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## **The Smithian/Spathian boundary (late Early Triassic): a review of ammonoid, conodont, and carbon-isotopic criteria.**

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4 1 The Smithian/Spathian boundary (late Early Triassic):5  
6 2 a review of ammonoid, conodont, and carbon-isotopic criteria7  
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21 16 \*Corresponding authors: [thomas.algeo@uc.edu](mailto:thomas.algeo@uc.edu) (T.J. Algeo); [zlscug@163.com](mailto:zlscug@163.com) (L.S. Zhao)22 17  
23 18 **Abstract**24 19 The transition from the Smithian substage to the Spathian substage of the Olenekian stage  
25 20 of the late Early Triassic was a critical time marked by a series of biological and environmental  
26 21 changes during the multimillion-year recovery interval following the end-Permian mass  
27 22 extinction. However, the Smithian/Spathian boundary (SSB) has not yet been formally defined,  
28 23 a shortcoming that inhibits targeted detailed studies of successive events during the Smithian-  
29 24 Spathian transition and the recovery of the marine ecosystem during the Early Triassic. Here,  
30 25 we review main biostratigraphic (i.e., ammonoid and conodont) studies of the Smithian and  
31 26 Spathian substages in historically important regions (e.g., the Canadian Arctic for the Boreal  
32 27 realm, western North America for the eastern Panthalassic Ocean) and more recently re-studied  
33 28 locations (e.g., Pakistan and India in the southern Tethys, South China in the eastern Tethys)  
34 29 as well as the carbon isotope chemostratigraphy of 29 major Smithian-Spathian sections  
35 30 globally. Key ammonoid genera (e.g., *Wasatchites*, *Anasibirites*, *Glyptophiceras* and  
36 31 *Xenoceltites* of the late Smithian, and *Bajarunia*, *Tirolites* and *Columbites* of the early  
37 32 Spathian), conodont species (e.g., *Scythogondolella milleri*, *Novispathodus waageni*, and  
38 33 *Borinella buurensis* of the late Smithian, and ‘*Triassospathodus*’ *hungaricus*, *Neogondolella*  
39 34 aff. *sweeti*, and *Icriospathodus* spp. of the early Spathian), and carbonate carbon isotope  
40 35 excursions provide appropriate markers for constraining the SSB. Use of the first occurrence  
41 36 of the conodont *Novispathodus pingdingshanensis* as a potential marker of the SSB is also  
42 37 discussed. Based on correlations of biostratigraphic and carbon isotope data globally, we  
43 38 propose to revise previous placements of the SSB transition in some sections. Finally, we show  
44 39 that the Smithian Thermal Maximum (STM; herein named) was middle Smithian in age and  
45 40 not correlative with the SSB, as inferred in some earlier studies, and that the SSB coincided  
46 41 with a subsequent major global cooling event.  
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63 43 *Keywords:* Carbon isotopes; Olenekian; Boreal; Tethyan; Smithian Thermal Maximum;  
64 44 hyperwarming;  
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## 66 46 67 47 **Outline**

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## 103 77 **1. Introduction**

106 79 The Early Triassic is officially divided into two stages, the Induan and Olenekian, with the  
107 80 latter divided into two substages, the Smithian (ca. 0.7 Myr long) and Spathian (ca. 3 Myr long)  
108 81 (Fig. 1; Ovtcharova et al., 2006, 2015; Lehrmann et al., 2006; Galfetti et al., 2007; Mundil et  
109 82 al., 2010; Baresel et al., 2017). An alternative timescale based on cyclostratigraphic analysis of  
110 83 successions in Germany and China has assigned durations of 1.7 and 1.4 Myr to the Smithian  
111 84 and Spathian substages, respectively (Li et al., 2016a). The boundary between the Smithian  
112 85 and Spathian substages is an important transition during the recovery of marine ecosystems  
113 86 following the end-Permian mass extinction (EPME). Marine faunas show major rapid changes

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121 87 during the late Smithian (over <0.12 Myr; Brühwiler et al., 2010) that continued across the  
122 88 Smithian/Spathian boundary (SSB), including a severe loss of biodiversity among conodonts  
123 89 and ammonoids (Brayard et al., 2006; Orchard, 2007; Stanley, 2009), size changes among  
124 90 surviving conodont taxa (Chen-YL et al., 2013; Leu et al., 2016, 2018), and greater  
125 91 cosmopolitanism among surviving ammonoid taxa (Brayard et al., 2006, 2007a; Fig. 1).  
126 92 Vegetation on land was marked by a rebound of arborescent forms (gymnosperms) during the  
127 93 late Smithian, following a prolonged interval of dominance by shrubby disaster-type taxa  
128 94 following the EPME (Galfetti et al., 2007a; Schneebeili-Hermann et al., 2012; Saito et al., 2012;  
129 95 Hochuli et al., 2016). In addition, a significant marine transgression occurred during the  
130 96 Smithian, followed by a marked regression across the SSB (e.g., Embry, 1997; Twitchett and  
131 97 Barras, 2004; Henderson et al., 2018). In some areas, dominantly argillaceous rocks and  
132 98 organic-rich shales of the late Smithian were replaced by massive carbonate rocks during the  
133 99 early Spathian (e.g., South China, Galfetti et al., 2008). Major perturbations in the global  
134 100 carbon (C) cycle were recorded by a negative  $\delta^{13}\text{C}$  shift during the middle Smithian (i.e., the  
135 101 N3 minimum; note: the numbering system of Early Triassic C-isotopic excursions is from  
136 102 Song-HY et al., 2013, 2014, and used here for convenience in correlation among different  
137 103 studied regions), followed by a large positive shift across the SSB (to the P3 maximum) (Fig.  
138 104 1). These excursions represent the fluctuations in a ~1.5-Myr-long interval of rapid, large C-  
139 105 isotope fluctuations that commenced at the EPME, and it was followed by muted C-isotope  
140 106 variation during the Spathian substage (e.g., Payne et al., 2004; Tong et al., 2007). The SSB  
141 107 transition was also characterized by strong tropical sea-surface cooling (Sun et al., 2012;  
142 108 Romano et al., 2013), and a likely steepening of the latitudinal temperature gradient (Brayard  
143 109 et al., 2009a). It also corresponds to the establishment of first known complex and diversified  
144 110 biotas after the EPME (Brayard et al., 2017). This amalgam of biotic, environmental, and  
145 111 climatic changes at the SSB transition is known as the “SSB Event” (e.g., Galfetti et al., 2007a).

152 112 Biostratigraphic analysis of the SSB transition began with studies of ammonoids in the  
153 113 Alps (Austria, Italy and Bosnia), the Himalayas (India), and the Salt Range (Pakistan) by a  
154 114 number of workers during the late nineteenth and early twentieth centuries, including Edmund  
155 115 von Mojsisovics (1839-1907), Wilhelm Heinrich Waagen (1841-1900), and Carl Diener (1862-  
156 116 1928). A key paper was Mojsisovics et al. (1895), which presented an ammonoid biozonation  
157 117 that was used to define series and stages in the first complete formal subdivision of the Triassic  
158 118 system. Important early work on ammonoids in the western United States was undertaken by  
159 119 James Perrin Smith (1864-1931) and Norman John Silberling (1928-2011), among others. The  
160 120 substages of the Early Triassic were established based on extensive and detailed studies of  
161 121 ammonoids from marine faunas collected in the Canadian Arctic by geologists from the  
162 122 Geological Survey of Canada (Tozer, 1962, 1965, 1967, 1971, 1984, 1994). Tozer (1994) first  
163 123 reported an ammonoid biozonation for both the Smithian and Spathian substages. As a result  
164 124 of these investigations, the Triassic portion of the Standard Global Chronostratigraphic Scale  
165 125 was based exclusively on ammonoid biostratigraphy until the 1990s, and ammonoid studies  
166 126 have been continued by later researchers (e.g., Galfetti et al., 2007b; Shigeta et al., 2009; Guex  
167 127 et al., 2010; Jenks et al., 2015, and references therein).

171 128 The comparative scarcity of ammonoids in some Lower Triassic successions and the  
172 129 relative inaccessibility of ammonoid-based type sections in the Canadian Arctic, however,  
173 130 generated interest in the use of conodonts, which are generally abundant in both tropical and  
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181 131 boreal sections, for biostratigraphic subdivision of the Lower Triassic beginning in the late  
182 132 1960s and 1970s (Mosher, 1968, 1970; Sweet, 1970a, b). Initially, most of this work was  
183 133 undertaken in the Tethyan region, for example Pakistan (Salt Range), Kashmir (Guryul Ravine)  
184 134 (Sweet, 1970a, b), and later in South China Craton (Yangtze area) (e.g., Yin et al., 1986, 1996)  
185 135 and North America (Henderson, 1997; Henderson et al., 2001). This was the case for the P/Tr  
186 136 and Induan/Olenekian boundaries, which now have ratified or proposed global stratotype  
187 137 sections and points (GSSPs) based on the first appearance datums (FADs) of *Hindeodus parvus*  
188 138 (Yin et al., 2001) and *Neospathodus* ex gr. *waageni* (Zhao et al., 2002, 2004, 2008a, b; Tong  
189 139 et al., 2003, 2004; Goudemand, 2014a), respectively. Subsequently, high-resolution conodont  
190 140 biozonation studies of the Lower Triassic have been undertaken broadly around the world (e.g.,  
191 141 Krystyn et al., 2005; Henderson and Mei, 2007; Nakrem et al., 2008; Orchard, 2008; Orchard  
192 142 and Zonneveld, 2009; Zhao et al., 2013a; Chen-YL et al., 2015; Lyu et al., 2017).

195 143 Despite its importance and the considerable research efforts lavished on it in recent decades,  
196 144 the SSB has yet to be formally defined by the International Commission on Stratigraphy  
197 145 (ICS)'s Subcommittee on Triassic Stratigraphy (STS) ([www.stratigraphy.org/index.php/ics-](http://www.stratigraphy.org/index.php/ics-gssps)  
198 146 [gssps](http://www.stratigraphy.org/index.php/ics-gssps)). The ICS is currently working on stage boundary definitions and substage boundaries  
199 147 will not be addressed for some time yet. However, there is considerable value in establishing a  
200 148 precise (not formal) definition for the SSB to direct future work. The present contribution has  
201 149 several goals: (1) we review the history of studies of the Smithian-Spathian transition by region  
202 150 globally, (2) we summarize known key features of ammonoid and conodont biostratigraphy as  
203 151 well as carbon isotope chemostratigraphy that may prove useful for future formal definition of  
204 152 the SSB, and (3) we examine placements of the SSB in earlier studies, considering problematic  
205 153 placements and offering corrections in some cases. The present study may serve as an important  
206 154 reference for the future formal definition of the SSB and in investigation of the major events  
207 155 associated with it.

## 210 156 211 157 **2. Evolutionary history of ammonoids and conodonts during the Smithian-Spathian** 212 158 **transition** 213 159

214 160 Following the EPME, the diversity (*sensu* taxonomic richness) of ammonoids and  
215 161 conodonts increased and their turnover rates became more rapid than those of most other  
216 162 marine invertebrate clades (Brayard et al., 2006, 2009b; Orchard, 2007; Brühwiler et al., 2010a,  
217 163 b, c; Ware et al., 2015). They thus provide an appropriate basis for construction of a detailed,  
218 164 accurate biostratigraphic framework for the Early Triassic. Both ammonoids and conodonts  
219 165 show relatively similar patterns of rapid diversifications and extinctions during the Early  
220 166 Triassic: rising diversity during the Griesbachian was followed by a minimum in the middle  
221 167 Dienerian, and then by major radiative bursts in the early Smithian (Tozer, 1981a, b; Brayard  
222 168 et al., 2006, 2009b; Orchard, 2007; Brühwiler et al., 2010a, b, c; Zakharov and Abnavi, 2013;  
223 169 Ware et al., 2015). Both clades experienced a second deep-cutting extinction at the beginning  
224 170 of the late Smithian, followed by another rapid diversification in the early Spathian. The late  
225 171 Smithian also corresponds to a drastic reduction of the ammonoid morphological disparity with  
226 172 the disappearance of sphaeroconic forms (Brosse et al., 2013). These diversity (*sensu lato*)  
227 173 fluctuations correspond to the large carbonate C-isotope shifts and temperature fluctuations of  
228 174 the Early Triassic, likely reflecting the sensitivity of these clades to climatic and environmental  
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175 perturbations (Brayard et al., 2006, Orchard, 2007; Stanley, 2009; Leu et al., 2018; Goudemand  
176 et al., 2018).

177 The turnover among ammonoids during the late Smithian has long been recognized (e.g.,  
178 Tozer, 1982). It is now dated to the base of the *Anasibirites*-*Wasatchites* Zone, which is  
179 globally recognized (see Jenks et al., 2015 for a review, and Jattiot et al., 2016 for discussion  
180 of the significance of the iconic taxon *Anasibirites*). Generic diversity decreased markedly from  
181 the early-middle Smithian to the SSB transition, followed by a rebound by the middle to late  
182 Spathian, as for instance inferred from Canadian (Stanley, 2009; Fig. 1) or western USA (Guex  
183 et al., 2010) ammonoid data. The Meekocerataceae superfamily suffered deep losses at the  
184 middle/late Smithian boundary, including extinction of the Lanceolitidae, Paranannitidae and  
185 Inyoitidae families (Brayard et al., 2006; Fig. 2). Many ammonoid taxa that are important for  
186 zonation of the early late Smithian, e.g., Prionitidae such as *Anasibirites* and *Wasatchites*, show  
187 highly cosmopolitan distributions at that time (e.g., Tozer, 1994; Orchard and Tozer, 1997;  
188 Zakharov et al., 2004; Jattiot et al., 2016, 2017, 2018). They were then replaced in the latest  
189 Smithian by a few taxa, mainly belonging to the Xenoceltitidae (*Xenoceltites*, *Glyptopheras*)  
190 and Hedenstroemiidae (*Pseudosageceras augustum*), that had also similar cosmopolitan  
191 distributions (e.g., Brühwiler et al., 2010b, c; Jenks et al., 2015; Jattiot et al., 2017). The  
192 surviving lineages underwent a new rediversification during the earliest Spathian, marked by  
193 the rapid origination of many new families (Doricranitidae, Tirolitidae, Columbidae,  
194 Albanitidae) and several genera of uncertain phylogenetic affinities such as *Bajarunia* (e.g.,  
195 Balini et al., 2010; Guex et al., 2010; Zakharov and Abnavi, 2013; Jenks et al., 2013; Shigeta  
196 et al., 2014; Fig. 2). Most of these new early Spathian ammonoid taxa are now widely used for  
197 zonation, e.g., *Columbites* and *Procolumbites* among the Columbidae, and *Tirolites* among  
198 the Tirolitidae (see e.g., Guex et al., 2010; Jenks et al., 2015).

199 Among the conodonts, the SSB Event marked the largest loss of diversity prior to their  
200 complete extinction at the end of the Triassic (Orchard, 2007). The number of conodont species  
201 globally declined from >30 species in the mid-Smithian to ~8 at the SSB transition and 2 at the  
202 earliest Spathian before rebounding to >20 in the mid-Spathian (simplified estimates based on  
203 Stanley, 2009; Fig. 1). Two important clades of the Smithian, the Ellisoniidae family and  
204 Mullerinae subfamily, mostly went extinct during the late Smithian or at the SSB (Orchard,  
205 2007; Fig. 3). In contrast, the Novispathodinae subfamily was characterized by the survival of  
206 genera that had been extant since the early Olenekian (e.g., *Novispathodus*) as well as  
207 origination of the new genus *Triassospathodus* in the early Spathian (Orchard, 2007; Fig. 3).  
208 Other taxa that are important for conodont biozonation appeared in the Spathian, including  
209 *Icriospathodus* (affinity unknown) in the early Spathian, and *Triassospathodus*  
210 (Novispathodinae subfamily) in the early to middle Spathian. Less is known about  
211 *Neogondolella*-like taxa, although they are important for biostratigraphy at high latitudes. The  
212 survival and rebound of *Novispathodus* and similar genera were maybe due in part to their high  
213 diversity prior to the SSB Event (>30 species in the mid-Smithian) (Orchard, 2007) as well as  
214 their probable survival in deep-water refugia (Song-HJ et al., 2014). However, this later  
215 hypothesis is now challenged (Leu et al., 2018). The above cited genera are among the most  
216 important for conodont biozonation in the late Smithian to early Spathian (Zhao et al., 2003a,  
217 2007a; Krystyn et al., 2005; Chen-YL et al., 2015, 2018).

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### 3. Global review of Smithian-Spathian sections

Historically, the Olenekian Stage (the second stage of the Early Triassic) was defined in the Boreal realm (originally on sections along the Olenek River in Siberia), in contrast to the Induan Stage (the first stage of the Early Triassic), which was defined in the tropical Tethyan realm (Salt Range, Pakistan) (Kiparisova and Popov, 1956, 1961). In the following decades, detailed ammonoid biostratigraphic studies of the Olenekian were carried out elsewhere in the Boreal realm (Canadian Arctic) (Tozer, 1967, 1994), eastern Panthalassa (western Canada and western USA) (Silberling and Tozer, 1968; Tozer, 1994, Orchard and Tozer, 1997; Lucas and Orchard, 2007; Guex et al., 2010; Brayard et al. 2013), eastern Tethys (South China) (Tong et al., 2004; Galfetti et al., 2007b, c), and southern Tethys (India and Pakistan) (Brühwiler et al., 2007, 2012a, b; Krystyn et al., 2007a, b), as reviewed in Jenks et al. (2015) (Fig. 4A-C).

By the late 1990s and early 2000s, biostratigraphic research had shifted to a large degree from Boreal and Panthalassic to Tethyan sections, due to their abundance and generally greater accessibility, in which both ammonoids and conodonts were shown to be highly useful for biozonation owing to their wide distributions and rapid evolution during the Early Triassic (Zhao et al., 2002, 2003a, b, 2005a, b, c; Tong et al., 2004; Brühwiler et al., 2007, 2012a, b; Galfetti et al., 2007b, c). The co-occurrence of ammonoids and conodonts in Lower Triassic successions makes it possible to construct parallel biozonation schemes (e.g., Canadian Arctic, Tozer, 1994, Orchard, 2008; Chaohu, Zhao et al., 2003a, 2007a, b, Tong et al., 2004; Spiti, Brühwiler et al., 2007, Krystyn et al., 2005), which facilitates global correlations. Correlations based on C-isotope chemostratigraphy have also been used, especially when fossil records are sparse, as for some sections in the Tethyan (Horacek et al., 2007a, b; Zhang et al., 2015), Boreal (Grasby et al., 2016; Wignall et al., 2016), and Panthalassic regions (Zhang et al., 2017). Below, we review ammonoid- and conodont-based biostratigraphic as well as C-isotopic chemostratigraphic studies of the Olenekian in key geographic regions, their intercalibration, and their significance for definition of the SSB.

Boreal and Tethyan faunas experienced fluctuating patterns of endemism and cosmopolitanism throughout the Early Triassic related to recurrent environmental stresses and large geographic distances (Brayard and Bucher, 2015). Boreal ammonoid faunas are generally different and less diverse than those of the Tethyan realm (Tozer, 1981b; Dagys, 1988). Brayard et al. (2006, 2007a) studied the global patterns of latitudinal diversity gradients and assemblage similarity, showing that ammonoid faunas exhibit a clear latitudinal diversity gradient during most of the Smithian and Spathian stages, and a return to cosmopolitan distributions in the late Smithian. Boreal ammonoids were characterized by peak endemism during the Spathian (Kummel, 1973; Dagys, 1997). During the Spathian, ammonoid diversity in high-latitude areas was generally lower than at low latitudes (Brayard et al., 2006; Fig. 1). In northeastern British Columbia, Boreal and Tethyan ammonoid faunas can be found together, thus facilitating correlations between high- and low-latitude regions (Tozer, 1994).

The Smithian and Spathian substages have been subdivided recently into early/middle/late subunits on the basis of global ammonoid biostratigraphy (Brühwiler et al., 2010; Guex et al., 2010; Brayard et al., 2013; Jenks et al. 2015; Fig. 5). The early Smithian corresponds to first flemingitid and kashmiritid occurrences, and the middle Smithian represents the flourishing of families such as the Paranannitidae, Inyoitidae, Aspenitidae and Lanceolitidae (Fig. 2). The

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263 late Smithian, which began with a major extinction among several ammonoid families,  
264 corresponds to a marked diversification of highly cosmopolitan prionitids such as *Anasibirites*  
265 and *Wasatchites* followed by the occurrence of cosmopolitan xenoceltitid (*Xenoceltites* sp.,  
266 *Glyptophiceras*) and hedenstroemiid (*Pseudosageceras augustum*) taxa (Fig. 2). The early  
267 Spathian is marked by the first occurrences of *Bajarunia* and *Doricranites* and continues up to  
268 the *Procolumbites* Zone. The middle and late Spathian span the *Subcolumbites* and  
269 *Neopopanoceras haugi* zones, respectively. It should be noted that some ammonoid zones/beds  
270 are of regional significance and not found globally. These ultrafine subdivisions are possible  
271 primarily due to the practice of identifying ammonoid assemblages, which provide a high level  
272 of biostratigraphic resolution (Fig. 5). It should also be noted that the basal Smithian cannot be  
273 precisely delineated until the Induan/Olenekian boundary is formalized.

274 The record of sedimentation during the Smithian-Spathian transition was significantly  
275 affected by contemporaneous eustatic fluctuations. Short-term eustatic variation can be due to  
276 changes in continental ice mass and thermal expansion/contraction of seawater linked to  
277 changing global climate conditions (Milne et al., 2009; Dutton et al., 2015), or to  
278 astronomically forced land–ocean watermass exchange during geologic epochs lacking ice  
279 sheets (as postulated for the Early Triassic by Li et al., 2018). Large temperature changes were  
280 the likely cause of eustatic fluctuations during the SSB transition. The middle Smithian was an  
281 interval of hyperwarming (the Smithian Thermal Maximum, or STM; see Section 5.5) that  
282 coincided with a global transgression, and the SSB interval proper was an interval of  
283 pronounced cooling that coincided with a sharp eustatic fall (Sun et al., 2012; Romano et al.,  
284 2013; Zhang et al., 2017; see Section 5.5). The eustatic fall at the SSB resulted in widespread  
285 deposition of regressive systems tracts and/or sedimentary hiatuses, as in northern Italy  
286 (Twitchett and Barras, 2004), Iran (Horacek et al., 2007b), and Japan (Zhang et al., 2017),  
287 although the SSB succession in the western USA is thought to be nearly continuous (Guex et  
288 al., 2010; Brayard et al., 2013) due to regional tectonic controls (e.g., Caravaca et al., 2018).  
289 As such, the issue of stratigraphic condensation at the SSB is one that will have to be evaluated  
290 carefully in the context of selecting a suitable section as the GSSP of the SSB. A potential way  
291 to circumvent this problem is, for instance, to give preference to deeper-water sections.

### 292 293 **3.1 Canadian Arctic (western Boreal)**

#### 294 295 **3.1.1 Ammonoid and conodont biostratigraphy**

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297 The Canadian Arctic has long been central to an ammonoid-based subdivision of the  
298 Triassic in the northern Pangea region owing to a near-continuous marine succession from the  
299 lower Griesbachian to the upper Norian (Thorsteinsson and Tozer, 1970; Tozer, 1994).  
300 Substages of the Early Triassic were named for type sections in this area, i.e., the Griesbachian,  
301 Dienerian, Smithian, and Spathian were derived from Griesbach Creek on Axel Heiberg Island,  
302 and the Diener, Smith, and Spath creeks on Ellesmere Island (Tozer, 1965, 1967) (Fig. 4B).  
303 The thick (>2000 m) Lower Triassic successions in the Arctic accumulated in the Sverdrup  
304 Basin, grading from sandstones of the Bjerne Formation on the basin margin to shaly siltstones  
305 of the Blind Fjord Formation in the basin center (Tozer, 1961; Embry, 1986, 1991). The Blind  
306 Fjord Formation consists of three members, the Confederation Point Member (Griesbachian to



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417 307 Dienerian in age), Smith Creek Member (Smithian in age), and Svartfjeld Member (mostly  
418 308 Spathian in age) (Embry, 1986; Orchard, 2008).

419 309 Despite the discontinuous stratigraphic distribution of ammonoid-bearing beds in these  
420 310 units, a succession of Early Triassic ammonoid zones were recognized (Tozer, 1994) and  
421 311 provided a basis for broad definition of the SSB. These ammonoid zones (in ascending order)  
422 312 are the *Hedenstroemia hedenstroemi*, *Euflemingites romunderi*, and *Anawasatchites tardus* for  
423 313 the Smithian (Tozer, 1994) and the *Olenikites pilaticus* and *Keyserlingites subrobustus* for the  
424 314 late early and latest Spathian, respectively (Tozer, 1967; Fig. 5A). Most of the early Spathian  
425 315 strata in this region are devoid of ammonoids. For example, at Smith Creek, no ammonoids  
426 316 were found above the upper Smithian *A. tardus* beds (Fig. 6A). The Spathian *Olenikites*  
427 317 *pilaticus* Zone is found only in limited areas south of Svartevaeg on Axel Heiberg Island (Tozer,  
428 318 1967), where it directly overlies *Arctoceras gigas* n. sp. beds (GSC loc. 64719 above GSC loc.  
429 319 64718) that have been tentatively correlated with the *A. tardus* Zone (Tozer, 1994), but this  
430 320 attribution is doubtful (see Section 5.1). In this area, the SSB is thus bracketed by the late  
431 321 Smithian *A. tardus* Zone and the late early Spathian *Olenikites pilaticus* Zone. This represents  
432 322 an important information gap, but the SSB is usually placed just above the *A. tardus* Zone (e.g.,  
433 323 Grasby et al. 2013) as it corresponds to a complex assemblage of several typical late Smithian  
434 324 taxa (e.g., *Anawasatchites*, *Xenoceltites*).

435 325 The most detailed biostratigraphic studies of Early Triassic conodonts in the Canadian  
436 326 Arctic to date were carried out by Mosher (1973) and Orchard (2008). At Smith and Spath  
437 327 creeks, conodonts were recovered mainly from ammonoid-bearing limestones, whereas other  
438 328 lithologies (e.g., shales) are conodont-poor (Orchard, 2008). In the lower Smith Creek Member,  
439 329 no conodont species are known from the *Hedenstroemia hedenstroemi* beds, whereas the  
440 330 *Euflemingites romunderi* beds are more productive of conodonts of congruent mid-Smithian  
441 331 age (Mosher, 1973; Orchard, 2008) (Fig. 6A). This increased diversity of conodonts was  
442 332 attributed to the explosive radiation that occurred during the early Smithian (Orchard, 2007;  
443 333 Stanley, 2009) (Fig. 1). Higher in the section, the upper Smithian *Anawasatchites tardus* beds  
444 334 of the upper Smith Creek Member yielded less diverse faunas, including conodonts such as *Nv.*  
445 335 *waageni*, *Sc. milleri* and *Sc. mosheri* (Orchard, 2008). The lower Spathian strata in this area  
446 336 lack carbonate and are not amenable to recovery of conodonts. Conodonts thus cannot serve to  
447 337 complement the ammonoid biostratigraphical scale in this area.

### 448 338 449 339 3.1.2 Carbon-isotope chemostratigraphy

450 340  
451 341 So far, carbon isotope chemostratigraphy of the Smithian and Spathian substages in  
452 342 Canadian Arctic has only been reported from Smith Creek, shown as organic carbon isotopes  
453 343 ( $\delta^{13}\text{C}_{\text{org}}$ ) (Grasby et al., 2013). At Smith Creek,  $\delta^{13}\text{C}_{\text{org}}$  shows higher values (ca.  $-27$  to  $-25$  ‰)  
454 344 in the lower Smithian (P2\*; the asterisk indicating that the timing of peaks in the organic  $\delta^{13}\text{C}$   
455 345 record might differ somewhat from those in the carbonate  $\delta^{13}\text{C}$  record), a large negative  
456 346 excursion to ca.  $-33$  ‰ in the middle Smithian (N3\*), followed by recovery to a maximum of  
457 347 ca.  $-27$  ‰ (P3\*) at the SSB (top of the *Anawasatchites tardus* beds), and a subsequent drop to  
458 348 ca.  $-33$  ‰ (N4\*) much later in the Spathian (Grasby et al., 2013; Fig. 7). It should be noted  
459 349 that the  $\delta^{13}\text{C}_{\text{org}}$  profile at Smith Creek exhibits a second positive excursion in the upper Spathian,  
460 350 before the Spathian/Anisian boundary.

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## 3.2 Spitsbergen (eastern Boreal)

### 3.2.1 Ammonoid and conodont biostratigraphy

Triassic clastic rocks are known to crop out extensively in the Svalbard archipelago, including on the largest island—Spitsbergen (Buchan et al., 1965). Stratigraphic successions of Olenekian age consist of the Tvillingodden Formation (lower Iskletten Member and upper Kaosfjellet Member) in western Svalbard and the Vikinghøgda Formation (lower Lusitaniadalen Member and upper Vendomdalen Member) in eastern Svalbard (Hounslow et al. 2008; Mørk et al., 2013). The Tvillingodden Formation mainly consists of sandstone in the regressive part of the unit, due to closer proximity to the basin margin, whereas the Vikinghøgda Formation is a shale or mudstone without substantial sandstone or siltstone beds, which generally grades upward into mudstone with thin sandstone or siltstone beds (Mørk et al. 1982).

The ammonoid zones identified on Svalbard are, in ascending order, the *Euflemingites romunderi* and *Anawasatchites tardus* for the Smithian, and the *Bajarunia euomphala*, *Parasibirites grambergi* and *Keyserlingites subrobustus* for the Spathian (Dagys and Weitschat, 1993). Ammonoid studies of the Lusitaniadalen Member (~88 m) and Vendomdalen Member (~92 m) in the Deltadalen area (east-central Spitsbergen) yielded first occurrences of *E. romunderi* and *A. tardus* at, respectively, ~28 m and ~4 m below the base of the Vendomdalen Member (Mørk et al., 1999; Hounslow et al., 2008; Fig. 6B). The main co-occurring ammonoids in the middle Smithian *E. romunderi* Zone are *Arctoceras blomstrandii* and *Paranannites spathi* (Mørk et al., 1999). In the latest Smithian *A. tardus* Zone, which is found across central and eastern Spitsbergen (Hounslow et al., 2008), various prionitids and *Xenoceltites subevolutus* are present into the base of the Vendomdalen member indicating a late Smithian age for these levels (Mørk et al., 1999; Piazza et al., 2017). The base of the *B. euomphala* Zone of earliest Spathian age is ~17 m above the base of the Vendomdalen Member (Mørk et al. 1999; Hounslow et al. 2008), resulting in a biostratigraphic gap of ~15 m above the latest Smithian beds within which the SSB must be located. Ammonoids of middle Spathian age are apparently lacking on Spitsbergen, but late Spathian taxa are present (Hounslow et al. 2008).

The conodont *Scythogondolella mosheri* was recognized from the lower part of the Iskletten Member in Pitnerodden, indicating a Smithian age (Clark and Hatleberg, 1983; Hatleberg and Clark, 1984). Upwards in the Iskletten Member, *Eurygnathodus* sp. (assigned to *Icriospathodus collinsoni* by Hatleberg and Clark, 1984), *Borinella buurensis* and *Neogondolella elongata* (both assigned to *Ng. jubata* by Hatleberg and Clark, 1984, later, re-assigned by Nakrem et al., 2008 to *Borinella* or *Scythogondolella* taxa) of Smithian age have also been reported (Nakrem et al., 2008). Conodonts from the top of the Iskletten Member (Skilisen Bed) in Akseløya are *Borinella?* sp., *Ng. sp. B*, *Ns. pakistanensis* and *Borinella buurensis* (Nakrem et al., 2008). Only *Ng. ex. gr. regalis* was reported from the Kaosfjellet Member in Reinodden, co-occurring with *Keyserlingites subrobustus* and “*Posidonia*” *aranea* and indicating a late Spathian age (Nakrem et al., 2008).

Previous conodont studies in Milne Edwardsfjellet recognized *Novispathodus waageni*

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534 395 from 2 m below the top of the Lusitaniadalen Member, co-occurring with an ammonoid fauna  
535 396 consisting of *Xenoceltites subevolutus* and various prionitids, within the late Smithian *A. tardus*  
536 397 Zone (Nakrem et al., 2008). Weitschat and Lehmann (1978) also reported a late Smithian  
537 398 conodont fauna with *Sc. milleri*, *Sc. mosheri*, *Borinella* aff. *buurensis* and *Nv. waageni*, from  
538 399 7 m below the top of the Lusitaniadalen Member, within the *A. tardus* Zone on the southern  
539 400 shore of Sassenfjorden (close to Botneheia). No conodonts were recovered from the lower part  
540 401 of the Vendomdalen Member (lowermost Spathian), but gondolellids are present at 31 to 54.4  
541 402 m above the base of the Vendomdalen Member, within the range of the late Spathian  
542 403 *Keyserlingites* sp. (Nakrem et al., 2008). *Neogondolella* ex. gr. *regalis* (assigned to *Ng. jubata*  
543 404 by Dagis and Korčinskaja, 1989) was also reported from the *Keyserlingites subrobustus* Zone  
544 405 (Nakrem et al., 2008). Conodont data are thus lacking for the early Spathian but overall support  
545 406 placement of the SSB between the *X. subevolutus* and *B. euomphala* beds.  
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### 550 408 3.2.2 Carbon-isotope chemostratigraphy 551 409

552 410 Carbon isotope studies of the Smithian and Spathian substages in Spitsbergen, shown as  
553 411  $\delta^{13}\text{C}_{\text{org}}$ , are from Dicksonfjellet (Galfetti et al., 2007a), Festningen (Grasby et al., 2016), and  
554 412 Vindodden (Wignall et al., 2016) sections (Fig. 7). Ammonoid data are available in  
555 413 Dicksonfjellet (Weitschat and Dagys, 1989), while no biostratigraphic work has been done to  
556 414 date in the Festningen and Vindodden sections. At Dicksonfjellet, the  $\delta^{13}\text{C}_{\text{org}}$  profile exhibits  
557 415 low values (ca.  $-34$  to  $-33$  ‰) in the middle Smithian (within the *Euflemingites romunderi*  
558 416 Zone), followed by a positive excursion beginning from the base of the upper Smithian to ca.  
559 417  $-28$  ‰ (P3\*) in the lowermost Spathian (base of the *Euomphala* Zone), and then a gradual  
560 418 decrease to ca.  $-32$  ‰ in the upper Spathian (within the *Subrobustus* Zone) (Galfetti et al.,  
561 419 2007a). The  $\delta^{13}\text{C}_{\text{org}}$  profile at Festningen was chemostratigraphically correlated with Smith  
562 420 Creek by Grasby et al. (2016), who showed a  $\delta^{13}\text{C}_{\text{org}}$  maximum of ca.  $-25$  ‰ (P2\*) in the  
563 421 lowermost Smithian, then a negative excursion to a minimum of ca.  $-33$  ‰ (N3\*) at what they  
564 422 considered as the SSB (but which more likely represents the middle Smithian), followed by a  
565 423 rebound to ca.  $-29$  ‰ (P3\*) in the lower Spathian, and a gradual decrease to ca.  $-32$  ‰ (N4\*)  
566 424 in the middle Spathian. The  $\delta^{13}\text{C}_{\text{org}}$  profile at Vindodden was correlated with the nearby  
567 425 Festningen section by Wignall et al. (2016) following the same chemostratigraphic approach.  
568 426 They showed stable and low values (ca.  $-32$  ‰; N3\*) during the middle Smithian, then a  
569 427 positive excursion following a  $\delta^{13}\text{C}_{\text{org}}$  minimum at their inferred SSB (however, this level is  
570 428 actually the N3 event, which is of middle Smithian age; see Section 5.3). The lower Spathian  
571 429 is characterized by a peak at ca.  $-28$  ‰ (P3\*), followed by a gradual decrease to ca.  $-30$  ‰  
572 430 in the middle Spathian.  
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## 578 432 3.3 Western Canadian Sedimentary Basin (eastern Panthalassa) 579 433

### 580 434 3.3.1 Ammonoid and conodont biostratigraphy 581 435

582 436 The Western Canadian Sedimentary Basin (WCSB) contains ammonoid faunas that have  
583 437 been used, generally in conjunction with Canadian Arctic data, in the construction of a  
584 438 preliminary Early Triassic biozonation scheme for northwestern Pangea (Tozer, 1994). Triassic  
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439 strata are best exposed in the eastern Cordillera (e.g., Rocky Mountains and foothills) in  
440 northeastern British Columbia (Tozer, 1982). Lower Triassic stratigraphic successions mainly  
441 consist of the Phroso Formation (siltstone) and Vega Formation (siltstone) in the south, and the  
442 Grayling Formation (gray shale and sandstone) and Toad Formation (dark gray calcareous  
443 siltstone and shale) in the north (Gibson, 1971).

444 The Toad Formation contains ammonoids of the middle and late Smithian *Euflemingites*  
445 *romunderi* and *Anawasatchites tardus* Zones and the late Spathian *Keyserlingites subrobustus*  
446 Zone, in ascending order (McLearn and Kindle, 1950; Tozer, 1965, 1967, 1994; Orchard and  
447 Tozer, 1997) (Fig. 5B). The *E. romunderi* Zone had also been reported from the Vega  
448 Formation in the southern British Columbia (Tozer, 1967). The type locality of the *A. tardus*  
449 Zone is on the Toad River of the northeastern British Columbia (McLearn and Kindle, 1950;  
450 Tozer, 1967, 1994), and it is also known from the Liard River and Ursula Creek (Orchard and  
451 Tozer, 1997). In general, Early Triassic ammonoid occurrences in western Canada correspond  
452 to the zonal divisions previously established in the Canadian Arctic region (Tozer, 1994).

