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The Smithian/Spathian boundary (late Early Triassic):

a review of ammonoid, conodont, and carbon-isotopic criteria

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Abstract

The transition from the Smithian substage to the Spathian substage of the Olenekian stage of the late Early Triassic was a critical time marked by a series of biological and environmental changes during the multimillion-year recovery interval following the end-Permian mass extinction. However, the Smithian/Spathian boundary (SSB) has not yet been formally defined, a shortcoming that inhibits targeted detailed studies of successive events during the Smithian-Spathian transition and the recovery of the marine ecosystem during the Early Triassic. Here, we review main biostratigraphic (i.e., ammonoid and conodont) studies of the Smithian and Spathian substages in historically important regions (e.g., the Canadian Arctic for the Boreal realm, western North America for the eastern Panthalassic Ocean) and more recently re-studied locations (e.g., Pakistan and India in the southern Tethys, South China in the eastern Tethys) as well as the carbon isotope chemostratigraphy of 29 major Smithian-Spathian sections globally. Key ammonoid genera (e.g., *Wasatchites*, *Anasibirites*, *Glyptophiceras* and *Xenoceltites* of the late Smithian, and *Bajarunia*, *Tirolites* and *Columbites* of the early Spathian), conodont species (e.g., *Scythogondolella milleri*, *Novispathodus waageni*, and *Borinella buurensis* of the late Smithian, and ‘*Triassospathodus*’ *hungaricus*, *Neogondolella* aff. *sweeti*, and *Icriospathodus* spp. of the early Spathian), and carbonate carbon isotope excursions provide appropriate markers for constraining the SSB. Use of the first occurrence of the conodont *Novispathodus pingdingshanensis* as a potential marker of the SSB is also discussed. Based on correlations of biostratigraphic and carbon isotope data globally, we propose to revise previous placements of the SSB transition in some sections. Finally, we show that the Smithian Thermal Maximum (STM; herein named) was middle Smithian in age and not correlative with the SSB, as inferred in some earlier studies, and that the SSB coincided 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;
65 45

66 46 67 47 **Outline**

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102 76 103 77 **1. Introduction**

104 78

105 79 The Early Triassic is officially divided into two stages, the Induan and Olenekian, with the
106 79 latter divided into two substages, the Smithian (ca. 0.7 Myr long) and Spathian (ca. 3 Myr long)
107 80 (Fig. 1; Ovtcharova et al., 2006, 2015; Lehrmann et al., 2006; Galfetti et al., 2007; Mundil et
108 81 al., 2010; Baresel et al., 2017). An alternative timescale based on cyclostratigraphic analysis of
109 82 successions in Germany and China has assigned durations of 1.7 and 1.4 Myr to the Smithian
110 83 and Spathian substages, respectively (Li et al., 2016a). The boundary between the Smithian
111 84 and Spathian substages is an important transition during the recovery of marine ecosystems
112 84 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; Schneebeli-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
187 136 sections and points (GSSPs) based on the first appearance datums (FADs) of *Hindeodus parvus*
188 137 (Yin et al., 2001) and *Neospathodus* ex gr. *waageni* (Zhao et al., 2002, 2004, 2008a, b; Tong
189 138 et al., 2003, 2004; Goudemand, 2014a), respectively. Subsequently, high-resolution conodont
190 139 biozonation studies of the Lower Triassic have been undertaken broadly around the world (e.g.,
191 140 Krystyn et al., 2005; Henderson and Mei, 2007; Nakrem et al., 2008; Orchard, 2008; Orchard
192 140 and Zonneveld, 2009; Zhao et al., 2013a; Chen-YL et al., 2015; Lyu et al., 2017).

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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
199 146 will not be addressed for some time yet. However, there is considerable value in establishing a
200 147 precise (not formal) definition for the SSB to direct future work. The present contribution has
201 148 several goals: (1) we review the history of studies of the Smithian-Spathian transition by region
202 149 globally, (2) we summarize known key features of ammonoid and conodont biostratigraphy as
203 150 well as carbon isotope chemostratigraphy that may prove useful for future formal definition of
204 151 the SSB, and (3) we examine placements of the SSB in earlier studies, considering problematic
205 152 placements and offering corrections in some cases. The present study may serve as an important
206 153 reference for the future formal definition of the SSB and in investigation of the major events
207 154 associated with it.
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212 157 **2. Evolutionary history of ammonoids and conodonts during the Smithian-Spathian** 213 158 **transition**

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215 160 Following the EPME, the diversity (*sensu* taxonomic richness) of ammonoids and
216 161 conodonts increased and their turnover rates became more rapid than those of most other
217 161 marine invertebrate clades (Brayard et al., 2006, 2009b; Orchard, 2007; Brühwiler et al., 2010a,
218 162 b, c; Ware et al., 2015). They thus provide an appropriate basis for construction of a detailed,
219 163 accurate biostratigraphic framework for the Early Triassic. Both ammonoids and conodonts
220 164 show relatively similar patterns of rapid diversifications and extinctions during the Early
221 165 Triassic: rising diversity during the Griesbachian was followed by a minimum in the middle
222 166 Triassic: rising diversity during the Griesbachian was followed by a minimum in the middle
223 166 Dienerian, and then by major radiative bursts in the early Smithian (Tozer, 1981a, b; Brayard
224 167 et al., 2006, 2009b; Orchard, 2007; Brühwiler et al., 2010a, b, c; Zakharov and Abnavi, 2013;
225 168 Ware et al., 2015). Both clades experienced a second deep-cutting extinction at the beginning
226 169 of the late Smithian, followed by another rapid diversification in the early Spathian. The late
227 170 Smithian also corresponds to a drastic reduction of the ammonoid morphological disparity with
228 171 the disappearance of sphaeroconic forms (Brosse et al., 2013). These diversity (*sensu lato*)
229 172 fluctuations correspond to the large carbonate C-isotope shifts and temperature fluctuations of
230 172 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.

3.1 Canadian Arctic (western Boreal)

3.1.1 Ammonoid and conodont biostratigraphy

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

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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

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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)

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580 434 3.3.1 Ammonoid and conodont biostratigraphy

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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

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

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

3.5.2. Carbon-isotope chemostratigraphy

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

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

3.6. Chaohu area, eastern China (eastern Tethys)

3.6.1. Ammonoid and conodont biostratigraphy

The Chaohu area of eastern Anhui Province, eastern China, has come under intense investigation in recent years, including studies of its sedimentology (Li et al., 2007; Chen-ZQ et al., 2011), geochemistry (Tong et al., 2002, 2007; Zuo et al., 2006; Horacek et al., 2007c; Chen-JB et al., 2015; Zhao and Zheng, 2015), cyclostratigraphy (Li et al., 2007; Li et al., 2016a, b), and other topics (Chen-ZQ et al., 2010; Motani et al., 2015; Huang et al., 2017). During the Early Triassic, it was situated on a deep ramp on the northern margin of the Yangtze Platform, eastern China (Tong et al., 2004). At Chaohu, the Lower Triassic consists of the Yinkeng, Helongshan and Nanlinghu formations, in ascending order, in which are developed a multilevel hierarchy of mudstone and limestone cycles (Li et al., 2007; Tong et al., 2007). The Yinkeng and Helongshan formations comprise interbedded mudstone and (muddy) limestone, whereas 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. *kwangiana* 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
1013 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
1020 759 that some small specimens of *Nv. pingdingshanensis* were of late Smithian age (see Maekawa
1021 760 and Komatsu, 2014; Komatsu et al., 2016 in An Chau Basin, Section 3.8) and placed the SSB
1022 761 within the *Nv. pingdingshanensis* Zone, between the first occurrence of *Nv. pingdingshanensis*
1023 762 and the *Columbites* beds. Chen-YL et al. (2018) recently revised conodont occurrences in
1024 763 Jiarong and confirmed the late Smithian occurrence of *Nv. pingdingshanensis*. At Mingtang
1025 764 and Shitouzhai, reports of early Spathian conodonts are not well-established. Thus, the SSB
1026 765 was placed based only on global correlations of carbon isotope profiles (Zhang et al., 2015;
1027 766 Liang et al., 2016; see Section 3.7.2). At Bianyang, the SSB was not clearly located because
1028 767 only early Spathian *Icriospathodus collinsoni* was recovered (Yan et al., 2013). At Qingyan,
1029 768 the Olenekian strata were assigned to the *Nv. waageni* and *Triassospathodus homeri* conodont
1030 769 zones, and the FAD of *Nv. crassatus* and *Nv. pingdingshanensis* are (nearly) the same as the
1031 770 first occurrence of *Tr. homeri*, making placement of the SSB somewhat equivocal (Ji et al.,
1032 771 2011).

