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# 1 **High-resolution Early Triassic ammonoid biostratigraphy of** 2 **South Tibet, China and implications for global correlations**

3  
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15  
16 **Abstract.** Ammonoids are key fossil indexes for Triassic biochronology, as all  
17 Triassic stages and substages were initially defined on ammonoid faunas. In recent  
18 decades, the temporal resolution of ammonoid biostratigraphical scales for the Early  
19 Triassic has been greatly improved. However, many uncertainties in zones correlation  
20 and superpositions remain, mainly due to sampling heterogeneities, preservation  
21 biases and faunal endemism. In this work, we present the first comprehensive Early  
22 Triassic ammonoid zonation from the South Tibet, China, a previously poorly  
23 investigated region. Ammonoids were sampled from the Kangshare Formation at four  
24 sections (Selong, Paizi, Qubu and Xialong), representing a total of 140 species,  
25 ranging from the Griesbachian to the Smithian. These new robust data allow the  
26 construction of a high-resolution biostratigraphy using the Unitary Association (UA)  
27 method. A total of 22 Unitary Association zones (UAZs) were recognized, including

28 two UAZs for the Griesbachian, nine for the Dienerian, and 11 for the Smithian. Then,  
29 we integrated data from neighboring basins, i.e., Spiti (India) and the Salt Range  
30 (Pakistan), and the new data from South Tibet to construct synthetic, laterally  
31 reproducible Dienerian-Smithian ammonoid UAZs, which include 12 UAZs for the  
32 Dienerian and 16 UAZs for the Smithian. Based on the newly obtained data and  
33 high-resolution biostratigraphic scales, we revised global correlations known for the  
34 ammonoid biostratigraphy in the Griesbachian, Dienerian and Smithian. Finally, the  
35 high-resolution ammonoid zones are generally in agreement with conodont zones in  
36 defining stage/substage boundaries. They also provide a robust and accurate time  
37 calibration for Early Triassic carbon isotope trend and temperature changes.

38

39 **Keywords:** South Tibet, Neotethys, Unitary Association zone, Griesbachian,  
40 Dienerian, Smithian

## 41 **1 Early Triassic ammonoid biostratigraphy: state of the art**

### 42 **1.1 Early Triassic and its subdivisions**

43 The Early Triassic was a crucial time interval (~251.9 Ma to ~247.1 Ma, Burgess  
44 et al., 2014; Ovtcharova et al., 2015) in geological history. The Permian-Triassic mass  
45 extinction (PTME) is the most severe known biotic catastrophe of the Phanerozoic,  
46 which wiped out more than 80% of marine species (Raup, 1979; Stanley, 2016; Dal  
47 Corso et al., 2022). After the PTME, the Early Triassic was characterized by a series  
48 of environmental and climate upheavals, including large perturbations of the carbon  
49 cycle (Payne et al., 2004; Galfetti et al., 2007a; Tong et al., 2007), recurrent  
50 anoxic-euxinic conditions in oceans (Song et al., 2012; Grasby et al., 2013), repeated  
51 warming events (Sun et al., 2012; Romano et al., 2013; Goudemand et al., 2019), and  
52 dramatic increases in atmospheric CO<sub>2</sub> concentrations (Wu et al., 2021; Joachimski et  
53 al., 2022). Coinciding with these environmental changes, life in the Early Triassic  
54 experienced significant evolutionary turnovers, for instance, the transition from the

55 Paleozoic Evolutionary Fauna to the Modern Evolutionary Fauna and the rise of  
56 modern marine ecosystems (Sepkoski, 1981; Brayard et al., 2017; Smith et al., 2021;  
57 Benton and Wu, 2022; Dai et al., 2023), the transition from non-motile dominated  
58 marine ecosystems to ones dominated by nektonic clades (Song et al., 2018).

59 To study the deep-time biotic-abiotic co-evolution, a robust and accurate  
60 timescale is a prerequisite. Formally, the Early Triassic is divided into two stages, i.e.,  
61 the Induan and Olenekian, in ascending order, which were proposed by Kiparisova  
62 and Popov (1956) based on ammonoid assemblages. This two-stage subdivision of the  
63 Early Triassic was adopted by the Subcommittee on Triassic Stratigraphy in 1991  
64 (Visscher, 1992). The Induan corresponds to the Griesbachian and Dienerian, and the  
65 Olenekian corresponds to the Smithian and Spathian (Fig. 1). The four stages model  
66 was initially proposed by Tozer (1965, 1967) based on the ammonoid record from  
67 Arctic Canada, which was regarded as substages when the two stages model was  
68 accepted. During recent decades, conodonts have also played a significant role in the  
69 Early Triassic biostratigraphy (Orchard, 2010). However, the heterogeneous fossil  
70 record between tropical and boreal domains and between the Tethyan and Panthalassic  
71 basins, as well as the different standards among conodont and ammonoid workers,  
72 lead to intense debates on definitions of the Early Triassic stages and substages (see  
73 e.g., Jenks et al., 2015; Zhang et al., 2019). In this work, we use the four substage  
74 subdivision, as it well reflects major ammonoid evolutionary events during the Early  
75 Triassic and especially highlights the importance of the late Smithian crisis. The  
76 Induan/Olenekian (or Dienerian/Smithian) boundary has not yet been formally  
77 defined and is highly debated among different proposals. Here, we tentatively use the  
78 definition proposed by Brühwiler et al. (2010c) based on the occurrence of  
79 *Flemingites bhargavai* in bed 10 in the Mud section, Spiti, northern India. The bed 10  
80 also corresponds to the first appearance of two Smithian ammonoid families, the  
81 Flemingitidae and Kashmiritidae (Brühwiler et al., 2010c). Other proposals include  
82 the basal *Hedenstroemia hendenstroemi* Zone in the high-latitude regions (Dagys,  
83 1994a, 1994b; Tozer, 1994) and the basal *Hedenstroemia bosphorensis* Zone in South  
84 Primorye (Zakharov et al., 2000). Conodont proposals include the first appearance

85 datum of *Novispathodus waageni* in the Chaohu section, South China (Tong et al.,  
86 2005; Zhao et al., 2007), and the first appearance datum of *Novispathodus waageni* or  
87 *Eurygnathodus costatus* in the Mud section (Krystyn et al., 2007; 2017).

## 88 **1.2 Early Triassic substages and characteristic ammonoids**

89 Ammonoids exhibit high evolutionary rates in the Triassic and are also widely  
90 distributed in Triassic fossiliferous exposures. They therefore constitute an  
91 unavoidable index fossil for biostratigraphic zonations and correlations, as well as  
92 evolutionary studies at different geographic scales (Balini et al., 2010; Jenks et al.,  
93 2015). All Triassic stages and substages were initially defined on ammonoid  
94 evolutionary events (Mojsisovics, 1895; Tozer, 1965; Balini et al., 2010). The  
95 resolution and robustness of Triassic ammonoid biostratigraphic scales were largely  
96 improved during the last decades, especially for the Early Triassic and Anisian,  
97 leading to highly resolved zonations in some basins (Monnet and Bucher, 2005;  
98 Brühwiler et al., 2010a; Ware et al., 2015). For example, 13 UAZs have been  
99 recognized for the Smithian in the Salt Range, Pakistan (Brühwiler et al., 2010a,  
100 2011). However, the application of such high-resolution biozonation at a global scale  
101 is more limited owing to the sometimes lack of bed-rock-controlled samplings,  
102 taxonomical homogenization, and marked biotic provinciality (Brayard et al., 2006;  
103 Dai and Song, 2020).

104 Based on ammonoid assemblages, the Griesbachian can be subdivided into two  
105 parts (early and late; Tozer, 1965, 1967). The early Griesbachian is mainly dominated  
106 by Permian holdovers, e.g., xenodiscids and otoceratids, while the late Griesbachian  
107 assemblages contain newly-originated families, such as ophiceratids, proptychitids,  
108 and mullericeratids (Ware et al., 2015; Fig. 1).