453 In the WCSB, conodonts were recovered not only from the *Euflemingites romunderi* and  
454 *Anawasatchites tardus* beds of middle to late Smithian age, but also from overlying  
455 (?lowermost Spathian) strata in which ammonoids are apparently absent (Orchard and Tozer,  
456 1997; Orchard and Zonneveld, 2009). The *E. romunderi* beds yielded conodonts such as *Ns.*  
457 *pakistanensis* and *Nv. waageni* at Mount Ludington and Liard River in northeastern British  
458 Columbia (Orchard and Tozer, 1997), and additionally *Scythogondolella lachrymiformis*,  
459 *Paullella meeki*, *Discretella discreta*, and *Wapitiodus robustus* from the Sulphur Mountain  
460 Formation in the Wapiti Lake area, western British Columbia (Orchard and Zonneveld, 2009).  
461 Orchard (2008) also reported the conodont species *Neospathodus posterolongatus*, *Ns.*  
462 *cristagalli*, *Guangxidella bransoni*, and *Paullella meeki* from *E. romunderi* Zone in British  
463 Columbia. The *A. tardus* beds yielded conodonts such as *Sc. milleri*, *Sc. mosheri*,  
464 *Novispathodus. ex gr. waageni* and *Borinella buurensis*, which are also similar to assemblages  
465 from correlative units at Smith Creek in the Canadian Arctic (Orchard and Tozer, 1997). *Sc.*  
466 *milleri* and *Sc. mosheri* have also been reported in the *Xenoceltites* beds of the *A. tardus* Zone  
467 in the Wapiti Lake area (Orchard and Zonneveld, 2009). Orchard and Zonneveld (2009)  
468 established three conodont zones of the Smithian age in the Wapiti Lake area, which are (in  
469 ascending order) the *Sc. lachrymiformis*, *Paullella meeki* and *Sc. mosheri* zones, with the last  
470 subdivided into the *Sc. phryna* and *Sc. milleri* subzones. Therefore, ammonoid-conodont  
471 assemblages of the WCSB are nearly identical to those in age-equivalent strata of the Canadian  
472 Arctic (Orchard, 2008). Just 1 m above the top of the *A. tardus* Zone at Toad River, the  
473 overlying strata yielded the conodont *Neogondolella aff. sweeti* (=Ng. n. sp. D sensu Orchard,  
474 2007), which was suggested to be indicative of an earliest Spathian age based on correlation  
475 with Californian successions (Orchard and Tozer, 1997). These observations confine the  
476 position of the SSB above the first occurrence of *Sc. milleri* and below the first occurrence of  
477 *Ng. aff. sweeti*.

### 478 479 3.3.2 Carbon-isotope chemostratigraphy

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481 To date, no carbon isotope profile of the Smithian and Spathian substages is available  
482 from the WCSB.



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654 484 **3.4 Western United States (eastern Panthalassa)**  
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656 486 **3.4.1 Ammonoid and conodont biostratigraphy**  
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658 488 Ammonoid-bearing marine deposits are widely distributed in the western United States.  
659 489 Brayard et al. (2009c, 2011, 2013), Jenks et al. (2010), Jattiot et al. (2016, 2017, 2018) and  
660 490 Jenks and Brayard (2018) reported Smithian ammonoid faunas, which are characterized by  
661 491 increasing diversity from the lower Smithian to the middle Smithian. Within this basin, late  
662 492 Smithian ammonoid beds are, in ascending order, the *Anasibirites kingianus* and the overlying  
663 493 *Xenoceltitidae* beds, which contain *Glyptophiceras*, *Xenoceltites* and *Pseudosageceras*  
664 494 *augustum*. They correspond respectively to the UAZ5 and UAZ6 of Jattiot et al. (2017) and  
665 495 can be easily correlated with Tethyan sections along the North Indian Margin. The UAZ6  
666 496 contains the latest Smithian ammonoids reported worldwide so far.

669 497 Guex et al. (2005a, b; 2010) and Jenks et al. (2013) identified ammonoids from Spathian  
670 498 successions including, in ascending order, the early Spathian *Bajarunia confusionensis* beds,  
671 499 *Tirolites harti* beds, *Columbites* beds, and *Procolumbites* beds, followed by the middle  
672 500 Spathian *Subcolumbites* Zone and the late Spathian *Neopopanoceras haugi* Zone (Fig. 5C).  
673 501 The Cowboy Pass site in western Utah was inferred to contain the oldest Spathian ammonoids,  
674 502 i.e., *B. confusionensis*, but the lack of Smithian ammonoids in these sections does not constrain  
675 503 placement of the SSB well (Guex et al., 2010; Brayard et al., 2013; Fig. 6C). In addition, the  
676 504 nearby Confusion Range in western Utah recorded a series of Smithian ammonoid assemblages,  
677 505 in which *Anasibirites*, *Wasatchites* and *Xenoceltites* sp. indet. were discovered, indicative of a  
678 506 late Smithian age (Brayard et al., 2013). Based on the ammonoid data in the Confusion Range  
679 507 area, the SSB is located between the *Anasibirites* beds and the *B. confusionensis* beds. Sampled  
680 508 ammonoid faunas in Idaho also show a similar scheme with the first *Bajarunia* specimens  
681 509 occurring above the *Xenoceltitidae* beds (Brayard et al., work in progress).

685 510 In the western United States, lower-middle Smithian rocks yielded not only the conodonts  
686 511 *Neospathodus pakistanensis*, *Novispathodus waageni*, *Discretella discreta*, but also  
687 512 *Conservatella conservativa*, *Guangxidella bransoni*, and *Paullella meeki* (Orchard and Tozer,  
688 513 1997; Orchard, 2008; Orchard and Zonneveld, 2009). Conodont assemblages from the late  
689 514 Smithian *Anasibirites multiformis* beds are similar to those from the WCSB, containing  
690 515 *Scythogondolella milleri*, *Sc. mosheri*, *Nv. ex gr. waageni* and *Borinella buurensis* (Müller,  
691 516 1956; Orchard and Tozer, 1997; Orchard, 2008). Moreover, Orchard and Zonneveld (2009)  
692 517 reported both *Nv. waageni* and *Nv. pingdingshanensis* with *Spathicuspus* sp. from *Xenoceltites*  
693 518 beds of the upper *A. multiformis* Zone in Georgetown, Idaho and with *Borinella buurensis* and  
694 519 *Sc. milleri* in the Tardus Zone at Crittenden Springs, Nevada. The latest Smithian occurrence  
695 520 of *Nv. pingdingshanensis* in the western United States is thus similar to that reported from the  
696 521 subsurface of the WCSB (Henderson et al., 2018). Although Spathian successions in the  
697 522 western United States are more complete and better studied than those in the WCSB, relatively  
698 523 few conodonts have been described (Orchard and Tozer, 1997; Lucas and Orchard, 2007;  
699 524 Orchard, 2008). According to Orchard and Tozer (1997), the lowermost Spathian in the Darwin  
700 525 Canyon section in California contains *Neogondolella* aff. *sweeti*-*Ns. crassatus*, which has been  
701 526 tentatively correlated with the post-Tardus Zone fauna on the Toad River in northeastern  
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527 British Columbia. The Darwin faunas, which are presently under review (Goudemand et al.,  
528 2006), also include *Nv. pingdingshanensis* and *Ic. zaksi* and should provide an important North  
529 American SSB reference section for conodonts. Lucas and Orchard (2007) reported the  
530 conodonts *Icriospathodus collinsoni* and *Nv. abruptus* from the lower Spathian *Tirolites* beds  
531 and *Ng. elongata* from the overlying *Columbites* beds, all of which are indicative of an early  
532 Spathian age (Orchard and Tozer, 1997). These conodont occurrences constrain the position of  
533 the SSB to between the first occurrences of *Sc. milleri* and *Ng. aff. sweeti*, which is comparable  
534 to its placement in the WCSB. For the western United States generally, ammonoid biozonations  
535 are more highly resolved than those for conodonts, indicating a SSB placement between the  
536 top of the Xenoceltitidae beds and the base of the *Bajarunia* beds.

### 3.4.2. Carbon-isotope chemostratigraphy

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540 In the western United States, detailed continuous C-isotope profiles of the Smithian-  
541 Spathian transition are available for the Mineral Mountains section in Utah (Thomazo et al.  
542 2016; Fig. 7) and the Hot Springs section in southeastern Idaho (Caravaca et al., 2017). At  
543 Mineral Mountains, the  $\delta^{13}\text{C}_{\text{carb}}$  profile exhibits values close to 0 ‰ in the lowermost Smithian,  
544 a gradual negative excursion to a minimum of ca. -4 ‰ (N3) in the middle Smithian (*Owenites*  
545 ammonoid beds), and a rebound through the *Anasibirites kingianus* and Xenoceltitidae 'gen.  
546 indet.' A. beds to a maximum of ca. +2 ‰ (P3) in the early Spathian (Thomazo et al., 2016;  
547 Fig. 7). A similar trend is observed at Hot Springs, with the most negative values recorded in  
548 the uppermost beds of the middle Smithian and a strong increase in  $\delta^{13}\text{C}$  through the SSB and  
549 into the early Spathian (Caravaca et al., 2017). Biostratigraphic control is largely lacking for  
550 the SSB at the Hot Springs section, however.

## 3.5 Kamura and Inuyama, Japan (central Panthalassa)

### 3.5.1. Ammonoid and conodont biostratigraphy

555 The Kamura section represents a shallow-water (atoll) environment that was located in  
556 the central Panthalassic Ocean at the time of its accumulation (Zhang et al., 2017). The Triassic  
557 carbonate succession lithologically belongs to the Kamura Formation, which is composed  
558 mainly of micritic, microbial, and bioclastic limestones with some coarsely crystalline dolomite  
559 in its lower part (Kanmera and Nakazawa, 1973; Zhang et al., 2017). A thick Smithian  
560 succession consisting largely of bioclastic limestones is well-preserved, whereas the Spathian  
561 is largely or completely missing (Zhang et al., 2017). Conodont biostratigraphic work has been  
562 undertaken at Kamura, but no ammonoid data are available (Watanabe et al., 1979; Horacek et  
563 al., 2009; Zhang et al., 2017). It should be noted that ammonoid data are available from  
564 Japanese sections but in other tectonic and environmental contexts (e.g., Ehiro, 2016; Ehiro et  
565 al., 2016). The conodont taxa *Novispathodus ex gr. waageni*, *Parachirognathus*, *Discretella*  
566 and *Wapitiodus*(?) have been recovered from the middle part of the Kamura Formation, within  
567 the *Nv. ex gr. waageni-Parachirognathus* Zone, indicating a Smithian age (Zhang et al., 2017).  
568 Koike (1979) reported Spathian-age conodonts (e.g., "*Neospathodus?* sp. G. Sweet et al."  
569 (= *?Icriospathodus collinsoni*), *Triassospathodus homeri* and *Tr. triangularis*) from this section,  
570 but they were not illustrated in that paper and have not been rediscovered in later studies. The

571 SSB apparently lies above the *Nv. ex gr. waageni-Parachirognathus* Zone and below the first  
572 occurrence of *?Icriospathodus collinsoni*.

573 The Inuyama section represents a deep-water (abyssal) environment that was located in  
574 the central Panthalassic Ocean at the time of its accumulation (Sakuma et al., 2012). It consists  
575 of a series of disconnected stratal blocks scattered through the Mino Belt, composed of black  
576 shales, argillaceous cherts, and siliceous mudstones, in ascending order (Yao and Kuwahara,  
577 1997; Tada et al., 2005; Sakuma et al., 2012). Lower Smithian to lower Spathian successions  
578 were recognized based on conodonts and radiolarians, but no ammonoid data are available  
579 (Sakuma et al., 2012). The conodont taxa *Guangxidella bransoni* and *Neogondolella milleri*,  
580 which are indicative of a late Smithian age, were recovered from the argillaceous cherts. The  
581 overlying siliceous mudstone yields *Neospathodus symmetricus* of early Spathian age.  
582 Therefore, the SSB can be constrained to within a ~2 m interval between the first occurrences  
583 of *Ng. milleri* and *Ns. symmetricus*.

### 585 3.5.2. Carbon-isotope chemostratigraphy

587 At Kamura, the  $\delta^{13}\text{C}_{\text{carb}}$  profile shows a negative excursion from ca. +2.5 ‰ (P2) in the  
588 lowermost Smithian to ca. 0 ‰ (N3) in the middle Smithian, followed by a rebound to ca. +4 ‰  
589 (P4) above the unconformity at which most or all of the Spathian is missing (Zhang et al., 2017;  
590 Fig. 7). Below the unconformity, the positive  $\delta^{13}\text{C}_{\text{carb}}$  shift rises to a peak value of ca. +3.5 ‰  
591 (Horacek et al., 2009), which is typical of the P3 maximum in other sections globally (e.g.,  
592 Galfetti et al., 2007c; Horacek et al., 2007a, b) and thus suggests that the SSB and earliest  
593 Spathian may be present just below the unconformity.

594 At Inuyama, the  $\delta^{13}\text{C}_{\text{org}}$  profile shows a negative excursion from ca. -27 ‰ in the lower  
595 Smithian to ca. -32 ‰ (N3\*) in the middle Smithian, followed by a positive excursion to ca.  
596 -27 ‰ across the SSB (Sakuma et al., 2012; Fig. 7). Above the SSB, the  $\delta^{13}\text{C}_{\text{org}}$  profile  
597 exhibits fluctuations between ca. -27 ‰ and -29 ‰ in the lower Spathian and a negative  
598 excursion to ca. -30 ‰ (N4\*?) in the early to middle Spathian.

## 600 3.6. Chaohu area, eastern China (eastern Tethys)

### 602 3.6.1. Ammonoid and conodont biostratigraphy

604 The Chaohu area of eastern Anhui Province, eastern China, has come under intense  
605 investigation in recent years, including studies of its sedimentology (Li et al., 2007; Chen-ZQ  
606 et al., 2011), geochemistry (Tong et al., 2002, 2007; Zuo et al., 2006; Horacek et al., 2007c;  
607 Chen-JB et al., 2015; Zhao and Zheng, 2015), cyclostratigraphy (Li et al., 2007; Li et al., 2016a,  
608 b), and other topics (Chen-ZQ et al., 2010; Motani et al., 2015; Huang et al., 2017). During the  
609 Early Triassic, it was situated on a deep ramp on the northern margin of the Yangtze Platform,  
610 eastern China (Tong et al., 2004). At Chaohu, the Lower Triassic consists of the Yinkeng,  
611 Helongshan and Nanlinghu formations, in ascending order, in which are developed a multilevel  
612 hierarchy of mudstone and limestone cycles (Li et al., 2007; Tong et al., 2007). The Yinkeng  
613 and Helongshan formations comprise interbedded mudstone and (muddy) limestone, whereas  
614 the Nanlinghu Formation is composed of thin shale and interbedded thin and thick limestone

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(Zhao et al., 2005b). The Olenekian successions in the Chaohu area extend from the middle of the Yingkeng Formation to the top of the Nanlinghu Formation. The SSB transition is present in three closely spaced sections (<1 km apart): West Pingdingshan (31°38′00″N, 117°49′43″E), North Pingdingshan (31°38′14″N, 117°49′53″E), and South Majiashan (31°37′33″N, 117°49′21″E). They provide a continuous and complete succession from the lowermost Smithian to the upper Spathian, and the West Pingdingshan section has been nominated as a candidate for the GSSP of the Induan/Olenekian boundary (Zhao et al., 2002, 2003a, 2007a, b, 2008a, b; Tong et al., 2003, 2004, 2005, 2007).

The Olenekian successions in the Chaohu area have received detailed study of both their ammonoid and conodont faunas. Tong et al. (2004, 2005, 2007) reported four ammonoid zones in the Olenekian Stage, including the *Flemingites-Euflemingites* and *Anasibirites* zones of Smithian age and the *Tirolites-Columbites* and *Subcolumbites* zones of Spathian age, in ascending order (Fig. 5D). Numerous ammonoids recovered at South Majiashan provide constraints on the SSB, limiting it to an ~8-m stratigraphic interval between occurrences of the late Smithian *Anasibirites* (including *A. kingianus*, *A. onoi* and *A. plicatus*; note: all these determinations will have to be revised per e.g., Jattiot et al., 2016) in the upper Helongshan Formation (Beds 6 and 13) and the early Spathian *Tirolites-Columbites* (including *C. cf. parisianus*, *C. contractus*, *T. latumbilicatus*, *T. ?cf. spinosus* and *Xenoceltites* sp.) in the lower Nanlinghu Formation (Bed 18) (Tong et al., 2004, 2005, 2007) (Fig. 8). *Euflemingites* and *Anasibirites cf. kwangsiensis* were also recovered from the middle Helongshan Formation at North Pingdingshan (Beds 56-57) and the upper Helongshan Formation at West Pingdingshan (Beds 50-51) (Figs. 9-10). However, these two genera do not co-occur elsewhere as they are respectively of middle and late Smithian age. One issue at Chaohu is the relatively poor preservation of ammonoid fossils, which makes firm taxonomic assignments difficult. Further work on the Chaohu ammonoid fauna will be needed to resolve inconsistencies.

This area contains an especially rich and diverse conodont fauna of the tropical biogeographic province that accumulated in an open-shelf setting at intermediate water depths (of a few hundred meters). Conodont biozonation offers narrower constraints on placement of the SSB in the Chaohu area. Zhao et al. (2007a, 2008a, b) reported five conodont zones in the Olenekian Stage, including the *Novispathodus waageni eowaageni* and *Nv. waageni waageni* of Smithian age and *Nv. pingdingshanensis*, *Triassospathodus homeri* and *Neospathodus anhuinensis* of Spathian age (Fig. 5D). They defined the *Nv. pingdingshanensis* Zone as ranging from the first occurrence of *Nv. pingdingshanensis* to the first occurrence of *Triassospathodus homeri*, with the lowermost occurrence of *Nv. pingdingshanensis* representing the SSB. The first occurrences of *Nv. pingdingshanensis* recognized were located at 48 cm above the base of Bed 52 (uppermost Helongshan Formation) at West Pingdingshan, ~40 cm above the base of Bed 61 (uppermost Helongshan Formation) at North Pingdingshan, and ~120 cm above the base of Bed 15 (lowermost Nanlinghu Formation) at South Majiashan (Figs. 8-10). In a higher-resolution study of the SSB transition in the Chaohu area, Liang et al. (2011) collected 38 samples from Beds 49-54 at West Pingdingshan and recovered 4 genera and 15 species. The first specimens of *Nv. pingdingshanensis* were found at a slightly lower stratigraphic level than in the earlier work by Zhao and others, i.e., at 30 cm above the base of Bed 52 (Fig. 10). Occurrences of the early Spathian conodont species *Tr. homeri* (Bed 64 at North Pingdingshan; Bed 56 at West Pingdingshan), *Ns. abruptus* (Beds 64 and 52, respectively), and



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659 *Nv. spathi* (Beds 64 and 56, respectively) are useful in placing an upper stratigraphic limit on  
660 the position of the SSB (Tong et al., 2007; Zhao et al., 2007a). In this context, placement of the  
661 SSB in the Chaohu area at the first occurrence of *Nv. pingdingshanensis* is consistent with the  
662 existing constraints based on local ammonoid data, but it may be diachronous with respect to  
663 occurrences of *Nv. pingdingshanensis* in upper Smithian beds globally (Orchard and Zonneveld,  
664 2009; Komatsu et al., 2016; Chen-YL et al., 2018; Leu et al., 2018; Goudemand et al., 2018).

### 3.6.2. Carbon-isotope chemostratigraphy

666 The North Pingdingshan and West Pingdingshan sections show similar  $\delta^{13}\text{C}_{\text{carb}}$  profiles  
667 from the lower Smithian to the lower Spathian, and South Majiashan yields a continuous  
668  $\delta^{13}\text{C}_{\text{carb}}$  profile from the uppermost Smithian to the upper Spathian (Figs. 8-10). At North  
669 Pingdingshan and West Pingdingshan, the  $\delta^{13}\text{C}_{\text{carb}}$  profiles exhibit high values (ca. 0 ‰) in the  
670 lowermost Smithian (base of the *Novispathodus waageni eowaageni* Zone; close to P2),  
671 followed by negative excursions to ca. -7 to -4 ‰ in the middle Smithian (mid-*Nv. waageni*  
672 *waageni* Zone; N3), and then a rebound to ca. +4 ‰ in the lowermost Spathian (lower *Nv.*  
673 *pingdingshanensis* Zone; P3) (Zuo et al., 2003, 2004; Tong et al., 2007). At South Majiashan,  
674 the  $\delta^{13}\text{C}_{\text{carb}}$  profile also shows a positive excursion from ca. -2 ‰ in the uppermost Smithian  
675 to ca. +4 ‰ in the lowermost Spathian (lower *Nv. pingdingshanensis* Zone; P3) (Tong et al.,  
676 2007). The  $\delta^{13}\text{C}_{\text{carb}}$  profiles of all three sections show relatively stable values (ca. +2 to +4 ‰)  
677 in the lower Spathian (within the *Nv. pingdingshanensis* and *Triassospathodus homeri* zones  
678 or *Columbites-Tirolites* Zone), followed by a gradual decrease to ca. -2 ‰ in the middle to  
679 upper Spathian (within the *Neospathodus anhuiensis* Zone or *Subcolumbites* Zone;  
680 approaching N4, although it is unclear whether the N4 minimum is reached).

681 The proximity of the three Chaohu sections allows an evaluation of the relationships  
682 between biostratigraphic markers and features of their carbon isotope profiles (Figs. 8-10).  
683 Taking *Nv. pingdingshanensis* as an example, the first occurrence of this taxon shows  
684 somewhat variable locations relative to the major features of the  $\delta^{13}\text{C}$  profiles (i.e., N3 and P3).  
685 At South Majiashan, Interval II is 19.57 m thick and extends from -6.3 ‰ (N3) to +4.3 ‰  
686 (P3), and the first occurrence of *Nv. pingdingshanensis* is located 0.90 m below P3 (Interval I-  
687 IV was divided based on Olenekian carbon isotope excursions, see Section 4.1), which  
688 corresponds to a  $\delta^{13}\text{C}$  value of ~2.0 ‰ that represents ~80 % of the rise from N3 to P3 (Fig.  
689 8). At North Pingdingshan, Interval II is 8.28 m thick and extends from -7.3 ‰ (N3) to +3.8 ‰  
690 (P3), and the first occurrence of *Nv. pingdingshanensis* is located approximately at P3, which  
691 corresponds to a  $\delta^{13}\text{C}$  value of +4.0 ‰ that represents ~100 % of the rise from N3 to P3 (Fig.  
692 9). At West Pingdingshan, Interval II is 24.22 m thick and extends from -4.3 ‰ (N3) to +4.2 ‰  
693 (P3), and the first occurrence of *Nv. pingdingshanensis* is at 5.33 m below P3, which  
694 corresponds to a  $\delta^{13}\text{C}$  value of ~0 ‰ that represents ~50 % of the rise from N3 to P3 (Fig. 10).  
695 It is unlikely that *Nv. pingdingshanensis* was not present in all three sections simultaneously  
696 (since they are within 1 km of each other), and the differences in stratigraphic placement of its  
697 first occurrence likely results from local environmental and taphonomic controls, with the West  
698 Pingdingshan section recording the oldest first occurrence and the other two sections slightly  
699 younger first occurrences (“Signor-Lipps Effect”; Signor and Lipps, 1982; Raup, 1986). Given  
700 that this problem exists in such a limited area as at Chaohu, it must be a common phenomenon

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948 703 at other locales around the world and at a more global scale, implying that many first  
949 704 occurrence are local and diachronous and obviously do not represent the true first appearance  
950 705 of a specific taxon in a given area, especially when only limited work has been done.  
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### 952 707 **3.7. Nanpanjiang Basin, southwestern China (eastern Tethys)**

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#### 954 709 **3.7.1. Ammonoid and conodont biostratigraphy**

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956 711 During the Early Triassic, the Nanpanjiang Basin (mainly northwestern Guangxi and  
957 712 southern Guizhou provinces) was an epicontinental sea between the Yangtze Platform and the  
958 713 western Panthalassic Ocean (Enos et al., 2006). In Nanpanjiang Basin, the Lower Triassic  
959 714 mainly consists of the Luolou Formation (limestone and limestone-shale interbeds) and part of  
960 715 the overlying Ziyun Formation (thick-bedded micritic and intraclastic limestone with thin  
961 716 argillites) (Enos et al., 2006). Studies of Olenekian ammonoid biostratigraphy have been  
962 717 undertaken mainly in the Jinya area (northwestern Guangxi) (Galfetti et al., 2007b, c; Brayard  
963 718 and Bucher, 2008) and Jiarong section (southern Guizhou) (Chen-YL et al., 2015). Detailed  
964 719 conodont biostratigraphic analyses have been reported from a number of sections including  
965 720 Guandao (Wang et al., 2005; Lehrmann et al., 2015), Mingtang (Liang et al., 2016), Jiarong  
966 721 (Chen-YL et al., 2015, 2018), Shitouzhai (Zhang et al., 2015), Baiyang (Yan et al., 2013) and  
967 722 Qingyan (Ji et al., 2011) in southern Guizhou, and Zuodeng (Tong et al., 2007, revised after  
968 723 Yang et al., 1984) in northwestern Guangxi.

969 724 In the Jinya area, ammonoid biostratigraphic studies led to the recognition of eleven  
970 725 beds/zones in the Smithian and Spathian substages (Galfetti et al., 2007b, c; Fig. 5E) of which  
971 726 some can be further refined (Brayard and Bucher, 2008). Olenekian conodont data from this  
972 727 area are largely unpublished (Goudemand, 2014a). The Smithian ammonoid beds/zones are the  
973 728 *Clypites* sp. indet. beds, *Kashmirites kapila* beds, *Flemingites rursiradiatus* beds, *Owenites*  
974 729 *koeneni* beds (subdivided in *Ussuria*, *Hanielites* and *Inyoites* horizons) and *Anasibirites*  
975 730 *multiformis* beds (with *Anasibirites* and *Xenoceltites-Pseudosageceras augustum* assemblages  
976 731 respectively at the base and top of these beds), and those from the Spathian are the Tirolitid n.  
977 732 gen. A beds, *Tirolites/Columbites* beds, *Procolumbites* beds, *Hellenites* beds, and  
978 733 *Neopopanoceras haugi* Zone, in ascending order (Galfetti et al., 2007b; Brayard and Bucher,  
979 734 2008). The SSB was placed at the base of the Tirolitid n. gen. A. beds, ~1-2 m above the late  
980 735 Smithian *Xenoceltites-Pseudosageceras augustum* assemblage of the *A. multiformis* beds (Fig.  
981 736 6D). Note that another ammonoid assemblage of undetermined taxa, and thus of uncertain age,  
982 737 occurs between the late Smithian *Xenoceltites-Pseudosageceras augustum* assemblage and the  
983 738 earliest Spathian *Tirolitid* n. gen. A beds (Brayard and Bucher, 2008). This undetermined  
984 739 assemblage could correspond either to latest Smithian or earliest Spathian ammonoid beds.

985 740 Conodont biostratigraphic studies reported only the *Novispathodus waageni* Zone within  
986 741 the Smithian in the Guandao, Mingtang, Shitouzhai, and Zuodeng sections (Tong et al., 2004,  
987 742 2007; Zhang et al., 2015; Lehrmann et al., 2015; Liang et al., 2016) (Fig. 11). In the Jiarong  
988 743 section, reported Smithian conodont zones are in ascending order, the *Nv. waageni eowaageni*,  
989 744 *Nv. waageni waageni*, *Discretella discreta* and *Pachycladina-Parachirognathus* zones (Chen-  
990 745 YL et al., 2015; but see Chen-YL et al., 2018, for an update based on quantitative  
991 746 biostratigraphic methods). In the Baiyang section, they are the *Ds. discreta* and *Pachycladina-*

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1007 747 *Parachirognathus* (Yan et al., 2013). Spathian conodont zones are in ascending order, the *Nv.*  
1008 748 *crassatus* and *Triassospathodus homeri* zones at Guandao (Tong et al., 2004; Lehrmann et al.,  
1009 749 2015); the *Tr. homeri-Tr. triangularis* Zone at Mingtang (Liang et al., 2016); the *Nv.*  
1010 750 *pingdingshanensis*, *Icriospathodus collinsoni*, *Tr. homeri* and *Tr. triangularis* zones at Jiarong  
1011 751 (Chen-YL et al., 2015, 2018); the *Nv. pingdingshanensis* and *Tr. homeri* zones at Shitouzhai  
1012 752 and Zuodeng (Tong et al., 2007; Zhang et al., 2015); and the *Ic. collinsoni* and *Tr. homeri* zones  
1014 753 at Bianyang (Yan et al., 2013) (Fig. 11).

1015 754 At Guandao and Zuodeng, the SSB was placed at the first occurrences of *Novispathodus*  
1016 755 *crassatus* and *Nv. pingdingshanensis*, respectively (Tong et al., 2004, 2007; Lehrmann et al.,  
1017 756 2015) (Fig. 11). At Jiarong, only one ammonoid zone of early Spathian age was recognized,  
1018 757 i.e., the *Columbites* beds in the upper part of the Luolou Formation, ~5 m above the first  
1019 758 occurrence of *Nv. pingdingshanensis* (Chen-YL et al., 2015). Chen-YL et al. (2015) inferred  
1021 759 that some small specimens of *Nv. pingdingshanensis* were of late Smithian age (see Maekawa  
1022 760 and Komatsu, 2014; Komatsu et al., 2016 in An Chau Basin, Section 3.8) and placed the SSB  
1023 761 within the *Nv. pingdingshanensis* Zone, between the first occurrence of *Nv. pingdingshanensis*  
1024 762 and the *Columbites* beds. Chen-YL et al. (2018) recently revised conodont occurrences in  
1025 763 Jiarong and confirmed the late Smithian occurrence of *Nv. pingdingshanensis*. At Mingtang  
1027 764 and Shitouzhai, reports of early Spathian conodonts are not well-established. Thus, the SSB  
1028 765 was placed based only on global correlations of carbon isotope profiles (Zhang et al., 2015;  
1029 766 Liang et al., 2016; see Section 3.7.2). At Bianyang, the SSB was not clearly located because  
1030 767 only early Spathian *Icriospathodus collinsoni* was recovered (Yan et al., 2013). At Qingyan,  
1032 768 the Olenekian strata were assigned to the *Nv. waageni* and *Triassospathodus homeri* conodont  
1033 769 zones, and the FAD of *Nv. crassatus* and *Nv. pingdingshanensis* are (nearly) the same as the  
1034 770 first occurrence of *Tr. homeri*, making placement of the SSB somewhat equivocal (Ji et al.,  
1035 771 2011).

### 1036 772 1037 773 3.7.2. Carbon-isotope chemostratigraphy 1039 774

1040 775 In Nanpanjiang Basin, carbon isotope profiles of the Olenekian Stage have been generated  
1041 776 for multiple sections, including Jinya area (Galfetti et al., 2007c), Guandao (Tong et al., 2007),  
1042 777 Zuodeng (Tong et al., 2007), Jiarong (Chen-YL et al., 2013), Mingtang (Liang et al., 2016) and  
1043 778 Shitouzhai (Zhang et al., 2015) (Fig. 11). Guandao and Mingtang show similar  $\delta^{13}\text{C}_{\text{carb}}$  trends,  
1045 779 with a negative excursion from high values (ca. +4 to +6 ‰) in the lowermost Smithian to ca.  
1046 780 -2 ‰ (N3) in the middle Smithian, a rebound to ca. +2.5 ‰ in the lowermost Spathian, a long  
1047 781 plateau in the lower Spathian, a second negative excursion to ca. -1 ‰ (N4) in the middle  
1048 782 Spathian, and finally a positive excursion to ca. +4 ‰ in the uppermost Spathian (Tong et al.,  
1049 783 2007; Liang et al., 2016). The  $\delta^{13}\text{C}_{\text{carb}}$  profile at Jiarong is similar to that at Mingtang except  
1051 784 for the absence of a plateau in the lower Spathian (Chen-YL et al., 2013). At Zuodeng,  $\delta^{13}\text{C}_{\text{carb}}$   
1052 785 shows high values (ca. +4 ‰) in the lowermost Smithian, a decrease to ~0 ‰ (N3) in the middle  
1053 786 Smithian, a rebound to ca. +3 ‰ (P3) in the lower Spathian (base of the *Nv. pingdingshanensis*  
1054 787 Zone), a minor negative excursion (to ca. +1 ‰; N4) in the mid-Spathian, and finally  
1055 788 fluctuations between ~0 and +4 ‰ in the upper Spathian (Tong et al., 2007). The  $\delta^{13}\text{C}_{\text{carb}}$  profile  
1057 789 at Jinya is similar to that at Zuodeng except for a gradual increase in the late Spathian (Galfetti  
1058 790 et al., 2007c). At Shitouzhai,  $\delta^{13}\text{C}_{\text{carb}}$  varies between ca. +1 ‰ and -3 ‰ (Zhang et al., 2015),  
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1065 791 which is lower than in other Nanpanjiang Basin sections, although its plateau in the lower  
1066 792 Spathian is comparable to those at Guandao and Mingtang.  
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### 1069 794 **3.8. An Chau Basin, northern Vietnam (eastern Tethys)**

#### 1070 795 1071 796 *3.8.1. Ammonoid and conodont biostratigraphy*

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1073 798 The An Chau Basin was another epicontinental sea connected to the Nanpanjiang Basin  
1074 799 and bordering the western Panthalassic Ocean during the Early Triassic. In this basin, the  
1075 800 Lower Triassic succession consists of the Lang Son Formation (siliciclastics) of Induan-early  
1076 801 Olenekian age and the Bac Thuy Formation (fossiliferous carbonates, limestone breccia,  
1077 802 hemipelagic basinal marl and mudstone) of Olenekian age (Komatsu and Dang 2007; Maekawa  
1078 803 and Komatsu, 2014; Maekawa et al. 2015; Komatsu et al., 2016).

1081 804 To date, only the Bac Thuy Formation has yielded both ammonoids and conodonts of  
1082 805 Olenekian age. Komatsu et al. (2016) reported four ammonoid beds from KC-02 (in ascending  
1083 806 order, the *Owenites koeneni* and *Xenoceltites variocostatus* beds of middle and late Smithian  
1084 807 age, respectively, and the *Tirolites* cf. *cassianus* and *T. sp. nov.* beds of early Spathian age) and  
1085 808 three conodont zones (the *Novispathodus* ex gr. *waageni* Zone of Smithian age, the *Nv.* ex gr.  
1086 809 *pingdingshanensis* Zone straddling the SSB, and the *Icriospathodus collinsoni* Zone of early  
1087 810 Spathian age) (Fig. 11). The conodont *Nv.* ex gr. *pingdingshanensis* was reported at three  
1088 811 stratigraphic levels: (1) from the lower part of the uppermost Smithian *X. variocostatus* beds  
1089 812 (KC02-08); (2) from the top of the basal Spathian *Tirolites* cf. *cassianus* beds (KC02-10); and  
1090 813 (3) from strata between the *Tirolites* cf. *cassianus* and *Tirolites* sp. nov. beds (between KC02-  
1091 814 10 and KC02-14) (Maekawa and Komatsu, 2014; Komatsu et al., 2016).

1094 815 Based on ammonoid data, Komatsu et al. (2016) placed the SSB in the An Chau Basin at  
1095 816 the base of the *T. cf. cassianus* beds, which is ~0.95 m above the first occurrence of the *Nv.* ex  
1096 817 gr. *pingdingshanensis*, and proposed that the conodont *Nv.* ex gr. *pingdingshanensis* ranged  
1098 818 from the uppermost Smithian into the lowermost Spathian. The ammonoid *Xenoceltites* sp. was  
1099 819 also reported from the *T. cf. cassianus* and *Columbites* sp. beds of the An Chau Basin (i.e.,  
1100 820 Sample 14 in Komatsu et al., 2016). However, this placement of the SSB may be called into  
1101 821 question owing to some uncertainties in taxonomic identifications in this study. After  
1102 822 reconsideration of *Xenoceltites variocostatus* specimens from KC02-10 illustrated in Shigeta  
1103 823 et al. (2014), these may not pertain to this late Smithian species. Some illustrated specimens of  
1104 824 KC02-11 also resemble some early Spathian *Bajarunia (sensu lato)* forms. Overall, if true,  
1105 825 these few new tentative assignments may imply that the top of the *X. variocostatus* beds has to  
1106 826 be only slightly shifted downward, as well as their considered SSB, as other determinations of  
1107 827 *X. variocostatus* appear robust. Thus, *Nv.* ex gr. *pingdingshanensis* in KC02-10 and overlying  
1108 828 beds may be of earliest Spathian age. A reconsideration of *Nv.* ex gr. *pingdingshanensis* from  
1109 829 KC02-08 suggest it may not pertain to this species. However, at NT01-07, well-preserved  
1110 830 specimens of *X. variocostatus* specimens co-occur with *Nv.* ex gr. *pingdingshanensis*, thus  
1111 831 supporting a FAD of *Nv.* ex gr. *pingdingshanensis* within the late Smithian as observed in other  
1112 832 some other basins (also see discussion in Section 5.2).  
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#### 1114 834 *3.8.2. Carbon-isotope chemostratigraphy*

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1126 836 In the An Chau Basin, the  $\delta^{13}\text{C}_{\text{carb}}$  profile exhibits stable values of ca. -2 ‰ through the  
1127 837 middle Smithian (up to the top of the *Owenites koeneni* beds; N3), followed by a positive  
1128 838 excursion to maximum values of ca. +6 ‰ in the uppermost Smithian (within the *X.*  
1129 839 *variocostatus* beds; P3) or earliest Spathian if we took into account our potential revised  
1130 840 assignment, and finally a negative excursion to ca. +1 ‰ from this point into the lower Spathian  
1132 841 (Komatsu et al., 2016; Fig. 11).  
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### 1134 843 **3.9. Salt Range and Surghar Range, Pakistan (southern Tethys)**

#### 1135 844 1136 845 *3.9.1. Ammonoid and conodont biostratigraphy*

1137 846  
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1139 848 A highly resolved Smithian ammonoid zonation based on the quantitative Unitary  
1140 849 Association (UA) method has been proposed by Brühwiler et al. (2010c, 2011) using sections  
1141 850 from the North Indian Margin. A total of 14 UA zones have been defined based on material  
1142 851 from Pakistan (Salt Range), northern India (Spiti) and Tulong (Tibet) allowing detailed  
1143 852 calibration and correlation of Smithian  $\delta^{13}\text{C}$  curves.