1033 772 3.7.2. Carbon-isotope chemostratigraphy

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1036 775 In Nanpanjiang Basin, carbon isotope profiles of the Olenekian Stage have been generated
1037 776 for multiple sections, including Jinya area (Galfetti et al., 2007c), Guandao (Tong et al., 2007),
1038 777 Zuodeng (Tong et al., 2007), Jiarong (Chen-YL et al., 2013), Mingtang (Liang et al., 2016) and
1039 778 Shitouzhai (Zhang et al., 2015) (Fig. 11). Guandao and Mingtang show similar $\delta^{13}\text{C}_{\text{carb}}$ trends,
1040 779 with a negative excursion from high values (ca. +4 to +6 ‰) in the lowermost Smithian to ca.
1041 780 -2 ‰ (N3) in the middle Smithian, a rebound to ca. +2.5 ‰ in the lowermost Spathian, a long
1042 781 plateau in the lower Spathian, a second negative excursion to ca. -1 ‰ (N4) in the middle
1043 782 Spathian, and finally a positive excursion to ca. +4 ‰ in the uppermost Spathian (Tong et al.,
1044 783 2007; Liang et al., 2016). The $\delta^{13}\text{C}_{\text{carb}}$ profile at Jiarong is similar to that at Mingtang except
1045 784 for the absence of a plateau in the lower Spathian (Chen-YL et al., 2013). At Zuodeng, $\delta^{13}\text{C}_{\text{carb}}$
1046 785 shows high values (ca. +4 ‰) in the lowermost Smithian, a decrease to ~0 ‰ (N3) in the middle
1047 786 Smithian, a rebound to ca. +3 ‰ (P3) in the lower Spathian (base of the *Nv. pingdingshanensis*
1048 787 Zone), a minor negative excursion (to ca. +1 ‰; N4) in the mid-Spathian, and finally
1049 788 fluctuations between ~0 and +4 ‰ in the upper Spathian (Tong et al., 2007). The $\delta^{13}\text{C}_{\text{carb}}$ profile
1050 789 at Jinya is similar to that at Zuodeng except for a gradual increase in the late Spathian (Galfetti
1051 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** 1072 797 1073 798

1074 798 The An Chau Basin was another epicontinental sea connected to the Nanpanjiang Basin
1075 799 and bordering the western Panthalassic Ocean during the Early Triassic. In this basin, the
1076 800 Lower Triassic succession consists of the Lang Son Formation (siliciclastics) of Induan-early
1077 801 Olenekian age and the Bac Thuy Formation (fossiliferous carbonates, limestone breccia,
1078 802 hemipelagic basinal marl and mudstone) of Olenekian age (Komatsu and Dang 2007; Maekawa
1080 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
1086 808 three conodont zones (the *Novispathodus* ex gr. *waageni* Zone of Smithian age, the *Nv.* ex gr.
1087 809 *pingdingshanensis* Zone straddling the SSB, and the *Icriospathodus collinsoni* Zone of early
1088 810 Spathian age) (Fig. 11). The conodont *Nv.* ex gr. *pingdingshanensis* was reported at three
1089 811 stratigraphic levels: (1) from the lower part of the uppermost Smithian *X. variocostatus* beds
1090 812 (KC02-08); (2) from the top of the basal Spathian *Tirolites* cf. *cassianus* beds (KC02-10); and
1092 813 (3) from strata between the *Tirolites* cf. *cassianus* and *Tirolites* sp. nov. beds (between KC02-
1093 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
1104 823 et al. (2014), these may not pertain to this late Smithian species. Some illustrated specimens of
1105 824 KC02-11 also resemble some early Spathian *Bajarunia (sensu lato)* forms. Overall, if true,
1106 825 these few new tentative assignments may imply that the top of the *X. variocostatus* beds has to
1107 826 be only slightly shifted downward, as well as their considered SSB, as other determinations of
1108 827 *X. variocostatus* appear robust. Thus, *Nv.* ex gr. *pingdingshanensis* in KC02-10 and overlying
1110 828 beds may be of earliest Spathian age. A reconsideration of *Nv.* ex gr. *pingdingshanensis* from
1111 829 KC02-08 suggest it may not pertain to this species. However, at NT01-07, well-preserved
1112 830 specimens of *X. variocostatus* specimens co-occur with *Nv.* ex gr. *pingdingshanensis*, thus
1113 831 supporting a FAD of *Nv.* ex gr. *pingdingshanensis* within the late Smithian as observed in other
1114 832 some other basins (also see discussion in Section 5.2).
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1116 834 **3.8.2. Carbon-isotope chemostratigraphy** 1117 1118 1119 1120 1121

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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*

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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 *Glyptopliceras sinuatum* beds (including *Xenoceltites*
1161 870 *variocostatus*) (Fig. 6E). As in other area worldwide, the *Glyptopliceras 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‰ in the middle Smithian (N3), a positive
1213 905 excursion to ca. $+2\text{‰}$ across the SSB, and then a decrease to ca. -2‰ 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‰) in the lower Smithian, followed by a negative
1218 910 excursion to ca. -33‰ (N3*) in the middle Smithian (*Pseudoceltites multiplicatus* beds), then
1219 911 back to ca. -26‰ (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‰ (N4*?) then an increase to ca.
1221 913 -26‰ 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.

1225 917 1226 918 3.10. Spiti Valley, India (southern Tethys)

1227 919 1228 920 3.10.1. Ammonoid and conodont biostratigraphy

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1230 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](#)).
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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 1109 to have another pre-P3 geochemical marker. The mdpt(N3-P3) marker can serve this purpose
1491 1109 because by the midpoint of the N3-to-P3 shift, $\delta^{13}\text{C}$ was rising rapidly in many SSB sections,
1492 1110 and this point can therefore be roughly correlated at a global scale in the absence of
1493 1111 biostratigraphic data.

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1496 1114 Most SSB sections exhibit a rapid shift from N3 to P3 (i.e., Interval II; see Fig. 13A). We
1497 1114 are particularly concerned with variation between the lowermost Smithian and lowermost
1498 1115 Spathian (i.e., Intervals I and II), within which we identified four major different patterns of
1499 1116 $\delta^{13}\text{C}$ variation (Fig. 13B). This variation is mainly related to the shape and position of the N3
1500 1117 minimum, with implications for placement of the Interval I/II contact (see discussion in Section
1501 1118 5.3). Pattern 1 is characterized by an N3 minimum in the middle Smithian, followed by a slow
1502 1118 rise in $\delta^{13}\text{C}$ through the late Smithian before a rapid rise across the SSB. Pattern 2 is
1503 1119 characterized by a protracted $\delta^{13}\text{C}$ minimum during the middle Smithian, before a rapid rise in
1504 1120 the late Smithian. Pattern 3 is characterized by a slow decline in $\delta^{13}\text{C}$ through the early Smithian,
1505 1121 reaching the N3 minimum during the middle Smithian, before a rapid late Smithian rise. Pattern
1506 1122 4 is a variant on Pattern 3, in which the decline in $\delta^{13}\text{C}$ from the P2 maximum to the N3
1507 1123 minimum apparently does not show distinct rapid and slow stages (as in Pattern 3; Fig. 13B).

1511 1126 1512 1127 **4.2. Other chemostratigraphic records ($\Delta\delta^{13}\text{C}_{\text{DIC}}$, $\delta^{34}\text{S}$ and $^{87}\text{Sr}/^{86}\text{Sr}$)**

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1514 1129 In addition to $\delta^{13}\text{C}$, various other chemostratigraphic records show pronounced variations
1515 1129 during the Early Triassic. Meyer et al. (2011) and Song-HY et al. (2013) documented changes
1516 1130 in the vertical gradient of $\delta^{13}\text{C}$ of dissolved inorganic carbon (DIC) in Early Triassic seawater
1517 1131 based on secular differences in the $\delta^{13}\text{C}_{\text{carb}}$ profiles of sections deposited at different water
1518 1132 depths. Song-HY et al. (2013) showed that $\Delta\delta^{13}\text{C}_{\text{DIC}}$ reached high values (ca. +4 to +7 ‰)
1519 1133 during the middle-late Smithian, when a hot climate prevailed, and subsequently declined to
1520 1134 ca. 0 ‰ in the early Spathian, coincident with climatic cooling (Fig. 14A). Song-HY et al.
1521 1134 (2013) linked this pattern to the influence of temperature changes on the vertical temperature
1522 1135 structure of the water column, with warming leading to intensified water-column stratification,
1523 1136 reduced vertical overturn, and thus higher $\Delta\delta^{13}\text{C}_{\text{DIC}}$ values (sustained by the “biological
1524 1137 pump”), and cooling leading to reduced stratification, invigorated overturn, and lower $\Delta\delta^{13}\text{C}_{\text{DIC}}$
1525 1138 values.

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1529 1141 The $\delta^{34}\text{S}$ values of carbonate-associated sulfate (CAS) and evaporites, which are used as
1530 1142 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).