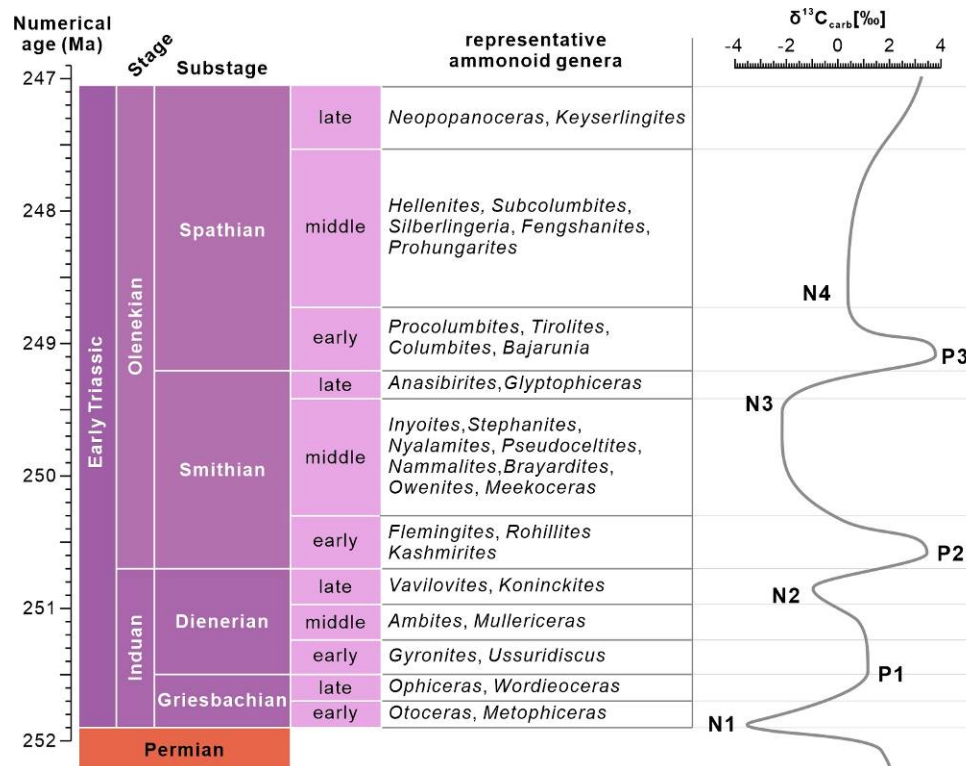
109 The Dienerian substage was erected by Tozer (1965, 1967) based on ammonoid  
110 records from Arctic Canada, with two ammonoid zones, the *Proptychites candidus*  
111 Zone and the *Paranorites sverdrupi* Zone, in ascending order. Recently, Ware et al.  
112 (2015) proposed an exhaustive revision of the Dienerian ammonoid taxonomy and

113 biochronology based on extensive sampling of Dienerian ammonoids from the Salt  
114 Range (Pakistan) and Spiti (India). A total of 12 ammonoid UAZs have been  
115 established in these regions (Ware et al., 2015). This exceptionally high resolution  
116 ammonoid zonation allows the subdivision of the Dienerian into three parts: lower,  
117 middle and late (Ware et al., 2015). The early Dienerian is represented by the  
118 co-occurrence of *Gyronites* and *Ussuridiscus* together with the youngest  
119 representative of ophiceratids (*Ghazalaites*) (Ware et al., 2015). The middle Dienerian  
120 is characterized by the co-occurrence of *Ambites* and *Mullericeras* (note that  
121 *Mullericeras* occurs earlier in South China; Dai et al., 2019). The late Dienerian  
122 corresponds to the oldest occurrences of paranoritids (e.g., *Vavilovites*, *Koninckites*,  
123 and *Awanites*) and hedenstroemiids (*Clypites* and *Pseudosageceras*).

124 The Smithian substage was also proposed by Tozer (1965, 1967) and initially  
125 comprised two ammonoid zones in Arctic Canada, *Euflemingites romunderi* Zone and  
126 *Wasatchites tardus* Zone. In recent decades, Smithian ammonoids have been  
127 intensively sampled and studied in the western USA basin (Brayard et al., 2013;  
128 Jattiot et al., 2017; Jenks and Brayard, 2018; Brayard et al., 2020, 2021), the Salt  
129 Range (Brühwiler et al., 2011, 2012c), Spiti (Brühwiler et al., 2010c, 2012b), North  
130 Vietnam (Shigeta et al., 2014), South Primorye (Shigeta et al., 2009; Zakharov et al.,  
131 2013; Zakharov et al., 2021), and South China (Brayard and Bucher, 2008; Dai et al.,  
132 2021). Among these sites, the Salt Range and Spiti show the most complete Smithian  
133 ammonoid successions so far, comprising 14 UAZs (Brühwiler et al., 2010a, 2011).  
134 Based on these zones, threefold subdivisions (early, middle and late) of the Smithian  
135 have been proposed by Brühwiler et al. (2010a, 2011). The early Smithian is  
136 characterized by the dominance of flemingitids, kashmiritids, and paranoritids. During  
137 the middle Smithian, the relative dominance of these 3 families largely decreased, and  
138 newly originating families, such as Arctoceratidae, Galfettitidae, Aspenitidae, and  
139 Inyoitidae, became dominant. The late Smithian witnessed severe ammonoid  
140 extinction, with many families flourishing in the early and middle Smithian being  
141 wiped out (Brühwiler et al., 2010a; Brayard et al., 2021). The early late Smithian was  
142 strongly dominated by Prionitidae, while the second part of the late Smithian was

143 characterized by the co-occurrence of a few xenoceltitids (e.g., *X. subevolutus*,  
144 *Glyptohiceras sinuatum*) and *Pseudosageceras* species (Brayard et al., 2021; Dai et  
145 al., 2021). Recently, a potential third zone representing the latest Smithian was  
146 mentioned (Widmann et al., 2020), but its faunal content and correlation have not  
147 been published yet.

148 The Spathian substage was proposed by Tozer (1965, 1967) based on two  
149 ammonoid zones in Arctic Canada, the *Olenikites pilaticus* Zone and the  
150 *Keyserlingites subrobustus* Zone. After the Tozer's proposal, the temporal resolution  
151 of the Spathian ammonoid biozonations has been greatly improved based on the  
152 extensive fieldworks conducted within the western USA basin (Guex et al., 2010;  
153 Jenks et al., 2013; Brayard et al., 2019), Japan (Ehiro et al., 2016; Ehiro, 2022;  
154 Shigeta, 2022), Western Tethys (Gaetani et al., 1992; Posenato, 1992), and South  
155 China (Galfetti et al., 2007b; Ji et al., 2015). However, many uncertainties remain for  
156 large-scale correlations, partly reflecting the marked endemism existing during the  
157 middle and late Spathian (Brayard et al., 2006; Dai and Song, 2020). To date, the most  
158 complete succession of Spathian ammonoid faunas has been documented from the  
159 western US basin (Guex et al., 2010; Jenks et al., 2013). It presently contains 8 zones  
160 and 23 horizons. According to this succession, the Spathian can be subdivided into  
161 three parts: early, middle and late. The early Spathian was dominated by tirolitids and  
162 columbitids. The middle Spathian contains two zones, the  
163 *Fengshanites/Prohungarites* Zone and the *Silberlingeria* Zone. The late Spathian is  
164 represented by two zones as well, the *Neopopanoceras haugi* Zone and the  
165 *Keyserlingites subrobustus* Zone (Guex et al., 2010). However, the correlation of  
166 these high-resolution Spathian ammonoid zonations in the western USA basin awaits  
167 similar high-resolution biostratigraphical scales from other regions.