1144 853 The Salt Range, located on the northern Gondwanan shelf in the southern Tethys Ocean  
1145 854 during the Early Triassic, has an Olenekian succession consisting of, in ascending order, the  
1146 855 Ceratite Beds (Ceratite Marls and Ceratite Sandstone members), Bivalve Limestone (Upper  
1147 856 Ceratite Limestone and Bivalve Beds members), and Dolomite Group (Dolomitic Beds and  
1148 857 Topmost Limestone members) (Waagen, 1895; Kummel and Teichert, 1973; Guex, 1978).  
1149 858 Recently, PJRG (1985) proposed subdivision of the succession into the Mittiwali (comprising  
1150 859 Units 1 to 5) and Narmia members in the Salt Range and the nearby Surghar Range, in which  
1151 860 Unit 2 (mudstone) was equivalent to the Ceratite Marls, Unit 3 (shale-sandstone) to the  
1152 861 Ceratite Sandstone, Unit 4 (limestone) to the Upper Ceratite Limestone and lower part of the  
1153 862 Bivalve Beds, Unit 5 (sandstone-shale) to the upper part of the Bivalve Beds and Dolomitic  
1154 863 Beds, and the Narmia Member to the Topmost Limestone. Important sections for Lower  
1155 864 Triassic biostratigraphic studies include the Nammal Gorge, Chidru and Zaluch locales in the  
1156 865 western Salt Range, and the Narmia and Chitta-Landu in the Surghar Range.

1157 866 The high-resolution ammonoid zonation established from different sections in Salt Range  
1158 867 and Surghar Range by Brühwiler et al. (2010c, 2011, 2012a) consists of 13 Smithian UA zones  
1159 868 of which 2 are late Smithian (Fig. 5F): the *Wasatchites distractus* beds (including the iconic  
1160 869 genus *Anasibirites*), and the *Glyptophiceras sinuatum* beds (including *Xenoceltites*  
1161 870 *variocostatus*) (Fig. 6E). As in other area worldwide, the *Glyptophiceras sinuatum* beds are of  
1162 871 latest Smithian age (e.g., Jenks et al., 2015). The SSB is thus placed just above the *G. sinuatum*  
1163 872 Zone within the “Bivalve Beds” (BB; Brühwiler et al., 2012a).

1164 873 These upper Smithian ammonoid assemblages are relatively similar to those reported in  
1165 874 earlier studies by PJRG (1985) based on material from the Narmia, Nammal Gorge, and  
1166 875 Chhidru sections. Late Smithian ammonoids from the lower part of Unit 4 (equivalent to the  
1167 876 upper part of Upper Ceratite Limestone) include *Anasibirites kingianus* and *Xenoceltites* sp.  
1168 877 (PJRG, 1985). The upper part of Unit 4 includes *A. kingianus* and *X. aff. evolutus* (PJRG, 1985).

1169 878 Early Spathian *Tirolites* sp. was recently sampled a few meters above the BB at Chitta-  
1170 879 Landu. *Procolumbites* was found at the top of the BB at Nammal, but as *Procolumbites* is  
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1183 879 younger than *Tirolites* (e.g., Guex et al., 2010), a sedimentary gap at this place is likely within  
1184 880 the BB (Hermann et al., 2011). Spathian rocks being eroded above the BB at Chhidru, this  
1185 881 section is uninformative for Spathian biostratigraphy. Overall, these ammonoid data constrains  
1186 882 the position of the SSB in Pakistan to between the *Glyptoniceras sinuatum* beds and the  
1187 883 *Tirolites* sp. beds.

1189 884 The first conodont study in Nammal Gorge and Narmia yielded three zones, in ascending  
1190 885 order, the *Novispathodus waageni* and *Neogondolella elongata* zones of Smithian age and the  
1191 886 *Triassospathodus triangularis-Tr. homeri* Zone of Spathian age (PJR, 1985; Fig. 5F). The  
1192 887 *Sc. milleri* Zone, occupying a narrow interval between the *Nv. waageni* and *Ng. elongata* zones,  
1193 888 was recognized only at Chhidru. Spathian conodont species in the *Tr. triangularis-Tr. homeri*  
1194 889 Zone, including *Tr. triangularis*, *Tr. homeri*, *Ng. elongata* and *Ng. jubata*, range through a ~40-  
1195 890 m-thick stratigraphic interval from the top of Unit 4 to near the top of the Narmia Member  
1196 891 (PJR, 1985). Therefore, based on these conodont data, the SSB can be constrained to between  
1197 892 the first occurrences of the *Ng. elongata* and *Tr. triangularis*. Recent works of Romano et al.  
1198 893 (2013), Leu et al. (2018), and Goudemand et al. (2018) reported several new occurrences of  
1199 894 conodonts in Nammal and especially confirmed the occurrence of *Nv. pingdingshanensis*  
1200 895 within the late Smithian *Glyptoniceras sinuatum* ammonoids beds.

### 1204 896 1205 897 3.9.2. Carbon-isotope chemostratigraphy 1206 898

1207 899 Carbon isotope profiles for the Olenekian Stage have been reported from the Nammal  
1208 900 (Baud et al., 1996; Galfetti et al., 2007c, modified after Baud et al., 1989, and Atudorei, 1999)  
1209 901 and Chhidru of the Salt Range, and Chitta-Landu of the Surghar Range in Pakistan (Baud et  
1210 902 al., 1996; Hermann et al., 2011) (Fig. 12). The ammonoid and carbon isotope studies at Salt  
1211 903 Range and Surghar Range facilitate intercalibrations (Hermann et al., 2011). The  $\delta^{13}\text{C}_{\text{carb}}$   
1212 904 profile in Nammal exhibits stable values of ca.  $-2\text{‰}$  in the middle Smithian (N3), a positive  
1213 905 excursion to ca.  $+2\text{‰}$  across the SSB, and then a decrease to ca.  $-2\text{‰}$  by the mid-Spathian.  
1214 906 In the composite section (Nammal, Chhidru, Chitta-Landu and Narmia gorges) of Hermann et  
1215 907 al. (2011, 2012),  $\delta^{13}\text{C}_{\text{carb}}$  values were only reported from the middle to uppermost Smithian,  
1216 908 showing similar variations as in Galfetti et al. (2007c). The  $\delta^{13}\text{C}_{\text{org}}$  profile of the composite  
1217 909 section exhibits high values (ca.  $-24$  to  $-28\text{‰}$ ) in the lower Smithian, followed by a negative  
1218 910 excursion to ca.  $-33\text{‰}$  (N3\*) in the middle Smithian (*Pseudoceltites multiplicatus* beds), then  
1219 911 back to ca.  $-26\text{‰}$  (P3\*) in the lowermost Spathian (Hermann et al., 2011, 2012). Within the  
1220 912 Spathian, the  $\delta^{13}\text{C}_{\text{org}}$  signal shows a slight decrease to ca.  $-30\text{‰}$  (N4\*?) then an increase to ca.  
1221 913  $-26\text{‰}$  in the upper Spathian. In the Salt Range and Surghar Range, however, the  $\delta^{13}\text{C}_{\text{org}}$  profile  
1222 914 of the Smithian interval is slightly different from those of other sections globally (Figs. 7, 11-  
1223 915 12), possibly due to unusual sedimentation rates, or diagenetic alteration or contamination of  
1224 916 the organic carbon isotope record.

## 1229 917 1230 918 3.10. Spiti Valley, India (southern Tethys)

### 1231 919 1232 920 3.10.1. Ammonoid and conodont biostratigraphy

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1234 922 In the Spiti Valley of northern India, Olenekian strata belong to the Mikin Formation,  
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1243 923 which consists of the Smithian Limestone and Shale Members, and the Spathian Niti Limestone  
1244 924 Member (Brühwiler et al., 2010a). Lower Triassic ammonoids and conodonts have been  
1245 925 studied in a series of sections including Mud, Guling, Lalung, and Losar (Brühwiler et al.,  
1246 926 2007, 2012b; Krystyn et al., 2007a, b). To date, biostratigraphic works in the Spiti Valley have  
1247 927 focused mainly on the Permian/Triassic and Induan/Olenekian boundaries, as well as Smithian  
1248 928 ammonoids (Orchard and Krystyn, 1998, 2007; Krystyn et al., 2004; Orchard, 2007).

1249 929 At Mud, Brühwiler et al. (2010a, 2012b) reported fourteen ammonoid UA zones of  
1251 930 Smithian age, including the late Smithian *Wasatchites distractus*, *Subvishnuites posterus* and  
1252 931 *Glyptopliceras sinuatum* beds, in ascending order (Fig. 5G and 6F). The *W. distractus* beds  
1253 932 also contain abundant specimens of *Anasibirites*; this assemblage can be correlated worldwide  
1254 933 (e.g., Jenks et al. 2015; Jattiot et al. 2016, 2017). The *S. posterus* beds contain *S. posterus*,  
1255 934 *Pseudosageceras augustum*, and *Xenocelties* cf. *variocostatus*. This interval, together with the  
1257 935 overlying *G. sinuatum* beds, are indicative of the latest Smithian (Brühwiler et al., 2010a;  
1258 936 Jattiot et al. 2017). *Tirolites* is reported from overlying lower Spathian beds (Brühwiler et al.  
1259 937 2010a, 2011), but with uncertainty on its exact occurrence. Nevertheless, based on ammonoids  
1260 938 the SSB can be placed above the *G. sinuatum* beds and below the *Tirolites* beds.

1261 939 The corresponding conodont zones at Mud are the lower-middle Smithian *Novispathodus*  
1263 940 *waageni eowaageni* and *Nv. waageni waageni*, the upper Smithian *Scythogondolella milleri*,  
1264 941 and the Spathian *Icriospathodus collinsoni* and *Chiosella gondolelloides* zones, in ascending  
1265 942 order (Bhatt et al., 1999; Krystyn et al., 2004, 2005; Orchard and Krystyn, 2007) (Fig. 5G).  
1266 943 Therefore, the SSB could be placed at or below the first occurrence of *Ic. collinsoni*.

### 1269 945 3.10.2. Carbon-isotope chemostratigraphy

1270 946  
1271 947 Carbon isotope profiles have been reported from the Mud and Losar sections, Mud profile  
1272 948 covering the upper Dienerian to lower Smithian (Krystyn et al., 2007a), and the Losar profile  
1273 949 covering the whole Olenekian (Atudorei, 1999; Galfetti et al., 2007c) (Fig. 12). At Mud, the  
1274 950  $\delta^{13}\text{C}_{\text{carb}}$  profile shows a gradual decrease from ca. 0 ‰ at the Induan/Olenekian boundary to  
1276 951 ca. -2 ‰ in the lower/middle Smithian (i.e., within the *Flemingites-Euflemingites* ammonoid  
1277 952 Zone and the *Neospathodus spitiensis* conodont Zone; close to N3). At Losar, the  $\delta^{13}\text{C}_{\text{carb}}$   
1278 953 profile exhibits a gradual decrease from ca. +0.5 ‰ in the lowermost Smithian (close to P2) to  
1280 954 ca. -3 ‰ in the middle Smithian (at ~1 below the *Nyalamites angustecostatus* beds; N3), a  
1281 955 positive excursion to ca. +2.5 ‰ (P3) across the SSB, a gradual negative excursion to ca. -1 ‰  
1282 956 by the middle Spathian (N4), and finally a rebound to ca. +2 ‰ in the uppermost Spathian  
1283 957 (close to P4) (Galfetti et al., 2007c; Fig. 12).

## 1286 959 3.11. Southern Europe, Caucasus, and Middle East (western Tethys)

### 1288 961 3.11.1. Ammonoid and conodont biostratigraphy

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1290 963 Various localities in southern Europe have yielded ammonoid assemblages, but most of  
1291 964 them are poorly preserved with a rather low diversity (e.g., Romania, Cavin and Gradinaru,  
1292 965 2014; Hungary, Hips and Pelikan, 2002; Balkans, Kittl, 1903; Krystyn, 1974; Golubić, 1996,  
1293 966 2000). Additionally, mostly reported faunas are early Spathian, and detailed biostratigraphic

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967 zonations are rare, preventing a firm definition of the SSB within this area based on  
968 ammonoids. However, Smithian material is beginning to be described relatively finely in  
969 some places (e.g., Đacović, 2017), suggesting that future biostratigraphic improvements  
970 around the SSB are possible. Sections in the Caucasus mainly include Smithian ammonoids  
971 (e.g., Popov, 1964), whereas reported taxa from Mangyshlak are mainly early Spathian in age  
972 (e.g., Balini et al., 2000). Here again, future improvements in ammonoid biostratigraphy may  
973 help to better constrain the SSB. Detailed ammonoid zonal schemes for the SSB in the  
974 Middle East are also lacking, in part due to the limited accessibility of this area (e.g., Iran,  
975 Balini et al., 2009, Vaziri, 2011). However, some abundant and diversified assemblages are  
976 known from the Smithian and Spathian of Oman (Tozer and Calon, 1990; Brühwiler et al.,  
977 2012c), suggesting that future biostratigraphic improvements are also possible in this region.

978 Latest Permian-Early Triassic conodonts have been extensively studied in Europe, for  
979 example, in Italy (Huckriede, 1958; Assereto et al., 1973; Mostler, 1982; Perri, 1986; Perri  
980 and Andraghetti, 1987; Samankassou, 1995; Perri and Farabegoli, 2003), Slovenia (Kolar-  
981 Jurkovšek and Jurkovšek, 2007; Kolar-Jurkovšek et al., 2011a, b), Croatia (Aljinović et al.,  
982 2006, 2011) and Serbia (Sudar et al., 2007; Nestell et al., 2009; Crasquin et al., 2010), including  
983 conodonts of the Olenekian age (Staesche, 1964; Perri, 1991; Kolar-Jurkovšek et al., 2013,  
984 2015, 2017; Sudar et al., 2014; Chen-YL et al., 2016). Generally, conodont data in this area are  
985 rarer (e.g., Italy) than elsewhere and also endemic. This does not facilitate correlation with  
986 other regions. For example, some classical Smithian taxa (e.g., *Novispathodus waageni*) and  
987 taxa considered as markers of the earliest/early Spathian (e.g., *Nv. pingdingshanensis*,  
988 *Icriospathodus collinsoni*) are often absent. Sudar et al. (2014) reported two lower Smithian  
989 conodont zones, in ascending order, the *Pachycladina obliqua*–*Foliella gardenae* and  
990 *Neospathodus planus* zones, from the Gučevo mountain area in northwestern Serbia. In  
991 northern Italy, the *Pa. obliqua* Zone ranges through almost the entire Olenekian (Perri, 1991).  
992 Posenato (2008) suggested that *F. gardenae* may have ranged from the late Dienerian to the  
993 late Smithian. A lower Smithian *Pa. obliqua* Zone was reported from Croatia by Aljinović et  
994 al. (2011), which included the conodont taxa *Hadrodontina anceps*, *Parachirognathus*  
995 *ethingtoni*, *Foliella* sp. or ?*Furnishius* sp. Kolar-Jurkovšek et al. (2013) and Kolar-Jurkovšek  
996 and Jurkovšek (2015) reported Olenekian conodont assemblages from the Julian Alps area in  
997 Slovenia, in which *Triassospathodus hungaricus* was regarded as indicative of an earliest  
998 Spathian age. In Chen-YL et al. (2016), nine discrete conodont UA zones were recognized in  
999 the Olenekian of the Idrija–Žiri area in Slovenia, namely the *Eurygnathodus costatus*,  
1000 *Eurygnathodus hamadai*, *F. gardenae*, *Ns. robustus*, *Platyvillosus corniger*, *Pl. regularis*, *Tr.*  
1001 *hungaricus*, *Tr. symmetricus*, and *Ns. robustispinus* UAZs. The *F. gardenae* Zone from the Žiri  
1002 road section, which contains *F. gardenae*, *Pa. obliqua* and *Pa. inclinata*, was proposed as  
1003 indicative of the SSB transition based on its co-occurrence with the P3 carbon-isotope  
1004 maximum (Chen-YL et al., 2016) (see Section 5.3). However, the *F. gardenae* UAZ may also  
1005 include the N3 carbon-isotope minimum, thus constraining the SSB to within the *F. gardenae*  
1006 UAZ. Only limited Lower Triassic conodont biostratigraphic data are available for sections  
1007 from the Middle East (Brühwiler et al., 2012c; Chen-YL et al., 2018) and most of them are  
1008 focused on the Permian/Triassic boundary (e.g., Gallet et al., 2000; Hauser et al., 2001; Groves  
1009 et al., 2005; Horacek et al., 2007b; Richoz et al., 2010).



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1361 1011 3.11.2. Carbon-isotope chemostratigraphy  
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1363 1013 Carbon isotope studies of the Slovenian sections revealed a  $\delta^{13}\text{C}_{\text{carb}}$  shift from ca. +0.5 to  
1364 1014 +7 ‰ within the *Foliella gardenae* Zone (Interval II), followed by a decrease from ca. +5 ‰  
1365 1015 in the *Neospathodus robustus* Zone (lower Spathian; close to P3) to ca. +1 ‰ in the *Ns.*  
1366 1016 *robustispinus* (middle Spathian; close to N4) (Chen-YL et al., 2016). Recently, Aljinović et al.  
1367 1017 (2018) reported a continuous Olenekian  $\delta^{13}\text{C}_{\text{carb}}$  curve from Croatia, showing a negative  
1368 1017 excursion of  $\delta^{13}\text{C}_{\text{carb}}$  from ca. +5 ‰ in the lower Smithian (P2) to ca. -3 ‰ in the middle  
1369 1018 Smithian (N3), followed by a positive excursion to ca. +3 ‰ in the lower Spathian (P3). The  
1370 1019  $\delta^{13}\text{C}_{\text{carb}}$  curve then decreased to ca. -2 ‰ in the mid-Spathian (N4) and back to ca. +3 ‰ in  
1371 1020 the upper Spathian (close to P4). More extensive carbon-isotope work has been undertaken in  
1372 1021 Italy. At L'Uomo, the  $\delta^{13}\text{C}_{\text{carb}}$  profile shows a sharp negative excursion from ca. +6 ‰ in the  
1373 1022 lowest Smithian (P2) to ca. -2 ‰ during the middle Smithian (N3), followed by a positive  
1375 1023 excursion to ca. +2 ‰ in the lower Spathian (P3) (Horacek et al., 2007a). At  
1376 1024 Lungenfrischgraben, the  $\delta^{13}\text{C}_{\text{carb}}$  profile shows a gradual decrease from ca. +4 ‰ at the IOB  
1377 1025 (P2) to ca. -2 ‰ (N3) in the middle Smithian, a rebound to ca. +3 ‰ in the lowermost Spathian  
1378 1026 (P3), and finally a negative excursion to ca. -2 ‰ in the mid-Spathian (N4) (Horacek et al.,  
1379 1027 2010). The  $\delta^{13}\text{C}_{\text{carb}}$  profile at Trudener Bach is similar to that at L'Uomo, showing a shift from  
1381 1028 ca. -2 ‰ in the middle Smithian (N3) to ca. +3 ‰ at the lower Spathian (P3) (Horacek et al.,  
1382 1029 2010).  
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1384 1031 In the Middle East, carbon isotope studies on the Smithian-Spathian transition have been  
1385 1032 carried out for the Zal, Abadeh and Amol sections in Iran (Horacek et al., 2007b), the  
1387 1033 Musandam section in the United Arab Emirates (Clarkson et al., 2013), the Wadi sections (i.e.  
1388 1034 Sahtan, Shuyab, Maqam, Wasit Sud) and Sal and Radio Tower sections in Oman (Hauser et  
1389 1035 al., 2001; Richoz, 2006, Chen-YL et al., 2018), and the Taşkent section in Turkey (Richoz et  
1390 1036 al., 2006; Lau et al., 2016). In the Iranian sections, the  $\delta^{13}\text{C}_{\text{carb}}$  profiles show negative  
1391 1037 excursions from +5 to +8 ‰ at the Induan/Olenekian boundary (P2) to -2 to -4 ‰ in the middle  
1392 1037 Smithian (N3), sharp rebounds to +2 to +3 ‰ at the SSB (P3), and then gradual decreases to  
1393 1038 ca. -4 ‰ in the mid-Spathian (N4) (Horacek et al., 2007b; Fig. 12). At Musandam, the  $\delta^{13}\text{C}_{\text{carb}}$   
1394 1039 profile shows a gradual negative excursion from ca. +3 ‰ in the lowermost Smithian (P2) to  
1395 1040 ca. 0 ‰ in the middle Smithian (N3), a slow rebound to ca. +4 ‰ in the lower Spathian (P3),  
1396 1041 a decrease to ca. +2 ‰ in the middle to upper Spathian (N4), and finally an increase to ca. +3 ‰  
1397 1042 in the uppermost Spathian (close to P4) (Clarkson et al., 2013; Fig. 12). In Taşkent, the  $\delta^{13}\text{C}_{\text{carb}}$   
1399 1043 profile shows a negative excursion from ca. +6 ‰ in the lowermost Smithian (P2) to ca. -2 ‰  
1400 1044 in the middle Smithian (N3), a positive excursion to ca. +4 ‰ in the lower Spathian (P3),  
1401 1045 followed by the second negative excursion to -2 ‰ in the middle to upper Spathian (N4), and  
1402 1046 finally an increase to ca. +4 ‰ in the uppermost Spathian (close to P4) (Lau et al., 2016). In  
1403 1047 Oman, the  $\delta^{13}\text{C}_{\text{carb}}$  profiles show negative shifts from +4 to +6 ‰ in the lowermost Smithian  
1405 1048 (P2) to 0 to -2 ‰ in the middle Smithian (N3), a positive excursion to a maximum of ca. +8 ‰  
1406 1049 in the lower Spathian (P3), a gradual negative excursion to -1 to -3 ‰ in the middle to upper  
1407 1050 Spathian (N4), and finally a rebound to positive values in the upper Spathian (Richoz, 2006;  
1408 1051 Clarkson et al., 2016; Chen-YL et al., 2018). Despite the frequent lack of biostratigraphic data,  
1409 1052 the position of the SSB is generally constrained by the well-defined N3-to-P3 shift in the carbon  
1411 1053 isotope profiles of these sections, but new biostratigraphic data will likely help to better  
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1420 1055 constrain the SSB in this area (see [Chen-YL et al., 2018](#)).  
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#### 1422 1057 **4. Chemostratigraphic records for the Smithian-Spathian transition**

##### 1423 1058 1424 1059 **4.1. Carbon-isotope chemostratigraphy** 1425 1060 1426 1061

1427 1061 The Early Triassic was an interval marked by large successive secular fluctuations in  
1428 1062 carbon isotope records, beginning at the EPME and ending around the Early/Middle Triassic  
1429 1063 boundary (e.g., [Payne et al., 2004](#); [Tong et al., 2007](#)). These high-amplitude carbon isotopic  
1430 1064 variations were often assumed to be related to rapid marine faunal overturns and to a delayed  
1431 1065 marine ecosystem recovery following the EPME ([Erwin, 2001](#); [Bottjer et al., 2008](#); [Chen and](#)  
1432 1066 [Benton, 2012](#)). During this time, there is evidence of recurrent extreme environmental  
1434 1067 perturbations, e.g., high tropical sea-surface temperatures ([Sun et al., 2012](#); [Romano et al.,](#)  
1435 1068 [2013](#)), relatively widespread oceanic anoxia ([Wignall and Twitchett, 1996](#); [Grice et al., 2005](#);  
1436 1069 [Xie et al., 2007](#); [Galfetti et al., 2008](#); [Algeo et al., 2010](#); [Hermann et al., 2011](#); [Grasby et al.,](#)  
1437 1070 [2013](#); [Zhao et al., 2013b](#); [Feng et al., 2014](#); [Tian et al., 2014](#); [Clarkson et al., 2016](#); [Lau et al.,](#)  
1438 1071 [2016](#); [Huang et al., 2017](#); [Song-HY et al., 2019](#)), and ocean acidification ([Payne et al., 2010](#);  
1440 1072 [Hinojosa et al., 2012](#); [Clarkson et al., 2015](#); [Silva-Tamayo et al., 2018](#)). Following the middle  
1441 1073 Smithian hyperwarming ([Sun et al., 2012](#); [Romano et al., 2013](#)), the Smithian-Spathian  
1442 1074 transition was marked by a climatic cooling event ([Goudemand et al., 2013, 2014a, 2018](#)),  
1443 1075 weakened ocean stratification ([Song-HY et al., 2013](#)), and increased marine productivity linked  
1444 1076 to upwelling of sequestered deep-water nutrients at some places ([Takahashi et al., 2009](#); [Zhang](#)  
1446 1077 [et al., 2015](#); [Song-HY et al., 2019](#)). A concurrent major perturbation to the global carbon cycle  
1447 1078 before and across the SSB resulted in the largest excursions in marine  $\delta^{13}\text{C}$  records of the Early  
1448 1079 Triassic ([Payne et al., 2004](#); [Tong et al., 2007](#); [Galfetti et al., 2007a, b, c](#); [Horacek et al., 2007a,](#)  
1449 1080 [b](#); [Brühwiler et al., 2009](#)). Such excursions in Early Triassic marine  $\delta^{13}\text{C}$  records have multiple  
1451 1081 proposed causes, including volcanic emissions ([Galfetti et al., 2007b](#); [Payne and Kump, 2007](#)),  
1452 1082 soil organic matter inputs ([Sephton et al., 2005](#)), marine productivity changes ([Meyer et al.,](#)  
1453 1083 [2011](#)), or combinations of these factors ([Algeo et al., 2011](#)). In addition, regional authigenic  
1454 1084 and/or diagenetic effects can also modify carbon isotope signals depending on the  
1455 1085 environmental settings ([Schobben et al., 2016](#); [Thomazo et al., 2016](#); [Caravaca et al., 2017](#)).  
1456 1086

1457 1086 These large global  $\delta^{13}\text{C}$  fluctuations can therefore be useful for global correlation when  
1458 1087 coupled with biostratigraphic data (e.g., [Galfetti et al., 2007c](#); [Horacek et al., 2007a, b](#); [Grasby](#)  
1459 1088 [et al., 2016](#); [Wignall et al., 2016](#); [Thomazo et al., 2016](#)). Most  $\delta^{13}\text{C}$  profiles exhibit a series of  
1460 1089 alternating minima (N1 to N4) and maxima (P1 to P4; [Fig. 1](#)). During the Olenekian,  $\delta^{13}\text{C}$   
1461 1090 profiles generally exhibit a positive peak (P2) close to the Dienerian/Smithian boundary, a  
1462 1091 major negative excursion in the middle Smithian (N3), a rebound across the SSB to a second  
1464 1092 positive peak (P3) in the earliest Spathian, a second negative excursion (N4) in the middle  
1465 1093 Spathian, and a third positive excursion (P4) in the lowermost Anisian, after which  $\delta^{13}\text{C}$   
1466 1094 stabilized during the Middle Triassic (e.g., [Payne et al., 2004](#); [Tong et al., 2007](#)). The cause(s)  
1467 1095 of these large carbon-isotopic excursions are not known with certainty. For instance, the P3  
1469 1096 excursion has been tentatively partly related to increased marine productivity during the SSB  
1470 1097 cooling event ([Song-HY et al., 2013](#); [Zhang et al., 2015](#); [Caravaca et al., 2017](#); [Goudemand et](#)  
1471 1098 [al., 2018](#)).  
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1479 1099 Although nearly all Lower Triassic marine sections examined to date yield the same  
1480 1100 pattern of large-scale carbon-isotopic fluctuations, as described above, there are nonetheless  
1481 1101 small differences in  $\delta^{13}\text{C}$  profiles that may have significance for global correlation of the SSB.  
1482 1102 To facilitate discussion of carbon-isotopic variations, we have divided the Olenekian into four  
1483 1103 intervals, with Interval I representing the P2 to N3 shift, Interval II the N3 to P3 shift, Interval  
1484 1104 III the P3 to N4 shift, and Interval IV the N4 to P4 shift (Fig. 13A). Furthermore, we define  
1485 1105 “mdpt(N3-P3)” as the midpoint in units of per mille PDB between the absolute  $\delta^{13}\text{C}$  value of  
1486 1106 the N3 minimum and that of the P3 maximum in a given stratigraphic section. Present  
1487 1107 indications are that the SSB may slightly predate the P3 maximum, which is early Spathian.  
1488 1108 Because the N3 minimum may not be correlative between sections (owing to a slow initial rise  
1489 1109 and consequent difficulties in uniquely locating this point in some sections), it can be useful  
1490 1110 to have another pre-P3 geochemical marker. The mdpt(N3-P3) marker can serve this purpose  
1491 1111 because by the midpoint of the N3-to-P3 shift,  $\delta^{13}\text{C}$  was rising rapidly in many SSB sections,  
1492 1112 and this point can therefore be roughly correlated at a global scale in the absence of  
1493 1113 biostratigraphic data.

1494 1114 Most SSB sections exhibit a rapid shift from N3 to P3 (i.e., Interval II; see Fig. 13A). We  
1495 1115 are particularly concerned with variation between the lowermost Smithian and lowermost  
1496 1116 Spathian (i.e., Intervals I and II), within which we identified four major different patterns of  
1497 1117  $\delta^{13}\text{C}$  variation (Fig. 13B). This variation is mainly related to the shape and position of the N3  
1498 1118 minimum, with implications for placement of the Interval I/II contact (see discussion in Section  
1499 1119 5.3). Pattern 1 is characterized by an N3 minimum in the middle Smithian, followed by a slow  
1500 1120 rise in  $\delta^{13}\text{C}$  through the late Smithian before a rapid rise across the SSB. Pattern 2 is  
1501 1121 characterized by a protracted  $\delta^{13}\text{C}$  minimum during the middle Smithian, before a rapid rise in  
1502 1122 the late Smithian. Pattern 3 is characterized by a slow decline in  $\delta^{13}\text{C}$  through the early Smithian,  
1503 1123 reaching the N3 minimum during the middle Smithian, before a rapid late Smithian rise. Pattern  
1504 1124 4 is a variant on Pattern 3, in which the decline in  $\delta^{13}\text{C}$  from the P2 maximum to the N3  
1505 1125 minimum apparently does not show distinct rapid and slow stages (as in Pattern 3; Fig. 13B).

#### 1511 1126 4.2. Other chemostratigraphic records ( $\Delta\delta^{13}\text{C}_{\text{DIC}}$ , $\delta^{34}\text{S}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ )

1512 1127 In addition to  $\delta^{13}\text{C}$ , various other chemostratigraphic records show pronounced variations  
1513 1128 during the Early Triassic. Meyer et al. (2011) and Song-HY et al. (2013) documented changes  
1514 1129 in the vertical gradient of  $\delta^{13}\text{C}$  of dissolved inorganic carbon (DIC) in Early Triassic seawater  
1515 1130 based on secular differences in the  $\delta^{13}\text{C}_{\text{carb}}$  profiles of sections deposited at different water  
1516 1131 depths. Song-HY et al. (2013) showed that  $\Delta\delta^{13}\text{C}_{\text{DIC}}$  reached high values (ca. +4 to +7 ‰)  
1517 1132 during the middle-late Smithian, when a hot climate prevailed, and subsequently declined to  
1518 1133 ca. 0 ‰ in the early Spathian, coincident with climatic cooling (Fig. 14A). Song-HY et al.  
1519 1134 (2013) linked this pattern to the influence of temperature changes on the vertical temperature  
1520 1135 structure of the water column, with warming leading to intensified water-column stratification,  
1521 1136 reduced vertical overturn, and thus higher  $\Delta\delta^{13}\text{C}_{\text{DIC}}$  values (sustained by the “biological  
1522 1137 pump”), and cooling leading to reduced stratification, invigorated overturn, and lower  $\Delta\delta^{13}\text{C}_{\text{DIC}}$   
1523 1138 values.

1524 1139 The  $\delta^{34}\text{S}$  values of carbonate-associated sulfate (CAS) and evaporites, which are used as  
1525 1140 a proxy for contemporaneous seawater sulfate  $\delta^{34}\text{S}$ , show large variations throughout the Early  
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1538 1143 Triassic (Marenco et al., 2008; Horacek et al., 2010; Song-HY et al., 2014; Bernasconi et al.,  
1539 1144 2017; Lyu et al., 2018; Stebbins et al., 2018a, b; Thomazo et al., 2018).  $\delta^{34}\text{S}_{\text{CAS}}$  profiles in  
1540 1145 South China exhibit a negative excursion from a maximum of ca. +40 ‰ (P2s) in the earliest  
1541 1146 Smithian to a minimum of ca. +20 ‰ (N3s) in the middle Smithian, a rebound to a maximum  
1542 1147 of ~33 ‰ (P3s) in the early Spathian, and finally a slow decline in the middle to late Spathian  
1543 1148 to values of ca. +15 ‰ by the Middle Triassic (Song-HY et al., 2014; Fig. 14B; note: the ‘s’  
1544 1149 suffix indicates a S-isotope excursion, whereas excursion numbers without a suffix indicate a  
1545 1149 C-isotope excursion). Recent studies revealed relatively similar variations of  $\delta^{34}\text{S}_{\text{CAS}}$  during  
1546 1150 the Smithian and Spathian in the Spiti Valley (India), Jesmond (Canada), and Mineral  
1547 1151 Mountains (USA) sections (Stebbins et al., 2018a, b; Thomazo et al., 2018). These fluctuations  
1548 1152 here parallel those in  $\delta^{13}\text{C}$  profiles, and this relationship has been attributed to co-burial of  
1549 1153 reduced carbon (organic matter) and reduced sulfur (pyrite), both of which are isotopically light  
1550 1154 compared to their seawater sources (DIC and sulfate, respectively). In this scenario, positive  
1551 1154 (vs. negative) shifts in  $\delta^{34}\text{S}_{\text{CAS}}$  and  $\delta^{13}\text{C}_{\text{carb}}$  were the result of increased (vs. reduced) burial of  
1552 1155 organic matter and pyrite, due to increased (vs. reduced) primary productivity and intensity of  
1553 1156 microbial sulfate reduction controlled by climate changes. Concomittant changes in  
1554 1157 bioturbation may have also played a role (Thomazo et al., 2018). The coupling of these two  
1555 1158 isotopic systems during the Early Triassic (which is not seen in the Cenozoic) was because of  
1556 1159 the much lower concentration of seawater sulfate at that time (2.5 to 9.1 mM; Algeo et al.,  
1557 1159 2015), resulting in a shorter residence time for seawater sulfate that more closely matched that  
1558 1160 of seawater DIC (Luo et al., 2010; Stebbins et al., 2018b). The decoupling of the marine C and  
1559 1161 S cycles that occurred during the middle to late Spathian was thus probably due to increases in  
1560 1162 seawater sulfate concentrations that resulted in residence times longer than that of DIC (Song-  
1561 1162 HY et al., 2014).

1566 1167 Climate warming also potentially enhanced continental weathering during the Early  
1567 1168 Triassic, as revealed by a sharp increase in seawater  $^{87}\text{Sr}/^{86}\text{Sr}$ . This rise commenced in the early  
1568 1168 Griesbachian from a baseline of ~0.7072, reaching ~0.7076 by the earliest Smithian and then  
1569 1169 ~0.7079 by the earliest Spathian (Sedlacek et al., 2014; Song-HJ et al., 2015; Fig. 14C).  
1570 1170 Thereafter, the rise in seawater  $^{87}\text{Sr}/^{86}\text{Sr}$  slowed sharply, reaching only ~0.7081 by the late  
1571 1171 Spathian. The abrupt break in the seawater  $^{87}\text{Sr}/^{86}\text{Sr}$  profile at the SSB has been attributed to a  
1572 1172 sharp global cooling at that time and a consequent decrease in continental weathering rates  
1573 1173 (Algeo and Twitchett, 2010; Sedlacek et al., 2014; Zhang-L et al., 2015; Zhang-F et al., 2018).