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 *Glyptophteras*, *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 1234 5.2. Constraints from conodont biozonation

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1236 Conodont taxa characteristic of the late Smithian substage are useful in constraining the
1237 SSB. The Ellisoniidae family (e.g., *Pachycladina*, *Foliella*, *Parachirognathus*, *Furnishius* and
1238 *Hadrodontina*) and Mullerinae subfamily (e.g., *Discretella*, *Wapitiodus*, *Guangxidella*,
1239 *Conservatella* and *Scythogondolella*) mostly went extinct before or at the SSB (Orchard, 2007).
1240 Diagnostic late Smithian taxa of the Ellisoniidae family have been identified in many areas,
1241 e.g., *Pachycladina* from southwestern China (Yan et al., 2013; Chen-YL et al., 2015), *Pa.*
1242 *obliqua* and *Pa. inclinata* from southern Europe (Perri, 1991; Aljinović et al., 2011; Sudar et
1243 al., 2014; Chen-YL et al., 2016); *Foliella* from Croatia (Aljinović et al., 2011), *F. gardenae*
1244 from other southern European locales (Sudar et al., 2014; Chen-YL et al., 2016);
1245 *Parachirognathus* from Japan (Zhang et al., 2017) and southwestern China (Yan et al., 2013;
1246 Chen-YL et al., 2015), *Pa. ethingtoni*, and *Furnishius* and *Hadrodontina anceps* from southern
1247 Europe (Aljinović et al., 2011). Members of the Mullerinae subfamily that are characteristic of
1248 the late Smithian include *Discretella* from Japan (Zhang et al., 2017), *Ds. discreta* from the
1249 Canadian Arctic (Mosher, 1973; Orchard, 2008), western British Columbia (Orchard and
1250 Zonneveld, 2009), western United States (Orchard and Tozer, 1997; Orchard, 2008; Orchard
1251 and Zonneveld, 2009), and southwestern China (Yan et al., 2013; Chen-YL et al., 2015);
1252 *Wapitiodus*(?) from Japan (Zhang et al., 2017), *W. robustus* from western British Columbia
1253 (Orchard and Zonneveld, 2009); *Guangxidella bransoni* from British Columbia Orchard (2008)
1254 and the western United States (Orchard and Tozer, 1997; Orchard, 2008; Orchard and
1255 Zonneveld, 2009); *Conservatella conservativa* from Canadian Arctic (Mosher, 1973; Orchard,
1256 2008) and the western United States (Orchard and Tozer, 1997; Orchard, 2008; Orchard and
1257 Zonneveld, 2009); *Sc. lachrymiformis*, *Sc. rhomboidea*, *Sc. milleri* and *Sc. mosheri* from the
1258 Canadian Arctic (Orchard, 2008), *Sc. milleri* and *Sc. mosheri* from Spitsbergen (Weitschat and
1259 Lehmann, 1978; Clark and Hatleberg, 1983; Hatleberg and Clark, 1984) and the western United
1260 States (Müller, 1956; Orchard and Tozer, 1997; Orchard, 2008), *Sc. lachrymiformis*, *Sc. milleri*,
1261 *Sc. mosheri* and *Sc. phryna* from western British Columbia (Orchard and Zonneveld, 2009),
1262 *Sc. milleri* from the Spiti Valley (Bhatt et al., 1999; Krystyn et al., 2004, 2005; Orchard and
1263 Krystyn, 2007) and the Salt Range (PJRG, 1985).

1264 Some genera of the Novispathodinae (e.g., *Novispathodus*, *Triassospathodus*) and
1265 Neogondolellinae (e.g., *Neogondolella*) subfamilies survived and rediversified after the late
1266 Smithian extinction (Orchard, 2007), generating key early Spathian taxa that could be used in
1267 the definition of the SSB. Commonly assumed members of this surviving and recovery fauna
1268 included ‘*Tr.*’ *hungaricus*, *Ng. aff. sweeti*, and *Nv. pingdingshanensis*, which were first
1269 reported from Hungary (Kozur and Mostler, 1970), the WCSB/western USA (Orchard and
1270 Tozer, 1997), and Chaohu (Zhao et al., 2007a), respectively. Later, ‘*Tr.*’ *hungaricus* was also
1271 reported from Sichuan Province, South China (Tian et al., 1983), the western USA (Lucas and
1272 Orchard, 2007), and various localities in Europe (Kolar-Jurkovšek et al., 2013; Chen-YL et al.,
1273 2016); *Ng. aff. sweeti* was reported from Chaohu (Zhao et al., 2007a); and *Nv.*
1274 *pingdingshanensis* was reported from multiple sections in the South China region (Tong et al.,

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1275 2007; Ji et al., 2011; Chen-YL et al., 2015; Zhang et al., 2015), the WCSB (Orchard and
1276 Zonneveld, 2009), and the An Chau Basin (Komatsu et al., 2016).

1277 Newly evolved conodont species of Spathian age, and their intercalibrations with
1278 ammonoid biozonation data, may serve an important role in the future definition of the SSB.
1279 In North America, *Neogondolella* aff. *sweeti* is known from strata overlying the
1280 *Anawasatchites tardus* Zone in the WCSB, and is of probable Spathian age in California. This
1281 species, as yet undescribed, differs from *Ng. sweeti* associated with Smithian *Neospathodus*
1282 *pakistanensis* in the Mittiwali Formation of Pakistan (Orchard and Tozer, 1997). In Hungary,
1283 ‘*Triassospathodus*’ *hungaricus* occurs in the *Tirolites* ammonoid beds (Kozur and Mostler,
1284 1970), thus may serve as a marker for the lower Spathian, within rocks equivalent to the
1285 *Tirolites cassianus* ammonoid Zone (Kozur, 2003). Kolar-Jurkovšek et al. (2013) inferred that
1286 the ‘*Tr.* *hungaricus*’ fauna lies within the lower Spathian in the shallow western Tethys, where
1287 the *Icriospathodus collinsoni* fauna is missing. Chen-YL et al. (2016) speculatively proposed
1288 that ‘*Tr.* *hungaricus*’ could be correlated with *Novispathodus pingdingshanensis* because of
1289 their small size and co-occurrence with the ammonoid *Tirolites* (e.g., Hungary, Kozur and
1290 Mostler, 1970). At Chaohu, *Nv. pingdingshanensis* is found within the *Columbites-Tirolites*
1291 ammonoid Zone of the Nanlinghu Formation, between the late Smithian *Anasibirites* beds and
1292 the early Spathian *Tirolites* beds, thus leading to its proposed use as an earliest Spathian
1293 indicator (Zhao et al., 2007a, 2008a, b; Fig. 15). There, the first occurrence of *Nv.*
1294 *pingdingshanensis* is coincident with the first occurrence of *Ng.* aff. *sweeti* and below the first
1295 occurrence of *Ic. collinsoni* (Zhao et al., 2007a, 2008a, b). Thus, even though both *Nv.*
1296 *pingdingshanensis* and ‘*Tr.* *hungaricus*’ may be indicative of the earliest Spathian, *Nv.*
1297 *pingdingshanensis* is the older of these two taxa in South China.

1298 The taxon *Nv. pingdingshanensis* was first introduced by Zhao et al. (2007a), who
1299 identified it as a marker for the SSB in South China. Since its discovery, this taxon has been
1300 reported from a number of other locations globally, including the western USA (Orchard and
1301 Zonneveld, 2009), western Canada (Henderson et al., 2018), Vietnam (Komatsu et al., 2016),
1302 Salt Range (Romano et al., 2013; Leu et al., 2018; Goudemand et al., 2018), Kashmir (Leu et
1303 al., 2018), Oman (Chen-YL et al., 2018) and the Zuodeng (Tong et al., 2007; Goudemand et
1304 al., 2012), Youping (Goudemand et al., 2012) and Jiarong sections in South China (Chen-YL
1305 et al., 2015). Although the first occurrence of *Nv. pingdingshanensis* has been used to identify
1306 the SSB in South China (Zhao et al., 2007a; Tong et al., 2007; Chen-YL et al., 2015), several
1307 studies elsewhere have claimed that the oldest specimens of *Nv. pingdingshanensis* are of late
1308 Smithian age because of specimens that co-occur with *Xenoceltites* in the AW and GXP
1309 ammonoid assemblages (Orchard and Zonneveld, 2009; Goudemand et al., 2012; Komatsu et
1310 al., 2016; Romano et al., 2013; Chen-YL et al., 2018; Leu et al., 2018; Goudemand et al., 2018).
1311 In earlier literature, the genus *Xenoceltites* ranged from the late Smithian to the early Spathian
1312 (Guex et al., 2010), but the rare early Spathian specimens assigned to this genus are now
1313 excluded from *Xenoceltites* (Brayard et al., 2019; Leu et al., 2018), thus making key
1314 *Xenoceltites* taxa found in the AW and GXP assemblages (e.g., *X. variocostatus* and *X.*
1315 *subevolutus*) exclusively late Smithian in age. On this basis, some studies (e.g., Leu et al., 2018)
1316 have inferred that *Nv. pingdingshanensis* may not be a suitable marker for the SSB, but more
1317 work will be needed to definitively address the issue of a possibly diachronous first occurrence
1318 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](#)).