168

169 Figure 1. Early Triassic subdivisions and their representative ammonoid genera,  
 170 associated with simplified carbon isotopic curve for the Early Triassic. Numerical  
 171 ages for each stage/substage are from Burgess et al. (2014), Ovtcharova et al. (2015),  
 172 Widmann et al. (2020) and Dai et al. (2023). Note that in the latest version of the ICS  
 173 International Chronostratigraphic Chart (v2022/10), the age of the Induan/Olenekian  
 174 boundary is 251.2 Ma based on sample CHIN40 (Ovtcharova et al., 2006). Recently,  
 175 this sample has been re-analyzed and the new resulting age is  $250.647 \pm 0.064$  Ma ( $2\sigma$ )  
 176 (Widmann et al., 2020). Subdivisions and respective representative ammonoid genera  
 177 for the Griesbachian are from Tozer (1965, 1967), for the Dienerian are from Ware et  
 178 al. (2015), for the Smithian are from Brühwiler et al. (2010a), and for the Spathian are  
 179 from Guex et al. (2010). Carbon isotopic curve is modified from Galfetti et al. (2008),  
 180 Hermann et al. (2011), and Sun et al. (2021). The definition of the carbon isotopic  
 181 excursions (N1-N4, P1-P3) refers to Song et al. (2013)

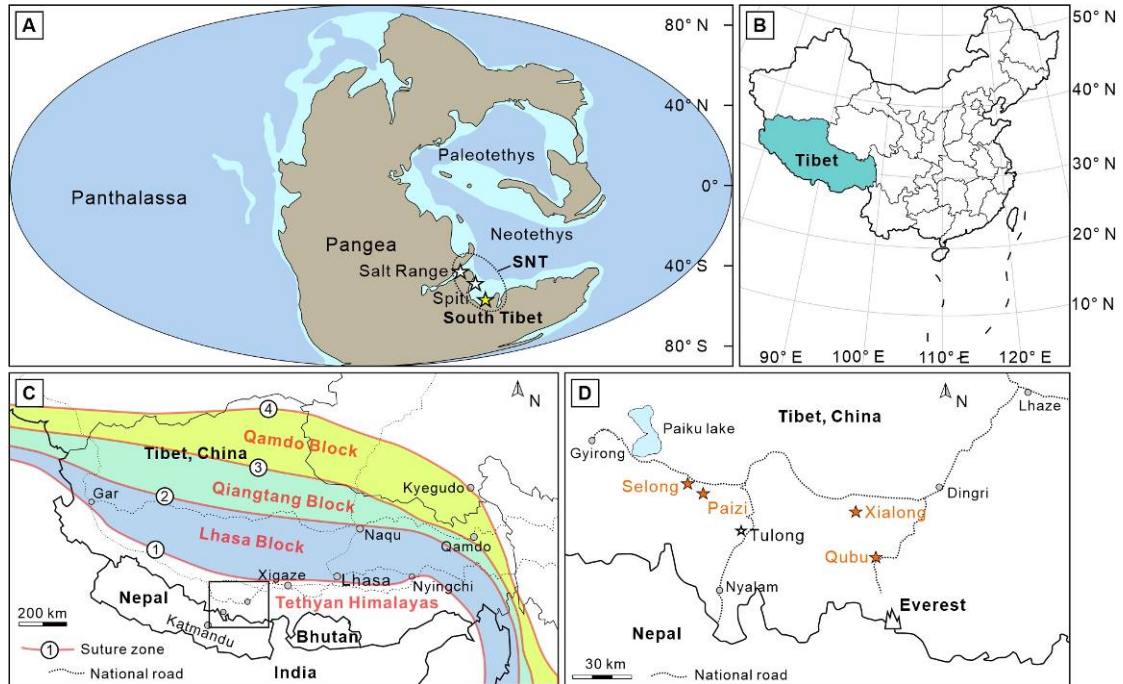
## 182 2 New Early Triassic ammonoid data from South Tibet

### 183 2.1 Geological settings

184 The Tibetan Plateau is a complex assembly of blocks and terranes separated by  
 185 major suture zones. These are, from south to north, the Tethyan Himalaya, the  
 186 Yarlung-Zangbo suture zone, the Lhasa Block, the Bangong-Nujiang suture zone, the



187 Qiangtang Block, the Longmu Co-Shuanghu-Lancangjiang suture zone, the Qamdo  
 188 Block, and the Jinshajiang suture zone (Yin and Harrion, 2000). South Tibet is located  
 189 in the Tethyan Himalaya, which was situated on the northern Gondwana passive  
 190 margin during the Early Triassic (Fig. 2).



191  
 192 Figure 2. Locations of the studied region and sections. (A) Early Triassic  
 193 paleogeographic map modified from Scotese (2014). SNT, Southern Neotethys. (B)  
 194 Present-day position of Tibet, China. (C) Simplified tectonic map of Tibet and  
 195 location of the study area (rectangle), modified from Zhang et al. (2013). Suture zones:  
 196 1, Yarlung-Zangbo; 2, Bangong-Nujiang; 3, Longmu Co-Shuanghu-Lancangjiang; 4,  
 197 Jinshajiang. (D) Locations of the four studied sections (yellow stars) and the Tulong  
 198 section (white star), which is a reference section previously studied by Brühwiler et al.  
 199 (2010b).

200

201 The regional Permian-Triassic lithological succession is represented by the  
 202 Permian Selong Group, the Lower Triassic Kangshare Formation and the Middle  
 203 Triassic Laibuxi Formation (Wang et al., 1980). The Kangshare Formation is  
 204 dominated by carbonate and shale deposits formed in middle to outer ramp settings  
 205 (Li et al., 2019a, 2019b). After careful field observations and correlations, we can  
 206 divide the Kangshare Formation into six lithological units (Figs. 3, 4).

207 Unit A is Griesbachian and is composed of thin- to medium-bedded, yellowish  
 208 dolomites (Fig. 4A). It corresponds to unit Ia at Tulong (Brühwiler et al., 2009). This

209 unit is usually barren of macrofossils. However, at some sites (e.g., Selong), it  
210 contains common but poorly preserved ammonoids. The formation of this dolomitized  
211 unit is assumed to have been induced by sulphate-reducing bacteria under elevated  
212 seawater alkalinity caused by sulphate reduction coupled with elevated surface ocean  
213 temperatures (Li et al., 2018a, 2019b).

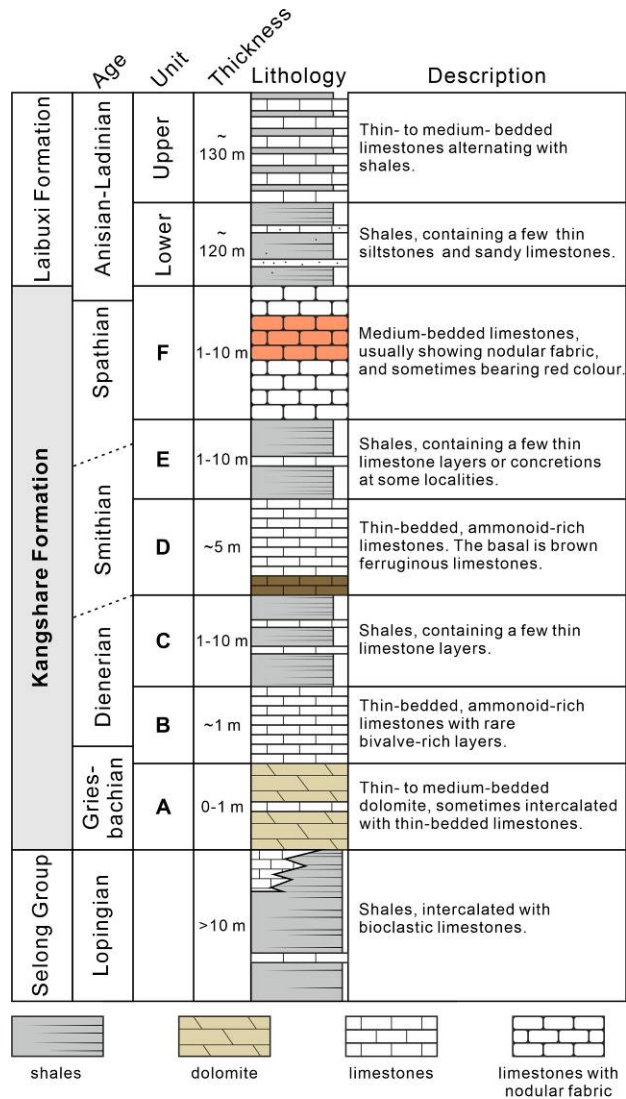
214 Unit B covers the Griesbachian-Dienerian transition and is characterized by  
215 thin-bedded, grey limestones, with a total thickness of ~ 1 m (Fig. 4A, B), identical to  
216 unit Ib at Tulong (Brühwiler et al., 2009). Unit B contains abundant ammonoids and  
217 occasionally bivalve-rich beds. However, these limestones are usually highly  
218 cemented, preventing easy excavation and preparation of ammonoid specimens.

219 Unit C is Dienerian and Smithian in age. It is dominated by shales, with rare  
220 occurrences of thin-bedded limestones (Fig. 4C), identical to unit II at Tulong  
221 (Brühwiler et al., 2009). Shales are usually barren of fossils, while limestone beds  
222 sometimes contain abundant ammonoids and some bivalve specimens.