## 1576 1175 1577 1176 **5. Future formalization of the Smithian/Spathian boundary**

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1580 1178 Biological and environmental studies of the Smithian-Spathian transition will ultimately  
1581 1179 lead to a formal definition of the SSB, and the present study provides a first background for  
1582 1180 moving forward toward this objective. Both ammonoids and conodonts offer numerous and  
1583 1181 widely distributed biostratigraphic markers that may be useful for future definitions of the SSB.  
1584 1182 The definition of any GSSP ideally employs multiple bio-, chemo-, and physical criteria, and  
1585 1183 when fossils are rare or lacking, as is the case for some SSB sections, then alternate proxies  
1586 1183 must be sought. The SSB transition corresponds to a rapid positive shift of  $\delta^{13}\text{C}$  from the middle  
1587 1184 Smithian N3 minimum to the early Spathian P3 maximum (Interval II; Fig. 13), making the  
1588 1185  $\delta^{13}\text{C}$  signal a potentially useful auxiliary proxy to locate the SSB (but not replacing  
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1597 1187 biostratigraphic data, if available). In this section, we review (1) potential ammonoid and  
1598 1188 conodont biostratigraphic as well as carbon-isotopic criteria that may prove useful for a future  
1599 1189 formal definition of the SSB, (2) placements of the SSB in earlier studies globally, and (3) the  
1600 1190 timing of the Smithian Thermal Maximum based on the criteria proposed in the present study.  
1601 1191 Note that these points can potentially evolve according to future discoveries that may be made.  
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### 1604 1193 5.1. Constraints from ammonoid biozonation

1605 1194  
1606 1195 The successive global events recorded by ammonoids during the late Smithian and early  
1607 1196 Spathian are well-constrained and provide multiple potential criteria for definition of the SSB.  
1608 1197 The base of the late Smithian is globally well-defined by a first major ammonoid extinction  
1609 1198 event (see Section 2 and Fig. 2) and is characterized by an assemblage grouping iconic taxa,  
1610 1199 notably prionitids, showing impressive cosmopolitan distributions, such as *Anasibirites* and  
1612 1200 *Wasatchites* (AW assemblage), and representing an almost perfect global timeline. The AW  
1613 1201 assemblage thus allows correlation at very large geographic scale among localities of different  
1614 1202 paleolatitudes and oceans (e.g., USA, Jattiot et al., 2016, 2017; South China, Tong et al., 2004,  
1615 1203 Brayard and Bucher, 2008; Pakistan, Brühwiler et al., 2011). The top of the late Smithian is  
1617 1204 also rather well-defined by an assemblage of cosmopolitan taxa, much poorer in generic  
1618 1205 richness and corresponding to a last Smithian turnover event. It is mainly found at low and  
1619 1206 mid-paleolatitudes of the Tethys and Panthalassic oceans and shows co-occurring taxa such as  
1620 1207 *Glyptophiceras*, *Xenoceltites* (*X. variocostatus* and *X. subevolutus*) and *Pseudosageceras*  
1621 1207 *augustum* (GXP assemblage). This latest Smithian assemblage (or characteristic species) has  
1622 1208 notably been reported from the USA (Brayard et al., 2013; Jattiot et al., 2017, 2018; Jenks and  
1623 1209 Brayard, 2018), Spitsbergen (Mørk et al., 1999), South China (Tong et al., 2004; Brayard and  
1624 1210 Bucher, 2008), Vietnam (Komatsu et al., 2016), and various localities of the North Indian  
1625 1211 Margin (Brühwiler et al., 2012a, b). The GXP assemblage can thus be used to define the  
1626 1212 uppermost Smithian at a very large number of localities. Another late Smithian assemblage  
1627 1213 (*Subvishnuites* beds) that is intermediate between AW and GXP has been reported from the  
1629 1214 North Indian Margin, but it is mostly endemic and not well-documented elsewhere. Earliest  
1630 1215 Spathian assemblages are generally characterized by widespread occurrences of typical taxa  
1631 1216 belonging to e.g., the genera *Tirolites*, *Bajarunia* and *Doricranites*. The first appearances of  
1632 1217 these taxa, as well as their co-occurrences (e.g., *Bajarunia* and *Tirolites*; BT assemblage) at  
1633 1218 some places, can serve as a potential basis for definition of the base of the Spathian (e.g.,  
1634 1219 Spitsbergen, Dagys and Weitschat, 1993; USA, Guex et al., 2010; Jenks et al., 2013; South  
1635 1219 China, Tong et al., 2004; Galfetti et al., 2007b; Vietnam, Komatsu et al., 2016). However, as  
1636 1220 these earliest Spathian taxa apparently exhibit rather more endemic distributions than late  
1637 1221 Smithian taxa, diagnostic assemblages or taxa may slightly vary from basin to basin. More  
1638 1222 work is needed to finely decipher earliest Spathian occurrences of these taxa at many places.  
1639 1223 Within the early Spathian, taxa co-occurring with *Columbites* are younger.

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1641 1224 Overall, based on published ammonoid data, the SSB is constrained above the global AW  
1642 1225 assemblage and between the latest Smithian GXP and earliest Spathian BT assemblages. Such  
1643 1226 a succession is frequently encountered and well-documented in the western USA, South China,  
1644 1227 Tibet, Vietnam and South Primorye (see Section 3). Detailed study of basins where the  
1645 1228 Smithian-Spathian transition was not affected by a eustatic regression, as is observed almost  
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1231 worldwide, or from sections representing deep water settings may help to definitively  
1232 determine the detailed succession of ammonoids assemblages across the SSB.

## 1233 5.2. Constraints from conodont biozonation

1234 Conodont taxa characteristic of the late Smithian substage are useful in constraining the  
1235 SSB. The Ellisoniidae family (e.g., *Pachycladina*, *Foliella*, *Parachirognathus*, *Furnishius* and  
1236 *Hadrodontina*) and Mullerinae subfamily (e.g., *Discretella*, *Wapitiodus*, *Guangxidella*,  
1237 *Conservatella* and *Scythogondolella*) mostly went extinct before or at the SSB (Orchard, 2007).  
1238 Diagnostic late Smithian taxa of the Ellisoniidae family have been identified in many areas,  
1239 e.g., *Pachycladina* from southwestern China (Yan et al., 2013; Chen-YL et al., 2015), *Pa.*  
1240 *obliqua* and *Pa. inclinata* from southern Europe (Perri, 1991; Aljinović et al., 2011; Sudar et  
1241 al., 2014; Chen-YL et al., 2016); *Foliella* from Croatia (Aljinović et al., 2011), *F. gardenae*  
1242 from other southern European locales (Sudar et al., 2014; Chen-YL et al., 2016);  
1243 *Parachirognathus* from Japan (Zhang et al., 2017) and southwestern China (Yan et al., 2013;  
1244 Chen-YL et al., 2015), *Pa. ethingtoni*, and *Furnishius* and *Hadrodontina anceps* from southern  
1245 Europe (Aljinović et al., 2011). Members of the Mullerinae subfamily that are characteristic of  
1246 the late Smithian include *Discretella* from Japan (Zhang et al., 2017), *Ds. discreta* from the  
1247 Canadian Arctic (Mosher, 1973; Orchard, 2008), western British Columbia (Orchard and  
1248 Zonneveld, 2009), western United States (Orchard and Tozer, 1997; Orchard, 2008; Orchard  
1249 and Zonneveld, 2009), and southwestern China (Yan et al., 2013; Chen-YL et al., 2015);  
1250 *Wapitiodus*(?) from Japan (Zhang et al., 2017), *W. robustus* from western British Columbia  
1251 (Orchard and Zonneveld, 2009); *Guangxidella bransoni* from British Columbia Orchard (2008)  
1252 and the western United States (Orchard and Tozer, 1997; Orchard, 2008; Orchard and  
1253 Zonneveld, 2009); *Conservatella conservativa* from Canadian Arctic (Mosher, 1973; Orchard,  
1254 2008) and the western United States (Orchard and Tozer, 1997; Orchard, 2008; Orchard and  
1255 Zonneveld, 2009); *Sc. lachrymiformis*, *Sc. rhomboidea*, *Sc. milleri* and *Sc. mosheri* from the  
1256 Canadian Arctic (Orchard, 2008), *Sc. milleri* and *Sc. mosheri* from Spitsbergen (Weitschat and  
1257 Lehmann, 1978; Clark and Hatleberg, 1983; Hatleberg and Clark, 1984) and the western United  
1258 States (Müller, 1956; Orchard and Tozer, 1997; Orchard, 2008), *Sc. lachrymiformis*, *Sc. milleri*,  
1259 *Sc. mosheri* and *Sc. phryna* from western British Columbia (Orchard and Zonneveld, 2009),  
1260 *Sc. milleri* from the Spiti Valley (Bhatt et al., 1999; Krystyn et al., 2004, 2005; Orchard and  
1261 Krystyn, 2007) and the Salt Range (PJRG, 1985).

1262 Some genera of the Novispathodinae (e.g., *Novispathodus*, *Triassospathodus*) and  
1263 Neogondolellinae (e.g., *Neogondolella*) subfamilies survived and rediversified after the late  
1264 Smithian extinction (Orchard, 2007), generating key early Spathian taxa that could be used in  
1265 the definition of the SSB. Commonly assumed members of this surviving and recovery fauna  
1266 included ‘*Tr.*’ *hungaricus*, *Ng. aff. sweeti*, and *Nv. pingdingshanensis*, which were first  
1267 reported from Hungary (Kozur and Mostler, 1970), the WCSB/western USA (Orchard and  
1268 Tozer, 1997), and Chaohu (Zhao et al., 2007a), respectively. Later, ‘*Tr.*’ *hungaricus* was also  
1269 reported from Sichuan Province, South China (Tian et al., 1983), the western USA (Lucas and  
1270 Orchard, 2007), and various localities in Europe (Kolar-Jurkovšek et al., 2013; Chen-YL et al.,  
1271 2016); *Ng. aff. sweeti* was reported from Chaohu (Zhao et al., 2007a); and *Nv.*  
1272 *pingdingshanensis* was reported from multiple sections in the South China region (Tong et al.,

2007; Ji et al., 2011; Chen-YL et al., 2015; Zhang et al., 2015), the WCSB (Orchard and Zonneveld, 2009), and the An Chau Basin (Komatsu et al., 2016).

Newly evolved conodont species of Spathian age, and their intercalibrations with ammonoid biozonation data, may serve an important role in the future definition of the SSB. In North America, *Neogondolella* aff. *sweeti* is known from strata overlying the *Anawasatchites tardus* Zone in the WCSB, and is of probable Spathian age in California. This species, as yet undescribed, differs from *Ng. sweeti* associated with Smithian *Neospathodus pakistanensis* in the Mittiwali Formation of Pakistan (Orchard and Tozer, 1997). In Hungary, ‘*Triassospathodus*’ *hungaricus* occurs in the *Tirolites* ammonoid beds (Kozur and Mostler, 1970), thus may serve as a marker for the lower Spathian, within rocks equivalent to the *Tirolites cassianus* ammonoid Zone (Kozur, 2003). Kolar-Jurkovšek et al. (2013) inferred that the ‘*Tr.* *hungaricus*’ fauna lies within the lower Spathian in the shallow western Tethys, where the *Icriospathodus collinsoni* fauna is missing. Chen-YL et al. (2016) speculatively proposed that ‘*Tr.* *hungaricus*’ could be correlated with *Novispathodus pingdingshanensis* because of their small size and co-occurrence with the ammonoid *Tirolites* (e.g., Hungary, Kozur and Mostler, 1970). At Chaohu, *Nv. pingdingshanensis* is found within the *Columbites-Tirolites* ammonoid Zone of the Nanlinghu Formation, between the late Smithian *Anasibirites* beds and the early Spathian *Tirolites* beds, thus leading to its proposed use as an earliest Spathian indicator (Zhao et al., 2007a, 2008a, b; Fig. 15). There, the first occurrence of *Nv. pingdingshanensis* is coincident with the first occurrence of *Ng. aff. sweeti* and below the first occurrence of *Ic. collinsoni* (Zhao et al., 2007a, 2008a, b). Thus, even though both *Nv. pingdingshanensis* and ‘*Tr.* *hungaricus*’ may be indicative of the earliest Spathian, *Nv. pingdingshanensis* is the older of these two taxa in South China.

The taxon *Nv. pingdingshanensis* was first introduced by Zhao et al. (2007a), who identified it as a marker for the SSB in South China. Since its discovery, this taxon has been reported from a number of other locations globally, including the western USA (Orchard and Zonneveld, 2009), western Canada (Henderson et al., 2018), Vietnam (Komatsu et al., 2016), Salt Range (Romano et al., 2013; Leu et al., 2018; Goudemand et al., 2018), Kashmir (Leu et al., 2018), Oman (Chen-YL et al., 2018) and the Zuodeng (Tong et al., 2007; Goudemand et al., 2012), Youping (Goudemand et al., 2012) and Jiarong sections in South China (Chen-YL et al., 2015). Although the first occurrence of *Nv. pingdingshanensis* has been used to identify the SSB in South China (Zhao et al., 2007a; Tong et al., 2007; Chen-YL et al., 2015), several studies elsewhere have claimed that the oldest specimens of *Nv. pingdingshanensis* are of late Smithian age because of specimens that co-occur with *Xenoceltites* in the AW and GXP ammonoid assemblages (Orchard and Zonneveld, 2009; Goudemand et al., 2012; Komatsu et al., 2016; Romano et al., 2013; Chen-YL et al., 2018; Leu et al., 2018; Goudemand et al., 2018). In earlier literature, the genus *Xenoceltites* ranged from the late Smithian to the early Spathian (Guex et al., 2010), but the rare early Spathian specimens assigned to this genus are now excluded from *Xenoceltites* (Brayard et al., 2019; Leu et al., 2018), thus making key *Xenoceltites* taxa found in the AW and GXP assemblages (e.g., *X. variocostatus* and *X. subevolutus*) exclusively late Smithian in age. On this basis, some studies (e.g., Leu et al., 2018) have inferred that *Nv. pingdingshanensis* may not be a suitable marker for the SSB, but more work will be needed to definitively address the issue of a possibly diachronous first occurrence of this taxon at a global scale.



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1774 1319 Because of its morphological similarity to antecedent taxa, *Nv. pingdingshanensis* must  
1775 1320 be carefully identified, and it is uncertain at present whether all reported occurrences of this  
1776 1321 taxon are correctly attributed. [Zhao et al. \(2008a\)](#) inferred a phyletic lineage in which *Nv.*  
1777 1322 *pingdingshanensis* evolved from the earlier taxon *Nv. waageni waageni*, with the latter  
1778 1323 evolving from *Ns. dieneri* Morphotype 3. The original taxonomic description of *Nv.*  
1779 1324 *pingdingshanensis* was based on 23 specimens from Beds 52 and 54-55 at West Pingdingshan  
1780 1325 (including the holotype from Bed 54) and Beds 61-64 at North Pingdingshan ([Zhao et al., 2007a](#)).  
1781 1326 *Nv. pingdingshanensis* is characterized by (1) four to nine robust, wide, and mostly fused  
1782 1327 denticles; (2) a straight basal margin in the lateral view; and (3) a large, broadly expanded oval  
1783 1328 to subrounded basal cavity that is upturned on the inner margin and flat to downturned on the  
1784 1329 outer margin. Later, additional criteria of *Nv. pingdingshanensis* were proposed by [Goudemand](#)  
1785 1329 [et al. \(2012\)](#), based on studies of conodont assemblages from the Nanpanjiang Basin in South  
1786 1330 China. In that study, the denticle axes of P1 elements of *Nv. pingdingshanensis* are distinctively  
1787 1331 curved in the posterior direction and consequently the two or three (wide) denticles anterior of  
1788 1332 the cusp are often conspicuously asymmetrical, the posterior edge of the free tip being much  
1789 1333 shorter than the anterior one. Moreover, [Goudemand et al. \(2012\)](#) showed the basal margin of  
1790 1334 the P1 element is not necessarily straight, but, contrary to the original diagnosis by [Zhao et al.](#)  
1791 1335 [\(2007a\)](#), may vary from substraight to slightly upturned posteriorly and, thus, cannot be used  
1792 1336 as a diagnostic feature.  
1793 1337

1794 1338 Apart from *Nv. pingdingshanensis*, other conodont species can assist with placement of  
1795 1339 the SSB. For example, the early Spathian *Icriospathodus crassatus*, which appears ~2 m above  
1796 1340 *Nv. pingdingshanensis* at Chaohu ([Zhao et al., 2007a](#); [Liang et al., 2011](#)), has been used as a  
1797 1341 marker for the SSB at Guandao ([Wang et al., 2005](#)) and in the western United States ([Orchard](#)  
1798 1342 [and Tozer, 1997](#)). *Ic. collinsoni* can also be another potentially useful indicator of an early  
1799 1343 Spathian age—it is found slightly above *Ic.?* *crassatus* at Guandao ([Wang et al., 2005](#)), within  
1800 1344 the *Columbites* beds in the western USA ([Orchard and Tozer, 1997](#)), and within the *Tirolites*  
1801 1345 sp. nov. beds in the An Chau Basin ([Komatsu et al., 2016](#)).  
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### 1803 1347 5.3. Constraints from carbon-isotope chemostratigraphy 1804 1348

1805 1349 When fossils are absent, carbonate carbon isotope records can be useful tools in global  
1806 1350 stratigraphic correlation because of the long residence time of dissolved inorganic carbon (DIC)  
1807 1351 in seawater. The Smithian-Spathian transition is characterized by a large positive shift in  $\delta^{13}\text{C}$   
1808 1352 (from the N3 minimum to the P3 maximum) that is globally correlatable and, hence, potentially  
1809 1353 useful as a proxy for the SSB. [Payne et al. \(2004\)](#) first reported from South China a positive  
1810 1354 excursion of  $\delta^{13}\text{C}_{\text{carb}}$  across the SSB, from N3 in the upper *Novispathodus waageni* Zone to P3  
1811 1355 in the lower *Nv. crassatus* Zone. Later, positive excursions of  $\delta^{13}\text{C}_{\text{carb}}$  or  $\delta^{13}\text{C}_{\text{org}}$  were reported  
1812 1356 from SSB sections globally (see [Section 4](#)), including a number of biostratigraphically well-  
1813 1357 studied sections in the eastern Tethyan region (e.g., [Galfeti et al., 2007b](#); [Tong et al., 2007](#);  
1814 1358 [Chen-YL et al., 2013](#); [Zhang et al., 2015](#); [Komatsu et al., 2016](#)).  
1815 1359

1816 1360 Most SSB sections exhibit a rapid shift from N3 to P3 (i.e., Interval II; see [Figs. 7, 11-13](#)).  
1817 1361 The early part of this shift occurred slowly in some sections (e.g.,  $\delta^{13}\text{C}$  Pattern 1), and it is  
1818 1362 unclear whether the point of onset is perfectly correlative at a global scale. For example, in  
1819 1363 sections on the North Indian Margin with well-constrained ammonoid zonations ([Fig. 12](#)), the  
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1833 1363 onset may be located in the middle Smithian. However, the bulk of the positive shift occurred  
1834 1364 rapidly, so both the midpoint of the shift ('mdpt(N3-P3)') and its termination (P3) in the early  
1835 1365 Spathian are likely to represent nearly synchronous datums globally. This is rather true even  
1836 1366 though the amplitude of the  $\delta^{13}\text{C}$  shift (in per mille units) within Interval II varies among  
1837 1367 different sections—variable amplitudes are merely the expression of local effects  
1838 1368 superimposed on the global N3-to-P3 carbon isotope excursion. Below, we evaluate the  
1839 1368 positions of N3, mdpt(N3-P3), and P3 relative to biostratigraphic constraints on placement of  
1840 1369 the SSB in order to assess the robustness of mdpt(N3-P3) as a potential proxy for the SSB  
1841 1370 (Figs. 7, 11-12) in the case of absence of biostratigraphic data.

1842 1371 Based on global ammonoid biostratigraphic constraints, N3 is generally located in the  
1843 1372 middle Smithian. Specifically, N3 in  $\delta^{13}\text{C}$  Pattern 1 is biostratigraphically well-constrained in  
1844 1373 the Salt Range and Surghar Ranges (within the *Pseudoceltites multiplicatus* beds; Hermann et  
1845 1373 al., 2012) and at Losar (between the *Nyalamites angustecostatus* beds and *Truempyceras*  
1846 1374 *compressum* beds; Galfetti et al., 2007c), and thus indicative of middle Smithian age (Fig. 12).  
1847 1375 Besides, the location of N3 within the upper part of the *Owenites koeneni* beds at Jinya ( $\delta^{13}\text{C}$   
1848 1376 Pattern 2; Galfetti et al., 2007c) and Mineral Mountains ( $\delta^{13}\text{C}$  Pattern 4; Thomazo et al., 2016)  
1849 1377 also yields similar age constraints (Figs. 7 and 11). Sections showing  $\delta^{13}\text{C}$  Pattern 3 are all  
1850 1378 located in the western Tethys, where biostratigraphic resolution is generally poorer (Figs. 12  
1851 1378 and 13B) and the position of N3 thus less well-constrained. Conodonts provide limited  
1852 1379 constraints on the timing of N3, which is roughly in the middle to upper part of the *Nv. waageni*  
1853 1380 Zone, the upper part of the *Ns. discreta* Zone, or the uppermost part of the *Pachycladina*  
1854 1381 *obliqua* Zone (Figs. 11-12).

1855 1382 The documented biostratigraphic constraints for P3 are often not as good as for N3, but  
1856 1382 an early Spathian age is inferred. Ammonoid biostratigraphy constrains P3 to above the  
1857 1383 uppermost AW and GXP Smithian assemblages (e.g., at Smith Creek, Grasby et al., 2013;  
1858 1383 Dicksonfjellet, Galfetti et al., 2007a; Mineral Mountains, Thomazo et al., 2016; Salt Range and  
1859 1385 Surghar Range, Hermann et al., 2012; and Tulong, Schneebeili-Hermann et al., 2012), and to  
1860 1386 just below or at the base of the lowermost Spathian *Tirolites* beds (e.g., Jinya, Galfetti et al.,  
1861 1387 2007c and Chaohu, Tong et al., 2004; Hot Springs, Caravaca et al., 2017). It should be noted  
1862 1388 that placement of P3 within the uppermost Smithian "*Xenoceltites variocostatus*" beds in the  
1863 1388 An Chau Basin is inconsistent with its placement in other localities globally (Komatsu et al.,  
1864 1389 2016; see Section 3.8.1 and 5.1). In the eastern Tethys, conodont biostratigraphy constrains the  
1865 1390 position of P3 to be above the first occurrences of *Nv. pingdingshanensis* (at Chaohu, Zhao et  
1866 1391 al., 2007a), *Ns. crassatus* (at Guandao, Lehrmann et al., 2015), and *Ic. collinsoni* (at Jiarong,  
1867 1392 Chen-YL et al., 2015), consistent with an early Spathian age.

1868 1393 In the eastern Tethys, evaluation of mdpt(N3-P3) as a potential proxy for the SSB is  
1869 1393 facilitated by the highly detailed ammonoid or/and conodont zonation schemes available for  
1870 1394 many sections (Fig. 11). In the majority of sections (6 of 8), mdpt(N3-P3) coincides rather well  
1871 1395 with the SSB within existing biostratigraphic constraints. Specifically, mdpt(N3-P3) is located  
1872 1396 at the first occurrences of the *Nv. pingdingshanensis* or *Nv. crassatus*, for example, at Chaohu,  
1873 1397 Guandao, Jiarong and Zuodeng sections. At Mingtang and Shitouzhai, conodont zonations for  
1874 1398 the lowermost Spathian are lacking, but the SSB was initially constrained as being close to  
1875 1399 mdpt(N3-P3) through carbon isotope correlations in South China. At Jinya, the SSB was placed  
1876 1399 immediately below the *Tirolitid* n. gen. A. beds, ~2-3 m above the last occurrences of

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1892 1407 *Anasibirites* and *Xenoceltites* specimens in the underlying beds. A placement of the SSB based  
1893 1408 on mdpt(N3-P3) corresponds well to ammonoid biostratigraphic constraints at Jinya and would  
1894 1409 fall into the stratigraphic interval in between the *Anasibirites* beds and the Tirolitid n. gen. A.  
1895 1410 In the An Chau Basin, the SSB was constrained to between the *Xenoceltites* and *Tirolites* beds,  
1896 1411 but the lower constraint is biostratigraphically questionable as discussed above (see [Sections](#)  
1897 1412 [3.8.1](#) and [5.1](#)).

1898 1413 In the southern Tethyan region, the Smithian and the SSB is better constrained  
1900 1414 biostratigraphically, e.g., at Salt and Sughar Ranges ([Hermann et al., 2012](#)), Losar ([Galfetti et](#)  
1901 1415 [al., 2007c](#)) and Tulong ([Brühwiler et al., 2009](#)), than western Tethyan region which is mainly  
1902 1416 based on carbon isotope correlations ([Fig. 12](#)), e.g., L'Uomo ([Horacek et al., 2007a](#)),  
1903 1417 Lungenfrischgraben and Trudener Bach ([Horacek et al., 2010](#)), Zal, Amol and Abadeh  
1904 1418 ([Horacek et al., 2007b](#)), and Musandam ([Clarkson et al., 2013](#)). In the Salt and Sughar Ranges,  
1906 1419 Tulong, and Losar, the SSB is close to P3 and above the mdpt(N3-P3). At Amol and Abadeh,  
1907 1420 the SSB was placed close to P3; at L'Uomo, Zal and Musandam, the SSB was placed below  
1908 1421 the mdpt(N3-P3) ([Fig. 12](#)). The SSB was not defined in the Lungenfrischgraben and Trudener  
1909 1422 Bach sections ([Horacek et al., 2010](#)). Thus, in these areas, small regional inconsistencies in  
1910 1423 placement of the SSB compare to the mdpt(N3-P3) can be noticed and highlight the influences  
1912 1424 of local conditions on the observed signal. However, mdpt(N3-P3) is most of time located not  
1913 1425 far from the SSB defined by biostratigraphic markers.

1914 1426 In the Boreal and eastern and central Panthalassic regions, ammonoid biostratigraphic data  
1915 1427 for the SSB interval are variable in terms of temporal resolution and quantity among basins  
1916 1428 ([Fig. 7](#)). For example, ammonoid biozonation of the late Smithian and early Spathian is  
1918 1429 available in Spitsbergen ([Weitschat and Dagys, 1989](#)), whereas only late Smithian ammonoid  
1919 1430 beds are known so far from the Canadian Arctic ([Tozer, 1967](#)). Thus, adequate biostratigraphic  
1920 1431 data allowing for constraining the SSB placement are available only in a few sections, leading  
1921 1432 to variable uncertainties in placements of the SSB when compared to mdpt(N3-P3) or P3. In  
1922 1433 these regions, carbon-isotope correlations were used in some sections for placement of the SSB,  
1924 1434 but the  $\delta^{13}\text{C}$  datum chosen was not consistent among different studies. For example, [Grasby et](#)  
1925 1435 [al. \(2013\)](#) placed the SSB at P3 in Smith Creek, [Grasby et al. \(2016\)](#) placed it at N3 in  
1926 1436 Festningen, [Galfetti et al. \(2007a\)](#) placed it near mdpt(N3-P3) in Dicksonfjellet (just above late  
1927 1437 Smithian *Anawasatchites tardus* beds), and [Wignall et al. \(2016\)](#) placed it between N3 and  
1928 1438 mdpt(N3-P3) in Vindodden. In the Mineral Mountains [Thomazo et al. \(2016\)](#) placed it near  
1930 1439 what it is mdpt(N3-P3), this one being located at the top of the late Smithian GXP assemblage.  
1931 1440 [Sakuma et al. \(2012\)](#) placed the SSB between mdpt(N3-P3) and P3 in Inuyama ([Fig. 7](#)).

1932 1441 To sum up, there is a rather good correspondence of mdpt(N3-P3) to known  
1933 1442 biostratigraphic constraints on the SSB although some regional to local influences can  
1934 1443 modulate this inference. An approximate placement of the SSB based at least partly on carbon  
1936 1444 isotope chemostratigraphy thus can help to systematize SSB placement and avoid too important  
1937 1445 miscorrelations related to inadequate biostratigraphic records (e.g., [Figs. 7 and 12](#)).  
1938 1446 Stratigraphic boundaries are not customarily based on chemostratigraphic records, but, based  
1939 1447 on present-day data, the use of mdpt(N3-P3) can be an auxiliary criterion to locate the SSB.

1941 1448 Obviously, the use of  $\delta^{13}\text{C}$  records for correlation or auxiliary definition of the SSB should  
1942 1449 be preceded by an evaluation of stratigraphic hiatuses and facies changes in the sections under  
1943 1450 investigation. The  $\delta^{13}\text{C}$  records of most SSB sections in South China are considered to be  
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1951 1451 stratigraphically continuous, including Chaohu (Tong et al., 2007), Jiarong (Chen-YL et al.,  
1952 1452 2015), and Shitouzhai (Zhang et al., 2015). In contrast, stratigraphic incompleteness is  
1953 1453 indicated by the  $\delta^{13}\text{C}$  records of the SSB sections at for instance Zal, Abadeh, and Amol in  
1954 1454 Iran, where abrupt  $\delta^{13}\text{C}$  shifts are associated with faults or regressive systems tracts (Horacek  
1955 1455 et al., 2007b) and at Kamura, Japan, which is characterized by a major biostratigraphically  
1956 1456 defined gap in the Spathian (Zhang et al., 2017). Moreover, the stratigraphic completeness of  
1957 1457 the Smith Creek section through the SSB transition interval is uncertain owing to a large (to ~4  
1959 1458 %), abrupt positive shift in  $\delta^{13}\text{C}_{\text{carb}}$  and a concurrent facies change from siliciclastic to  
1960 1459 carbonate sediments (Grasby et al., 2013). So far, no obvious stratigraphic hiatus was reported  
1961 1460 at the SSB transition in the western Tethys or localities in the Boreal and eastern Panthalassic  
1962 1461 realms, but it remains a possibility in a context of global regression.  
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#### 1965 1463 5.4. Placement of the Smithian/Spathian boundary in earlier studies

1966 1464  
1967 1465 To date, biostratigraphic studies of the SSB are especially well documented in the eastern  
1968 1466 (e.g., South China) and southern (e.g., Salt Range) Tethys. These provide a first basis for  
1969 1466 investigation of the relationships between ammonoid zonations, conodont zonations, and  
1970 1467 carbon isotope excursions through the SSB transition. Such relationships could also be used in  
1971 1468 boundary definitions especially in localities where biostratigraphic data are lacking.

1972 1469 Despite these existing high-resolution biostratigraphic studies, placement of the SSB is  
1973 1470 still inconsistent in some sections within these areas. For example, in the An Chau Basin,  
1974 1471 Komatsu et al. (2016) placed the SSB at the base of the *Tirolites* cf. *cassianus* beds (see  
1975 1472 discussion of biostratigraphic data in Section 3.8.1), which are stratigraphically above the P3  
1977 1473 carbon-isotope maximum. This placement is inconsistent with other sections worldwide, in  
1978 1474 which the SSB lies close to the mdpt(N3-P3) or below P3 (Fig. 11). The underlying problem  
1979 1475 here appears to have been the potentially doubtful attribution by Komatsu et al. (2016) of some  
1980 1476 poorly preserved ammonoid specimens to *Xenoceltites variocostatus*, which is usually  
1981 1476 considered as a marker for the late Smithian (see Section 3.8.1). Thus, more work is needed at  
1982 1477 this section to confirm the placement of the SSB, which probably is actually located between  
1983 1478 mdpt(N3-P3) and P3.

1984 1479 In the western Tethys, limited biostratigraphic data resulted in the SSB being identified  
1985 1480 mainly on the basis of carbon-isotope correlations, but (as noted in Section 5.3) there has been  
1986 1481 no consistent placement of the SSB within the  $\delta^{13}\text{C}$  chemostratigraphic framework of the Early  
1987 1482 Triassic (Fig. 12), creating the potential for global miscorrelations and misinterpretations of  
1988 1483 paleoceanographic signals. In the southern Tethys, the SSB was placed close to P3 at Salt and  
1989 1483 Surghar Ranges (Hermann et al., 2012), and Tulong (Brühwiler et al., 2009) and mdpt(N3-P3)  
1990 1484 falls in characteristic late Smithian ammonoid assemblages (Fig. 12). Compared to mdpt(N3-  
1991 1485 P3), this SSB placement is thus slightly higher stratigraphically than that favored for the eastern  
1992 1486 Tethys, but well highlight the differential local environmental and/or diagenetic conditions  
1993 1486 influencing the  $\delta^{13}\text{C}$  signal.

1994 1487 The biostratigraphy of the SSB transition in the Boreal realm is more poorly constrained  
1995 1488 owing to e.g., scarce fossil occurrences. Thus, carbon isotope excursions can be used to  
1996 1489 constrain the location of the SSB. We suggest placement of the SSB at mdpt(N3-P3), which is  
1997 1490 at or just above the top of the *Anawasatchites tardus* beds (or GXP assemblage if found) and  
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2010 1495 just below P3. In the Mineral Mountains, western USA, the SSB was placed at the top of the  
2011 1496 *Xenoceltitidae* 'gen. indet.' A. beds and fits rather well with the mdpt(N3-P3).  
2012 1497

### 2013 1498 5.5. Relationship to the Smithian Thermal Maximum 2014 1499

2015 1500 The lack of a formal definition for the SSB has resulted in inconsistent placements of the  
2016 1501 SSB in different published studies, with differences sometimes as large as one or two full  
2018 1502 ammonoid zones. This is particularly problematic for studies attempting to evaluate  
2019 1503 environmental or oceanographic changes accompanying the Smithian-Spathian transition,  
2020 1504 because incorrect placement of the SSB can result in incorrect conclusions concerning the  
2021 1505 timing and causes of such changes.

2022 1506 These problems are illustrated by the Sun et al. (2012) study, which proposed an Early  
2024 1507 Triassic tropical sea surface temperature (SST) profile based on conodont oxygen-isotope data  
2025 1508 measured in multiple sections (Jiarong, Jinya, Guandao, Zuodeng, and Bianyang) in the  
2026 1509 Nanpanjiang Basin of southwestern China. This study inferred a thermal maximum extending  
2027 1510 from the late Smithian to the earliest Spathian (i.e., spanning the SSB), followed by a cooling  
2028 1511 event later in the early Spathian (Fig. 16A). They concluded that the late Smithian extinction  
2030 1512 and associated oceanographic changes were the result of hyperthermy, although this conclusion  
2031 1513 is likely erroneous (Goudemand et al., 2013, 2018). A fundamental problem in the Sun et al.  
2032 1514 (2012) study is that the SSB, which was putatively based on the first occurrence of *Nv.*  
2033 1515 *pingdingshanensis*, is positioned close to the N3 carbon-isotope minimum. For example, at  
2034 1516 Jiarong, Sun et al. (2012) placed the SSB close to N3, corresponding to a  $\delta^{13}\text{C}_{\text{carb}}$  value of  $< -1$   
2036 1517 ‰, which is lower than the  $\sim 0$  ‰ for the SSB reported by Chen-YL et al. (2013). Furthermore,  
2037 1518 the placement of the SSB based on the FAD of *Nv. pingdingshanensis* in Sun et al. (2012) is  
2038 1519 stratigraphically lower than that of Chen-YL et al. (2013) based on the same criterion, and also  
2039 1520 lower than that of Chen-YL et al. (2015) (see Section 3.7). At Zuodeng, Sun et al. (2012) placed  
2040 1521 the SSB at a  $\delta^{13}\text{C}_{\text{carb}}$  value of  $\sim 0$  ‰, which is lower than the  $+2$  ‰ for the SSB reported by  
2042 1522 Tong et al. (2007). The same inconsistency also occurs at Jinya, where  $\delta^{13}\text{C}_{\text{carb}}$  at the SSB is  $\sim$   
2043 1523  $-2$  ‰ in Sun et al. (2012) but  $\sim +2$  ‰ in Galfetti et al. (2007c). Thus, systematic misplacement  
2044 1524 of the SSB (e.g., based on the first occurrence of *Nv. pingdingshanensis*) in multiple sections  
2045 1525 is one of the underlying causes of the erroneous conclusion concerning the timing of the  
2046 1526 Smithian Thermal Maximum in Sun et al. (2012).

2048 1527 Inconsistent placement of the SSB has thus resulted in different interpretations of  
2049 1528 Smithian-Spathian transition events (see Sun et al., 2012, 2013; Romano et al., 2013;  
2050 1529 Goudemand et al., 2013, 2018). Goudemand et al. (2013) recompiled a subset of  $\delta^{13}\text{C}$  and  
2051 1530  $\delta^{18}\text{O}_{\text{conodont}}$  data, originally from Sun et al. (2012), based on ammonoid biostratigraphic control  
2052 1531 (Fig. 16B) constraining the SSB to between the *Anasibirites* and *Tirolitid* beds, corresponding  
2054 1532 to the *Nv. pingdingshanensis* Zone (i.e., between the first occurrences of *Nv. pingdingshanensis*  
2055 1533 and *Ic. collinsoni*). Goudemand (2014b) updated the calibration between  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}_{\text{conodont}}$   
2056 1534 based on conodont zonations and absolute ages, and his placement of the SSB is close to the  
2057 1535 mdpt(N3-P3), below P3 (Fig. 13; see also Goudemand et al., 2018). Based on his work and the  
2058 1536 stratigraphic framework of the present study, the Smithian Thermal Maximum (herein named)  
2059 1537 peaked in the middle Smithian, around the N3 carbon-isotope minimum, rather than close to  
2060 1538 the SSB as shown in Sun et al. (2012) (see discussion in Goudemand et al. 2013, 2018 and  
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2069 1539 Goudemand, 2014b). The SSB transition proper was characterized by a cooling trend rather  
2070 1540 than by hyperwarming (Fig. 16).