1802 1346 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 Most SSB sections exhibit a rapid shift from N3 to P3 (i.e., Interval II; see [Figs. 7, 11-13](#)).
1816 1360 The early part of this shift occurred slowly in some sections (e.g., $\delta^{13}\text{C}$ Pattern 1), and it is
1817 1361 unclear whether the point of onset is perfectly correlative at a global scale. For example, in
1818 1362 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
1899 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 1417 ([Horacek et al., 2007b](#)), and Musandam ([Clarkson et al., 2013](#)). In the Salt and Sughar Ranges,
1905 1418 Tulong, and Losar, the SSB is close to P3 and above the mdpt(N3-P3). At Amol and Abadeh,
1906 1419 the SSB was placed close to P3; at L'Uomo, Zal and Musandam, the SSB was placed below
1907 1420 the mdpt(N3-P3) ([Fig. 12](#)). The SSB was not defined in the Lungenfrischgraben and Trudener
1908 1421 Bach sections ([Horacek et al., 2010](#)). Thus, in these areas, small regional inconsistencies in
1909 1422 placement of the SSB compare to the mdpt(N3-P3) can be noticed and highlight the influences
1910 1423 of local conditions on the observed signal. However, mdpt(N3-P3) is most of time located not
1911 1423 far from the SSB defined by biostratigraphic markers.

1912 1424
1913 1425
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 1427 ([Fig. 7](#)). For example, ammonoid biozonation of the late Smithian and early Spathian is
1917 1428 available in Spitsbergen ([Weitschat and Dagys, 1989](#)), whereas only late Smithian ammonoid
1918 1429 beds are known so far from the Canadian Arctic ([Tozer, 1967](#)). Thus, adequate biostratigraphic
1919 1430 data allowing for constraining the SSB placement are available only in a few sections, leading
1920 1431 to variable uncertainties in placements of the SSB when compared to mdpt(N3-P3) or P3. In
1921 1432 these regions, carbon-isotope correlations were used in some sections for placement of the SSB,
1922 1432 but the $\delta^{13}\text{C}$ datum chosen was not consistent among different studies. For example, [Grasby et](#)
1923 1433 [al. \(2013\)](#) placed the SSB at P3 in Smith Creek, [Grasby et al. \(2016\)](#) placed it at N3 in
1924 1434 Festningen, [Galfetti et al. \(2007a\)](#) placed it near mdpt(N3-P3) in Dicksonfjellet (just above late
1925 1435 Smithian *Anawasatchites tardus* beds), and [Wignall et al. \(2016\)](#) placed it between N3 and
1926 1436 mdpt(N3-P3) in Vindodden. In the Mineral Mountains [Thomazo et al. \(2016\)](#) placed it near
1927 1437 what it is mdpt(N3-P3), this one being located at the top of the late Smithian GXP assemblage.
1928 1437 [Sakuma et al. \(2012\)](#) placed the SSB between mdpt(N3-P3) and P3 in Inuyama ([Fig. 7](#)).

1929 1438
1930 1439
1931 1440 To sum up, there is a rather good correspondence of mdpt(N3-P3) to known
1932 1441 biostratigraphic constraints on the SSB although some regional to local influences can
1933 1442 modulate this inference. An approximate placement of the SSB based at least partly on carbon
1934 1443 isotope chemostratigraphy thus can help to systematize SSB placement and avoid too important
1935 1443 misrelations related to inadequate biostratigraphic records (e.g., [Figs. 7 and 12](#)).
1936 1444 Stratigraphic boundaries are not customarily based on chemostratigraphic records, but, based
1937 1445 on present-day data, the use of mdpt(N3-P3) can be an auxiliary criterion to locate the SSB.

1938 1446
1939 1447
1940 1447 Obviously, the use of $\delta^{13}\text{C}$ records for correlation or auxiliary definition of the SSB should
1941 1448 be preceded by an evaluation of stratigraphic hiatuses and facies changes in the sections under
1942 1449 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.
1963 1461
1964 1462

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
1973 1470 Despite these existing high-resolution biostratigraphic studies, placement of the SSB is
1974 1471 still inconsistent in some sections within these areas. For example, in the An Chau Basin,
1975 1471 Komatsu et al. (2016) placed the SSB at the base of the *Tirolites cf. cassianus* beds (see
1976 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
1985 1480 In the western Tethys, limited biostratigraphic data resulted in the SSB being identified
1986 1481 mainly on the basis of carbon-isotope correlations, but (as noted in Section 5.3) there has been
1987 1482 no consistent placement of the SSB within the $\delta^{13}\text{C}$ chemostratigraphic framework of the Early
1988 1483 Triassic (Fig. 12), creating the potential for global miscorrelations and misinterpretations of
1989 1483 paleoceanographic signals. In the southern Tethys, the SSB was placed close to P3 at Salt and
1990 1484 Surghar Ranges (Hermann et al., 2012), and Tulong (Brühwiler et al., 2009) and mdpt(N3-P3)
1991 1485 falls in characteristic late Smithian ammonoid assemblages (Fig. 12). Compared to mdpt(N3-
1992 1486 P3), this SSB placement is thus slightly higher stratigraphically than that favored for the eastern
1993 1486 Tethys, but well highlight the differential local environmental and/or diagenetic conditions
1994 1487 influencing the $\delta^{13}\text{C}$ signal.

1995 1488
1996 1489 The biostratigraphy of the SSB transition in the Boreal realm is more poorly constrained
1997 1490 owing to e.g., scarce fossil occurrences. Thus, carbon isotope excursions can be used to
1998 1490 constrain the location of the SSB. We suggest placement of the SSB at mdpt(N3-P3), which is
1999 1491 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 ~ 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 ~ 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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2077 1546

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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Figures and captions

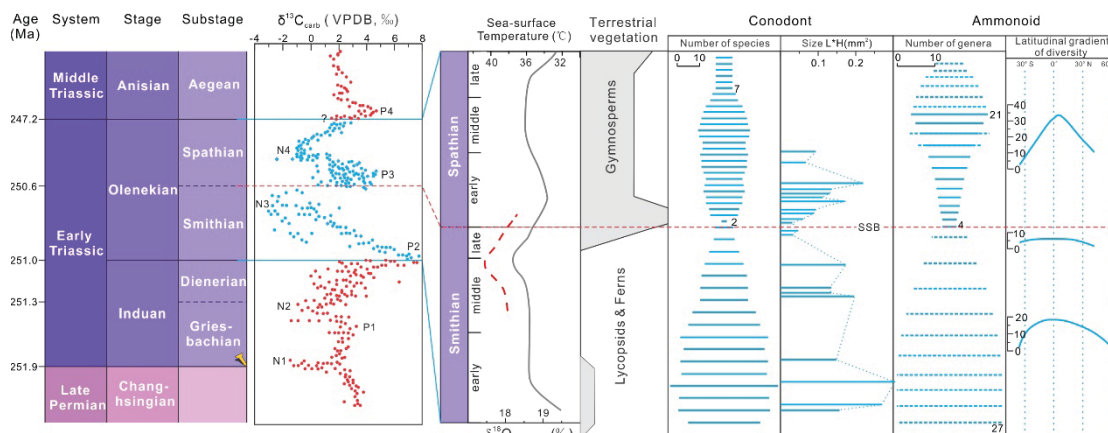


Fig. 1. Simplified carbonate carbon isotopic, climatic (sea-surface temperature) and biotic (floras, conodont and ammonoid) changes during the Smithian and Spathian substages of the Early Triassic. Carbon isotope data are from [Payne et al. \(2004\)](#) and [Chen and Benton \(2012\)](#), with numbering 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.

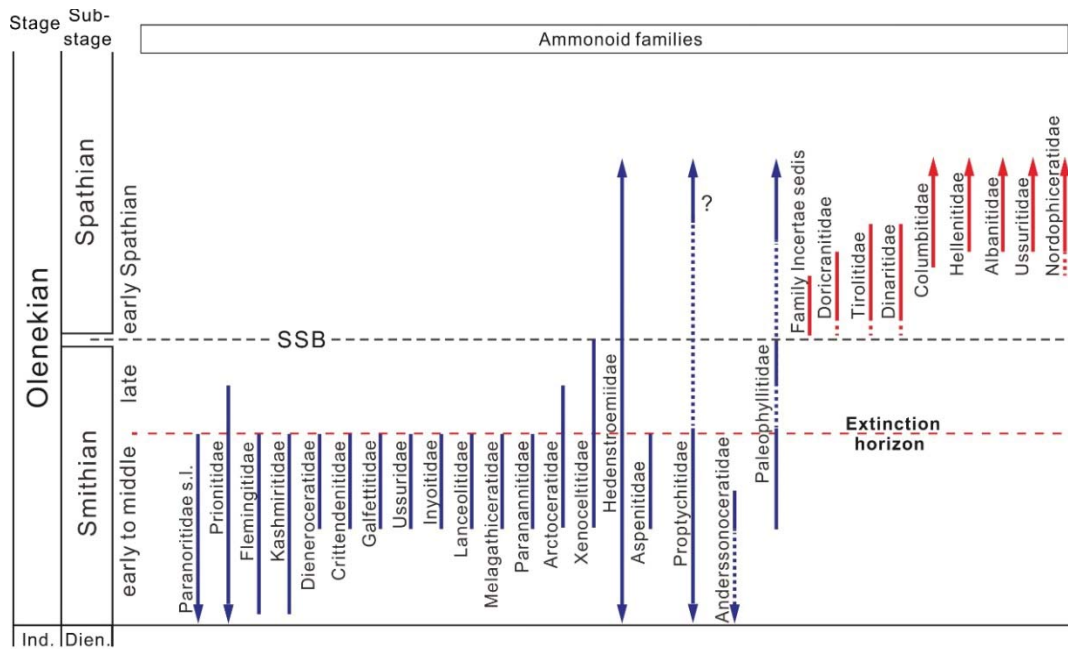


Fig. 2. Stratigraphic ranges of main ammonoid families through the Smithian and early Spathian. Based on ammonoid studies from Brayard et al. (2007b, 2013), Shigeta and Zakharov (2009), Brühwiler et al. (2010c, 2011, 2012a, b), Guex et al. (2010), Smyshlyaeva and Zakharov (2012), Jenks et al. (2013,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