223 The bottom of Smithian unit D is characterized by brown ferruginous limestone  
224 beds containing poorly preserved ammonoids (Fig. 4C). These ferruginous limestone  
225 beds are overlain by thin- to medium-bedded, light-grey, ammonoid-rich limestones  
226 (Fig. 4D). Ammonoids from these upper limestones are usually well preserved and  
227 easy to excavate and prepare. Bivalve-rich beds are also common in these upper beds.  
228 Overlying units E and F are Spathian in age.

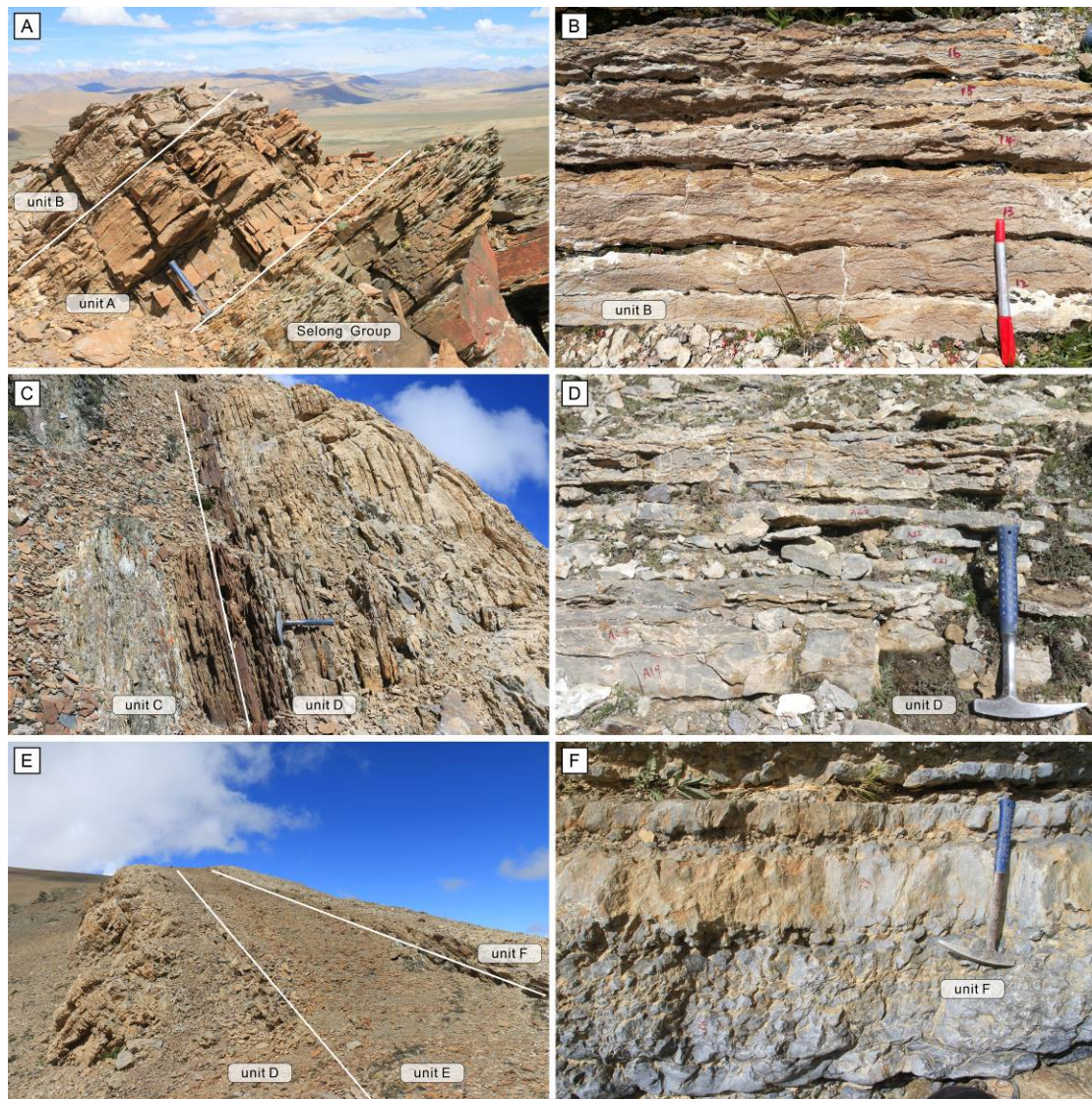
229 Unit E is similar to unit C and is dominated by shales intercalated with a few  
230 limestone beds (Fig. 4E). This unit is barren of macrofossils. This unit straddles the  
231 Smithian/Spathian boundary (Brühwiler et al., 2009).

232 Unit F includes medium-bedded, grey (sometimes red, such as at Tulong; see  
233 (Brühwiler et al., 2009; Li et al., 2019a), nodular limestones (Fig. 4F) containing  
234 moderately abundant ammonoids that are hard to excavate due to the high  
235 cementation of enclosing rock.



236

237 Figure 3. Synthetic lithological succession of the Kangshare Formation in South  
 238 Tibet.



239

240 Figure 4. Field observations for lithological units of the Kangshare Formation. (A)  
 241 ~~The b~~oundary between the Kangshare Formation and Selong Group at Paizi. (B)  
 242 Unit B showing thin-bedded limestones at Selong. (C) Units C and D in Paizi,  
 243 showing dark brown ferruginous beds at the base of unit D. (D) Thin bedded  
 244 ammonoid-rich limestones of unit D at Paizi. (E) Units D, E and F at Paizi. (F) Unit F  
 245 medium-bedded limestones bearing nodular fabric at Xialong.

## 246 2.2 Historical studies on Early Triassic ammonoids from South Tibet

247 The Himalayan Early Triassic ammonoids have been known since the pioneering  
 248 works of Griesbach (1880), Diener (1897), and Krafft and Diener (1909). However,  
 249 detailed studies of the Lower Triassic exposures from South Tibet were only  
 250 performed nearly one hundred years later (Mu et al., 1973; Wang and He, 1976; Wang  
 251 et al., 1980). Since then, numerous works on ammonoids (Brühwiler et al., 2010b;

252 Zhang et al., 2017), conodonts (Orchard et al., 1994; Wang and Wang, 1995; Wang et  
253 al., 2017) and sedimentological and geochemical contexts (Brühwiler et al., 2009; Li  
254 et al., 2018a, 2018b, 2019a, 2019b) have been published, leading South Tibet to be a  
255 potentially significant area to decipher the PTME and its subsequent biotic recovery  
256 (Shen et al., 2006; Li et al., 2019a).