2071 1541 Regardless of which fossil group is used in definition of the SSB, the N3-to-P3 positive  
2072 1542  $\delta^{13}\text{C}$  excursion is a good proxy for placement of the SSB. Therefore,  $\delta^{13}\text{C}$  chemostratigraphy  
2073 1543 can play an important role in the formal definition of the SSB. Re-evaluation of the timing of  
2074 1544 onset of the Smithian Thermal Maximum will help our understanding of the environmental and  
2075 1545 biotic changes across the SSB and more broadly during the Early Triassic recovery.  
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## 2078 1547 **6. Conclusions**

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2080 1549 This contribution reviewed the history and present status of global ammonoid and  
2081 1550 conodont biostratigraphic research on the Smithian and Spathian substages, coeval  
2082 1550 chemostratigraphic records of  $\delta^{13}\text{C}$ ,  $\Delta\delta^{13}\text{C}_{\text{DIC}}$ ,  $\delta^{34}\text{S}_{\text{CAS}}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$ , and their relationships to  
2083 1551 climate change during the Smithian-Spathian transition.  
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2085 1553 The Smithian/Spathian boundary (SSB) potentially can be defined on the basis of  
2086 1554 ammonoid or conodont data. Ammonoid faunas show a pronounced transition from late  
2087 1554 Smithian forms belonging to e.g., the genera *Wasatchites*, *Anasibirites*, *Glyptopliceras* and  
2088 1555 *Xenoceltites* to early Spathian forms belonging to e.g., *Bajarunia*, *Tirolites* and *Columbites*.  
2089 1556 The future definition of the SSB should be guided by existing ammonoid-based biostratigraphic  
2090 1557 constraints. Specifically, it should fall between strata containing late Smithian forms belonging  
2091 1558 to the AW and GXP assemblages and strata containing early Spathian forms belonging to the  
2092 1559 genera *Bajarunia*, *Doricranites*, and/or *Tirolites*. Conodont faunas change across this divide  
2093 1560 from late Smithian forms such as *Scythogondolella milleri*, *Borinella buurensis* and *Foliella*  
2094 1560 *gardenae* to early Spathian forms such as ‘*Triassospathodus*’ *hungaricus*, *Neogondolella* aff.  
2095 1561 *sweeti*, *Icriospathodus* spp., and *Novispathodus brevissimus*. The first appearance of  
2096 1562 *Novispathodus pingdingshanensis*, which has been proposed as a marker for the SSB, occurs  
2097 1563 in several places with both ammonoids (*Xenoceltites*) and conodonts (*Sc. milleri*) regarded as  
2098 1564 traditionally of late Smithian age. The ranges of these various taxa, as well as that of other  
2099 1564 conodonts with potential for definition of the SSB, requires more work.  
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2103 1568 Carbonate carbon-isotopes ( $\delta^{13}\text{C}_{\text{carb}}$ ) change rapidly through the Smithian-Spathian  
2104 1569 transition interval, from the middle Smithian N3 minimum to the early Spathian P3 maximum,  
2105 1569 providing potential isotopic markers that could be linked to a biostratigraphically defined SSB.  
2106 1570 In particular, the isotopic midpoint of the N3-to-P3 shift (herein termed ‘mdpt(N3-P3)’) is  
2107 1571 generally close to the level of the SSB based on biostratigraphic constraints and may serve as  
2108 1572 an auxiliary definition of the boundary. A test of the utility of the mdpt(N3-P3) marker as a  
2109 1573 proxy for the SSB based on biostratigraphically well-studied SSB sections shows that  
2110 1574 mdpt(N3-P3) is generally within 2 m of the accepted position of the SSB, especially for  
2111 1575 sections in the Tethys region. It should be noted that the actual  $\delta^{13}\text{C}$  value of mdpt(N3-P3) is  
2112 1575 site-specific, depending on water-depth and other local environmental factors.  
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2115 1578 Stratigraphic relationships among ammonoids, conodonts, and carbon isotope excursions  
2116 1579 show that the Smithian Thermal Maximum (herein named) was approximately synchronous  
2117 1579 with the N3 carbon-isotope minimum and, thus, of middle Smithian age. The  
2118 1580 Smithian/Spathian boundary proper coincided with a pronounced relative cooling event.  
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## References

- Algeo, T.J., Twitchett, R.J., 2010. Anomalous Early Triassic sediment fluxes due to elevated weathering rates and their biological consequences. *Geology* 38, 1023-1026.
- Algeo, T.J., Hinnov, L., Moser, J., Maynard, J.B., Elswick, E., Kuwahara, K., Sano, H., 2010. Changes in productivity and redox conditions in the Panthalassic Ocean during the latest Permian. *Geology* 38, 187-190.
- Algeo, T.J., Chen, Z.Q., Fraiser, M.L., Twitchett, R.J., 2011. Terrestrial-marine teleconnections in the collapse and rebuilding of Early Triassic marine ecosystems. *Palaeogeography, Palaeoclimatology, Palaeoecology* 308, 1-11.
- Algeo, T.J., Luo, G.M., Song, H.Y., Lyons, T.W., Canfield, D.E., 2015. Reconstruction of secular variation in seawater sulfate concentrations. *Biogeosciences* 12(7), 2131-2151.
- Aljinović, D., Kolar-Jurkovšek, T., Jurkovšek, B., 2006. The Lower Triassic shallow marine succession in Gorski Kotar region (External Dinarides, Croatia): lithofacies and conodont dating. *Rivista Italiana di Paleontologia e Stratigrafia* 112, 35-53.
- Aljinović, D., Kolar-Jurkovšek, T., Jurkovšek, B., Hrvatović, H., 2011. Conodont dating of the Lower Triassic sedimentary rocks in the external Dinarides (Croatia and Bosnia and Herzegovina). *Rivista Italiana di Paleontologia e Stratigrafia* 117, 135-148.
- Aljinović, D., Horacek, M., Krystyn, L., Richoz, S., Kolar-Jurkovšek, T., Smirčić, D., Jurkovšek B., 2018. Western Tethyan epeiric ramp setting in Early Triassic – an example from the central Dinarides (Croatia). *Journal of Earth Sciences (China University of Geosciences-Wuhan)* 29, 806-823.
- Assereto, R., Bosellini, A., Fantini Sestini, N., Sweet, W.C., 1973. The Permian–Triassic boundary in the southern Alps (Italy). In: Logan, A., Hill, L.V. (Eds.), *Permian and Triassic Systems and Their Mutual Boundary*. Canadian Society of Petroleum Geologists Memoir 2, pp. 176-199.
- Atudorei, V., 1999. Constraints on the Upper Permian to Upper Triassic marine carbon isotope curve. Case studies from the Tethys. Ph.D., University of Lausanne, Switzerland, 161 pp.
- Bagherpour, B., Bucher, H., Baud, A., Brosse, M., Venneman, T., Martini, R., Kuang, G., 2017. Onset, development, and cessation of basal Early Triassic microbialites (BETM) in the Nanpanjiang pull-apart Basin, South China Block. *Gondwana Research* 44, 178-204.

2184  
2185  
2186  
2187 1627 Balini, M., Gavrilova, V.A., Nicora, A., 2000. Biostratigraphical revision of the classic Lower  
2188 1628 Triassic Dolnapa section (Mangyshlak, West Kazakhstan). Zentralblatt für Geologie und  
2189 1629 Paläontologie, Teil I 11-12, 1441-1462.

2190 1630 Balini, M., Nicora, A., Berra, F., Garzanti, E., Levera, M., Mattei, M., Muttoni, G., Zanchi, A.,  
2191 1631 Bollati, I., Larghi, C., Zanchetta, S., Salamati, R., Mossavvari, F., 2009. The Triassic  
2192 1632 stratigraphic succession of Nakhlak (Central Iran), a record from an active margin. In:  
2193 1633 Brunet, M.-F., Wilmsen, M., Granath, J.W. (Eds.), South Caspian to Central Iran Basins,  
2194 1634 Geological Society of London Special Publication 312, pp. 287-321.

2195 1634  
2196 1635 Balini, M., Lucas, S.G., Jenks, J.F., Spielmann, J.A., 2010. Triassic ammonoid biostratigraphy:  
2197 1636 an overview. In: Lucas, S.G. (Ed.), The Triassic Timescale, Geological Society of London  
2198 1637 Special Publication 334, pp. 221-262.

2200 1638 Baresel, B., Bucher, H., Brosse, M., Cordey, F., Guodun, K., Schaltegger, U., 2017. Precise  
2201 1639 age for the Permian–Triassic boundary in South China from high-precision U-Pb  
2202 1640 geochronology and Bayesian age–depth modeling. Solid Earth 8(2), 361-378.

2203 1641 Baud, A., Magaritz, M., Holser, W.T., 1989. Permian–Triassic of the Tethys: carbon isotope  
2204 1642 studies. Geologische Rundschau 78, 649-677.

2205 1642  
2206 1643 Baud, A., Atudorei, V., Sharp, Z.D., 1996. Late Permian and Early Triassic evolution of the  
2207 1644 Northern Indian margin: carbon isotope and sequence stratigraphy. Geodinamica Acta 9,  
2208 1645 57-77.

2209 1646 Bernasconi, S.M., Meier, I., Wohlwend, S., Brack, P., Hochuli, P.A., Hansruedi Bläsi,  
2210 1647 Wortmann, U.G., Ramseyer, K., 2017. An evaporite-based high-resolution sulfur isotope  
2211 1648 record of late Permian and Triassic seawater sulfate. Geochimica et Cosmochimica Acta,  
2212 1649 204, 331-349.

2213 1649  
2214 1650 Bhatt, D.K., Joshi, V.K., Arora, R.K., 1999. Conodont biostratigraphy of the Lower Triassic in  
2215 1651 Spiti Himalaya, India. Journal of the Geological Society of India 54, 153-167.

2216 1651  
2217 1652 Bottjer, D.J., Clapham, M.E., Fraiser, M.L., Powers, C.M., 2008. Understanding mechanisms  
2218 1653 for the end-Permian mass extinction and the protracted Early Triassic aftermath and  
2219 1654 recovery. GSA Today 18, 4-10.

2220 1655 Brayard, A., Bucher, H., 2008. Smithian (Early Triassic) ammonoid faunas from northwestern  
2221 1656 Guangxi (South China): taxonomy and biochronology. Fossils and Strata 55, 179 pp.

2222 1656  
2223 1657 Brayard, A., Bucher, H., 2015. Permian-Triassic extinctions and rediversifications. In: Klug,  
2224 1658 C., Korn, D., De Baets, K., Kruta, I., Mapes, R.H. (Eds.), Ammonoid Paleobiology: From  
2225 1659 Macroevolution to Paleogeography. Springer, Dordrecht, pp. 465-473.

2226 1660 Brayard, A., Bucher, H., Escarguel, G., Fluteau, F., Bourquin, S., Galfetti, T., 2006. The Early  
2227 1661 Triassic ammonoid recovery: Paleoclimatic significance of diversity gradients.  
2228 1662 Palaeogeography, Palaeoclimatology, Palaeoecology 239, 374-395.

2229 1662  
2230 1663 Brayard, A., Escarguel, G., Bucher, H., 2007a. The biogeography of Early Triassic ammonoid  
2231 1664 faunas: clusters, gradients, and networks. Geobios 40, 749-765.

2232 1665 Brayard, A., Bucher, H., Brühwiler, T., Galfetti, T., Goumand, N., Guodun, K., Escarguel,  
2233 1666 G., Jenks, J., 2007b. *Proharpoceras* Chao: a new ammonoid lineage surviving the end-  
2234 1667 Permian mass extinction. Lethaia 40, 175-181.

2235 1667  
2236 1668 Brayard, A., Escarguel, G., Bucher, H., Brühwiler, T., 2009a. Smithian and Spathian (Early  
2237 1669 Triassic) ammonoid assemblages from terranes: Paleooceanographic and paleogeographic  
2238 1670 implications. Journal of Asian Earth Sciences 36, 420-433.

2239  
2240  
2241  
2242

2243  
2244  
2245  
2246 1671 Brayard, A., Escarguel, G., Bucher, H., Monnet, C., Brühwiler, T., Goudemand, N., Galfetti,  
2247 1672 T., Guex, J., 2009b. Good genes and good luck: ammonoid diversity and the end-Permian  
2248 1673 mass extinction. *Science* 325, 1118-1121.

2249 1674 Brayard, A., Brühwiler, T., Bucher, H., Jenks, J., 2009c. *Guodunites*, a low-palaeolatitude and  
2250 1675 trans-Panthalassic Smithian (Early Triassic) ammonoid genus. *Palaeontology* 52, 471-481.

2251 1676 Brayard, A., Vennin, E., Olivier, N., Bylund, K.G., Jenks, J., Stephen, D.A., Bucher, H.,  
2252 1677 Hofmann, R., Goudemand, N., Escarguel, G., 2011. Transient metazoan reefs in the  
2253 1678 aftermath of the end-Permian mass extinction. *Nature Geoscience* 4, 693-697.

2254 1678  
2255 1679 Brayard, A., Bylund, K.G., Jenks, J.F., Stephen, D.A., Olivier, N., Escarguel, G., Fara, E.,  
2256 1680 Vennin, E., 2013. Smithian ammonoid faunas from Utah: implications for Early Triassic  
2257 1681 biostratigraphy, correlation and basinal paleogeography. *Swiss Journal of Palaeontology*  
2258 1682 132, 141-219.

2260 1683 Brayard, A., Krumenacker, L. J., Botting, J. P., Jenks, J. F., Bylund, K. G., Fara, E., Vennin,  
2261 1684 E., Olivier, N., Goudemand, N., Saucède, T., Charbonnier, S., Romano, C., Doguzhaeva,  
2262 1685 L., Thuy, B., Hautmann, M., Stephen, D.A., Thomazo, C., Escarguel, G., 2017.  
2263 1686 Unexpected Early Triassic marine ecosystem and the rise of the Modern evolutionary  
2264 1687 fauna. *Science Advances*, 3 (e1602159), 1-11.

2266 1688 Brayard, A., Jenks, J.F., Bylund, K.G., and the Paris Biota team, 2019. Ammonoids and  
2267 1689 nautiloids from the earliest Spathian Paris Biota and other early Spathian localities in  
2268 1690 southeastern Idaho. *Geobios*, in press.

2269 1690  
2270 1691 Brosse, M., Brayard, A., Fara, E., Neige, P., 2013. Ammonoid recovery after the Permian–  
2271 1692 Triassic mass extinction: a re-exploration of morphological and phylogenetic diversity  
2272 1693 patterns. *Journal of the Geological Society of London* 170, 225-236.

2273 1694 Brühwiler, T., Bucher, H., Goudemand, N., Brayard, A., 2007. Smithian (Early Triassic)  
2274 1695 ammonoid successions of the Tethys: new preliminary results from Tibet, India, Pakistan  
2275 1696 and Oman. *The Global Triassic Bulletin* 41, 25-26.

2276 1696  
2277 1697 Brühwiler, T., Goudemand, N., Galfetti, T., Bucher, H., Baud, A., Ware, D., Hermann, E.,  
2278 1698 Hochuli, P.A., Martini, R., 2009. The Lower Triassic sedimentary and carbon isotope  
2279 1699 records from Tulong (South Tibet) and their significance for Tethyan palaeoceanography.  
2280 1700 *Sedimentary Geology* 222, 314-332.

2281 1701 Brühwiler, T., Ware, D., Bucher, H., Krystyn, L., Goudemand, N., 2010a. New early Triassic  
2282 1702 ammonoid faunas from the Dienerian/Smithian boundary beds at the Induan/Olenekian  
2283 1703 GSSP candidate at Mud (Spiti, Northern India). *Journal of Asian Earth Sciences* 39, 724-  
2284 1704 739.

2285 1704  
2286 1705 Brühwiler, T., Bucher, H., Goudemand, N., 2010b. Smithian (Early Triassic) ammonoids from  
2287 1706 Tulong, South Tibet. *Geobios* 43, 403-431.

2288 1706  
2289 1707 Brühwiler, T., Bucher, H., Brayard, A., Goudemand, N., 2010c. High-resolution biochronology  
2290 1708 and diversity dynamics of the Early Triassic ammonoid recovery: the Smithian faunas of  
2291 1709 the Northern Indian Margin. *Palaeogeography, Palaeoclimatology, Palaeoecology* 297,  
2292 1710 491-501.

2293 1711 Brühwiler, T., Bucher, H., Roohi, G., Yaseen, A., Rehman, K., 2011. A new early Smithian  
2294 1712 ammonoid fauna from the Salt Range (Pakistan). *Swiss Journal of Palaeontology* 130,  
2295 1713 187-201.

2296 1713  
2297 1714 Brühwiler, T., Bucher, H., Ware, D., Schneebeli-Hermann, E., Hochuli, P.A., Roohi, G.,  
2298  
2299  
2300  
2301



2302  
2303  
2304 1715 Rehman, K., Yaseen, A., 2012a. Smithian (Early Triassic) ammonoids from the Salt  
2305 1716 Range, Pakistan. *Special Papers in Palaeontology* 88, 1-114.  
2307 1717 Brühwiler, T., Bucher, H., Ware, D., Krystyn, L., 2012b. Middle and late Smithian (Early  
2308 1718 Triassic) ammonoids from Spiti, India. *Special Papers in Palaeontology* 88, 115-174.  
2309 1719 Brühwiler, T., Bucher, H., Goudemand, N., Galfetti, T., 2012c. Smithian (Early Triassic)  
2310 1720 ammonoid faunas from Exotic Blocks from Oman: taxonomy and biochronology.  
2311 1721 *Palaeontographica Abteilung A* 296, 3-107.  
2313 1722 Buchan, S.H., Challinor, A., Harland, W.B., Parker, J.R., 1965. The Triassic stratigraphy of  
2314 1723 Svalbard. *Norsk Polarinstitutts Skrifter* 135, 91 pp.  
2315 1724 Burgess, S.D., Bowring, S., Shen, S.Z., 2014. High-precision timeline for Earth's most severe  
2316 1725 extinction. *Proceedings of the National Academy of Sciences (U.S.A.)* 111, 3316-3321.  
2317 1725 Caravaca, G., Thomazo, C., Vennin, E., Olivier, N., Cocquerez, T., Escarguel, G., Fara, E.,  
2318 1726 Jenks, J.F., Bylund, K.G., Stephen, D.A., Brayard, A., 2017. Early Triassic fluctuations  
2319 1727 of the global carbon cycle: New evidence from paired carbon isotopes in the western USA  
2320 1728 basin. *Global and Planetary Change* 154, 10-22.  
2321 1729 Caravaca, G., Brayard, A., Vennin, E., Guiraud, M., Le Pourhiet, L., Grosjean, A.S., Thomazo,  
2322 1730 C., Olivier, N., Fara, E., Escarguel, G., Bylund, K.G., 2018. Controlling factors for  
2323 1731 differential subsidence in the Sonoma Foreland Basin (Early Triassic, western  
2324 1732 USA). *Geological Magazine* 155(6), 1305-1329.  
2325 1732 Cavin, L., Gradinaru, E., 2014. *Dobrogeria aegyssensis*, a new early Spathian (Early Triassic)  
2326 1733 coelacanth from North Dobrogea (Romania). *Acta Geologica Polonica* 64, 161-187.  
2327 1734 Chen, J.B., Algeo, T.J., Zhao, L.S., Chen, Z.Q., Cao, L., Zhang, L., Li, Y., 2015. Diagenetic  
2328 1735 uptake of rare earth elements by bioapatite, with an example from Lower Triassic  
2329 1736 conodonts of South China. *Earth-Science Reviews* 149, 181-202.  
2330 1737 Chen, Y.L., Twitchett, R.J., Jiang, H.S., Richoz, S., Lai, X.L., Yan, C.B., Sun, Y.D., Liu, X.D.,  
2331 1738 Wang, L., 2013. Size variation of conodonts during the Smithian-Spathian (Early Triassic)  
2332 1739 global warming event. *Geology* 41, 823-826.  
2333 1740 Chen, Y.L., Jiang, H.S., Lai, X.L., Yan, C.B., Richoz, S., Liu, X.D., Wang, L.N., 2015. Early  
2334 1741 Triassic conodonts of Jiarong, Nanpanjiang Basin, southern Guizhou Province, South  
2335 1742 China. *Journal of Asian Earth Sciences* 105, 104-121.  
2336 1743 Chen, Y.L., Kolar-Jurkovšek, T., Jurkovšek, B., Aljinović, D., Richoz, S., 2016. Early Triassic  
2337 1744 conodonts and carbonate carbon isotope record of the Idrija-Žiri area, Slovenia.  
2338 1745 *Palaeogeography Palaeoclimatology Palaeoecology* 444, 84-100.  
2339 1746 Chen, Z.Q., Benton, M.J., 2012. The timing and pattern of biotic recovery following the end-  
2340 1747 Permian mass extinction. *Nature Geoscience* 5, 375-383.  
2341 1748 Chen, Z.Q., Tong, J.N., Liao, Z.T., Chen, J., 2010. Structural changes of marine communities  
2342 1749 over the Permian–Triassic transition: ecologically assessing the end-Permian mass  
2343 1750 extinction and its aftermath. *Global and Planetary Change* 73, 123-140.  
2344 1751 Chen, Z.Q., Tong, J.N., Fraiser, M.L., 2011. Trace fossil evidence for restoration of marine  
2345 1752 ecosystems following the end-Permian mass extinction in the Lower Yangtze region,  
2346 1753 South China. *Palaeogeography, Palaeoclimatology, Palaeoecology* 299, 449-474.  
2347 1754 Clark, D.L., Hatleberg, E.W., 1983. Paleoenvironmental factors and the distribution of  
2348 1755 conodonts in the Lower Triassic of Svalbard and Nepal. *Fossils and Strata* 15, 171-175.  
2349 1756 Clarkson, M., Kasemann, S., Wood, R., Lenton, T., Daines, S., Richoz, S., Ohnemüller, F.,  
2350 1757  
2351 1758  
2352  
2353  
2354  
2355  
2356  
2357  
2358  
2359  
2360

2361  
2362  
2363 1759 Meixner, A., Poulton, S., Tipper, E., 2015. Ocean acidification and the Permo-Triassic  
2364 1760 mass extinction. *Science* 348, 229-232.  
2366 1761 Clarkson, M.O., Richoz, S., Wood, R.A., Maurer, F., Krystyn, L., Mcgurty, D.J., Astratti, D.,  
2367 1762 2013. A new high-resolution  $\delta^{13}\text{C}$  record for the Early Triassic: Insights from the Arabian  
2368 1763 Platform. *Gondwana Research* 24, 233-242.  
2369 1764 Clarkson, M.O., Wood, R.A., Poulton, S.W., Richoz, S., Newton, R.J., Kasemann, S.A.,  
2370 1765 Bowyer, F., Krystyn, L., 2016. Dynamic anoxic ferruginous conditions during the end-  
2372 1766 Permian mass extinction and recovery. *Nature Communications* 7, 12236.  
2373 1767 Crasquin, S., Sudar, M.N., Jovanović, D., Kolarjurkovšek T., 2010. Upper Permian ostracode  
2374 1768 assemblage from the Jadar Block (Vardar Zone, NW Serbia). *Geološki anali Balkanskoga*  
2375 1769 *poluostrva* 71, 23-35.  
2377 1770 Đacović, M., 2017. New Early Triassic (Smithian) ammonoids from Gornji Brčeli (southern  
2378 1771 Montenegro). *Austrian Journal of Earth Sciences* 110(2), 9 pp.  
2379 1772 Dagis, A.A., Korčinskaja, M.V., 1989. Triasovye konodonty Sval'barda. (Triassic conodonts  
2380 1773 of Svalbard.) In: Dagis, A.S., Dubatolov, V.N. (Eds.), *Verhnij Paleozoj i Trias Sibiri.*  
2381 1774 (Upper Paleozoic and Triassic of Siberia.) *Trudy Akademija Nauk SSSR, Sibirskoe*  
2382 1775 *otdelenie Instituta Geologii i Geofiziki* 732, 109-121.  
2384 1776 Dagys, A.S., 1988. Major features of the geographic differentiation of Triassic ammonoids. In:  
2385 1777 Wiedmann, J., Kullmann, J. (Eds.), *Cephalopods — Present and Past.* Schweizerbart'sche  
2386 1778 *Verlagsbuchhandlung, Stuttgart*, pp. 341-349.  
2387 1779 Dagys, A.S., 1997. A new Late Olenekian (Triassic) ammonoid of low paleolatitude affinity  
2388 1780 from Arctic Asia (Eastern Taimyr). *Paläontologische Zeitschrift* 71, 217–220.  
2390 1781 Dagys, A.S., Weitschat, W., 1993. Correlation of the Boreal Triassic: *Mitteilungen*  
2391 1782 *Geologisch-Paläontologisches Institut Universität Hamburg* 75, 249-256.  
2392 1783 Dutton, A., Carlson, A.E., Long, A.J., Milne, G.A., Clark, P.U., DeConto, R., Horton, B.P.,  
2393 1784 Rahmstorf, S., Raymo, M.E., 2015. Sea-level rise due to polar ice-sheet mass loss during  
2394 1785 past warm periods. *Science* 349(6244), aaa4019.  
2396 1786 Ehiro, M., 2016. Additional Early Triassic (late Olenekian) ammonoids from the Osawa  
2397 1787 Formation at Yamaya, Motoyoshi area, South Kitakami Belt, Northeast  
2398 1788 Japan. *Paleontological Research* 20(1), 1-6.  
2399 1789 Ehiro, M., Sasaki, O., Kano, H., 2016. Ammonoid fauna of the upper Olenekian Osawa  
2400 1790 Formation in the Utatsu area, South Kitakami Belt, Northeast Japan. *Paleontological*  
2401 1791 *Research* 20(2), 90-104.  
2403 1792 Embry, A.F., 1986. Stratigraphic subdivision of the Blind Fjord and Bjorne formations (Lower  
2404 1793 Triassic), Sverdrup Basin, Arctic Islands. *Current Research, Part B, Geological Survey of*  
2405 1794 *Canada, Paper 86-1B*, 329-340.  
2407 1795 Embry, A.F., 1991. Mesozoic history of the Arctic Islands. In Trettin, H. (Ed.), *Geology of the*  
2408 1796 *Innuitian Orogen and Arctic Platform of Canada and Greenland. Geology of Canada*, vol.  
2409 1797 3, pp. 369-433.  
2410 1798 Embry, A.F., 1997. Global sequence boundaries of the Triassic and their identification in the  
2411 1799 Western Canada Sedimentary Basin. *Bulletin of Canadian Petroleum Geology* 45(4), 415-  
2412 1800 433.  
2414 1801 Enos, P., Lehrmann, D.J., Wei, J.Y., Yu, Y.Y., Xiao, J.F., Chaikin, D.H., Minzoni, M., Berry,  
2415 1802 A.K., Montgomery, P., 2006. Triassic Evolution of the Yangtze Platform in Guizhou  
2416  
2417  
2418  
2419

2420  
2421  
2422  
2423 1803 Province, People's Republic of China, Geological Society of America Special Paper 417,  
2424 1804 105 pp.

2425 1805 Erwin, D.H., 2001. Lessons from the past: biotic recoveries from mass extinctions. Proceedings  
2426 1806 of the National Academy of Sciences (U.S.A.) 98, 5399-5403.

2427 1807 Feng, Q.L., Algeo, T.J., 2014. Evolution of oceanic redox conditions during the Permo-Triassic  
2428 1808 transition: Evidence from deepwater radiolarian facies. Earth-Science Reviews 137, 34-  
2430 1809 51.

2431 1810 Galfetti, T., Hochuli, P.A., Brayard, A., Bucher, H., Weissert, H., Vigran, J.O., 2007a.  
2432 1811 Smithian-Spathian boundary event: Evidence for global climatic change in the wake of  
2433 1812 the end-Permian biotic crisis. Geology 35, 291-294.

2434 1813 Galfetti, T., Bucher, H., Ovtcharova, M., Schaltegger, U., Brayard, A., Brühwiler, T.,  
2435 1814 Goudemand, N., Weissert, H., Hochuli, P.A., Cordey, F., 2007b. Timing of the Early  
2437 1815 Triassic carbon cycle perturbations inferred from new U-Pb ages and ammonoid  
2438 1816 biochronozones. Earth and Planetary Science Letters 258, 593-604.

2439 1817 Galfetti, T., Bucher, H., Brayard, A., Hochuli, P.A., Weissert, H., Guodun, K., Atudorei, V.,  
2440 1818 Guex, J., 2007c. Late Early Triassic climate change: insights from carbonate carbon  
2442 1819 isotopes, sedimentary evolution and ammonoid paleobiogeography. Palaeogeography,  
2443 1820 Palaeoclimatology, Palaeoecology 243, 394-411.

2444 1821 Galfetti, T., Bucher, H., Martini, R., Hochuli, P.A., Weissert, H., Crasquin-Soleau, S., Brayard,  
2445 1822 A., Goudemand, N., Brühwiler, T., Goudun, K., 2008. Evolution of Early Triassic outer  
2446 1823 platform paleoenvironments in the Nanpanjiang Basin (South China) and their  
2447 1824 significance for the biotic recovery. Sedimentary Geology 204, 36-60.

2449 1825 Gallet, Y., Krystyn, L., Besse, J., Saidi, A., Ricou, L.E., 2000. New constraints on the Upper  
2450 1826 Permian and Lower Triassic geomagnetic polarity timescale from the Abadeh section  
2451 1827 (central Iran). Journal of Geophysical Research: Solid Earth B105, 2805-2815.

2452 1828 Gibson, D.W., 1971. Triassic stratigraphy of the Sikanni Chief River-Pine Pass region. Rocky  
2454 1829 Mountain Foothills, northeastern British Columbia. Geological Survey of Canada, Paper  
2455 1830 70-31, 105 pp.

2456 1831 Golubić, V., 1996. Biostratigraphic distribution of Upper Scythian (Lower Triassic) ammonites  
2457 1832 in the river Zrmanja Area in northern Dalmatia, Croatia. Natura Croatica 5, 165-176.

2458 1833 Golubić, V., 2000. Biostratigraphic distribution of Upper Scythian ammonites in the referent  
2459 1834 area of Muć Gornji village, Croatia. Natura Croatica 9, 237-274.

2461 1835 Goudemand, N., 2014a. Note on the conodonts from the Induan-Olenekian Boundary.  
2462 1836 Albertiana 42, 49-51.

2463 1837 Goudemand, N., 2014b. Time calibrated Early Triassic  $\delta^{13}\text{C}_{\text{carb}}$ ,  $\delta^{18}\text{O}_{\text{apatite}}$  and SST curves from  
2464 1838 South China: an update. Albertiana 42, 41-48.

2465 1839 Goudemand, N., Orchard, M.J., Guobiao, L., Galfetti, T., Bucher, H., 2006. A new early  
2467 1840 Spathian (Early Triassic) conodont succession from North America. Abstracts and  
2468 1841 Proceedings, The Boreal Triassic, August 16-20, Longyearbyen, Svalbard, Norway.

2469 1842 Goudemand, N., Orchard, M.J., Urdy, S., Brühwiler, T., Brayard, A., Bucher, H., 2012. Early  
2470 1843 Triassic conodont clusters from South China: revision of the architecture of the 15 element  
2471 1844 apparatuses of the superfamily Gondolelloidea. Palaeontology 55, 1021-1034.

2473 1845 Goudemand, N., Romano, C., Brayard, A., Hochuli, P.A., Bucher, H. 2013. Comment on  
2474 1846 "Lethally hot temperatures during the Early Triassic greenhouse". Science 339, 1033.

2475  
2476  
2477  
2478

2479  
2480  
2481  
2482 1847 Goudemand, N., Romano, C., Leu, M., Bucher, H., Trotter, J., Williams, I., 2018. Dynamic  
2483 1848 interplay between climate and marine biodiversity upheavals during the Early Triassic  
2484 1849 Smithian-Spathian biotic crisis. *Earth-Sciences Reviews*, this volume.  
2485 1850 <https://doi.org/10.1016/j.earscirev.2019.01.013>  
2486 1851 Grasby, S.E., Beauchamp, B., Embry, A., Sanei, H., 2013. Recurrent Early Triassic ocean  
2487 1852 anoxia. *Geology* 41, 175-178.  
2488 1853 Grasby, S.E., Beauchamp, B., Bond, D.P., Wignall, P.B., Sanei, H., 2016. Mercury anomalies  
2490 1854 associated with three extinction events (Capitanian crisis, latest Permian extinction and  
2491 1855 the Smithian/Spathian extinction) in NW Pangea. *Geological Magazine* 153, 285-297.  
2492 1856 Grice, K., Cao, C., Love, G.D., Böttcher, M.E., Twitchett, R.J., Grosjean, E., Summons, R.E.,  
2493 1857 Turgeon, S.C., Dunning, W., Jin, Y., 2005. Photic zone euxinia during the Permian-  
2494 1858 Triassic superanoxic event. *Science* 307, 706-709.  
2496 1859 Groves, J.R., Altiner, D., Rettori, R., 2005. Extinction, survival, and recovery of Langenide  
2497 1860 foraminifers in the Permian-Triassic boundary interval, Central Taurides, Turkey. *Journal*  
2498 1861 *of Paleontology* 79, 1-38.  
2499 1862 Guex, J., 1978. Le Trias inférieur des Salt Ranges, Pakistan: problèmes biochronologiques.  
2500 1863 *Eclogae Geologicae Helveticae* 71, 105-141.  
2502 1864 Guex, J., Hungerbühler, A., Jenks, J.F., Taylor, D.G., Bucher, H., 2005a. Dix-huit nouveaux  
2503 1865 genres d'ammonites du Spathien (Trias inférieur) de l'ouest américain (Idaho, Nevada,  
2504 1866 Utah et Californie): Note préliminaire. *Bulletin de Géologie de Lausanne* 362, 32 pp.  
2505 1867 Guex, J., Hungerbühler, A., Jenks, J.F., Taylor, D.G., Bucher, H., 2005b. Dix-neuf nouvelles  
2506 1868 espèces d'ammonites du Spathien (Trias inférieur) de l'ouest américain (Idaho, Nevada,  
2507 1869 Utah et Californie): Note préliminaire. *Bulletin de Géologie de Lausanne* 363, 25 pp.  
2509 1870 Guex, J., Hungerbühler, A., Jenks, J.F., O'Dogherty, L., Atudorei, V., Taylor, D.G., Bucher,  
2510 1871 H., Bartolini, A., 2010. Spathian (Lower Triassic) ammonoids from western USA (Idaho,  
2511 1872 California, Utah and Nevada). *Mémoires de Géologie (Lausanne)* 49, 92 pp.  
2513 1873 Hatleberg, E.W., Clark, D.L., 1984. Lower Triassic conodonts and biofacies interpretations:  
2514 1874 Nepal and Svalbard. *Geologica et Palaeontologica* 18, 101-125.  
2515 1875 Henderson, C.M., 1997. Uppermost Permian conodonts and the Permian-Triassic boundary in  
2516 1876 the Western Canada sedimentary basin. *Bulletin of Canadian Petroleum Geology* 45, 693-  
2517 1877 707.  
2519 1878 Henderson, C.M., 2018. Permian conodont biostratigraphy. In: Lucas, S.G., Shen, S.Z. (Eds.),  
2520 1879 *The Permian Timescale*, Geological Society of London Special Publication 450, pp. 119-  
2521 1880 142.  
2522 1881 Henderson, C.M., Mei, S., 2007. Geographical clines in Permian and lower Triassic  
2523 1882 gondolellids and its role in taxonomy. *Palaeoworld* 16, 190-201.  
2524 1883 Henderson, C.M., Dunn, L., Fossener, K., 2001. Pennsylvanian to Permian Belloy Formation  
2526 1884 and Lower Triassic Montney Formation of the Western Canada Sedimentary Basin:  
2527 1885 Sequence Biostratigraphy, Paleogeography and Tectonics. Rock the Foundation  
2528 1886 Convention, Canadian Society of Petroleum Geologists 113-1, 495-497.  
2529 1887 Henderson, C.M. Golding, M.L., Orchard, M.J., 2018. Conodont sequence biostratigraphy of  
2530 1888 the Lower Triassic Montney Formation. *Bulletin of Canadian Petroleum Geology* 66, 1-  
2531 1889 16.  
2533 1890 Hermann, E., Hochuli, P.A., Méhay, S., Bucher, H., Brühwiler, T., Ware, D., Hautmann, M.,  
2534  
2535  
2536  
2537



2538  
2539  
2540  
2541 1891 Roohi, G., Yaseen, A., 2011. Organic matter and palaeoenvironmental signals during the  
2542 1892 Early Triassic biotic recovery: The Salt Range and Surghar Range records. *Sedimentary*  
2543 1893 *Geology* 234, 19-41.  
2544 1894 Hermann, E., Hochuli, P. A., Bucher, H., Roohi, G., 2012. Uppermost Permian to Middle  
2545 1895 Triassic palynology of the Salt Range and Surghar Range, Pakistan. *Review of*  
2546 1896 *Palaeobotany and Palynology* 169, 61-95.  
2547 1896 Hinojosa, J.L., Brown, S.T., Chen, J., DePaolo, D.J., Paytan, A., Shen, S.Z., Payne, J.L., 2012.  
2548 1897 Evidence for end-Permian ocean acidification from calcium isotopes in biogenic apatite.  
2549 1898 *Geology* 40, 743-746.  
2550 1899  
2551 1900 Hips, K., Pelikan, P., 2002. Lower Triassic shallow marine succession in the Bükk Mountains,  
2552 1901 NE Hungary. *Geologica Carpathica* 53, 351-367.  
2553 1901 Hochuli, P.A., Sanson-Barrera, A., Schneebeli-Hermann, E., Bucher, H., 2016. Severest crisis  
2554 1902 overlooked—Worst disruption of terrestrial environments postdates the Permian–Triassic  
2555 1903 mass extinction. *Scientific Reports* 6, 28372.  
2556 1904  
2557 1905 Horacek, M., Brandner, R., Abart, R., 2007a. Carbon isotope record of the P/T boundary and  
2558 1906 the Lower Triassic in the Southern Alps: evidence for rapid changes in storage of organic  
2559 1907 carbon. *Palaeogeography, Palaeoclimatology, Palaeoecology* 252, 347-354.  
2560 1907  
2561 1908 Horacek, M., Richoz, S., Brandner, R., Krystyn, L., Spötl, C., 2007b. Evidence for recurrent  
2562 1909 changes in Lower Triassic oceanic circulation of the Tethys: The  $\delta^{13}\text{C}$  record from marine  
2563 1910 sections in Iran. *Palaeogeography, Palaeoclimatology, Palaeoecology* 252, 355-369.  
2564 1910  
2565 1911 Horacek, M., Wang, X., Grossman E.L., Richoz, S., Cao Z., 2007c. The carbon-isotope curve  
2566 1912 from the Chaohu section, China: different trends at the Induan –Olenekian Boundary or  
2567 1913 diagenesis? *Albertiana* 35, 41-45.  
2568 1914  
2569 1915 Horacek, M., Koike, T., Richoz, S., 2009. Lower Triassic  $\delta^{13}\text{C}$  isotope curve from shallow-  
2570 1916 marine carbonates in Japan, Panthalassa realm: Confirmation of the Tethys  $\delta^{13}\text{C}$  curve.  
2571 1916 *Journal of Asian Earth Sciences* 36, 481-490.  
2572 1917  
2573 1918 Horacek, M., Brandner, R., Richoz, S., Povoden-Karadeniz, E., 2010. Lower Triassic sulphur  
2574 1919 isotope curve of marine sulphates from the Dolomites, N-Italy. *Palaeogeography,*  
2575 1919 *Palaeoclimatology, Palaeoecology* 290, 65-70.  
2576 1920  
2577 1920 Hounslow, M.W., Peters, C., Mork, A., Weitschat, W., Vigran, J.O., 2008.  
2578 1921 Biomagnetostratigraphy of the Vikinghogda Formation, Svalbard (Arctic Norway), and  
2579 1922 the geomagnetic polarity timescale for the Lower Triassic. *Geological Society of America*  
2580 1923 *Bulletin* 120, 1305-1325.  
2581 1924  
2582 1924 Huang, Y.G., Chen, Z.Q., Wignall, P.B., Zhao, L.S., 2017. Latest Permian to Middle Triassic  
2583 1925 redox condition variations in ramp settings, South China: Pyrite framboid evidence.  
2584 1926 *Geological Society of America Bulletin* 129, 229-243.  
2585 1927  
2586 1927 Huchkriede, R., 1958. Die conodonten der mediterranen Trias und ihr stratigraphischer Wert.  
2587 1928 *Paläontologische Zeitschrift* 32, 141-175.  
2588 1929  
2589 1929 Jattiot, R., Bucher, H., Brayard, A., Monnet, C., Jenks, J.F., Hautmann, M., 2016. Revision of  
2590 1930 the genus *Anasibirites* Mojsisovics (Ammonoidea): an iconic and cosmopolitan taxon of  
2591 1931 the late Smithian (Early Triassic) extinction. *Papers in Palaeontology* 2, 155-188.  
2592 1932  
2593 1932 Jattiot, R., Bucher, H., Brayard, A., Brosse, M., Jenks, J.F., Bylund, K.G., 2017. Smithian  
2594 1933 ammonoid faunas from northeastern Nevada: implications for Early Triassic  
2595 1934 biostratigraphy and correlation within the western USA basin. *Palaeontographica A* 309,  
2596