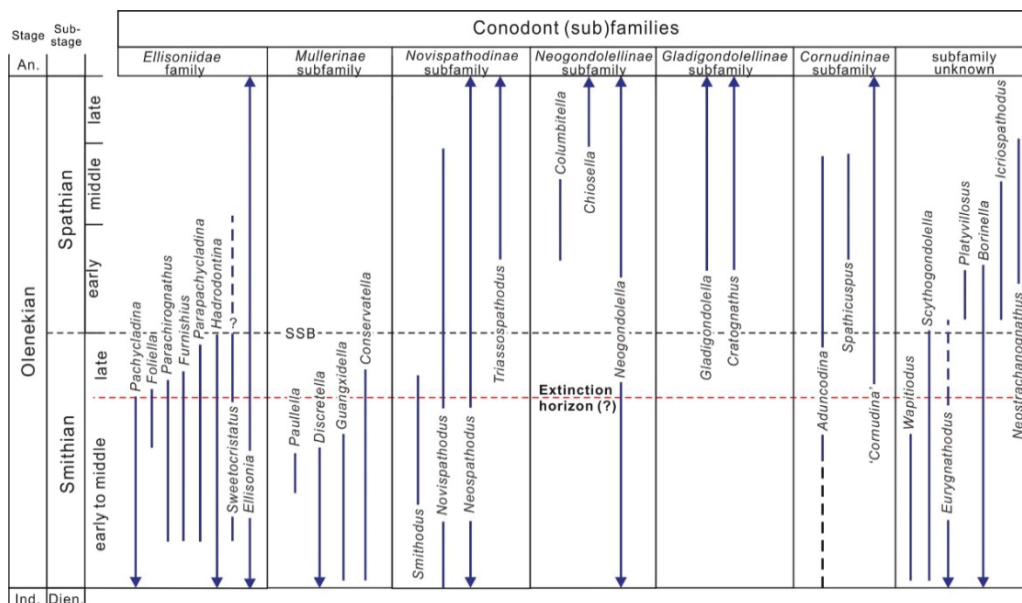


Fig. 3. Stratigraphic ranges of conodont genera through the Smithian and Spathian. Data from Orchard (2007). Dien. = Dienerian, Ind. = Induan, An. = Anisian, SSB = Smithian/Spashtian boundary.

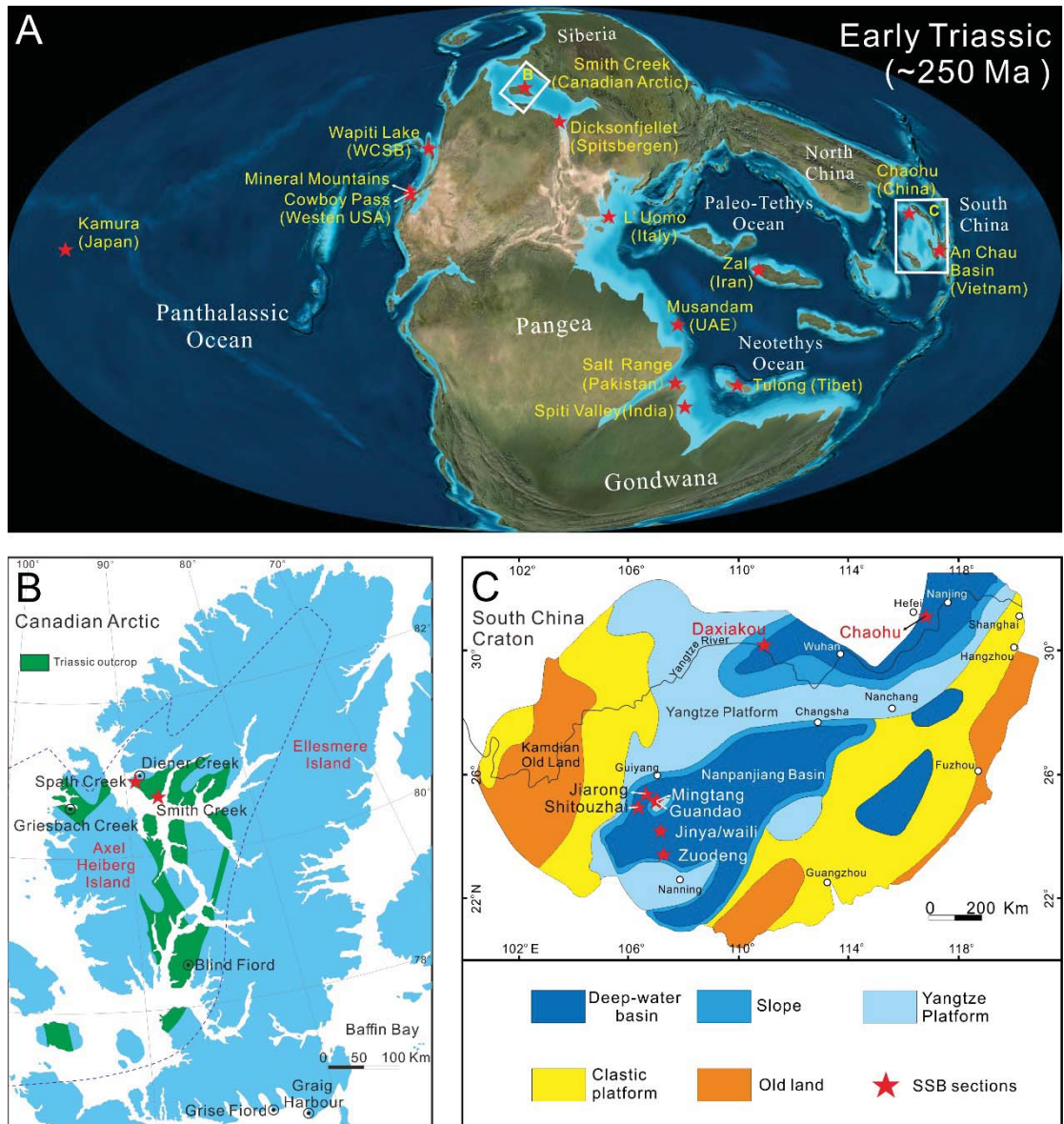


Fig. 4. Paleogeographic maps for key areas of Smithian-Spathian studies: (A) global, (B) Canadian Arctic, and (C) South China (see Bagherpour et al., 2017, for alternative facies distribution). Dotted line in B shows the margin of the Sverdrup Basin (Tozer, 1994). Map sources: base map of A is copyright 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				Siberlingeria 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 Wasatchites distractus beds	Ng. elongata Zone	Glyptopliceras sinuatum beds Subvishnites posterus beds Wasatchites distractus 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 Brayardites compressus beds E. cirratus beds C. superbum beds	Nv. waageni Zone	Nyalamites anguste. beds Pseudocelites multiplicatus b. Nammalites pilatoides beds 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	Kashmirites kapila beds	Nv. waageni eowaageni Zone	R. evolvens beds F. napus beds X. perplicatus beds S. rursiradiatus beds F. bhargavi beds		Rohillites rohilla beds V. pulcher beds Kashmiritidae beds F. bhargavi 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*.