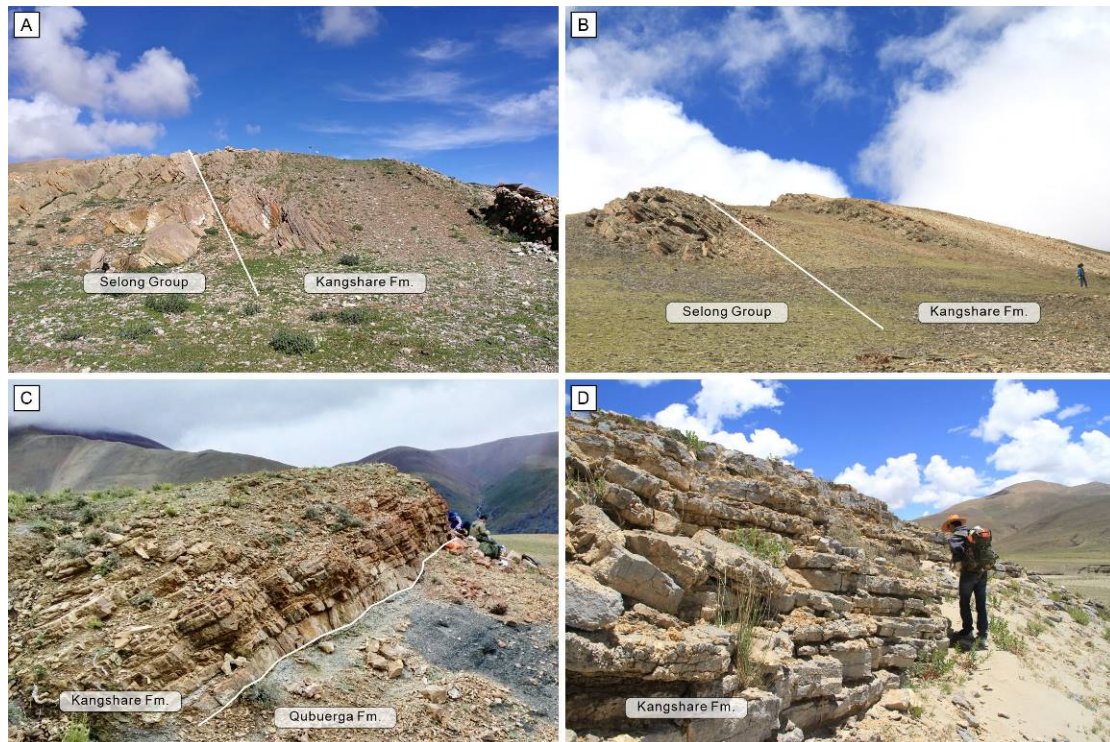
257 Wang and He (1976) originally recognized five ammonoid zones within the  
258 study area: the *Otoceras latilobatum* and *Ophiceras sakuntala* zones in the  
259 Griesbachian, the *Gyronites psilogyrus* Zone in the Dienerian, the *Owenites* Zone in  
260 the Smithian, and the *Procarnites-Anasibirites* Zone ranging from the late Smithian to  
261 the Spathian, in ascending order. Brühwiler et al. (2010b) established a  
262 high-resolution middle-late Smithian ammonoid biostratigraphy based on data from  
263 the Tulong section (Fig. 2D), which includes six ammonoid beds. Zhang et al. (2017)  
264 also described a few Griesbachian-Dienerian ammonoids from the Qubu section (Fig.  
265 2D) and identified three zones: the *Otoceras woodwardi* and *Ophiceras tibeticum*  
266 zones in the Griesbachian and the *Ambites* Zone for the middle Dienerian. Overall,  
267 compared with adjacent regions such as Spiti and the Salt Range (Brühwiler et al.,  
268 2010a; Ware et al., 2015), the resolution of the South Tibet ammonoid zonation is  
269 much lower.

## 270 **2.3 Studied sections**

### 271 **2.3.1 Selong**

272 The Selong section (Figs. 2D, 5A) was first reported by the Scientific Survey of  
273 the Everest area (1966 to 1968) [Wang and He, 1976]. Since then, this site has been  
274 thoroughly studied for brachiopods (Shen et al., 2000, 2001), ammonoids (Wang and  
275 He, 1976), and conodonts (Orchard et al., 1994; Wang and Wang, 1995; Wang et al.,  
276 2017; Yuan et al., 2018) and for geochemical purposes (Shen et al., 2006). Selong was  
277 also proposed as a candidate for the Permian/Triassic boundary Global Boundary  
278 Stratotype Section and Point (GSSP) (Jin et al., 1996). The Permian is represented by

279 the Selong Group and contains shales and bioclastic limestones, with thicknesses  
280 greater than 20 m. It yields abundant brachiopods, corals, and bryozoans (Shen et al.,  
281 2000; Shen et al., 2001; Sakagami et al., 2006). The uppermost part of the Selong  
282 Group contains late Changhsingian conodonts (Orchard et al., 1994; Wang et al., 2017;  
283 Yuan et al., 2018). Unit A of the Lower Triassic Kangshare Formation at Selong  
284 corresponds to a lenticular dolomite bed with a maximum thickness of ~1 m,  
285 including crinoid fragments and a few poorly preserved ammonoids. This unit also  
286 yields *Hindeodus parvus*, a conodont marker of the Permian/Triassic boundary (Yin et  
287 al., 2001). Wang and He (1976) recognized five Early Triassic ammonoid zones at  
288 Selong.



289  
290 Figure 5. Landscape views of the studied sections. (A) Selong section (GPS:  
291 28°39'52.8"N, 85°49'19.7"E). (B) Paizi section (GPS: 28°34'15.5"N, 85°57'50.9"E).  
292 (C) Qubu section (GPS: 28°18'43.6"N, 86°49'38.1"E). (D) Xialong section (GPS:  
293 28°30'60.0"N, 86°41'13.7"E). Fm. Formation.

### 294 2.3.2 Paizi

295 The Paizi section (Figs. 2D, 5D) is located ca. 20 km southeast of the Selong  
296 section. This section was discovered during a 2019 fieldwork. The lithological  
297 succession of the Kangshare Formation at Paizi is nearly identical to that of the

298 Selong section, with only minor differences in thickness. Abundant ammonoids were  
299 sampled from units B and D.

### 300 **2.3.3 Qubu**

301 The Qubu section (Figs. 2D, 5B) is situated approximately 15 km north of the Mt.  
302 Everest Base Camp, near Mt. Everest Road. The lithostratigraphic succession includes  
303 the Permian Qubu and Qubuerga Formations and the Early Triassic Kangshare  
304 Formation. The Qubu Formation is made of quartzose sandstone, alternating with  
305 black silty shales, yielding a *Glossopteris* flora (Hsu, 1976; Shen et al., 2003a). The  
306 overlying Qubuerga Formation is composed of siltstones interbedded with shales and  
307 bioclastic limestones, containing abundant brachiopods, bryozoans, corals, gastropods,  
308 bivalves and a few ammonoids (Shen et al., 2003b, 2004; Pan and Shen, 2008). The  
309 ammonoid *Roadoceras xizangense* was sampled from the lower part of the Qubuerga  
310 Formation, indicating a Late Capitanian-Early Wuchiapingian age (Shen et al., 2004).  
311 Unit A of the Kangshare Formation is dominated by ~1 m thick dolomite alternating  
312 with shales. The overlying unit B is characterized by thin-bedded limestones and  
313 shales, yielding abundant ammonoids (Zhang et al., 2017). This unit also includes the  
314 occurrence of a helicoprionid shark (Zhang, 1976).

### 315 **2.3.4 Xialong**

316 The Xialong section is located ~10 km southeast of Gangga, Tingri (Figs. 2D,  
317 5C). A small outcrop of unit D in the Kangshare Formation, ~ 4.2 m thick, was  
318 sampled. This succession is dominated by bioclastic limestones, yielding abundant but  
319 usually weathered ammonoids, bivalves and rare orthoconic nautiloids.

## 320 **2.4 Methods and data**

321 The four studied sections were logged and sampled bed by bed (Figs. 6–11).  
322 Specimens were extracted by mechanically decomposing dm-sized blocks from  
323 fossiliferous beds. Mechanical techniques, e.g., pneumatic air scribes, were also later