2597  
2598  
2599 89 pp.  
2600 1935  
2601 1936 Jattiot, R., Brayard, A., Bucher, H., Vennin, E., Caravaca, G., Jenks, J., Bylund, K.G.,  
2602 1937 Escarguel G., 2018. Palaeobiogeographical distribution of Smithian (Early Triassic)  
2603 1938 ammonoid faunas within the western USA basin and its controlling parameters.  
2604 1939 Palaeontology, 61, 963-980..  
2605 1940 Jenks, J.F., Brayard, A., 2018. Smithian (Early Triassic) ammonoids from Crittenden Springs,  
2606 1941 Elko County, Nevada: taxonomy, biostratigraphy and biogeography. New Mexico  
2608 1942 Museum of Natural History and Science Bulletin 78, 175 pp.  
2609 1943 Jenks, J.F., Brayard, A., Brühwiler, T., Bucher, H., 2010. New Smithian (Early Triassic)  
2610 1944 ammonoids from Crittenden Springs, Elko County, Nevada: Implications for taxonomy,  
2611 1945 biostratigraphy and biogeography. New Mexico Museum of Natural History and Science  
2613 1946 Bulletin 48, 41 pp.  
2614 1947 Jenks, J.F., Guex, J., Hungerbühler, A., Taylor, D.G., Bucher, H., 2013. Ammonoid  
2615 1948 biostratigraphy of the early Spathian *Columbites parisianus* zone (Early Triassic) at Bear  
2616 1949 Lake Hot Springs, Idaho. New Mexico Museum of Natural History and Science Bulletin  
2617 1950 61, 268-283.  
2618 1951 Jenks, J.F., Monnet, C., Balini, M., Brayard, A., Meier, M., 2015. Biostratigraphy of Triassic  
2620 1952 ammonoids. In: Klug, C., Korn, D., De Baets, K., Kruta, I., Mapes, R.H. (Eds.),  
2621 1953 Ammonoid Paleobiology: From Macroevolution to Paleogeography. Springer, Dordrecht,  
2622 1954 pp. 329-388.  
2623 1955 Ji, W.T., Tong, J.N., Zhao, L.S., Zhou, S.Q., Chen, J., 2011. Lower–Middle Triassic conodont  
2624 1956 biostratigraphy of the Qingyan section, Guizhou Province, Southwest China.  
2626 1957 Palaeogeography, Palaeoclimatology, Palaeoecology 308, 213-223.  
2627 1958 Kanmera, K., Nakazawa K., 1973. Permian–Triassic relationships and faunal changes in the  
2628 1959 eastern Tethys. In: Logan, A., Hills, L.V. (Eds.), The Permian and Triassic Systems and  
2629 1960 Their Mutual Boundary, Canadian Society of Petroleum Geologists Memoir 2, pp. 100-  
2631 1961 119.  
2632 1962 Kiparisova, L.D., Popov, I.N., 1956. The separation of the Lower Triassic system into  
2633 1963 stratums. Doklady Akademii Nauk SSSR 109, 842-845.  
2634 1964 Kiparisova, L.D., Popov, Y.N., 1961. On the subdivision of the Lower Triassic into two stages.  
2635 1965 Bull. Interdept. Stratigr. Comm., St. Petersburg 3, 24-37.  
2636 1966 Kittl, E., 1903: Die Cephalopoden der oberen Werfener Schichten von Muć in Dalmatien.  
2638 1967 Abhandlungen der Kaiserlich-Königlichen Geologischen Reichsanstalt 20, 1-77.  
2639 1968 Koike, T., 1979. Conodont biostratigraphy of Triassic Tahoe limestone in western Shikoku, SW  
2640 1969 Japan. In: Igo, H., Koike, T. (Eds.), Biostratigraphy of Permian and Triassic Conodonts  
2641 1970 and Holothurian Sclerites in Japan, Committee of Prof. M. Kanuma Retirement Ceremony,  
2642 1971 Tokyo, Japan, pp. 115-126.  
2644 1972 Kolar-Jurkovšek, T., Jurkovšek, B., 2007. First record of *Hindeodus–Isarcicella* population in  
2645 1973 Lower Triassic of Slovenia. Palaeogeography Palaeoclimatology Palaeoecology 252, 72-  
2646 1974 81.  
2647 1975 Kolar-Jurkovšek, T., Jurkovšek, B., 2015. Conodont zonation of Lower Triassic strata in  
2648 1976 Slovenia. Geologija 58, 155-174.  
2650 1977 Kolar-Jurkovšek, T., Jurkovšek, B., Aljinović, D., 2011a. Conodont biostratigraphy and  
2651 1978 lithostratigraphy across the Permian–Triassic boundary at the Lukač section in western  
2652  
2653  
2654  
2655

2656  
2657  
2658  
2659 1979 Slovenia. *Rivista Italiana di Paleontologia e Stratigrafia* 117, 115-133.  
2660 1980 Kolar-Jurkovšek, T., Jurkovšek, B., Aljinović, D., Nestell, P.G., 2011b. Stratigraphy of Upper  
2661 1981 Permian and Lower Triassic of the Žiri area (Slovenia). *Geologija* 54, 193-204.  
2662 1982 Kolar-Jurkovšek, T., Vuks, V.J., Aljinović, D., Hautmann, M., Kaim, A., Jurkovšek, B., 2013.  
2663 1983 Olenekian (Early Triassic) fossil assemblage from eastern Julian Alps (Slovenia). *Annales*  
2664 1984 *Societatis Geologorum Poloniae* 83, 213-227.  
2665 1984 Komatsu, T., Dang, T.H., 2007. Lower Triassic bivalve fossils from the Song Da and An Chau  
2666 1985 Basins, North Vietnam. *Paleontological Research* 11, 135-144.  
2667 1986 Komatsu, T., Takashima, R., Shigeta, Y., Maekawa, T., Tran, H.D., Cong, T.D, Sakata, S.,  
2668 1987 Dinh, H.D., Takahashi, O., 2016. Carbon isotopic excursions and detailed ammonoid and  
2669 1988 conodont biostratigraphies around Smithian-Spathian boundary in the Bac Thuy  
2670 1989 Formation, Vietnam. *Palaeogeography, Palaeoclimatology, Palaeoecology* 454, 65-74.  
2671 1990 Kozur, H., 2003. Integrated ammonoid, conodont and radiolarian zonation of the Triassic.  
2672 1991 *Hallesches Jahrbuch für Geowissenschaften* 25, 49-79.  
2673 1992 Kozur, H., Mostler, H., 1970. Neue Conodonten aus der Trias. *Ber. Nat.-Med. (Ver. Innsbruck)*  
2674 1993 58, 429-464.  
2675 1994 Krystyn, L., 1974. Die *Tirolites*-Fauna (Ammonoidea) der untertriassischen Werfener  
2676 1995 Schichten Europas und ihre stratigraphische Bedeutung. *Oesterreichische Akademie der*  
2677 1996 *Wissenschaften, Mathematisch-Naturwissenschaftliche Klasse, Abteilung I* 193, 29-50.  
2678 1997 Krystyn, L., Balini, M., Nicora, A., 2004. Lower and Middle Triassic stage and substage  
2679 1998 boundaries in Spiti. *Albertiana* 30, 40-53.  
2680 1999 Krystyn, L., Om, N.B., Devendra, K.B., 2005. Muth (Spiti, Indian Himalaya) □ a candidate  
2681 2000 Global Stratigraphic Section and Point (GSSP) for the base of the Olenekian Stage.  
2682 2001 *Albertiana* 33, 51-53.  
2683 2002 Krystyn, L., Bhargava, O.N., Richoz, S., 2007a. A candidate GSSP for the base of the  
2684 2003 Olenekian Stage: Mud at Pin Valley; district Lahul & Spiti, Himachal Pradesh (Western  
2685 2004 Himalaya), India. *Albertiana* 35, 5-29.  
2686 2005 Krystyn, L., Richoz, S., Bhargava, O.N., 2007b. The Induan-Olenekian Boundary (IOB) in  
2687 2006 Mud—an update of the candidate GSSP section M04. *Albertiana* 36, 33-45.  
2688 2007 Kummel, B., 1973. Lower Triassic (Scythian) molluscs. In: Hallam, A. (Ed.), *Atlas of*  
2689 2008 *Paleobiogeography*. Elsevier, Amsterdam, pp. 225-233.  
2690 2009 Kummel, B., Teichert, C., 1973. Stratigraphic boundary problems: Permian and Triassic of  
2691 2010 West Pakistan. *Journal of Geology* 81, 240-241.  
2692 2011 Lau, K.V., Maher, K., Altiner, D., Kelley, B.M., Kump, L.R., Lehrmann, D.J., Silva-Tamayo,  
2693 2012 J.C., Weaver, K.L., Yu, M., Payne, J.L., 2016. Marine anoxia and delayed Earth system  
2694 2013 recovery after the end-Permian extinction. *Proceedings of the National Academy of*  
2695 2014 *Sciences (U.S.A.)* 113, 2360-2365.  
2696 2015 Lehrmann, D.J., Ramezani, J., Bowring, S.A., Martin, M.W., Montgomery, P., Enos, P., Payne,  
2697 2016 J.L., Orchard, M.J., Wang, H.M., Wei, J.Y., 2006. Timing of recovery from the end-  
2698 2017 Permian extinction: Geochronologic and biostratigraphic constraints from south China.  
2699 2018 *Geology* 34(12), 1053-1056.  
2700 2019 Lehrmann, D.J., Stepchinski, L., Altiner, D., Orchard, M.J., Montgomery, P., Enos, P.,  
2701 2020 Ellwood, B.B., Bowring, S.A., Ramezani, J., Wang, H.M., 2015. An integrated  
2702 2021 biostratigraphy (conodonts and foraminifers) and chronostratigraphy (paleomagnetic  
2703 2022  
2704  
2705  
2706  
2707  
2708  
2709  
2710  
2711  
2712  
2713  
2714

2715  
2716  
2717  
2718 2023 reversals, magnetic susceptibility, elemental chemistry, carbon isotopes and  
2719 2024 geochronology) for the Permian–Upper Triassic strata of Guandao section, Nanpanjiang  
2720 2025 Basin, South China. *Journal of Asian Earth Sciences* 108, 117-135.

2721 2026 Leu, M., Bucher, H., Goudemand, N., 2018. Clade-dependent size response of conodonts to  
2722 2027 environmental changes during the late Smithian extinction. *Earth-Science Reviews*, this  
2723 2028 volume. <https://doi.org/10.1016/j.earscirev.2018.11.003>

2724 2028  
2725 2029 Li, M.S., Ogg, J., Zhang, Y., Huang, C.J., Hinnov, L., Chen, Z.Q., Zou, Z.Y., 2016a.  
2726 2030 Astronomical tuning of the end-Permian extinction and the Early Triassic Epoch of South  
2727 2031 China and Germany. *Earth and Planetary Science Letters* 441, 10-25.

2728 2032 Li, M.S., Huang, C.J., Hinnov, L., Ogg, J., Chen, Z.Q., Zhang, Y., 2016b. Obliquity-forced  
2729 2033 climate during the Early Triassic hothouse in China. *Geology* 44, 623-626.

2730 2033  
2731 2034 Li, M.S., Hinnov, L.A., Huang, C.J., Ogg, J.G., 2018. Sedimentary noise and sea levels linked  
2732 2035 to land–ocean water exchange and obliquity forcing. *Nature Communications* 9, 1004.

2733 2036 Li, S.Y., Tong, J.N., Liu, K.Y., Wang, F.J., Huo Y.Y., 2007. The Lower Triassic cyclic  
2734 2037 deposition in Chaohu, Anhui Province, China. *Palaeogeography, Palaeoclimatology,*  
2735 2038 *Palaeoecology* 252, 188-199.

2736 2038  
2737 2039 Liang, D., Tong, J.N., Zhao, L.S., 2011. Lower Triassic Smithian-Spathian boundary at West  
2738 2040 Pingdingshan section in Chaohu, Anhui Province. *Science in China D: Earth Sciences* 54,  
2739 2041 372-379.

2740 2042 Liang, L., Tong, J.N., Song, H.J., Song, T., Tian, L., Song, H.Y., Qiu, H.O., 2016. Lower-  
2741 2043 Middle Triassic conodont biostratigraphy of the Mingtang section, Nanpanjiang Basin,  
2742 2044 South China. *Palaeogeography Palaeoclimatology Palaeoecology* 459, 381-393.

2744 2045 Lucas, S.G., Orchard, M.J., 2007. Triassic lithostratigraphy and biostratigraphy north of Currie,  
2745 2046 Elko County, Nevada. *New Mexico Museum of Natural History and Science Bulletin* 40,  
2746 2047 119-126.

2747 2048 Luo, G.M., Kump, L.R., Wang, Y., Tong, J., Arthur, M.A., Yang, H., Huang, J., Yin, H., Xie,  
2748 2049 S., 2010. Isotopic evidence for an anomalously low oceanic sulfate concentration  
2750 2050 following end-Permian mass extinction. *Earth and Planetary Science Letters* 300, 101-111.

2751 2051 Lyu, Z.Y., Orchard, M.J., Chen, Z.Q., Wang, X.D., Zhao, L.S., Han, C., 2017. Uppermost  
2752 2052 Permian to Lower Triassic conodont successions from the Enshi area, western Hubei  
2753 2053 Province, South China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, in press.  
2754 2053 <https://doi.org/10.1016/j.palaeo.2017.08.015>.

2755 2054  
2756 2055 Lyu, Z.Y., Zhang, L., Algeo, T.J., Zhao, L.S., Chen, Z.Q., Li, C., Ma, B., Ye, F.H., 2018.  
2757 2056 Global-ocean circulation changes during the Smithian–Spathian transition inferred from  
2758 2057 carbon-sulfur cycle records. *Earth-Science Reviews*, this volume.  
2759 2058 <https://doi.org/10.1016/j.earscirev.2019.01.010>

2760 2058  
2761 2059 Maekawa, T., Komatsu, T., 2014. Conodont Succession, In: Shigeta, Y., Komatsu, T.,  
2762 2060 Maekawa, T., Tran, H.D. (Eds.), *Olenekian (Early Triassic) stratigraphy and fossil*  
2763 2061 *assemblages in Northeastern Vietnam*. National Museum of Nature and Science  
2764 2062 *Monographs* (Tokyo, Japan) 45, 51-54.

2765 2062  
2766 2063 Maekawa, T., Komatsu, T., Shigeta, Y., Huyen, D.T., Tien, D.C., 2015. First occurrence of  
2767 2064 Early Triassic conodonts from the Lang Son Formation, northeastern Vietnam.  
2768 2065 *Paleontological Research* 19, 312-320.

2769 2066 Marenco, P.J., Corsetti, F.A., Kaufman, A.J., Bottjer, D.J., 2008b Environmental and  
2770  
2771  
2772  
2773



2774  
2775  
2776  
2777 2067 diagenetic variations in carbonate associated sulfate: an investigation of CAS in the Lower  
2778 2068 Triassic of the western USA. *Geochimica et Cosmochimica Acta* 72, 1570-1582.

2779 2069 McLearn, F.H., Kindler, E.D., 1950. *Geology of Northeast British Columbia*. Geological  
2780 2070 Survey of Canada Memoir 259, 236 pp.

2781 2071 Meyer, K.M., Yu, M., Jost, A.B., Kelley, B.M., Payne, J.L., 2011.  $\delta^{13}\text{C}$  evidence that high  
2782 2072 primary productivity delayed recovery from end-Permian mass extinction. *Earth and*  
2783 2073 *Planetary Science Letters* 302, 378-384.

2785 2074 Milne, G.A., Gehrels, W.R., Hughes, C.W., Tamisiea, M.E., 2009. Identifying the causes of  
2786 2075 sea-level change. *Nature Geoscience* 2, 471-478.

2787 2076 Mojsisovics, E.V., Waagen, W., Diener, C., 1895. Entwurf einer Gliederung der pelagischen  
2788 2077 Sedimente des Trias-Systems. *Sitzberichte der kaiserlichen Akademie der Wissenschaften*  
2790 2078 *Wien* 104, 1271-1302.

2791 2079 Mørk, A., Knarud, R., Worsley, D., 1982, Depositional and diagenetic environments of the  
2792 2080 Triassic and Lower Jurassic succession of Svalbard, In: Embry, A.F., Balkell, H.R. (Eds.),  
2793 2081 *Arctic Geology and Geophysics: Canadian Petroleum Society Geological Memoir* 8, pp.  
2794 2082 371-398.

2795 2083 Mørk, A., Elvebakk, G., Forsberg, A.W., Hounslow, M.W., Nakrem, H.A., Vigran, J.O.,  
2797 2084 Weitschat, W., 1999. The type section of the Vikinghøgda Formation: A new Lower  
2798 2085 Triassic unit in central and eastern Svalbard. *Polar Research* 18, 51-82.

2799 2086 Mørk, A., Lord, G.S., Solvi, K.H., Dallmann, W.K., 2013. *Geological Map of Svalbard 1:100*  
2800 2087 *000, sheet G14G Hopen*. Norsk Polarinstitutt Temakart No. 50.

2801 2088 Mosher, L.C., 1968. Triassic conodonts from western North America and Europe and their  
2803 2089 correlation. *Journal of Paleontology* 42, 895-946.

2804 2090 Mosher, L.C., 1970. New conodont species as Triassic guide fossils. *Journal of Paleontology*  
2805 2091 44, 737-742.

2806 2092 Mosher, L.C., 1973. Triassic conodonts from British Columbia and the northern Arctic Islands.  
2807 2093 *Geological Survey of Canada Bulletin* 222, 141-193.

2809 2094 Mostler, H., 1982. Bozener Quarzporphyr und Werfener Schichten. In: Mostler, H. (Ed.),  
2810 2095 *Excursionsführer zur 4. Jahrestagung der Österreichischen Geologischen Gesellschaft,*  
2811 2096 *Seis am Schlern Südtirol*, H. Kowatsch, Innsbruck, pp. 43-79.

2812 2097 Motani, R., Jiang, D.Y., Chen, G.B., Tintori, A., Rieppel, O., Ji, C., Huang, J.D., 2015. A basal  
2813 2098 ichthyosauriform with a short snout from the Lower Triassic of China. *Nature* 517, 485-  
2815 2099 488.

2816 2100 Müller, K.J., 1956. Triassic conodonts from Nevada. *Journal of Paleontology* 30, 818-830.

2817 2101 Mundil, R., Pálffy, J., Renne, P.R., Brack, P., 2010. The Triassic timescale: new constraints and  
2818 2102 a review of geochronological data. In: Lucas, S.G. (Ed.), *The Triassic Timescale,*  
2819 2103 *Geological Society of London Special Publication* 334, pp. 41-60.

2821 2104 Nakrem, H.A., Orchard, M.J., Weitschat, W., Hounslow, M.W., Beatty, T.W., Mørk, A., 2008.  
2822 2105 Triassic conodonts from Svalbard and their Boreal correlations. *Polar Research* 27, 523-  
2823 2106 539.

2824 2107 Nestell, G.P., Sudar, M., Jovanović, D., Kolar-Jurkovšek, T., 2009. Latest Permian  
2825 2108 foraminifers from the Vlačić Mountain area, northwestern Serbia. *Micropaleontology* 55,  
2826 2109 495-513.

2827 2109 Orchard, M.J., 1995. Taxonomy and correlation of Lower Triassic (Spathian) segminate  
2828 2110  
2829  
2830  
2831  
2832

2833  
2834  
2835 2111 conodonts from Oman and revision of some species of Neospathodus. *Journal of*  
2836 2112 *Paleontology* 69, 110-122.

2838 2113 Orchard, M.J., 2007. Conodont diversity and evolution through the latest Permian and Early  
2839 2114 Triassic upheavals. *Palaeogeography, Palaeoclimatology, Palaeoecology* 252, 93-117.

2840 2115 Orchard, M.J., 2008. Lower Triassic conodonts from the Canadian Arctic, their intercalibration  
2841 2116 with ammonoid-based stages and a comparison with other North American Olenekian  
2842 2117 faunas. *Polar Research* 27, 393-412.

2844 2118 Orchard, M.J., Krystyn, L., 1998. Conodonts of the lowermost Triassic of Spiti, and new  
2845 2119 zonation based on *Neogondolella* successions. *Rivista Italiana di Paleontologia e*  
2846 2120 *Stratigrafia* 104, 341-368.

2847 2121 Orchard, M.J., Krystyn, L., 2007. Conodonts from the Induan-Olenekian boundary interval at  
2848 2122 Mud, Spiti. *Albertiana* 35, 30-34.

2850 2123 Orchard, M.J., Tozer, E.T., 1997. Triassic conodont biochronology, its calibration with the  
2851 2124 ammonoid standard, and a biostratigraphic summary for the western Canada sedimentary  
2852 2125 basin. *Bulletin of Canadian Petroleum Geology* 45, 675-692.

2853 2126 Orchard, M.J., Zonneveld, J.P., 2009. The Lower Triassic Sulphur Mountain Formation in the  
2854 2127 Wapiti Lake area: lithostratigraphy, conodont biostratigraphy, and a new biozonation for  
2855 2128 the lower Olenekian (Smithian) Earth Science Sector (ESS) Contribution 20080714.  
2856 2129 *Canadian Journal of Earth Sciences* 46, 757-790.

2857 2130 Ovtcharova, M., Bucher, H., Schaltegger, U., Galfetti, T., Brayard, A., Guex, J., 2006. New  
2858 2131 Early to Middle Triassic U–Pb ages from South China: calibration with ammonoid  
2859 2132 biochronozones and implications for the timing of the Triassic biotic recovery. *Earth and*  
2860 2133 *Planetary Science Letters* 243(3-4), 463-475.

2861 2134 Ovtcharova, M., Goudemand, N., Hammer, Ø., Guodun, K., Cordey, F., Galfetti, T.,  
2862 2135 Schaltegger, U., Bucher, H., 2015. Developing a strategy for accurate definition of a  
2863 2136 geological boundary through radio-isotopic and biochronological dating: The Early–  
2864 2137 Middle Triassic boundary (South China). *Earth-Science Reviews* 146, 65-76.

2865 2138 Pakistanese-Japanese Research Group (PJRJG), 1985. Permian and Triassic systems in the Salt  
2866 2139 Range and Surghar Range, Pakistan. In: Nakazawa, K.D., Dickins, J.M. (Eds.), *The*  
2867 2140 *Tethys, her Paleogeography and Paleobiogeography from Paleozoic to Mesozoic*. Takai  
2868 2141 University Press, Tokyo, pp. 221-312.

2869 2142 Payne, J.L., Kump, L.R., 2007. Evidence for recurrent Early Triassic massive volcanism from  
2870 2143 quantitative interpretation of carbon isotope fluctuations. *Earth and Planetary Science*  
2871 2144 *Letters* 256, 264-277.

2872 2145 Payne, J.L., Lehrmann, D.J., Wei, J.Y., Orchard, M.J., Schrag, D.P., Knoll, A.H., 2004. Large  
2873 2146 perturbations of the carbon cycle during recovery from the end-Permian extinction.  
2874 2147 *Science* 305, 506-509.

2875 2148 Payne, J.L., Turchyn, A.V., Paytan, A., DePaolo, D.J., Lehrmann, D.J., Yu, M., Wei, J., 2010.  
2876 2149 Calcium isotope constraints on the end-Permian mass extinction. *Proceedings of the*  
2877 2150 *National Academy of Sciences (U.S.A.)* 107, 8543-8548.

2878 2151 Perri, M.C., 1986. A Spathian conodont fauna from the Cencenighe Member of the Werfen  
2879 2152 Formation (Scythian), southwestern Dolomites, Italy. *Bollettino della Società*  
2880 2153 *Paleontologica Italiana* 24, 23-28.

2881 2154 Perri, M.C., 1991. Conodont biostratigraphy of the Werfen Formation (Lower Triassic),  
2882  
2883  
2884  
2885  
2886  
2887  
2888  
2889  
2890  
2891

2892  
2893  
2894  
2895  
2896  
2897  
2898  
2899  
2900  
2901  
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2935  
2936  
2937  
2938  
2939  
2940  
2941  
2942  
2943  
2944  
2945  
2946  
2947  
2948  
2949  
2950

- Southern Alps, Italy. *Bollettino della Societa Paleontologica Italiana* 30, 23-46.
- Perri, M.C., Andraghetti, M., 1987. Permian–Triassic boundary and Early Triassic conodonts from the Southern Alps. Italy. *Rivista Italiana di Paleontologia e Stratigrafia* 93, 291-328.
- Perri, M.C., Farabegoli, E., 2003. Conodonts across the Permian–Triassic boundary in the Southern Alps. *Courier Forschungsinstitut Senckenberg* 245, 281-313.
- Piazza, V., Hammer, Ø., Jattiot, R., 2017. New late Smithian (Early Triassic) ammonoids from the Lusitaniadalen Member, Vikinghøgda Formation, Svalbard. *Norwegian Journal of Geology* 97(2), 105-117.
- Popov, Y.D., 1964. Some Early Triassic ammonoids of northern Caucasus. *International Geology Review* 6, 700-705.
- Posenato, R., 2008. Global correlations of mid Early Triassic events: The Induan/Olenekian boundary in the Dolomites (Italy). *Earth-Science Reviews* 91, 93-105.
- Raup, D.M., 1986. Biological extinction in earth history. *Science* 231(4745), 1528-1533.
- Richoz, S., 2006. Stratigraphie et variations isotopiques du carbone dans le Permien supérieur et le Trias inférieur de quelques localités de la Néotéthys (Turquie, Oman et Iran). *Mémoire de Géologie de Lausanne* 46, 251 pp.
- Richoz, S., Krystyn, L., Baud, A., Brandner, R., Horacek, M., Mohtat-Aghai, P., 2010. Permian–Triassic boundary interval in the Middle East (Iran and N. Oman): Progressive environmental change from detailed carbonate carbon isotope marine curve and sedimentary evolution. *Journal of Asian Earth Sciences* 39, 236-253.
- Romano, C., Goudemand, N., Vennemann, T.W., Ware, D., Schneebeli-Hermann, E., Hochuli, P.A., Brühwiler, T., Brinkmann, W., Bucher, H., 2013. Climatic and biotic upheavals following the end-Permian mass extinction. *Nature Geoscience* 6, 57-60.
- Saito, R., Kaiho, K., Oba, M., Takahashi, S., Chen, Z. Q., Tong, J., 2012. A terrestrial vegetation turnover in the middle of the Early Triassic. *Global and Planetary Change* 105, 152-159.
- Sakuma, H., Tada, R., Ikeda, M., Kashiya, Y., Ohkouchi, N., Ogawa, N.O., Watanabe, S., Tajika, E., Yamamoto, S., 2012. High resolution lithostratigraphy and organic carbon isotope stratigraphy of the Lower Triassic pelagic sequence in central Japan. *Island Arc* 21, 79-100.
- Samankassou, E., 1995. Early Triassic (Scythian) conodonts from the Werfen Formation, Southern Alps, Italy. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte* 4, 248-256.
- Schneebeli-Hermann, E., Hochuli, P. A., Bucher, H., Goudemand, N., Brühwiler, T., Galfetti, T., 2012. Palynology of the Lower Triassic succession of Tulong, South Tibet—Evidence for early recovery of gymnosperms. *Palaeogeography, Palaeoclimatology, Palaeoecology* 339, 12-24.
- Schobben, M., Ullmann, C.V., Leda, L., Korn, D., Struck, U., Reimold, W.U., Ghaderi, A., Algeo, T.J., Korte, C., 2016. Discerning primary versus diagenetic signals in carbonate carbon and oxygen isotope records: An example from the Permian–Triassic boundary of Iran. *Chemical Geology* 422, 94-107.
- Sedlacek, A.R.C., Saltzman, M.R., Algeo, T.J., Horacek, M., Brandner, R., Foland, K., Denniston, R.F., 2014.  $^{87}\text{Sr}/^{86}\text{Sr}$  stratigraphy from the Early Triassic of Zal, Iran: Linking temperature to weathering rates and the tempo of ecosystem recovery. *Geology* 42, 779-

2951  
2952  
2953 2199 782.  
2954  
2955 2200 Sephton, M.A., Looy, C.V., Brinkhuis, H., Wignall, P.B., De Leeuw, J.W., Visscher, H., 2005.  
2956 2201 Catastrophic soil erosion during the end-Permian biotic crisis. *Geology* 33, 941-944.  
2957 2202 Shen, J., Schoepfer, S.D., Feng, Q.L., Zhou, L., Yu, J.X., Song, H.Y., Wei, H.Y., Algeo, T.J.,  
2958 2203 2015. Marine productivity changes during the end-Permian crisis and Early Triassic  
2959 2204 recovery. *Earth-Science Reviews* 149, 136-162.  
2960 2205 Shigeta, Y., Kumagae, T., 2016. Spathian (Late Olenekian, Early Triassic) Ammonoids from  
2962 2206 the Artyom Area, South Primorye, Russian Far East and Implications for the Timing of  
2963 2207 the Recovery of the Oceanic Environment. *Paleontological Research* 20, 48-60.  
2964 2208 Shigeta, Y., Nakajima, Y., 2017. Discovery of the Early Spathian (Late Olenekian, Early  
2965 2209 Triassic) Ammonoid *Tirolites* in the Hiraiso Formation, South Kitakami Belt, Northeast  
2966 2210 Japan. *Paleontological Research* 21, 37-43.  
2968 2211 Shigeta, Y., Zakharov, Y.D., 2009. Systematic Paleontology–Cephalopods. In: Shigeta, Y.,  
2969 2212 Zakharov, Y.D., Maeda, H., Popov, A.M. (Eds.), *The Lower Triassic system in the Abrek*  
2970 2213 *Bay area, South Primorye, Russia*. National Museum of Nature and Science, Tokyo, pp.  
2971 2214 44-140.  
2972 2215 Shigeta, Y., Zaharov, J.D., Maeda, H., Popov, A.M. (Eds.), 2009. *The Lower Triassic System*  
2974 2216 *in the Abrek Bay Area, South Primorye, Russia*. National Museum of Nature and Science  
2975 2217 (Tokyo), 218 pp.  
2976 2218 Shigeta, Y., Komatsu, T., Maekawa, T., Dang, H.T., 2014. Olenekian (Early Triassic)  
2977 2219 stratigraphy and fossil assemblages in northeastern Vietnam. *National Museum of Nature*  
2978 2220 *and Science Monograph* 38, Tokyo, Japan.  
2980 2221 Signor, P.W., Lipps, J.H., 1982. Sampling bias, gradual extinction patterns, and catastrophes  
2981 2222 in the fossil record. In: Silver, L.T., Schultz, P.H. (Eds.), *Geological Implications of*  
2982 2223 *Impacts of Large Asteroids and Comets on the Earth*, Geological Society of America  
2983 2224 *Special Paper* 190, pp. 291-296.  
2984 2225 Silberling, N.J., Tozer, E.T., 1968. Biostratigraphic Classification of the Marine Triassic in  
2986 2226 North America. *Geological Society of America Special Paper* 110, 63 pp.  
2987 2227 Silva-Tamayo, J.C., Lau, K.V., Jost, A.B., Payne, J. L., Wignall, P. B., Newton, R.J.,  
2988 2228 Eisenhauer, A., Depaolo, D.J., Brown, S., Maher, K., Lehrmann, D.J., Altiner, D., Yu,  
2989 2229 M.Y., Richoz, S., Paytan, A., 2018. Global perturbation of the marine calcium cycle  
2990 2230 during the Permian-Triassic transition. *Geological Society of America Bulletin* 130(7-8),  
2992 2231 1323-1338.  
2993 2232 Smyshlyaeva, O., Zakharov, Y., 2012. New representatives of the family Melagathiceratidae  
2994 2233 (Ammonoidea) from the Lower Triassic of South Primorye. *Paleontological Journal* 46,  
2995 2234 142-147.  
2996 2235 Song, H.J., Wignall, P.B., Chu, D.L., Tong, J.N., Sun, Y.D., Song, H.Y., He, W.H., Tian, L.,  
2998 2236 2014. Anoxia/high temperature double whammy during the Permian–Triassic marine  
2999 2237 crisis and its aftermath. *Scientific Reports* 4, art. 4132.  
3000 2238 Song, H.J., Wignall, P.B., Tong, J.N., Song, H.Y., Chen, J., Chu, D.L., Tian, L., Luo, M., Zong,  
3001 2239 K.Q., Chen, Y.L., 2015. Integrated Sr isotope variations and global environmental  
3002 2240 changes through the Late Permian to early Late Triassic. *Earth and Planetary Science*  
3004 2241 *Letters* 424, 140-147.  
3005 2242 Song, H.Y., Tong, J.N., Algeo, T.J., Horacek, M., Qiu, H.O., Song, H.J., Tian, L., Chen, Z.Q.,  
3006  
3007  
3008  
3009



3010  
3011  
3012  
3013 2243 2013. Large vertical  $\delta^{13}\text{C}_{\text{DIC}}$  gradients in Early Triassic seas of the South China craton:  
3014 2244 Implications for oceanographic changes related to Siberian Traps volcanism. *Global and*  
3015 2245 *Planetary Change* 105, 7-20.

3016 2246 Song, H.Y., Tong, J.N., Algeo, T.J., Song, H.J., Qiu, H.O., Zhu, Y.Y., Tian, L., Bates, S., Lyons,  
3017 2247 T.W., Luo, G.M., Kump, L.R., 2014. Early Triassic seawater sulfate drawdown.  
3018 2248 *Geochimica et Cosmochimica Acta* 128, 95-113.

3020 2249 Song, H.Y., Du, Y., Algeo, T.J., Tong, J.N., Owens, J.D., Song, H.J., Tian, L., Qiu, H., Zhu,  
3021 2250 Y.Y., Lyons, T.W., 2019. Cooling-driven oceanic anoxia during the Smithian-Spathian  
3022 2251 transition (mid-Early Triassic). *Earth-Science Reviews*, this volume.  
3023 2252 <https://doi.org/10.1016/j.earscirev.2019.01.009>

3024 2253 Staesche, U., 1964. Conodonten aus dem Skyth von Südtirol. *Neues Jahrbuch für Geologie und*  
3025 2254 *Paläontologie, Abhandlungen* 119, 247-306.

3027 2255 Stanley, S.M., 2009. Evidence from ammonoids and conodonts for multiple Early Triassic  
3028 2256 mass extinctions. *Proceedings of the National Academy of Sciences (U.S.A.)* 106, 15264-  
3029 2257 15267.

3030 2258 Stebbins, A., Algeo, T.J., Krystyn, L., Rowe, H.D., Brookfield, M., Williams, J., Nye, S.W.,  
3031 2259 Jr., and Hannigan, R., 2018a. Marine sulfur cycle evidence for upwelling and eutrophic  
3033 2260 stresses during Early Triassic cooling events. *Earth-Science Reviews*, this volume.  
3034 2261 <https://doi.org/10.1016/j.earscirev.2018.09.007>

3035 2262 Stebbins, A., Algeo, T.J., Olsen, C., Sano, H., Rowe, H.D., and Hannigan, R., 2018b. Sulfur-  
3036 2263 isotope evidence for recovery of seawater sulfate concentrations from a PTB minimum by  
3037 2264 the Smithian-Spathian transition. *Earth-Science Reviews*, this volume.  
3039 2265 <https://doi.org/10.1016/j.earscirev.2018.08.010>

3040 2266 Sudar, M.N., Jovanović, D., Kolar-Jurkovšek, T., 2007. Late Permian conodonts from Jadar  
3041 2267 Block (Vardar Zone, northwestern Serbia). *Geologica Carpathica* 58, 145-152.

3042 2268 Sudar, M.N., Chen, Y., Tea, K.J., Bogdan, J., Divna, J., Marie-Beatrice, F., 2014. Lower  
3043 2269 Triassic (Olenekian) microfauna from Jadar Block (Gučevo Mt. NW Serbia). *Geološki*  
3045 2270 *Anali Balkanskog Poluostrva* 75, 1-15.