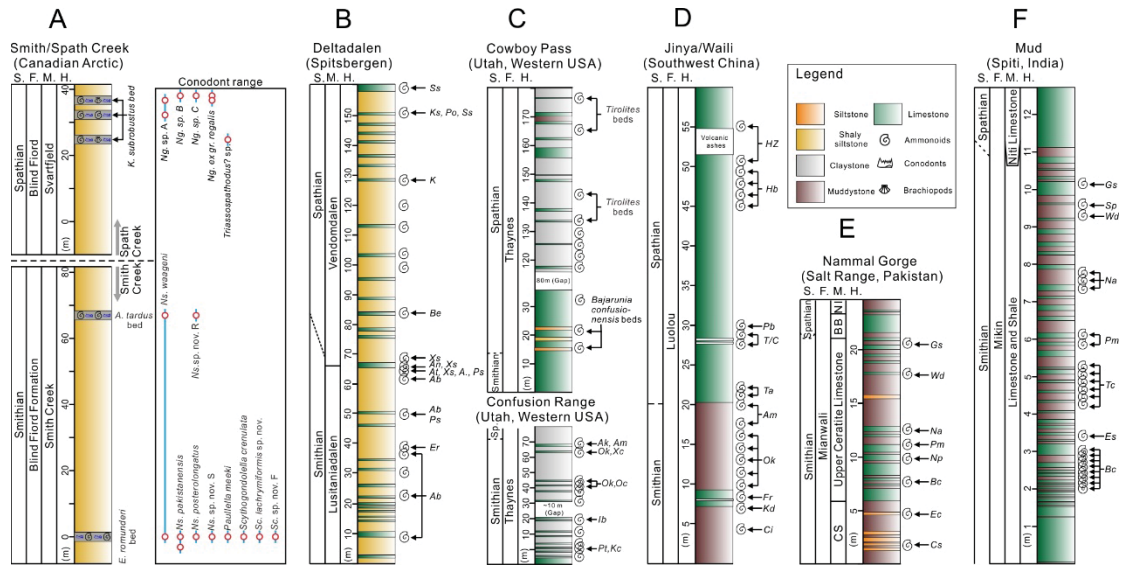


Fig. 6. Distributions of ammonoids and conodonts in some representative SSB sections. Data sources: Smith Creek and Spath Creek from Orchard (2008); Deltadalen from Mørk et al (1999); Cowboy Pass from Guex et al. (2010); Confusion Range from Brayard et al. (2013); Nammal Gorge from Brühwiler et al. (2010, 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.

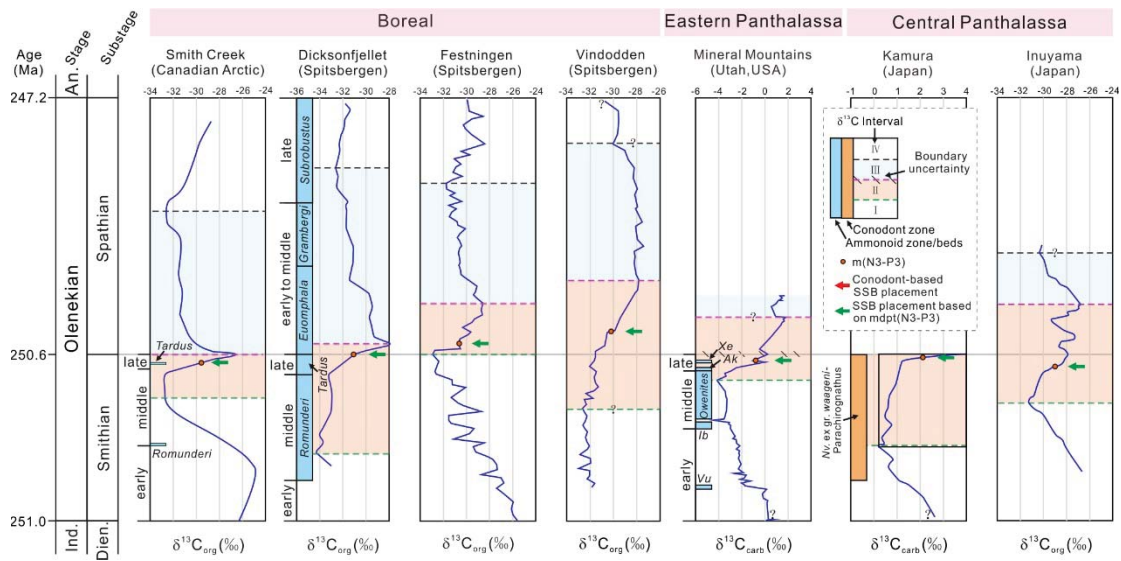


Fig. 7. Detailed correlations of Smithian-Spathian sections in the Boreal and eastern and central Panthalassic regions based on a combination of ammonoid and conodont biostratigraphy and C-isotope chemostratigraphy. Data sources: Smith Creek from Tozer (1967) and Grasby et al. (2013), Dicksonfjellet 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)

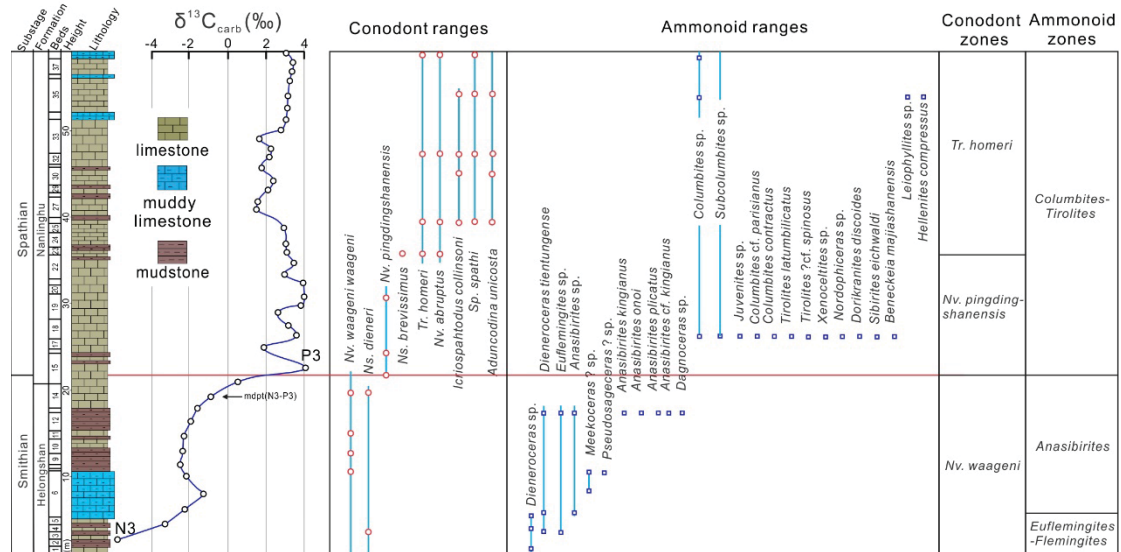


Fig. 8. Conodont, ammonoid and carbon isotopic stratigraphy at South Majiashan section in Chaohu area, eastern China. Data sources: carbon isotope from [Tong et al. \(2007\)](#); conodont ranges from [Zhao et al. \(2007a\)](#); ammonoid ranges from [Guo \(1982\)](#) and [Tong et al. \(2004\)](#). Abbreviations: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

North Pingdingshan (Chaohu, eastern China)

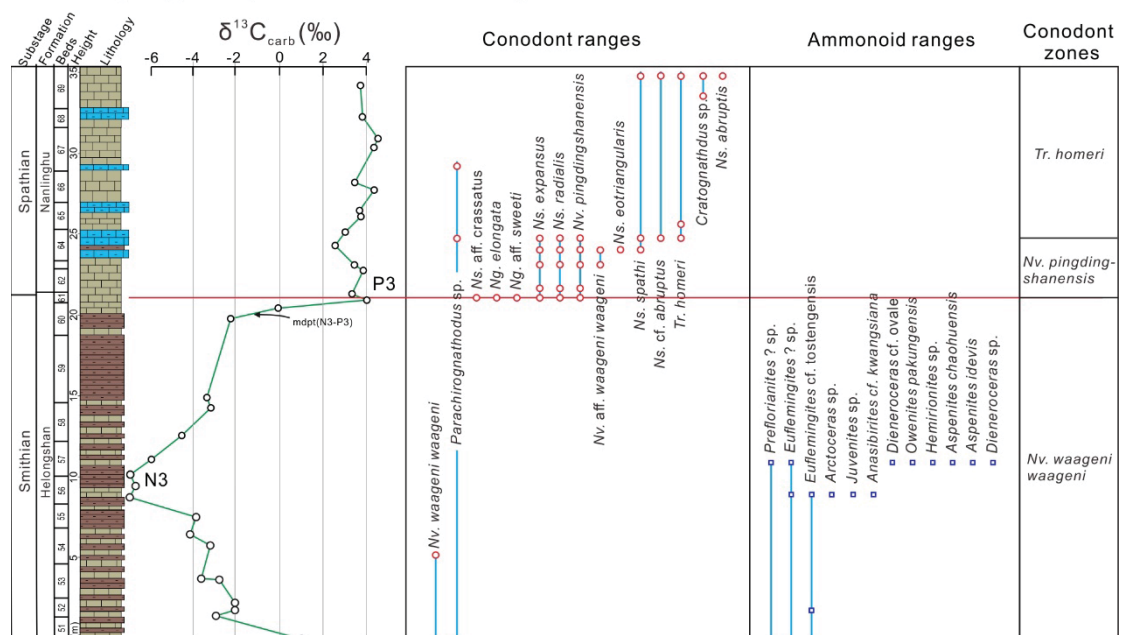


Fig. 9. Conodont, ammonoid and carbon isotopic stratigraphy at North Pingdingshan section in Chaohu area, eastern China. Data sources: carbon isotope from [Zuo et al. \(2004\)](#); conodont and ammonoid ranges from [Zhao et al. \(2007a\)](#). See [Figure 8](#) for legend and abbreviations.

