{13}\text{C}_{\text{org}}$ positive shift, a third order sequence boundary, a change in palynofacies with a decrease in amorphous organic matter (end of a period of anoxia) and the beginning of a spore diversification (Hermann et al. 2011, 2012), and the onset of an increase in $\delta^{18}\text{O}_{\text{cp}}$ VSMOW (Romano et al., 2013) linked with a cooling event.

GSSP PROPOSAL: NAMMAL NALA (SALT RANGE, PAKISTAN)

Nammal Nala is a classical section for the study of marine Early Triassic since the work of Kummel (1966). It is situated in the

Salt Range in Pakistan, about 170 km SW of the capital Islamabad and is easily reachable through a ca 3 hours drive from there, or from the closest city, Mianwali, within ca 30 mins drive. The Early Triassic sections are situated behind a quarry exploiting the Permian limestone, thus guaranteeing the access through permanently maintained paths.

There, the newly proposed IOB is within the stratigraphically expanded Ceratite Marls without any significant facies change (Fig. 1), thus representing an ideal configuration for the definition of this boundary. Several easily accessible sections within a couple kilometers in the area can be proposed to place the golden spike.

With its easy access, its extended and continuous sedimentary sequence, its excellent ammonoid and conodont fossil record, its quasi-absence of alteration making palynological, oxygen isotopes and magnetostratigraphy analyses possible (the latter needing yet to be done), all the conditions for the establishment of a GSSP are united, making Nammal Nala the best section to establish the IOB GSSP.

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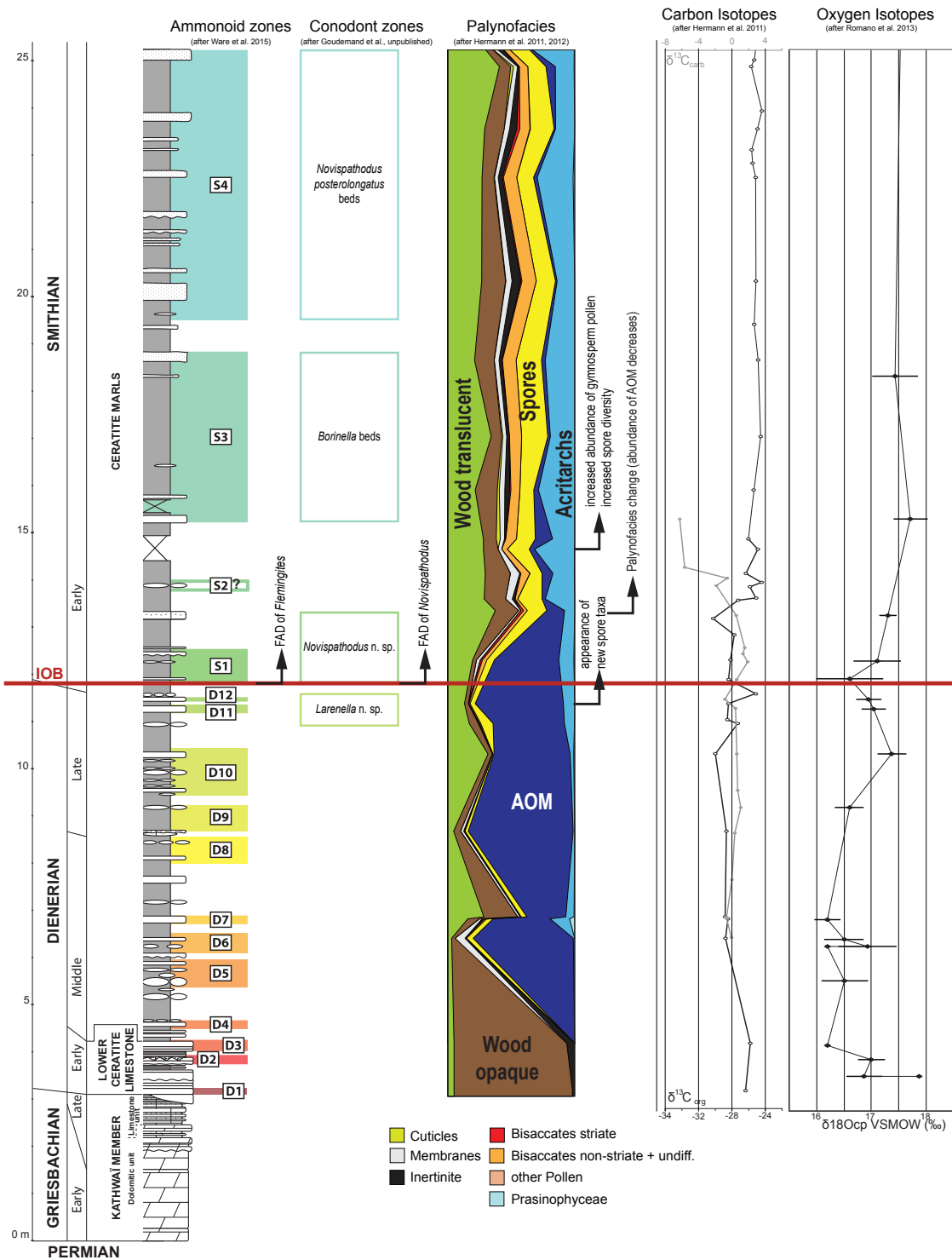


FIG. 1: Composite section of Nammal Nala, with ammonoid and conodont biozonation, palynofacies analyses and carbon and oxygen isotopes, and proposed position of the IOB. Ammonoid zones: D1: *Gyronites dubius* Zone; D2: *Gyronites plicosus* Zone; D3: *Gyronites frequens* Zone; D4: *Ambites atavus* Zone; D5: *Ambites radiatus* Zone; D6: *Ambites discus* Zone; D7: *Ambites superior* Zone; D8: *Ambites lilangensis* Zone; D9: *Vavilovites meridialis* Zone; D10: *Kingites davidsonianus* Zone; D11: *Koninckites vetustus* Zone; D12: *Awanites awani* Zone; S1: *Flemingites bhargavai* Zone; S2: *Shamaraites rursiradiatus* Zone; S3: *Xenodiscoides perplicatus* Zone; S4: *Flemingites nanus* Zone.

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