3046 2271 Sun, Y.D., Joachimski, M.M., Wignall, P.B., Yan, C.B., Chen, Y.L., Jiang, H.S., Wang, L.N.,  
3047 2272 Lai, X.L., 2012. Lethally hot temperatures during the Early Triassic greenhouse. *Science*  
3048 2273 338, 366-370.

3050 2274 Sun, Y.D., Joachimski, M.M., Wignall, P.B., Yan, C.B., Chen, Y.L., Jiang, H.S., Wang, L.N.,  
3051 2275 Lai, X.L., 2013. Response to Comment on "Lethally hot temperatures during the Early  
3052 2276 Triassic greenhouse". *Science* 339, 1033.

3053 2277 Sweet, W.C., 1970a. Uppermost Permian and Lower Triassic conodonts of the Salt Range and  
3054 2278 Trans-Indus Ranges, West Pakistan. In: Kummel, B., Teichert, C. (Eds.), *Stratigraphic*  
3055 2279 *Boundary Problems: Permian and Triassic of West Pakistan* 4, pp. 207-275.

3057 2280 Sweet, W.C., 1970b. Permian and Triassic conodonts from a section at Guryul Ravine, Vihi  
3058 2281 district, Kashmir. *University of Kansas Paleontological Contributions, Paper* 49, 10 pp.

3059 2282 Tada, R., Watanabe, S., Kashiyama, Y., Tajika, E., Kato, T., Yamamoto, S., Isozaki, Y.,  
3060 2283 Sakuma, H., 2005. High-resolution analysis of Late Paleozoic-Early Mesozoic variability  
3061 2284 of paleoceanographic system recorded in bedded chert sequence in the inner zone of  
3063 2285 southwest Japan. *Journal of Geography (Chigaku Zasshi)* 114, 638-642.

3064 2286 Takahashi, S., Oba, M., Kaiho, K., Yamakita, S., Sakata, S., 2009. Panthalassic oceanic anoxia  
3065  
3066  
3067  
3068

3069  
3070  
3071  
3072 2287 at the end of the Early Triassic: A cause of delay in the recovery of life after the end-  
3073 2288 Permian mass extinction: *Palaeogeography, Palaeoclimatology, Palaeoecology* 274, 185-  
3074 2289 195.  
3075 2290 Thomazo, C., Vennin, E., Brayard, A., Bour, I., Mathieu, O., Elmeknassi, S., Olivier, N.,  
3076 2291 Escarguel, E., Bylund, K.G., Jenks, J., Stephen, D.A., Fara, E., 2016. A diagenetic control  
3077 2292 on the Early Triassic Smithian-Spathian carbon isotopic excursions recorded in the marine  
3078 2292 settings of the Thaynes Group (Utah, USA). *Geobiology* 14, 1-17.  
3079 2293  
3080 2294 Thomazo, C., Brayard, A., Elmeknassi, S., Vennin, E., Olivier, N., Caravaca, G., Escarguel,  
3081 2295 G., Fara, E., Bylund, K.G., Jenks, J.F., Stephen, D.A., Killingsworth, B., Sansjofre, P.,  
3082 2296 Cartigny, P., 2018. Multiple sulfur isotope signals associated with the late Smithian event  
3083 2297 and the Smithian/Spathian boundary. *Earth-Science Reviews*, this volume.  
3084 2297 <https://doi.org/10.1016/j.earscirev.2018.06.019>  
3085 2298  
3086 2299 Thorsteinsson, R., Tozer, E.T., 1970. Geology of the Arctic Archipelago. In: Douglas, R.J.W.  
3087 2300 (Ed.), *Geology and Economic Minerals of Canada*. Geological Survey of Canada, pp. 547-  
3088 2301 590.  
3089 2302  
3090 2302 Tian, C.R., Dai, J., Tian, S.G., 1983. Triassic conodonts. In: Chengdu Institute of Geology and  
3091 2303 Mineral Resources, *Paleontological Atlas of Southwest China, Volume of Microfossils*.  
3092 2304 Geological Publishing House, Beijing, pp. 345-398.  
3093 2305  
3094 2305 Tian, L., Tong, J.N., Algeo, T.J., Song, H.J., Song, H.Y., Chu, D.L., Shi, L., Bottjer, D.J., 2014.  
3095 2306 Reconstruction of Early Triassic ocean redox conditions based on framboidal pyrite from  
3096 2307 the Nanpanjiang Basin, South China. *Palaeogeography, Palaeoclimatology,*  
3097 2308 *Palaeoecology* 412, 68-79.  
3098 2309  
3099 2310 Tong, J.N., Zhao L.S., 2011. Lower Triassic and Induan-Olenekian Boundary in Chaohu,  
3100 2311 Anhui Province, South China. *Acta Geologica Sinica* 85, 399-407.  
3101 2312  
3102 2312 Tong, J.N., Qiu, H.O., Zhao, L.S., Zuo, J.X., 2002. Lower Triassic inorganic carbon isotope  
3103 2313 excursion in Chaohu, Anhui Province, China. *Journal of China University of Geosciences*,  
3104 2314 13, 98-106.  
3105 2315  
3106 2315 Tong, J.N., Zakharov, Y.D., Orchard, M.J., Yin, H.F., Hansen, H.J., 2003. A candidate of the  
3107 2316 Induan–Olenekian Boundary stratotype in the Tethyan region. *Science in China D: Earth*  
3108 2317 *Sciences* 46, 1182-1200.  
3109 2318  
3110 2319 Tong, J.N., Zakharov, Y.D., Wu, S.B., 2004. Early Triassic ammonoid succession in Chaohu,  
3111 2320 Anhui Province. *Acta Palaeontologica Sinica* 43, 192-204.  
3112 2321  
3113 2321 Tong, J.N., Hansen, H.J., Zhao, L.S., Zuo, J.X., 2005. A GSSP candidate of the Induan–  
3114 2322 Olenekian Boundary-stratigraphic sequence of the West Pingdingshan Section, in Chaohu,  
3115 2323 Anhui Province. *Journal of Stratigraphy* 29, 205-212.  
3116 2324  
3117 2325 Tong, J.N., Zuo, J.X., Chen, Z.Q., 2007. Early Triassic carbon isotope excursions from South  
3118 2326 China: proxies for devastation and restoration of marine ecosystems following the end-  
3119 2327 Permian mass extinction. *Geological Journal* 42, 371-389.  
3120 2328  
3121 2328 Tozer, E.T., 1961. *Triassic Stratigraphy and Faunas, Queen Elizabeth Islands, Arctic*  
3122 2329 *Archipelago*. Geological Survey of Canada Memoir 316, 116 pp.  
3123 2330  
3124 2327 Tozer, E.T., 1962. *Illustrations of Canadian fossils: Triassic of western and Arctic Canada*.  
3125 2328 Geological Survey of Canada Paper 62-19, 26 pp.  
3126 2329  
3127 2329 Tozer, E.T., 1965. Lower Triassic stages and ammonoid zones of Arctic Canada. *Geological*  
3128 2330 *Survey of Canada Paper* 14, 12 pp.

- 3128  
3129  
3130  
3131 2331 Tozer, E.T., 1967. A standard for Triassic time. Geological Survey of Canada Bulletin 156,  
3132 2332 103 pp.  
3133 2333 Tozer, E.T., 1971. Triassic time and ammonoids: problems and proposals. Canadian Journal of  
3134 2334 Earth Sciences 8, 989-1031.  
3135 2335 Tozer, E.T., 1981a. Triassic ammonoidea: classification, evolution and relationship with  
3136 2336 Permian and Jurassic forms. In: House, M.R., Senior, J.R. (Eds.), The Ammonoidea. The  
3137 2337 Systematics Association, London, pp. 65-100.  
3138 2337 Tozer, E.T., 1981b. Triassic ammonoidea: geographic and stratigraphic distribution. In: House,  
3140 2339 M.R., Senior, J.R. (Eds.), The Ammonoidea. The Systematics Association, London, pp.  
3141 2340 397-431.  
3142 2341 Tozer, E.T., 1982. Marine Triassic faunas of North America: their significance for assessing  
3143 2342 plate and terrane movements. Geologische Rundschau 71, 1077-1104.  
3145 2343 Tozer, E.T., 1984. The Trias and its ammonoids: the evolution of a time scale. Geological  
3146 2344 Survey of Canada Miscellaneous Report 35, 171 pp.  
3147 2345 Tozer, E.T., 1994. Canadian Triassic ammonoid faunas. Geological Survey of Canada Bulletin  
3148 2346 467, 663 pp.  
3149 2346 Tozer, E.T., Calon, T.J., 1990. Triassic ammonoids from Jabal Safra and Wadi Alwa, Oman,  
3151 2348 and their significance. In: Robertson, A.H.F., Searle, M.P., Ries, A.C. (Eds.), The Geology  
3152 2349 and Tectonics of the Oman Region. Geological Society of London Special Publication 49,  
3153 2350 pp. 203-211.  
3154 2351 Twitchett, R.J., Barras, C.G., 2004. Trace fossils in the aftermath of mass extinction events. In:  
3155 2352 McIlroy, D. (Ed.), The Application of Ichnology to Palaeoenvironmental and  
3157 2353 Stratigraphic Analysis, Geological Society of London Special Publication 228, pp. 397-  
3158 2354 418.  
3159 2355 Vaziri, S.H., 2011. A review on Late Scythian to Middle Anisian ammonoids from the Alam  
3160 2356 Formation in Naxhlak area, Central Iran. Journal of Science, Islamic Azad University 21,  
3161 2357 201-212.  
3163 2358 Waagen, W., 1895. Salt-Range fossils. Vol. 2: Fossils from the Ceratite Formation.  
3164 2359 Palaeontologia Indica 13, 323 pp.  
3165 2360 Wang, H.M., Wang, X.L., Li, R.X., Wei, J.Y., 2005. Triassic conodont succession and stage  
3166 2361 subdivision of the Guandao section, Bianyang Luodian. Acta Palaeontologica Sinica 44,  
3168 2362 611-626.  
3169 2363 Ware, D., Bucher, H., Brayard, A., Schneebeli-Hermann, E., Brühwiler, T., 2015. High-  
3170 2364 resolution biochronology and diversity dynamics of the Early Triassic ammonoid  
3171 2365 recovery: the Dienerian faunas of the Northern Indian Margin. Palaeogeography,  
3172 2366 Palaeoclimatology, Palaeoecology 440, 363-373.  
3174 2367 Ware, D., Bucher, H., Brühwiler, T., Schneebeli-Hermann, E., Hochuli, P.A., Roohi, G., Ur-  
3175 2368 Rehman, K., Yaseen, A., 2017. Griesbachian and Dienerian (Early Triassic) ammonoids  
3176 2369 from the Salt Range, Pakistan. Fossils and Strata, in press. doi: 10.1130/B31969.1.  
3177 2370 Watanabe, K., Kanmera, K., Nakajima, K., 1979. Conodont biostratigraphy in the Kamura  
3178 2371 limestone (Triassic), Takachiho-cho, Nishiusuki-gun, Miyazaki Prefecture. In: Igo, H.,  
3179 2372 Koike, T. (Eds.), Biostratigraphy of Permian and Triassic Conodonts and Holothurian  
3181 2373 Sclerites in Japan, Committee of Prof. M. Kanuma Retirement Ceremony, Tokyo, Japan,  
3182 2374 pp. 127-137.  
3183  
3184  
3185  
3186

3187  
3188  
3189  
3190 2375 Weitschat, W., Dagys, A.S., 1989. Triassic biostratigraphy of Svalbard and a comparison with  
3191 2376 NE-Siberia. Mitteilungen des Geologisch-Paläontologisches Institut der Universität  
3192 2377 Hamburg 68, 179-213.  
3193 2378 Weitschat, W., Lehmann, U., 1978. Biostratigraphy of the uppermost part of the Smithian Stage  
3194 2379 (Lower Triassic) at the Botneheia, W-Spitsbergen. Mitteilungen des Geologischen-  
3195 2380 Paläontologischen Institut, Universität Hamburg 48, 85-100.  
3196 2380  
3197 2381 Wignall, P.B., Twitchett, R.J., 1996. Oceanic anoxia and the end Permian mass extinction.  
3198 2382 Science 272, 1155-1158.  
3199 2383 Wignall, P.B., Bond, D.P., Sun, Y., Grasby, S.E., Beauchamp, B., Joachimski, M.M., Blomeier,  
3200 2384 D.P., 2016. Ultra-shallow-marine anoxia in an Early Triassic shallow-marine clastic ramp  
3201 2385 (Spitsbergen) and the suppression of benthic radiation. Geological Magazine 153, 316-  
3202 2386 331.  
3203 2386  
3204 2387 Xie, S.C., Pancost, R.D., Huang, X., Jiao, D., Lu, L., Huang, J., Yang, F., Evershed, R.P., 2007.  
3205 2388 Molecular and isotopic evidence for episodic environmental change across the  
3206 2389 Permo/Triassic boundary at Meishan in South China. Global and Planetary Change 55,  
3207 2390 56-65.  
3208 2390  
3209 2391 Yan, C.B., Wang, L.N., Jiang, H.S., Wignall, P.B., Sun, Y.D., Chen, Y.L., Lai, X.L., 2013.  
3210 2392 Uppermost Permian to Lower Triassic conodonts at Bianyang section, Guizhou Province,  
3211 2393 South China. Palaios 28, 509-522.  
3212 2394 Yang, S.R., Wang, X.P., Hao, W.C., 1984. New knowledge on the Lower Triassic of Zuodeng,  
3213 2395 Tiandong County, Guangxi. In: Selected Papers for the Commemoration of Professor Yue  
3214 2396 Senxun engaged in Geological Education for 60 Years. Geological Publishing House,  
3215 2397 Beijing, pp. 105-117.  
3216 2397  
3217 2398 Yao, A., Kuwahara, K., 1997. Radiolarian faunal change from Late Permian to Middle Triassic  
3218 2399 times. News of Osaka Micropaleontologists 10, 87-96.  
3219 2400  
3220 2400 Yin, H.F., Yang, F.Q., Zhang, K.Q., Yang, W.P., 1986. A proposal to the biostratigraphic  
3221 2401 criterion of Permian/Triassic boundary. Memorie della Societa Geologica Italiana 34,  
3222 2402 329-344.  
3223 2403 Yin, H.F., Sweet, W.C., Glenister, B.F., Kotlyar, G., Kozur, H., Newell, N.D., Sheng, J.Z.,  
3224 2404 Yang, Z.Y., Zakharov, Y.D., 1996, Recommendation of the Meishan section as Global  
3225 2405 Stratotype Section and Point for basal boundary of Triassic System. Newsletter on  
3226 2405 Stratigraphy 34, 81-108.  
3227 2406  
3228 2407 Yin, H.F., Zhang, K.X., Tong, J.N., Yang, Z.Y., Wu, S.B., 2001. The Global Stratotype Section  
3229 2408 and Point (GSSP) of the Permian-Triassic boundary. Episodes 24, 102-114.  
3230 2409 Zakharov, Y.D., Abnavi, N.M., 2013. The ammonoid recovery after the end-Permian mass  
3231 2410 extinction: evidence from the Iran-Transcaucasia area, Siberia, Primorye, and Kazakhstan.  
3232 2410 Acta Palaeontologica Polonica 58, 127-147.  
3233 2411  
3234 2412 Zakharov, Y.D., Smyshlyaeva, O.P., 2016. New Middle Olenekian (Early Triassic)  
3235 2413 Ammonoids of South Primorye Paleontological Journal 50, 229-238.  
3236 2414 Zakharov, Y.D., Popov, A.M., Buryi, G.I., 2004. Triassic ammonoid succession in South  
3237 2415 Primorye: 2. Middle Olenekian *Tirolites-Amphistephanites* Zone. Albertiana 29, 29-37.  
3238 2415  
3239 2416 Zakharov, Y.D., Bondarenko, L.G., Smyshlyaeva, O.P., Andalexander M.P., 2013. Late  
3240 2417 Smithian (Early Triassic) ammonoids from the *Anasibirites nevolini* zone of South  
3241 2418 Primorye, Russian Far East. In: Tanner, L.H., Spielmann, J.A., Lucas, S.G. (Eds.), The  
3242  
3243  
3244  
3245



3246  
3247  
3248  
3249 2419 Triassic System. New Mexico Museum of Natural History and Science Bulletin 61, pp.  
3250 2420 597-612.  
3251 2421 Zhang, F.F., Romaniello, S.J., Algeo, T.J., Lau, K.V., Clapham, M.E., Richoz, S., Herrmann,  
3252 2422 A.D., Smith, H., Horacek, M., Anbar, A.D., 2018. Multiple episodes of extensive oceanic  
3253 2423 anoxia linked to global warming and continental weathering following the latest Permian  
3254 2424 mass extinction. Science Advances 4(4), e1602921.  
3255 2425 Zhang, L., Zhao, L.S., Chen, Z.Q., Algeo, T.J., Li, Y., Cao, L., 2015. Amelioration of marine  
3257 2426 environments at the Smithian-Spathian boundary, Early Triassic. Biogeosciences 12,  
3258 2427 1597-1613.  
3259 2428 Zhang, L., Orchard, M.J., Algeo, T.J., Chen, Z.Q., Lyu, Z.Y., Zhao, L.S., Han, C., Liu, S.J.,  
3260 2429 2017. An intercalibrated Triassic conodont succession and carbonate carbon isotope  
3261 2429 profile, Kamura, Japan. Palaeogeography, Palaeoclimatology, Palaeoecology, in press.  
3262 2430 <https://doi.org/10.1016/j.palaeo.2017.09.001>.  
3263 2431  
3264 2432 Zhao, L.S., Tong, J.N., Zuo, J.X., Ming, H.L., 2002. Discussion on Induan-Olenekia Boundary  
3265 2433 in Chaohu, Auhui Province, China, Journal of China University of Geosciences 3, 141-  
3266 2433 150.  
3267 2434  
3268 2435 Zhao, L.S., Tong, J.N., Zuo, J.X., 2003a. Lower Triassic Conodont Biostratigraphical  
3269 2436 Sequence at West Pingdingshan Section, Chaohu, Anhui Province, China. Earth Science  
3270 2436 28, 414-418.  
3271 2437  
3272 2438 Zhao, L.S., Tong, Jinnan, Orchard, M.J. 2003b. Morphological variation of the conodonts  
3273 2439 *Platyvillosus* from the Yinkeng Formation in Chaohu, Anhui Province, China. Journal of  
3274 2439 China University of Geosciences 19, 306-314.  
3275 2440  
3276 2441 Zhao, L.S., Orchard, M.J., Tong, J.N., 2004. Lower Triassic conodont biostratigraphy and  
3277 2442 speciation of *Neospathodus waageni* around the Induan-Olenekian Boundary of Chaohu,  
3278 2443 Anhui Province, China. Albertiana 29, 41-43.  
3279 2443  
3280 2444 Zhao, L.S., Orchard, M.J., Tong J.N., 2005a. Conodont sequences and its global correlation of  
3281 2445 the Induan-Olenekian Boundary in West Pingdingshan section, Chaohu, Anhui Province.  
3282 2446 Albertiana (Part II) 33, 108-111.  
3283 2447  
3284 2448 Zhao, L.S., Tong, J.N., Orchard, M.J., 2005b. Study on the Lower Triassic Conodont Sequence  
3285 2448 and the Induan-Olenekian Boundary in Chaohu, Anhui Province. China University of  
3286 2449 Geosciences Press, 140 pp.  
3287 2450  
3288 2451 Zhao, L.S., Tong, J.N., Orchard, M.J., Zuo, J.X., 2005c. Lower Triassic conodont zonations of  
3289 2452 Chaohu area, Anhui Province and their global correlation. Earth Science 30, 624-634.  
3290 2452  
3291 2453 Zhao, L.S., Orchard, M.J., Tong, J.N., Sun, Z.i., Zuo, J.X., Zhang, S.X., Yun, A.L., 2007a.  
3292 2454 Lower Triassic conodont sequence in Chaohu, Anhui Province, China and its global  
3293 2455 correlation. Palaeogeography, Palaeoclimatology, Palaeoecology 252, 24-38.  
3294 2455  
3295 2456 Zhao, L.S., Tong, J.N., Sun, Z.M., Chang, D.F., Zhang, K.X., Zhang, S.X., Orchard M.J.,  
3296 2457 2007b. High-Resolution Conodont Biostratigraphy in the Induan-Olenekian Boundary  
3297 2458 Strata at West Pingdingshan Section, Chaohu, Anhui Province. Earth Science 32, 91-302.  
3298 2458  
3299 2459 Zhao, L.S., Tong, J.N., Sun, Z.M., Orchard, M.J., 2008a. Detailed Lower Triassic conodont  
3300 2460 biostratigraphy and its implications at the GSSP candidate of the Induan-Olenekian  
3301 2461 boundary in Chaohu, Anhui Province. Progress in Natural Science 18, 79-90.  
3302  
3303  
3304

3305  
3306  
3307  
3308 2462 Induan-Olenekian Boundary Strata at West Pingdingshan Section, Chaohu, Anhui  
3309 2463 Province. *Journal of China University of Geosciences* 19, 207-216.  
3310 2464 Zhao, L.S., Chen, Y.L., Chen, Z.Q., Cao, L., 2013a. Uppermost Permian to Lower Triassic  
3311 2465 Conodont Zonation from Three Gorges area, South China, *Palaios* 28, 523-540.  
3312 2466 Zhao, L.S., Chen, Z.Q., Algeo, T.J., Chen, J.B., Chen, Y.L., Tong, J.N., Gao, S., Zhou, L., Hu,  
3313 2467 Z.C., Liu, Y.S., 2013b. Rare-earth element patterns in conodontal bid crowns: Evidence  
3314 2468 for massive inputs of volcanic ash during the latest Permian biocrisis? *Global and*  
3315 2469 *Planetary Change* 105, 135-151.  
3316 2470 Zhao, M.Y., Zheng, Y.F., 2015. The intensity of chemical weathering: geochemical constraints  
3317 2471 from marine detrital sediments of Triassic age in South China. *Chemical Geology* 391,  
3318 2472 111-122.  
3319 2473 Zuo, J.X., Tong, J.N., Qiu, H.O., Zhao, L.S., 2003. Carbon and oxygen isotopic stratigraphic  
3320 2474 correlation and its paleoenvironment significance during the Lower Triassic, Chaohu,  
3321 2475 Anhui Province, China. *Geology-Geochemistry* 31, 26-33.  
3322 2476 Zuo, J.X., Tong, J.N., Qiu, H.O., Zhao, L.S., 2004. Carbon and oxygen isotope stratigraphy of  
3323 2477 the Lower Triassic at Northern Pingdingshan section of Chaohu, Anhui Province, China.  
3324 2478 *Journal of Stratigraphy* 28, 35-47.  
3325 2479 Zuo, J.X., Tong, J.N., Qiu, H.O., Zhao, L.S., 2006. Carbon isotope composition of the Lower  
3326 2480 Triassic marine carbonates, Lower Yangtze region, South China. *Science in China*  
3327 2481 *D–Earth Sciences* 49, 225-241.  
3328  
3329  
3330  
3331  
3332  
3333  
3334  
3335  
3336  
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3338  
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## Figures and captions

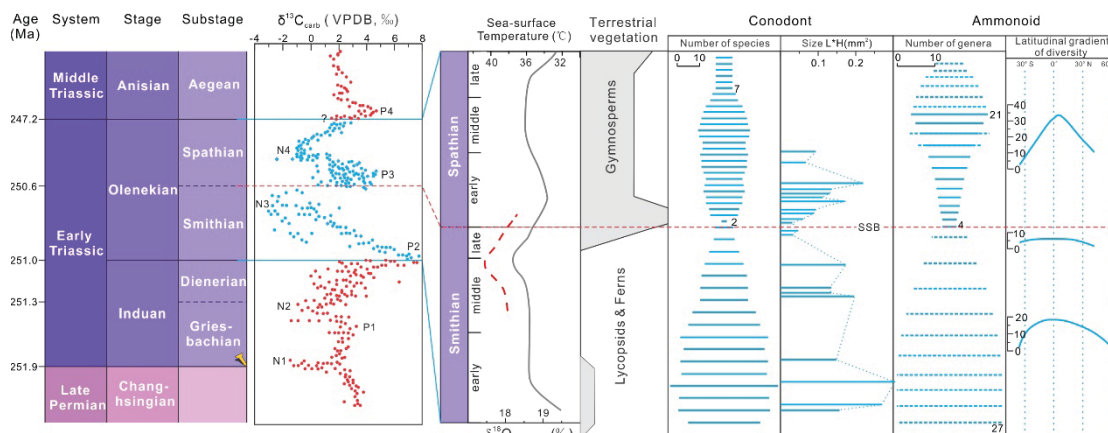


Fig. 1. Simplified carbonate carbon isotopic, climatic (sea-surface temperature) and biotic (floras, conodont and ammonoid) changes during the Smithian and Spathian substages of the Early Triassic. Carbon isotope data are from [Payne et al. \(2004\)](#) and [Chen and Benton \(2012\)](#), with numbering of negative and positive excursions (N1-N4, P1-P4) per [Song et al. \(2013\)](#). The Smithian and Spathian are subdivided into early, middle, and late intervals based on global ammonoid biostratigraphic studies summarized in [Jenks et al. \(2015\)](#). Sea-surface temperature modified after [Sun et al. \(2012\)](#) and [Romano et al. \(2013\)](#). Simplified terrestrial vegetation based on floral data from [Hochuli et al. \(2016\)](#). Conodont and ammonoid diversity profiles from [Stanley \(2009\)](#), which were drawn from global conodont records ([Orchard, 2007](#)) and regional (Canadian) ammonoid records ([Tozer, 1981a, b, 1994](#)). Conodont size data from [Chen-YL et al. \(2013\)](#), based on *Neospathodus*, *Triassospathodus* and *Novispathodus* taxa in South China (see also [Leu et al., 2018](#)). Ammonoid latitudinal gradients from [Brayard et al. \(2006\)](#). The geological time scale (note: non-linear ordinal axis) was simplified and adapted from [Burgess et al. \(2014\)](#) and [Shen et al. \(2015\)](#). SSB = Smithian/Spathian boundary.

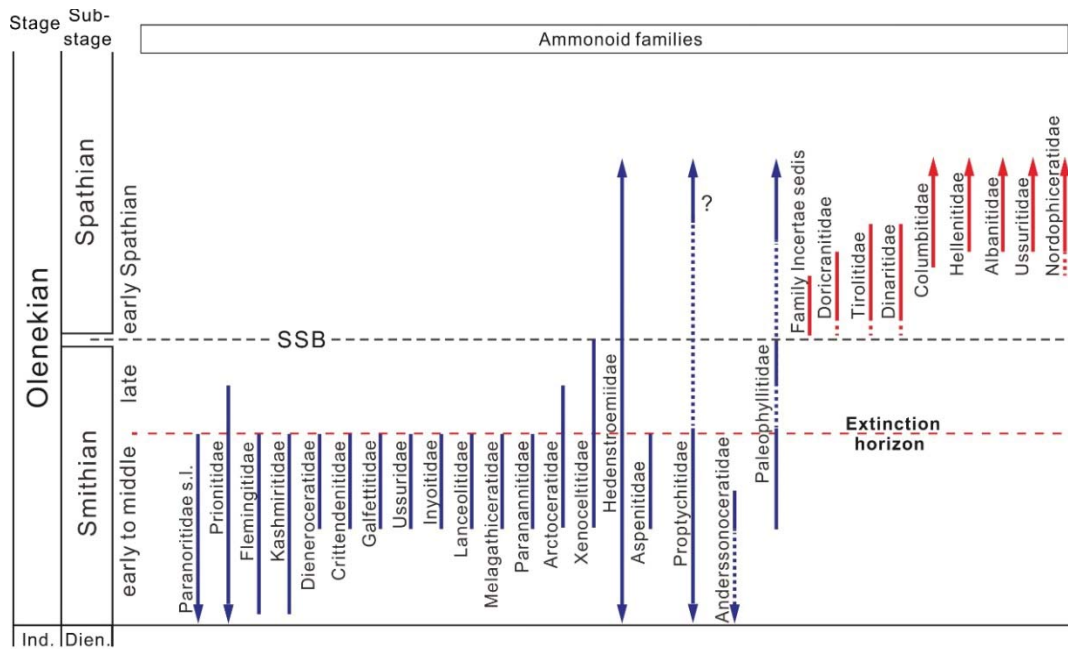


Fig. 2. Stratigraphic ranges of main ammonoid families through the Smithian and early Spathian. Based on ammonoid studies from Brayard et al. (2007b, 2013), Shigeta and Zakharov (2009), Brühwiler et al. (2010c, 2011, 2012a, b), Guex et al. (2010), Smyshlyayeva and Zakharov (2012), Jenks et al. (2013, 2015), Zakharov and Abnavi (2013), Zakharov et al. (2013), Shigeta et al. (2014), Jattiot et al. (2016, 2017), Shigeta and Kumagai (2016), Zakharov and Smyshlyayeva (2016), Shigeta and Nakajima (2017), Ware et al. (2017, 2019), and Jenks and Brayard (2018). Dien. = Dienerian, Ind. = Induan, SSB = Smithian/Spithian boundary.

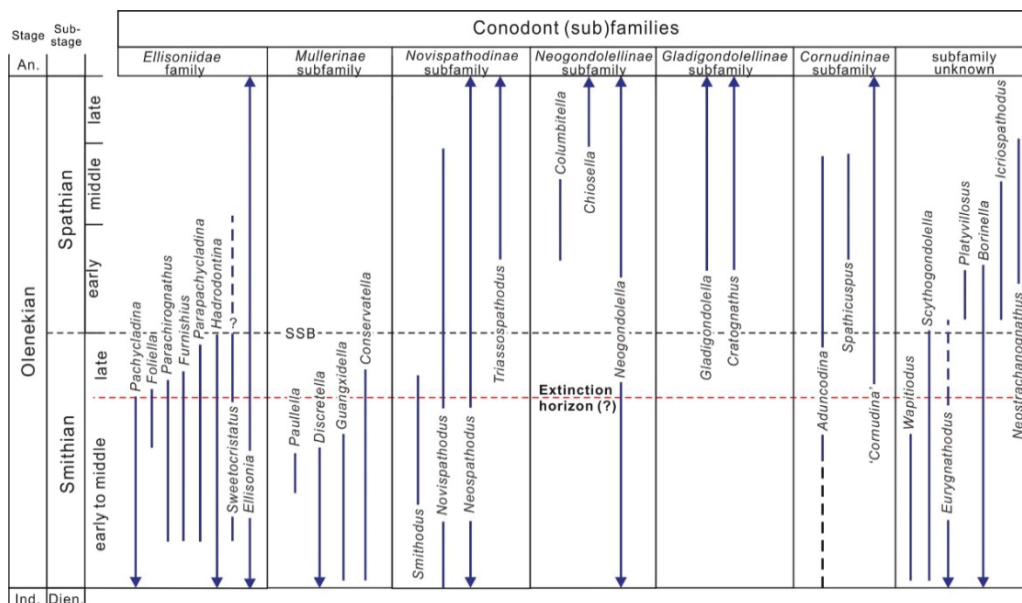


Fig. 3. Stratigraphic ranges of conodont genera through the Smithian and Spathian. Data from Orchard (2007). Dien. = Dienerian, Ind. = Induan, An. = Anisian, SSB = Smithian/Spithian boundary.



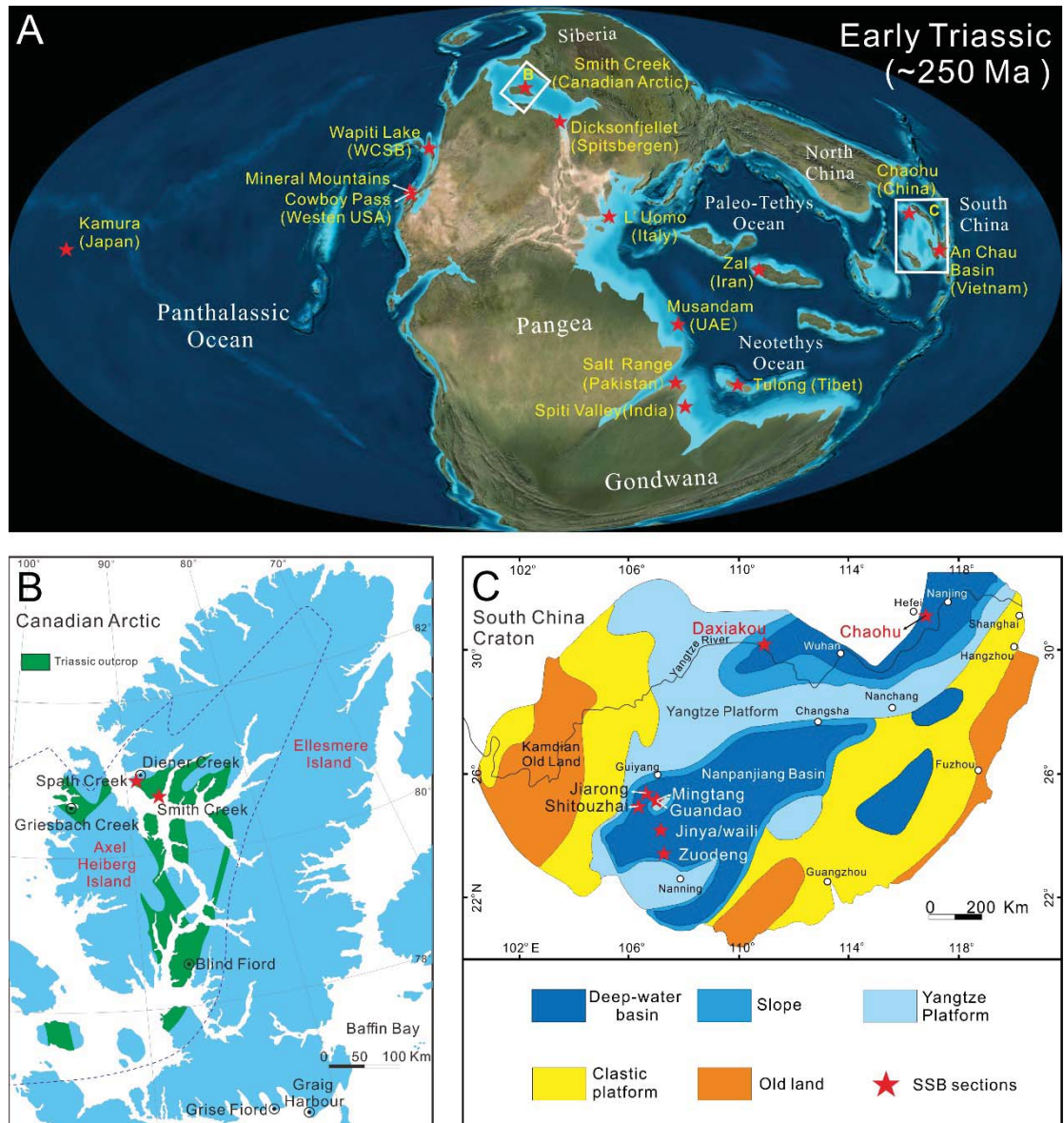


Fig. 4. Paleogeographic maps for key areas of Smithian-Spathian studies: (A) global, (B) Canadian Arctic, and (C) South China (see Bagherpour et al., 2017, for alternative facies distribution). Dotted line in B shows the margin of the Sverdrup Basin (Tozer, 1994). Map sources: base map of A is copyright Ron Blakey, Deep Time Maps; B is from Orchard (2008), and C is from Song et al. (2013).