West Pingdingshan (Chaohu, eastern China)

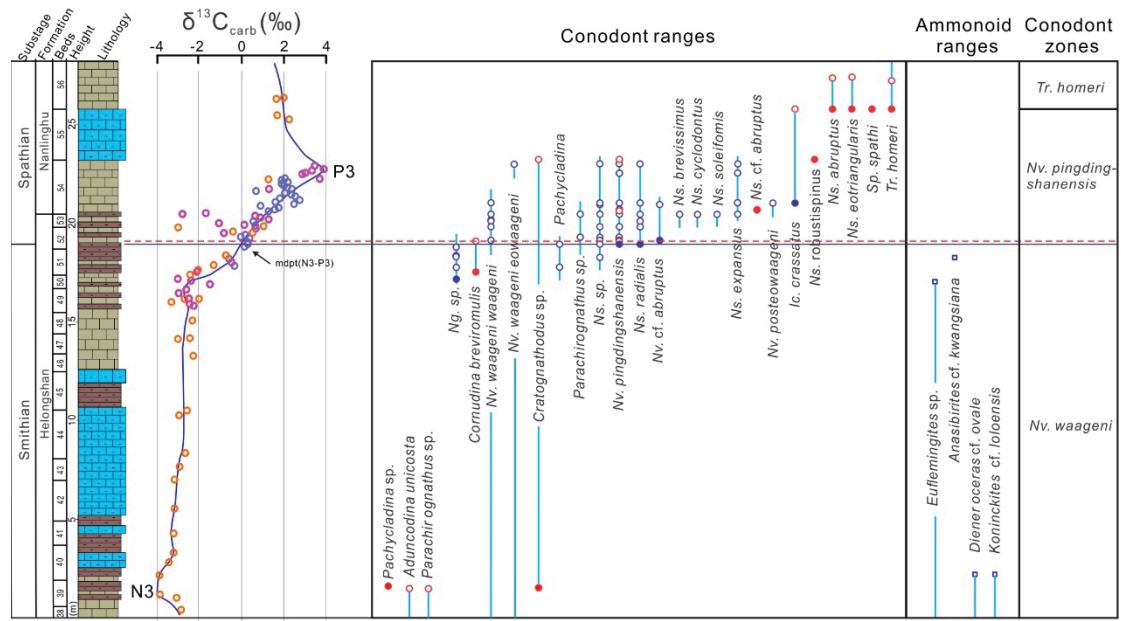


Fig. 10. Conodont, ammonoid and carbon isotopic stratigraphy at West Pingdingshan section in Chaohu area, eastern China. Data sources: carbon isotope from [Tong and Zhao \(2011\)](#) (orange), [Liang et al. \(2011\)](#) (pink) and [Zhao and Zheng \(2014\)](#) (light blue); conodont ranges from [Zhao 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.

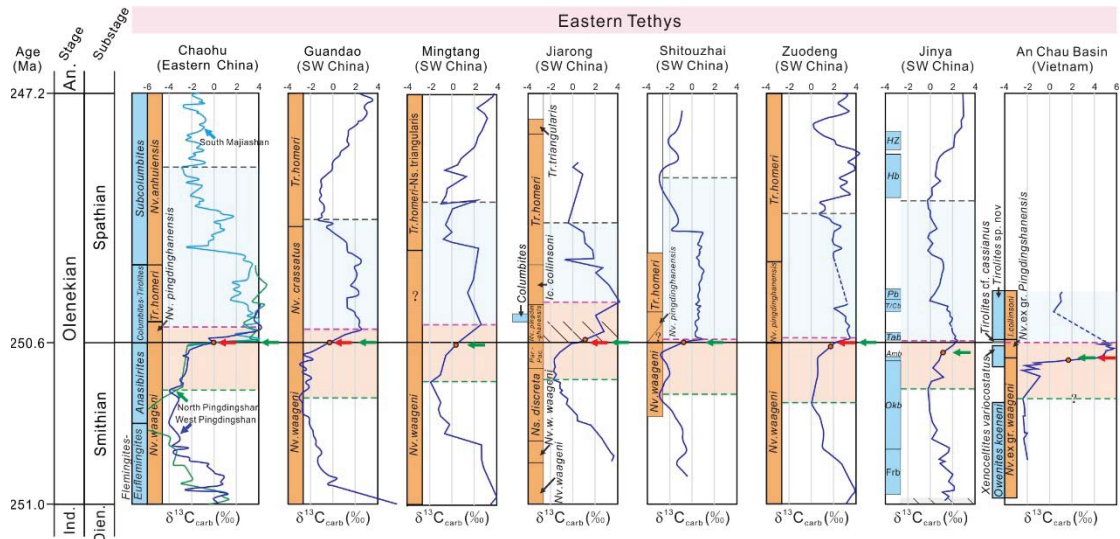


Fig. 11. Detailed correlations of Smithian-Spathian sections in the eastern Tethys region based on a combination of ammonoid and conodont biostratigraphy and C-isotope chemostratigraphy. Data sources: Chaohu from Zuo et al. (2003, 2004), Tong et al. (2004, 2007) and Zhao et al. (2007a); Guandao and Zuodeng 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).

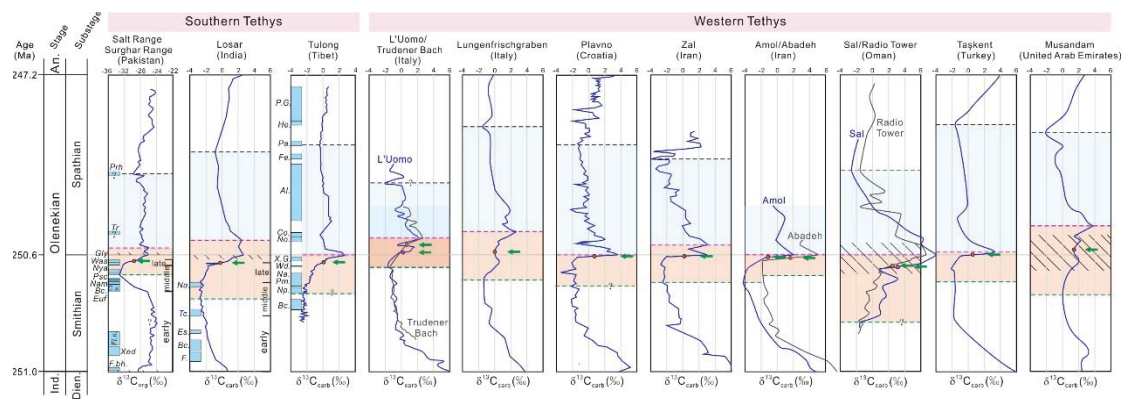


Fig. 12. Detailed correlations of Smithian-Spathian sections in the southern Tethys (North Indian Margin) and western Tethys regions based on a combination of ammonoid and conodont biostratigraphy and C-isotope chemostratigraphy. Data sources: Salt Range and Surghar Range from [Hermann et al. \(2012\)](#) (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 = *Glyptophiceras sinatum*, He. = *Hellenites*, Na. = *Nyalamites angustecostatus*, Nam = *Nammalites pilatoides*, No. = *Nordophiceras*, 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-Glyptophiceras*. See [Figure 1](#) for timescale and [Figure 7](#) for legend (including green and red arrows).