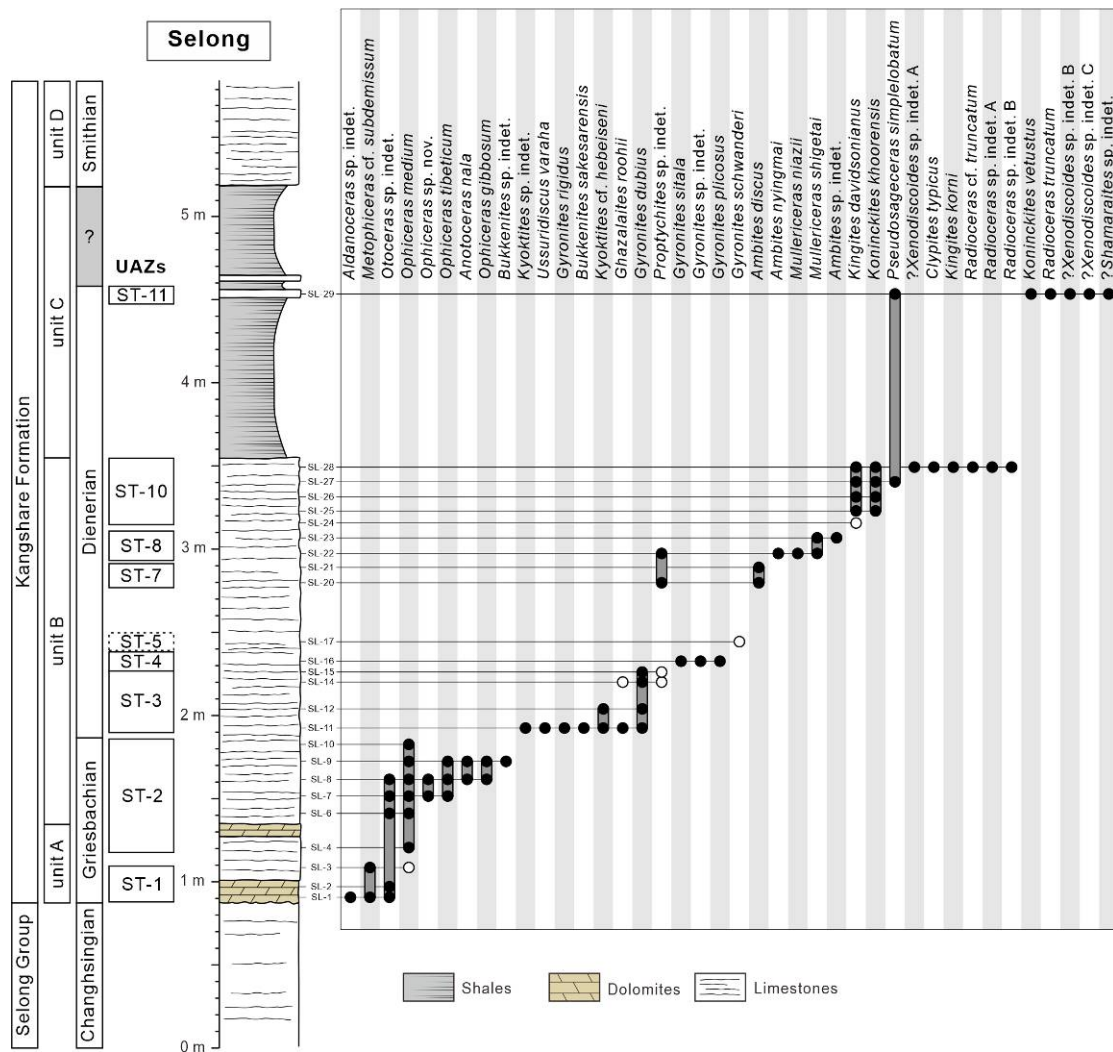
324 performed in the laboratory to work out morphologic details facilitating species-level  
325 identification. Specimens were whitened by magnesium, then photographed using a  
326 Canon 70D camera with a micro-lens EF 100 mm f/2.8. Systematic works mainly  
327 follow the classification established by Tozer (1994) and revised by Brühwiler et al.  
328 (2012a, 2012b, 2012c) and Ware et al. (2018a, 2018b). A total of 140 species were  
329 identified in the four studied sections from the Griesbachian to the Smithian (Figs.  
330 6–11). Representative ammonoid species of each substage are illustrated in Figures  
331 12–14. All studied specimens are housed at the Yifu Museum, China University of  
332 Geosciences (YFMCUG). Inventory numbers of the figured specimens are reported in  
333 respective captions.

334 The Unitary Associations (UA) method was used to construct the ammonoid  
335 biostratigraphical scale. A detailed description of the UA method is available in Guex  
336 et al. (2016). Compared with classical interval zones, which are based on first and last  
337 occurrences of specific taxa, the UA method utilizes the associations and  
338 superpositions of a set of taxa and provides more robust discrete biozones with a  
339 higher lateral reproducibility (Guex et al., 2016). The UA method has therefore been  
340 used in many regional and global biostratigraphic works (Brühwiler et al., 2010a;  
341 Ware et al., 2015; Klein and Korn, 2016; Jattiot et al., 2017; Xiao et al., 2018; Wu et  
342 al., 2020). The UA method implemented in PAST 3.0 (Hammer et al., 2001) was used  
343 in this study.

344 Taxa lacking a firm species-level identification, long-ranging taxa, occurrences  
345 based on poorly preserved material, and occurrences from potential  
346 condensed/reworked levels were omitted in our analyses, except some taxa from the  
347 Griesbachian, due to the rarity of ammonoid specimens from this substage. A total of  
348 59 species covering the Griesbachian-Smithian interval were included in the UA  
349 analyses. Previously removed taxa were reinserted into reconstructed UAZs. We  
350 performed a first set of analyses using the dataset of the four studied sections plus  
351 data from the Tulong section (Brühwiler et al., 2010b), providing a synthetic UA  
352 zonation for South Tibet. Then, we ran a second set of analyses using the South Tibet  
353 data together with published datasets from Spiti and the Salt Range (Brühwiler et al.,



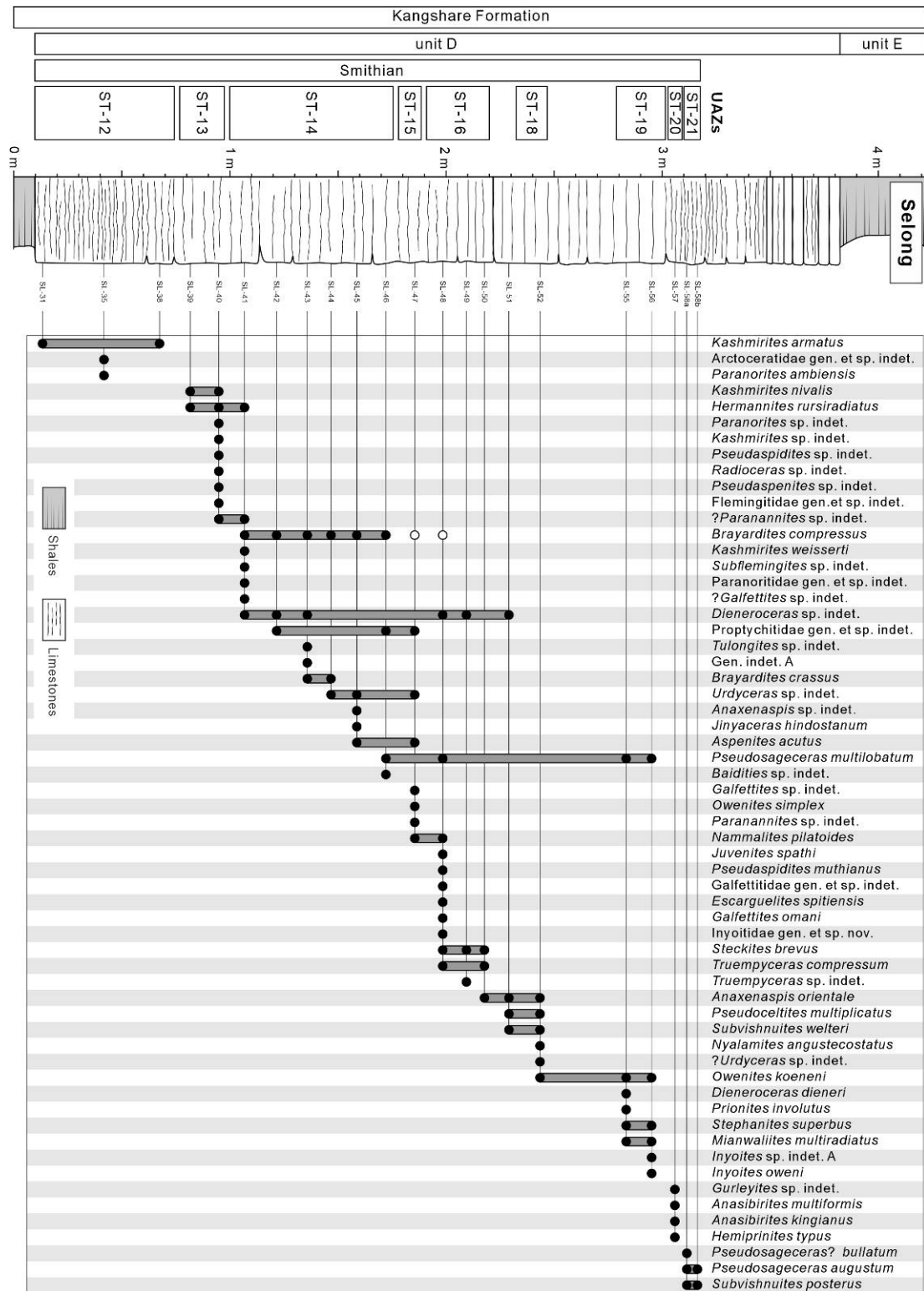
354 2010b, 2010c, 2011; Ware et al., 2015; Krystyn et al., 2017; Fig. 2A). A total of 93  
 355 species were included in this second set of analyses. This allows the construction of  
 356 integrated Dienerian and Smithian ammonoid UAZs for the Southern Neotethys  
 357 (SNT). Griesbachian ammonoids were not integrated in the second set of analyses  
 358 owing to their poorly documented occurrences and the lack of thorough taxonomic  
 359 revisions. Additionally, we did not integrate in our analyses ammonoid faunas from  
 360 the neighboring Nepal (Waterhouse, 1994....) as these specimens are very poorly  
 361 preserved and calibrated, and require thorough taxonomic revisions.