		A		B		C		D		E		F		G	
		Canadian Arctic		British Columbia		Western USA		Chaohu (Eastern China)		Nanpaniang Basin (Southwestern China)		Salt Range (Pakistan)		Spiti Valley (India)	
		Tozer 1994	Orchard 2008	Tozer 1994	Orchard and Tozer, 1997; Orchard and Zonneveld, 2009	Guex et al. 2010; Brayard et al., 2013; Jenks et al., 2013	Orchard, 1995, 2008	Tong et al. 2004	Zhao et al. 2007	Brayard and Bucher, 2008	Chen et al. 2015	Guex, 1978; PJRG, 1985; Brühwiler et al. 2011	Brühwiler et al. 2007, 2010a, 2012; Krystyn et al. 2007a, b	Bhatt et al. 1999; Krystyn et al. 2005	
Spathian	late	Keyserlingites subrobustus Zone	Ng. spp. Fauna	Keyserlingites subrobustus Zone	Ns. symmetricus-Ng. regalis Fauna	Subrobustus subzone Haugi subzone	Ns. symmetricus-Tr. triangularis Fauna		Ns. anhuiensis Zone	Neopanoceras Haugi Zone	Tr. triangularis Zone				
	middle	Olenikites pilaticus Zone				Silberlingeria subzone Fengshanites / Prohunganites subzone	Tr. homeri Fauna	Subcolumbites Zone	Tr. homeri Zone	Hellanites beds	Tr. homeri Zone	Nordopliceras sp. Zone Tozeroceras pakistanum Zone		Tozeroceras pakistanum Zone	Ch. gondolelloides Zone
	early					Pracolumbites subzone Columbites parisiensis subzone Tirolites harti beds	Ic. collinsoni Fauna	Tirolites-Columbites Zone	Nv. pingdingshanensis Zone	Procolumbites beds Tirolites/Columbites beds Tirolitid n. gen. A beds	Ic. collinsoni Zone Nv. pingdingshanensis Zone	Eophyllites sp. Zone Tirolites-Columbites Zone	Tr. triangularis - Tr. homeri Zone	Tirolites-Columbites Zone	Ic. collinsoni Zone
Smithian	late	Anawasatchites tardus Zone	Sc. milleri Fauna	Anawasatchites tardus Zone	Sc. mosheri Zone Sc. milleri Zone Sc. phryna Zone	Xenoceltitidae beds Anasibirites multiformis beds	Sc. milleri Fauna	Anasibirites Zone		Anasibirites multiformis beds	Pachycladina, Parachirognathus Zone	Glyptopliceras sinuatum beds	Ng. elongata Zone	Glyptopliceras sinuatum beds Subvishnites posterus beds	Sc. milleri Zone
	middle	Euflemingites romunduri Zone	Nv. waageni Fauna	Euflemingites romunduri Zone	Paullella meeki Zone Sc. lachrymiformis Zone	Inyoites beds Hanielites beds Minersvill beds	Nv. waageni Fauna	Flemingites-Euflemingites Zone	Nv. waageni waageni Zone	Inyoites beds Hanielites beds Ussuria beds Flemingites rursiradiatus beds	Nv. waageni waageni Zone	Owenites beds Nyalamites anguste. beds Pseudocelites multiplicatus b. Nammalites pilatoides beds	Nv. waageni Zone	Nyalamites anguste. beds Pseudocelites multiplicatus b. Shigetaceras b. Escarguelites b. Brayardites compressus beds Dieneroceras beds F. flemingianus beds	Nv. waageni Zone
	early	Hedenstroemia hedenstroemi Zone	Ns. pakistanensis Fauna		Borineilla nepalensis Zone	Flemingites beds I. baaverensis beds Pretlo. - Kash. beds M. millardense beds M. olivieri beds R. aff. evolvens beds V. undulatus beds	Nv. waageni eowaageni Zone		Kashmirites kapila beds		Nv. waageni eowaageni Zone	Brayardites compressus beds E. cirratus beds C. superbum beds R. evolvens beds F. napus beds X. perplicatus beds S. rursiradiatus beds F. bhargavai beds		Rohillites rohilla beds V. pulcher beds Kashmiritidae beds F. bhargavai beds	Nv. waageni eowaageni Zone

Fig. 5. Simplified correlation of some regional ammonoid-conodont zonation schemes for the Smithian-Spathian substages. Blue and orange bars at tops of columns represent ammonoid and conodont zonations, respectively. Note that ammonoid biozones are usually based on faunal assemblages that are not temporally continuous (see Jenks et al., 2015, for a detailed review), whereas conodont biozones are usually based on first occurrences of key conodont taxa and, thus, generally shown as temporally continuous. The two zonations may therefore not exactly

correlate. Correlations between ammonoid and conodont zonations are based on original published sources and are thus approximate and subject to further refinement (see text for details). Abbreviations (ammonoids): b. = beds; C. = *Clypeoceras*; E. = *Euflemingites*; F. = *Flemingites*; I. = *Inyoites*; Kash. = *Kashmirites*; M. = *Meekoceras*; Preflo = *Preflorianites*; R. = *Radioceras*; S. = *Shamaraites*; Ver. = *Vercherites*. X. = *Xenodiscoides*. Abbreviations (conodonts): Ng. = *Neogondolella*; Sc. = *Scythogondolella*; Ns. = *Neospathodus*; Nv. = *Novispathodus*; Tr. = *Triassospathodus*; Ic. = *Icriospathodus*; Ch. = *Chiosella*.

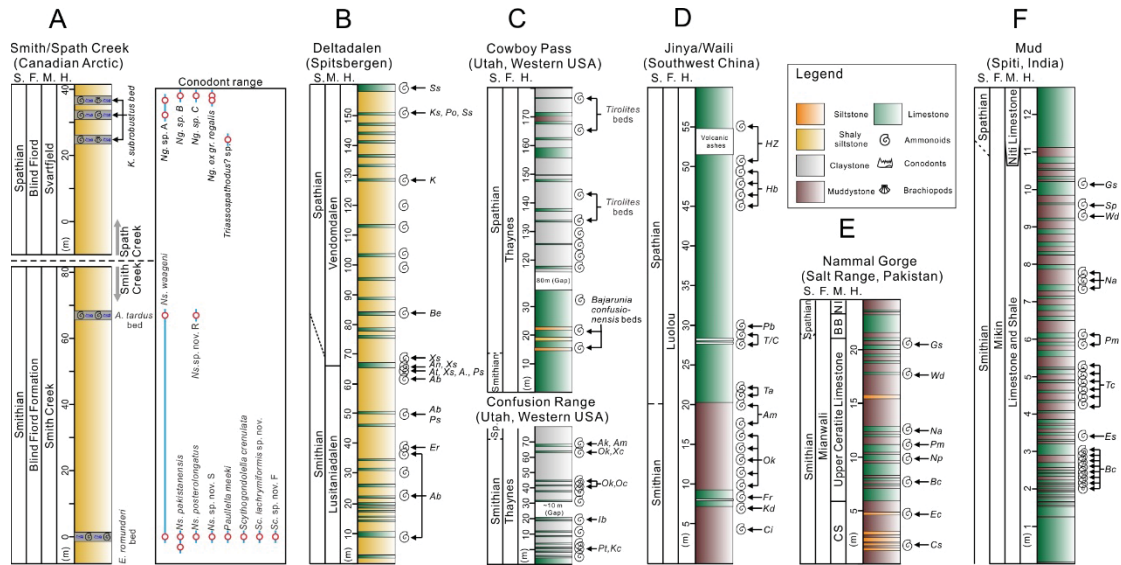


Fig. 6. Distributions of ammonoids and conodonts in some representative SSB sections. Data sources: Smith Creek and Spath Creek from Orchard (2008); Deltadalen from Mørk et al (1999); Cowboy Pass from Gux et al. (2010); Confusion Range from Brayard et al. (2013); Nammal Gorge from Brühwiler et al. (2010, 2011, 2012a); Mud from Brühwiler et al. (2012); and Jinya/Waili from Galfetti et al. (2007b). Abbreviations: S. = Stage, F. = Formation, M. = Member, H. = Height. BB = Bivalve Beds, NI = Niveaux Intermédiaires, A = *Anasibirites* sp., Ab = *Arctoceras blomstrandii*, Ak = *Anasibirites kingianus*, Am = *Anasibirites multififormis*, An = *Arctoprionites nodosus*, At = *Anawasatchites tardus*, Bc = *Brayardites compressus*, Be. = *Bajarunia ex gr. euomphala*, Ci = *Clypites* sp. indet, Cs = *Clypeoceras superbum*, Ec = *Euflemingites cirratus*, Er = *Euflemingites romunderi*, Es = *Escarguelites spitiensis*, Fr = *Flemingites rursiradiatus*, Gs = *Glyptophteras sinuatum*, H = *Hellenites*, HZ = *Haugi Zone*, Ib = *Inyoites beaverensis* sp. nov., K = *Keyserlingites* sp., Kc = *Kashmirites confusionensis*, Ks = *Keyserlingites subrobustus*, Na = *Nyalamites angustecostatus*, Np = *Nammalites pilatoides*, Ok = *Owenites carpenteri*, Ok = *Owenites koeneni*, P = *Procolumbites*, Pm = *Pseudoceltites multiplicatus*, Po = *Popovites occidentalis*, Pt = *Preflorianites toulai*, Sp = *Subvishnuites posterus*, Ss = *Svalbardiceras spitzbergense*, Ta = *Tirolitid* n. gen. A., Tc = *Truempyceras compressum*, T/C = *Tirolites/Columbites*, Wd = *Wasatchites distractus*, Xc = *Xenoceltites cordilleranus*, Xs = *Xenoceltites subevolatus*, Ps = *Pseudosageceras* sp.



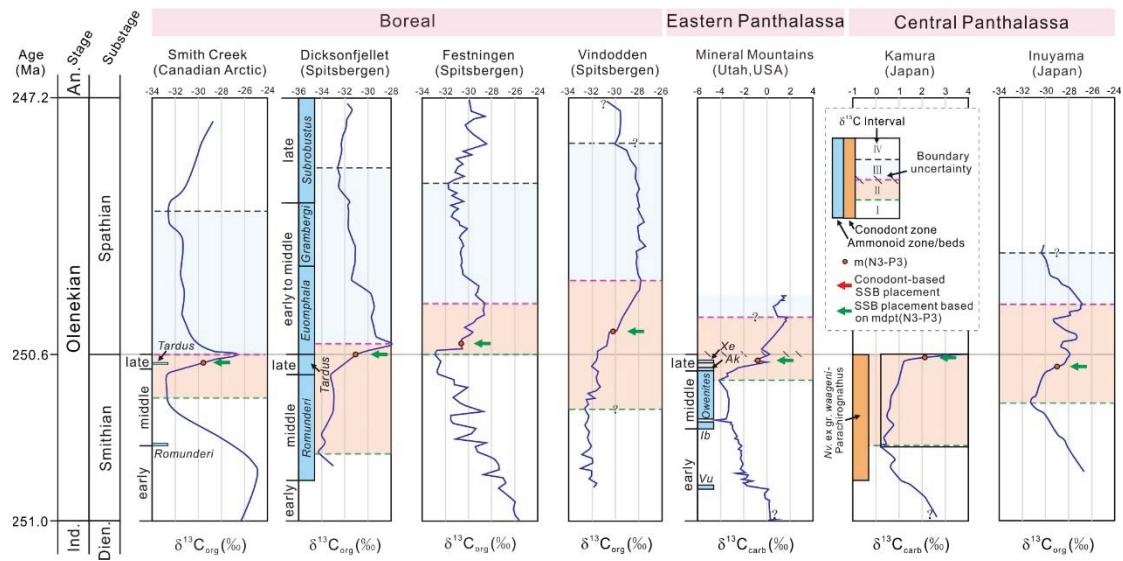


Fig. 7. Detailed correlations of Smithian-Spathian sections in the Boreal and eastern and central Panthalassic regions based on a combination of ammonoid and conodont biostratigraphy and C-isotope chemostratigraphy. Data sources: Smith Creek from Tozer (1967) and Grasby et al. (2013), Dicksonfjellet from Weitschat and Dagys (1989) and Galfetti et al. (2007a), Festningen from Grasby et al. (2016), Vindodden from Wignall et al. (2016), Mineral Mountains from Thomazo et al. (2016), Kamura from Zhang et al. (2017), and Inuyama from Sakuma et al. (2012). The SSB placements shown here are those from the original publications. In this study, we have divided each  $\delta^{13}\text{C}$  profile into intervals I-IV (for visualization purposes, Interval II is colored pink and Interval III blue) bracketed by correlatable datums (shown as green, red, and black dashed lines). Another correlatable feature is 'mdpt(N3-P3)' (shown as orange dots), which represents the isotopic midpoint between the middle/late Smithian N3 minimum and the earliest Spathian P3 maximum, and which may serve as an auxiliary marker for the SSB. Abbreviations: Vu = *Vercherites undulatus*; I.b. = *Inyoites beaverensis*; O = *Owenites*; Ak = *Anasibirites kingianus*; Xe = *Xenoceltitidae* 'gen. indet.' A.; Dien. = Dienerian, Ind. = Induan, An. = Anisian. See Figure 1 for time scale.

### South Majiashan (Chaohu, eastern China)

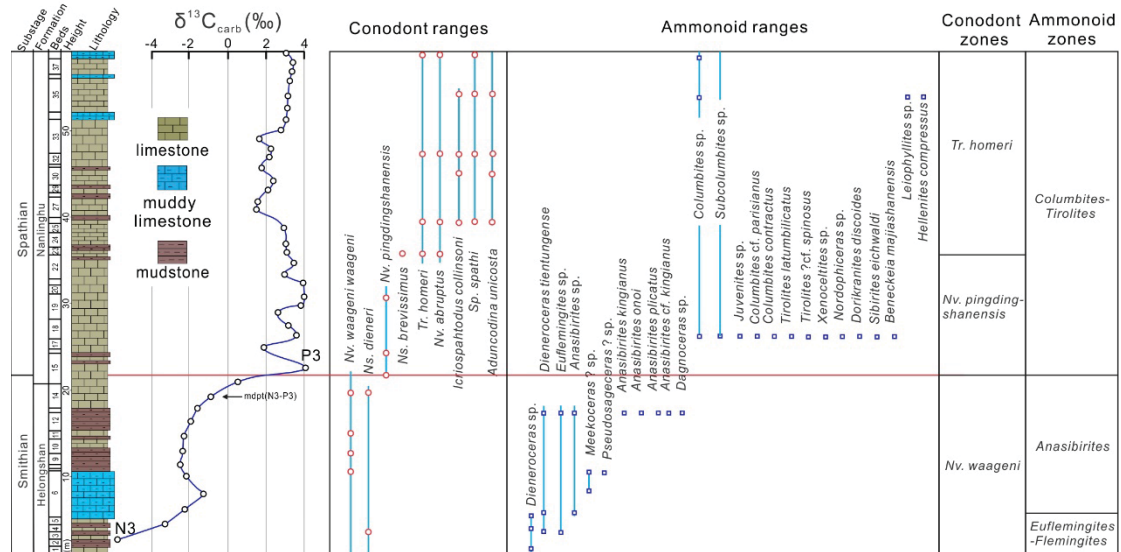


Fig. 8. Conodont, ammonoid and carbon isotopic stratigraphy at South Majiashan section in Chaohu area, eastern China. Data sources: carbon isotope from [Tong et al. \(2007\)](#); conodont ranges from [Zhao et al. \(2007a\)](#); ammonoid ranges from [Guo \(1982\)](#) and [Tong et al. \(2004\)](#). Abbreviations: Ng. = *Neogondolella*; Ns. = *Neospathodus*; Nv. = *Novispathodus*; Tr. = *Triassospathodus*.

### North Pingdingshan (Chaohu, eastern China)

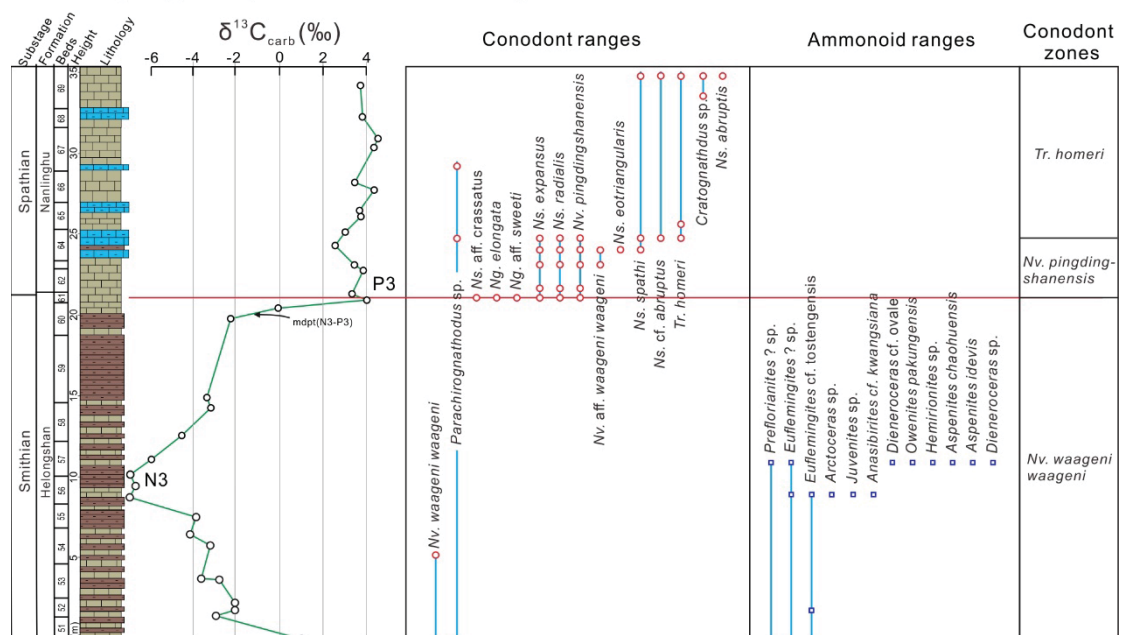


Fig. 9. Conodont, ammonoid and carbon isotopic stratigraphy at North Pingdingshan section in Chaohu area, eastern China. Data sources: carbon isotope from [Zuo et al. \(2004\)](#); conodont and ammonoid ranges from [Zhao et al. \(2007a\)](#). See [Figure 8](#) for legend and abbreviations.

West Pingdingshan (Chaohu, eastern China)

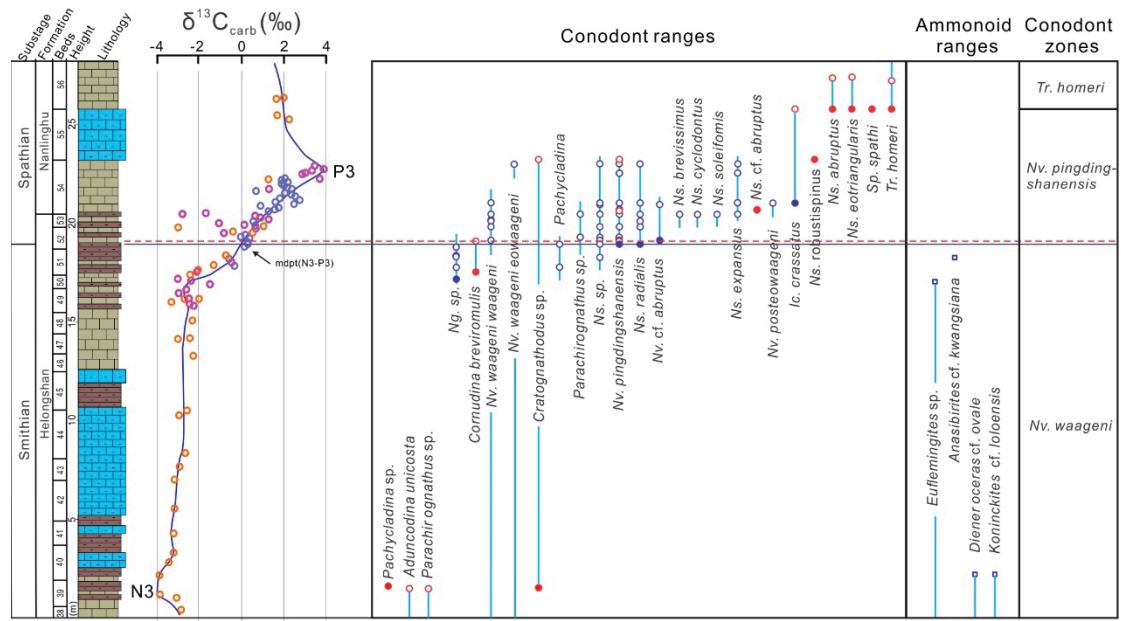


Fig. 10. Conodont, ammonoid and carbon isotopic stratigraphy at West Pingdingshan section in Chaohu area, eastern China. Data sources: carbon isotope from [Tong and Zhao \(2011\)](#) (orange), [Liang et al. \(2011\)](#) (pink) and [Zhao and Zheng \(2014\)](#) (light blue); conodont ranges from [Zhao et al. \(2007a\)](#) (red circles) and [Liang et al. \(2011\)](#) (blue circles); ammonoid ranges from [Zhao et al. \(2007a\)](#). Placement of the SSB (i.e., first occurrence of *Nv. pingdingshanensis*) by [Zhao et al. \(2007a\)](#) is shown as a red line and the revised datum by [Liang et al. \(2011\)](#) as a blue line. Solid circles represent first occurrences of individual conodont species. See [Figure 8](#) for legend and abbreviations.

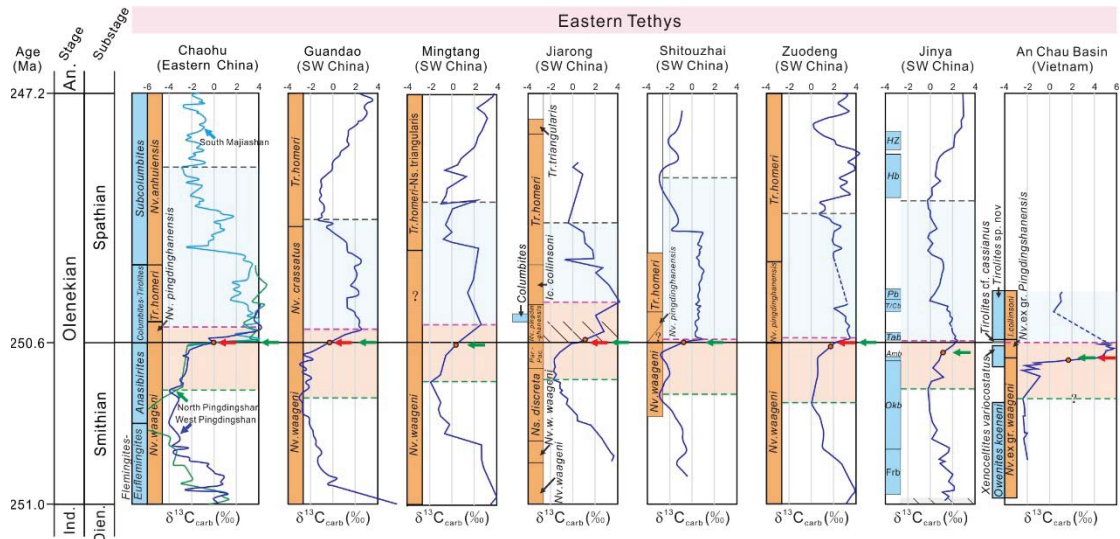


Fig. 11. Detailed correlations of Smithian-Spathian sections in the eastern Tethys region based on a combination of ammonoid and conodont biostratigraphy and C-isotope chemostratigraphy. Data sources: Chaohu from Zuo et al. (2003, 2004), Tong et al. (2004, 2007) and Zhao et al. (2007a); Guandao and Zuodeng from Wang et al. (2005), Tong et al. (2007), and Lehmann et al. (2015); Mingtang from Liang et al. (2016); Jiarong from Chen-YL et al. (2013, 2015) (note: oblique lines represent uncertainty in SSB placement); Shitouzhai from Zhang et al. (2015); Jinya from Galfetti et al. (2007c); and An Chau Basin from Komatsu et al. (2016). Abbreviations: Dien. = Dienerian, Ind. = Induan, An. = Anisian, HZ = *Haugi Zone*, Hb = *Hellenites beds*, Pb = *Procolumnites beds*, T/Cb = *Tirolites/Columbites beds*, TAb = *Tirolitid n. gen. A. beds*, Okb = *Owenites koeneni beds*, Amb = *Anasibirites multififormis beds*, Frb = *Flemingites rursiradiatus beds*. See Figure 1 for timescale and Figure 7 for legend (including green and red arrows).



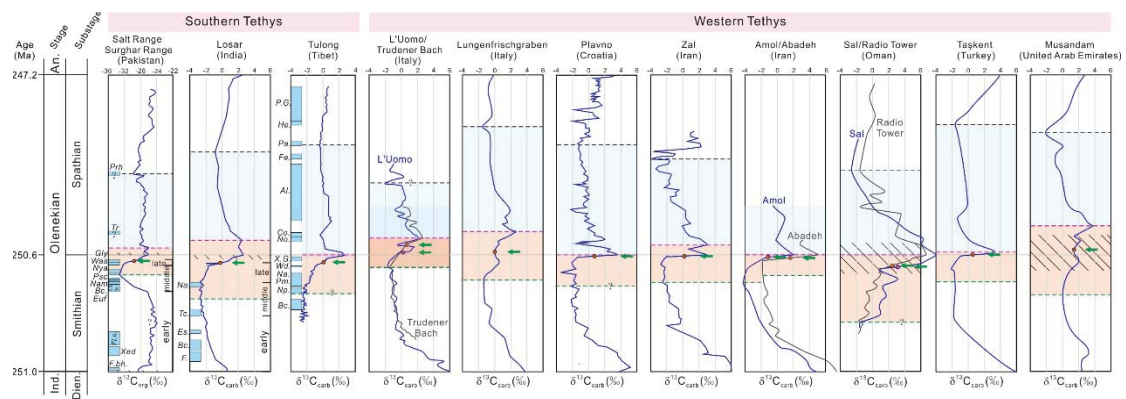


Fig. 12. Detailed correlations of Smithian-Spathian sections in the southern Tethys (North Indian Margin) and western Tethys regions based on a combination of ammonoid and conodont biostratigraphy and C-isotope chemostratigraphy. Data sources: Salt Range and Surghar Range from [Hermann et al. \(2012\)](#) (note: oblique lines represent uncertainty in SSB placement); Losar from [Galfetti et al. \(2007c\)](#); Tulong from [Brühwiler et al. \(2009, 2010\)](#) and [Schneebeli-Hermann et al. \(2012\)](#); L' Uomo from [Horacek et al. \(2007a\)](#); Trudener Bach and Lungenfrischgraben from [Horacek et al. \(2010\)](#); Plavno from [Aljinović et al. \(2018\)](#); Zal, Amol, and Abadeh from [Horacek et al. \(2007b\)](#); Sal from [Richoz \(2006\)](#); Radio Tower from [Clarkson et al. \(2016\)](#); Taşkent from [Lau et al. \(2016\)](#); Musandam from [Clarkson et al. \(2013\)](#). Abbreviations (sub/stages): Dien. = Dienerian, Ind. = Induan, An. = Anisian; (ammonoids): Al. = *Albanitid* n. gen, Bc. = *Brayardites compressus*, Co. = *Columbites*, C.s. = *Clypeoceras superbum*, Es. = *Escarguelites spitiensis*, Euf. = *Euflemingites cirratus*, F. = *Flemingites*, F.bh. = *Flemingites bhargavai*, Fe. = *Fengshanites*, Fl.n. = *Flemingites nanus*, Gly = *Glyptophticeras sinatum*, He. = *Hellenites*, Na. = *Nyalamites angustecostatus*, Nam = *Nammalites pilatoides*, No. = *Nordophticeras*, Np. = *Nammalites pilatoides*, Nya = *Nyalamites angustecostatus*, Pa. = *Paragoceras*, P.G. = *Pseudodanubites-Gymnites*, Pm. = *Pseudoceltites multiplicatus*, Prh = *Prohungarites*, Psc = *Pseudoceltites multiplicatus*, Tc. = *Truempyceras compressum*, Tr = *Tirolites*, Was = *Wasatchites distractus*, Wd. = *Wasatchites distractus*, Xed = *Xenodiscoides perplicatus*, X.G. = *Xenoceltites-Glyptophticeras*. See [Figure 1](#) for timescale and [Figure 7](#) for legend (including green and red arrows).

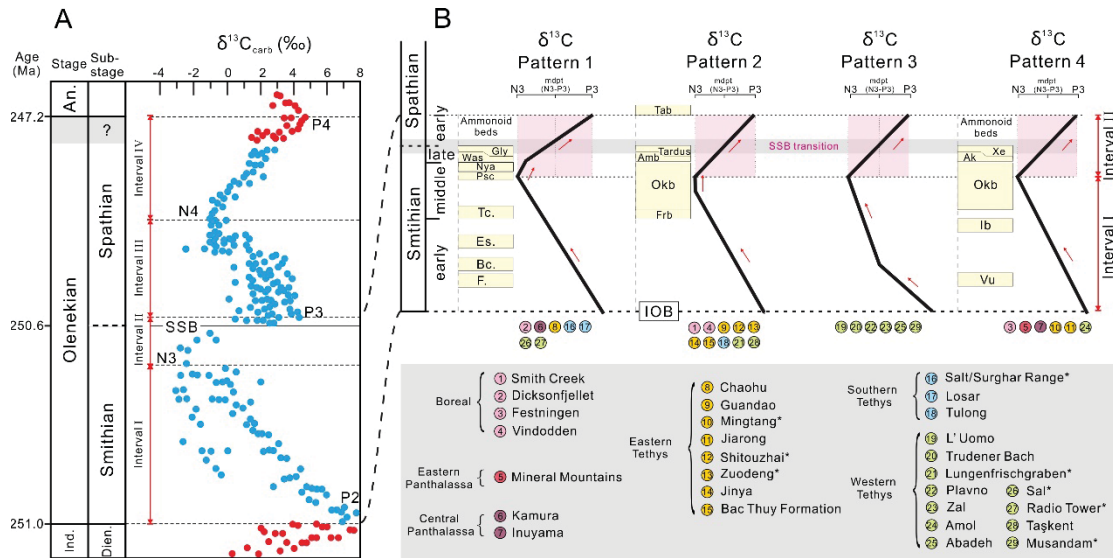


Fig. 13. (A) Carbon-isotope Intervals I to IV of the Olenekian substage.  $\delta^{13}C$  data from Payne et al. (2004) and Chen and Benton (2012); N2-N3 and P2-P4 represent  $\delta^{13}C$  minima and maxima per Song et al. (2013); and mdpt(N3-P3) is the isotopic midpoint between N3 and P3. (B)  $\delta^{13}C$  variation patterns 1 to 4 within the early Smithian to early Spathian (Intervals I-II) based on 29 sections globally; asterisks (\*) represent tentative assignments. The pink boxes highlight Interval II, which encompasses the SSB. The early/middle/late subdivisions of the Smithian and Spathian are based on ammonoid biostratigraphic studies as reviewed in Jenks et al. (2015). Representative ammonoid assemblages for Pattern 1 from Salt and Surghar ranges (Hermann et al., 2012) and Losar (Galfetti et al., 2007c), for Pattern 2 from Jinya (Galfetti et al., 2007c), and for Pattern 4 from Mineral Mountains (Thomazo et al., 2016). For abbreviations of ammonoid assemblages, see Figures 7, 11-12. See Figure 1 for other details.

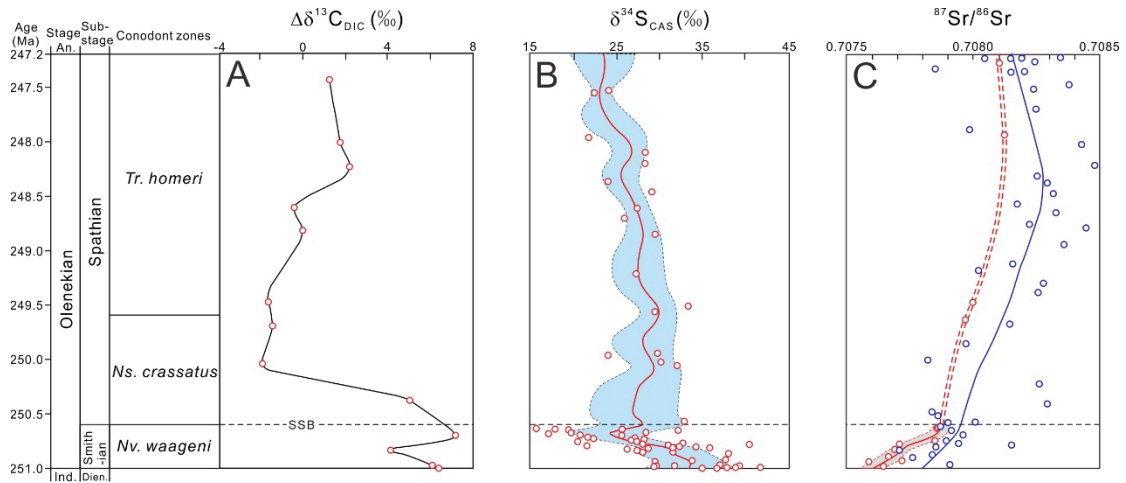


Fig. 14. Some other geochemical records for the Smithian and Spathian: (A)  $\Delta\delta^{13}\text{C}_{\text{DIC}}$  (from Song-HY et al., 2013), (B)  $\delta^{34}\text{S}_{\text{CAS}}$  (from Song-HY et al., 2014), and (C)  $^{87}\text{Sr}/^{86}\text{Sr}$  (dashed red line = Sedlacek et al., 2014; solid blue line = Song-HJ et al., 2015). Conodont zones are from Song-HY et al. (2013, 2014). Dien. = Dienerian, Ind. = Induan, An. = Anisian.

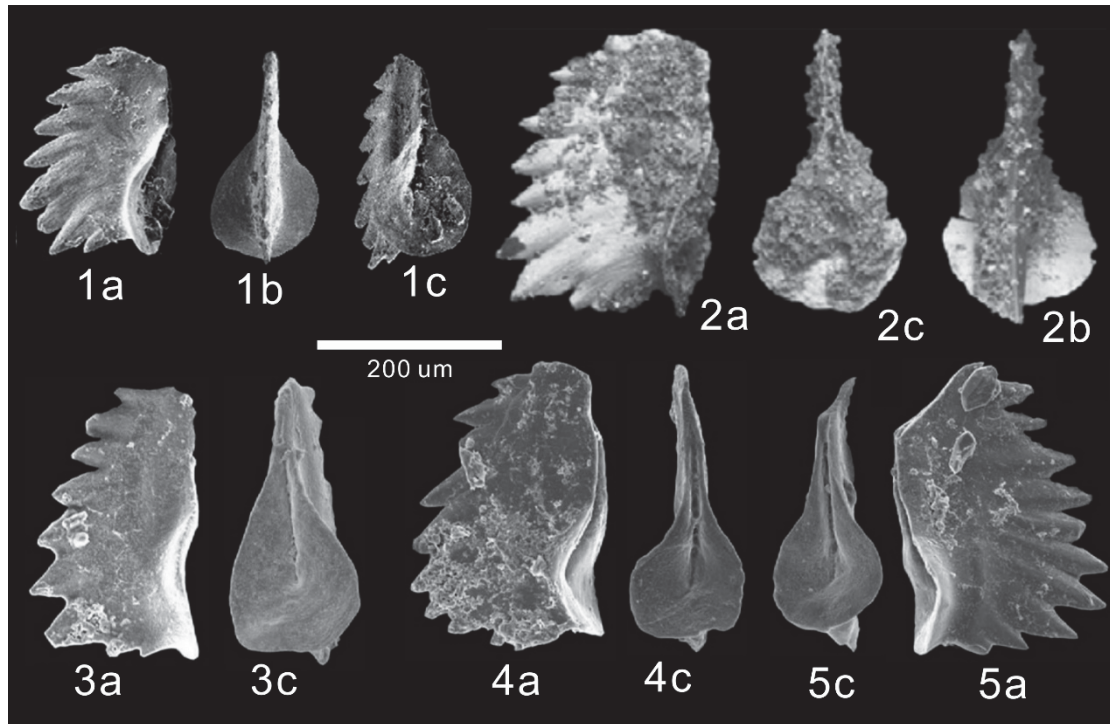


Fig. 15. Photographs of conodont *Novispathodus pingdingshanensis*. a = lateral view; b = upper view; c = lower view. 1) Holotype of *Nv. pingdingshanensis* (CUG03054) from West Pingdingshan, Chaohu area, eastern China (Zhao et al., 2007a); 2) *Nv. ex. gr. pingdingshanensis* (MPC25395) from the An Chau Basin, northeastern Vietnam (Komatsu et al., 2016); and 3-5) *Nv. pingdingshanensis* from Jiarong, Nanpanjiang Basin, southwestern China (Chen-YL et al., 2015).



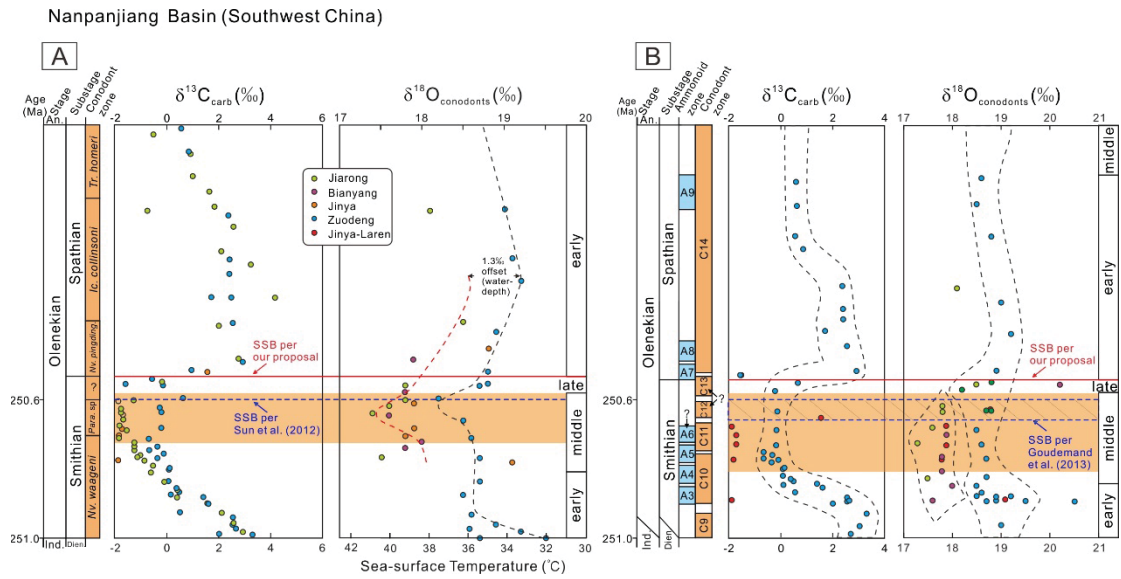


Fig. 16. Comparison of SSB placement based on mdpt(N3-P3) (red solid line; [this study](#)) with earlier SSB placements (blue dash lines) of [Sun et al. \(2012; A\)](#) and [Goudeband et al. \(2013; B\)](#). The orange field represents the interval of the Smithian Thermal Maximum (STM). Note that our SSB placement corresponds to a cooling event, as now widely accepted (e.g., [Goudeband, 2014b, 2018](#); [Zhang-L et al., 2017](#); [Zhang-F et al., 2018](#); [Stebbins et al., 2018a, b](#)). Abbreviations: *Nv. pingding.* = *Nv. pingdingshanensis*; A3 = *Kashmirites densistriatus*; A4 = *Flemingites rursiradiatus*; A5 = *Owenites koeneni*; A6 = *Anasibirites multiformis*; A7 = Tirolitid n. gen. A; A8 = *Tirolites/Columbites*; A9 = *Procolumnites*; C9 = *Neospathodus dieneri*; C10 = *Novispathodus waageni*; C11 = *Parachirognathus* sp.; C12 = *Nv. pingdingshanensis*; C13 = *Icriospathodus collinsoni*; C14 = *Triassospathodus homeri/Ns. symmetricus*. See [Figure 1](#) for other details.