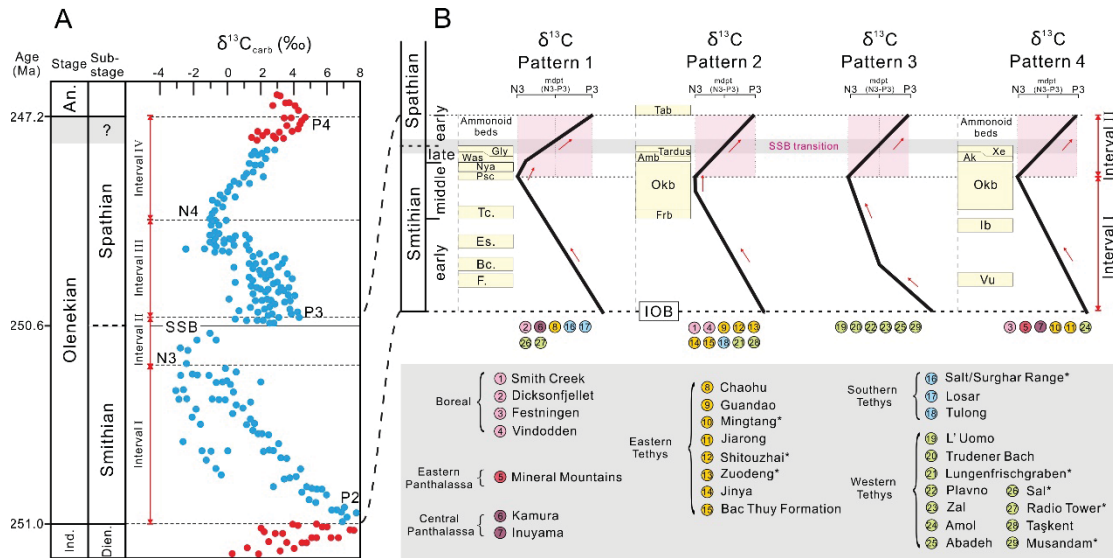


Fig. 13. (A) Carbon-isotope Intervals I to IV of the Olenekian substage. $\delta^{13}C$ data from Payne et al. (2004) and Chen and Benton (2012); N2-N3 and P2-P4 represent $\delta^{13}C$ minima and maxima per Song et al. (2013); and mdpt(N3-P3) is the isotopic midpoint between N3 and P3. (B) $\delta^{13}C$ 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.

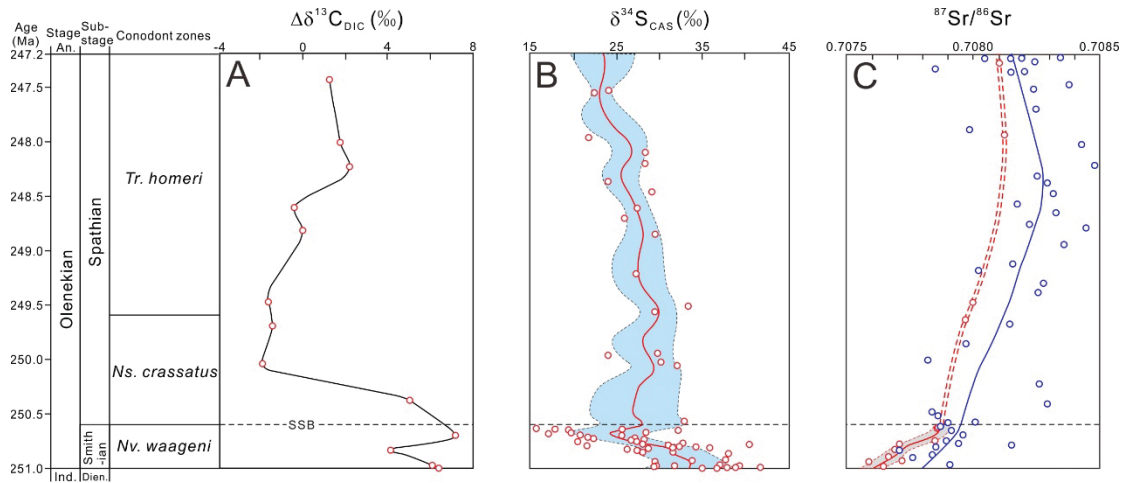


Fig. 14. Some other geochemical records for the Smithian and Spathian: (A) $\Delta\delta^{13}\text{C}_{\text{DIC}}$ (from Song-HY et al., 2013), (B) $\delta^{34}\text{S}_{\text{CAS}}$ (from Song-HY et al., 2014), and (C) $^{87}\text{Sr}/^{86}\text{Sr}$ (dashed red line = Sedlacek et al., 2014; solid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

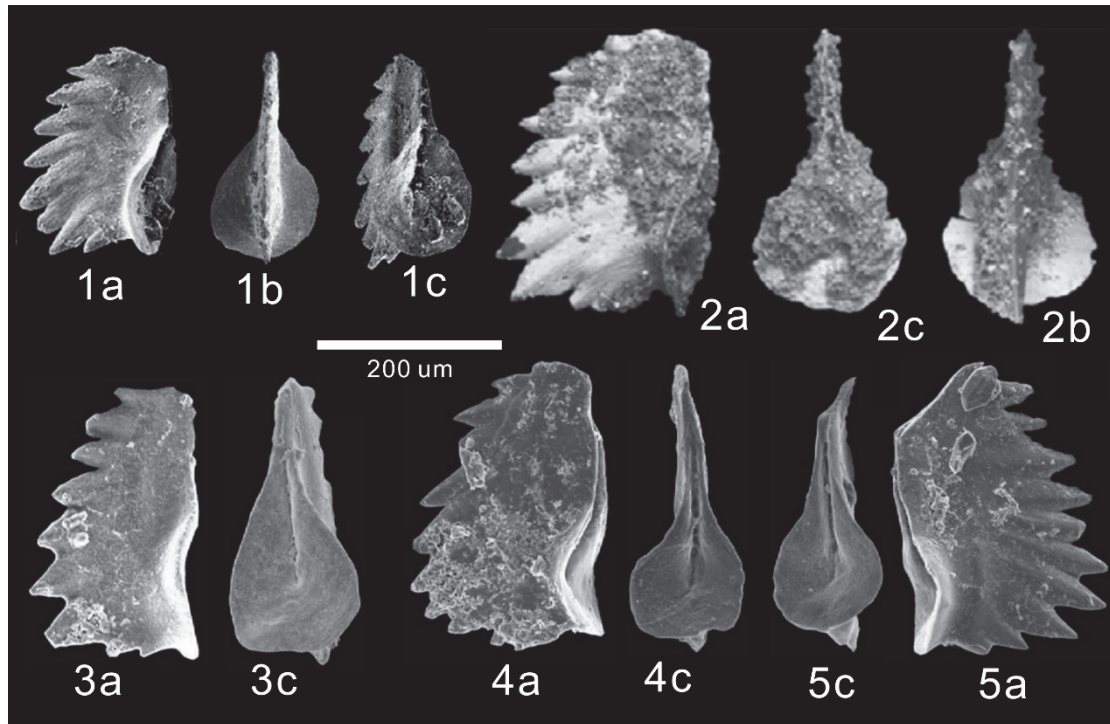


Fig. 15. Photographs of conodont *Novispathodus pingdingshanensis*. a = lateral view; b = upper view; c = lower view. 1) Holotype of *Nv. pingdingshanensis* (CUG03054) from West Pingdingshan, Chaohu area, eastern China (Zhao et al., 2007a); 2) *Nv. ex. gr. pingdingshanensis* (MPC25395) from the An Chau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

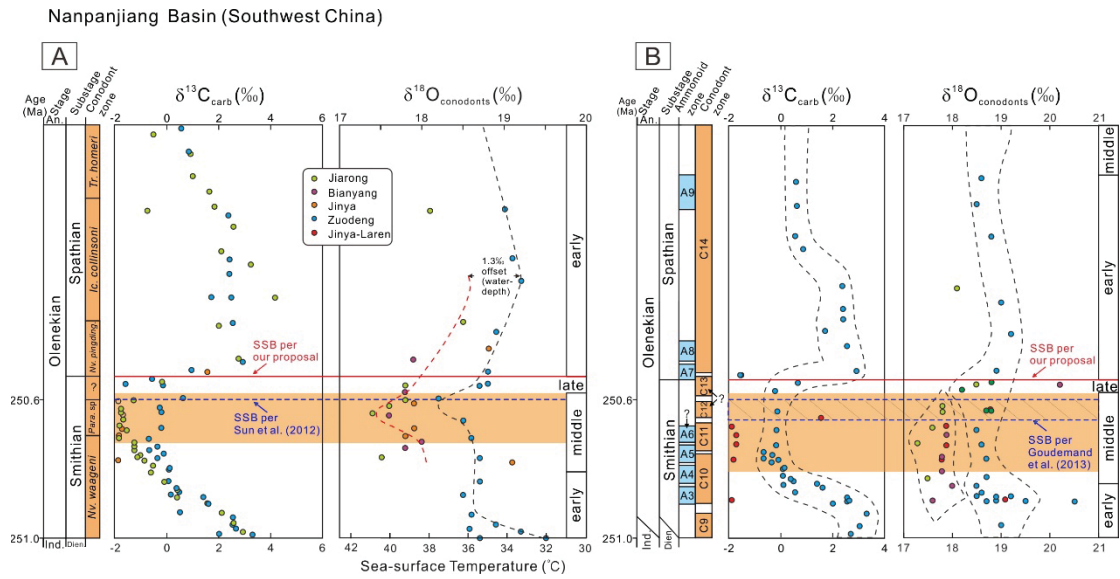


Fig. 16. Comparison of SSB placement based on mdpt(N3-P3) (red solid line; [this study](#)) with earlier SSB placements (blue dash lines) of [Sun et al. \(2012; A\)](#) and [Goudeband et al. \(2013; B\)](#). The orange field represents the interval of the Smithian Thermal Maximum (STM). Note that our 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.