362

363 Figure 6. Ammonoid distribution within units A to C of the Kangshare Formation at  
 364 Selong. Open circles represent occurrences based only on fragmentary or poorly  
 365 preserved material.

366



367

368

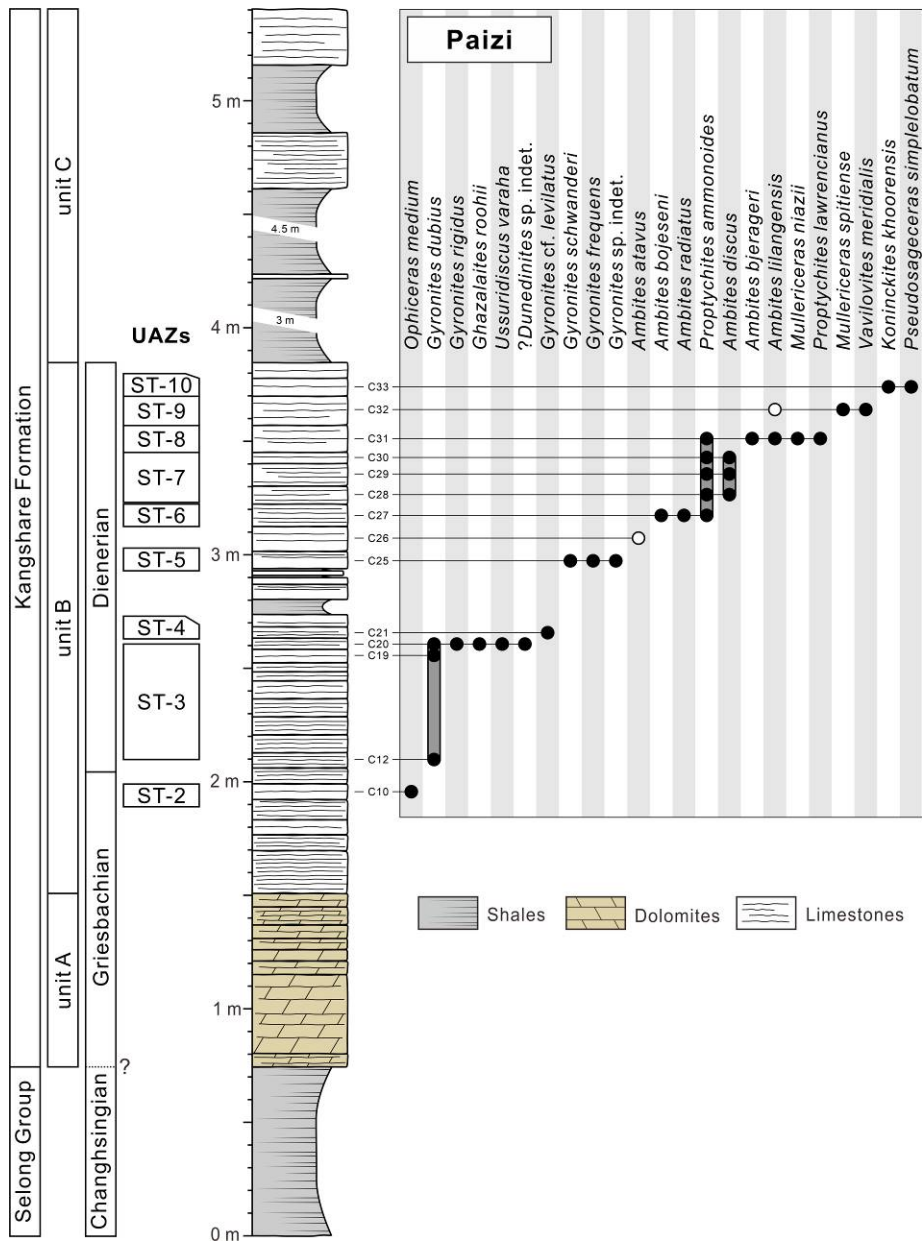
Figure 7. Ammonoid distribution in unit D of the Kangshare Formation at Selong.

369

Open circles represent occurrences based only on fragmentary or poorly preserved

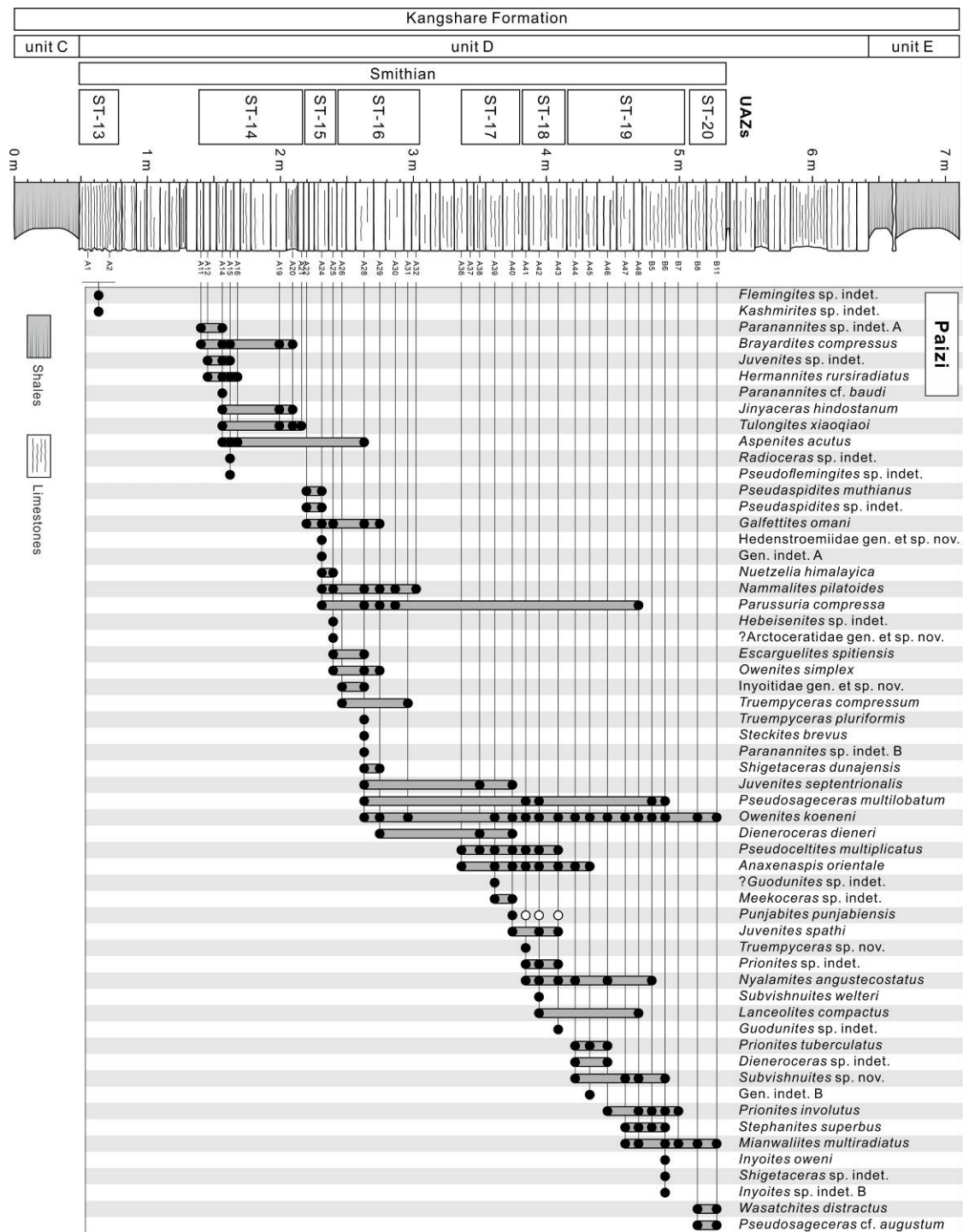
370

material.



371

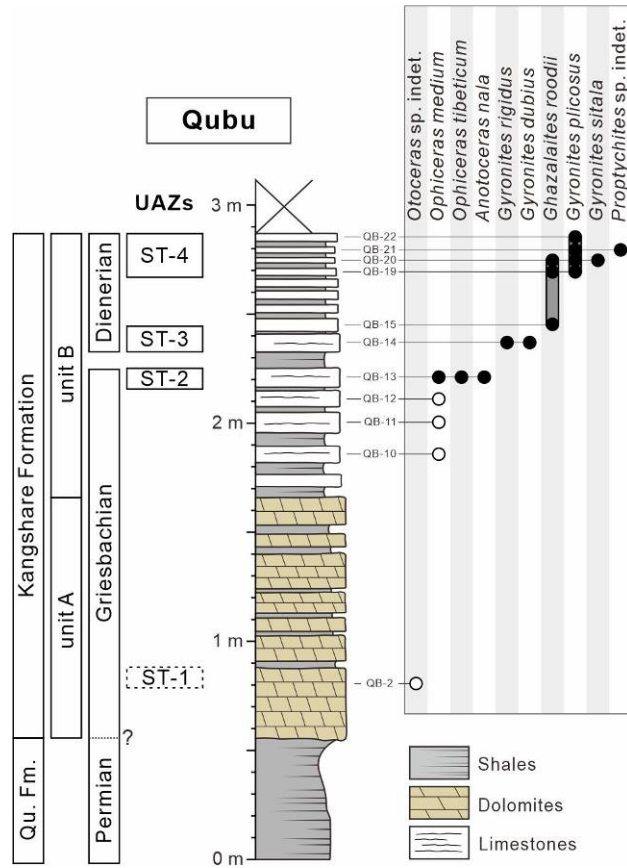
372 Figure 8. Ammonoid distribution in unit B of the Kangshare Formation at Paizi. Open  
 373 circles represent occurrences based only on fragmentary or poorly preserved material.



374

375 Figure 9. Ammonoid distribution in unit D of the Kangshare Formation at Paizi. Open

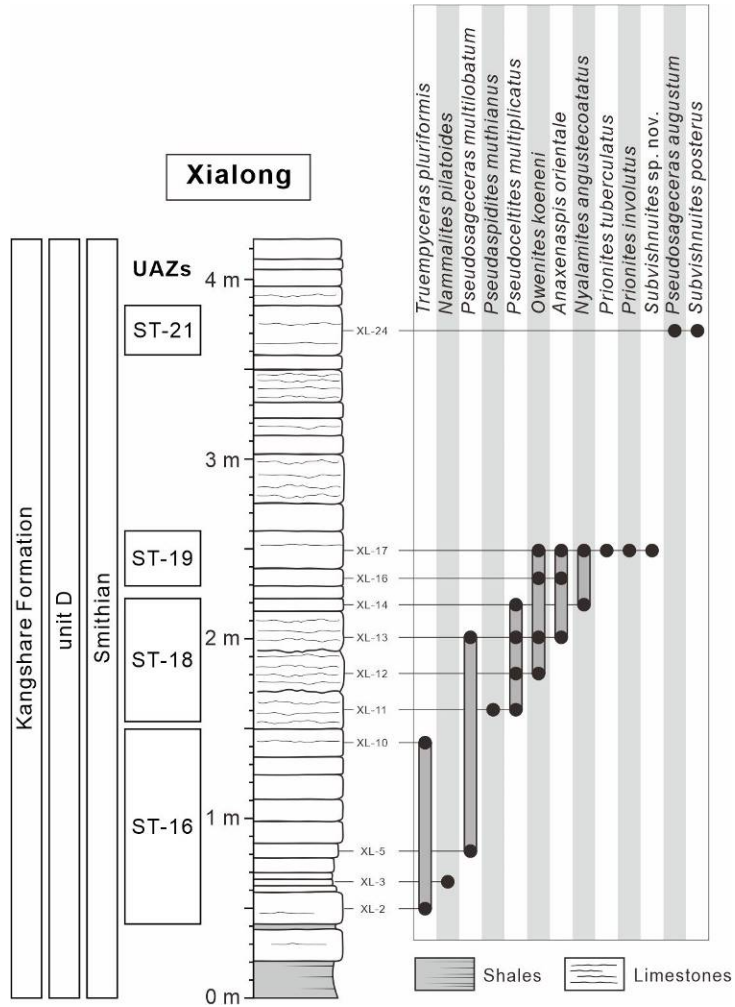
376 circles represent occurrences based only on fragmentary or poorly preserved material.



377

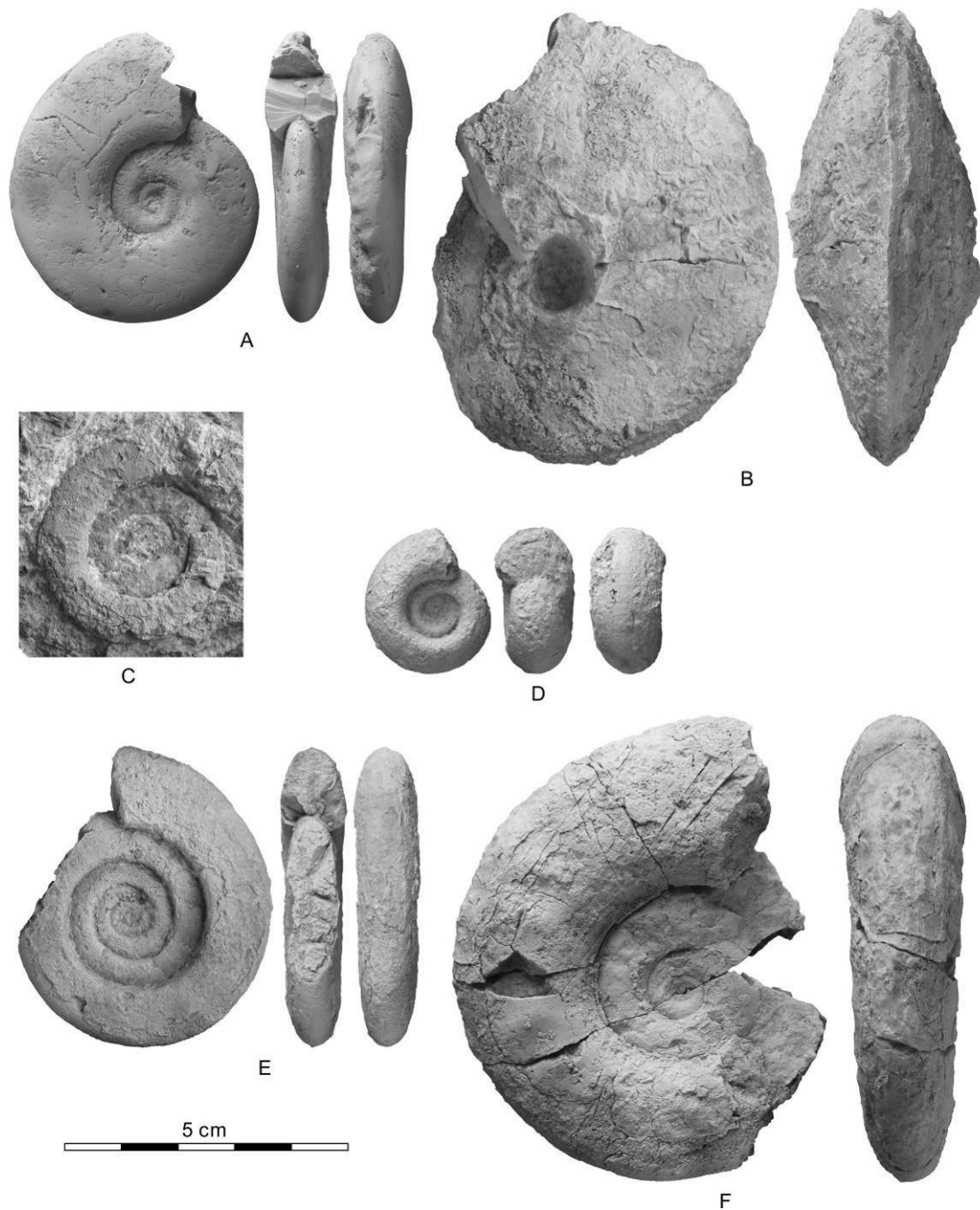
378 Figure 10. Ammonoid distribution in units A and B of the Kangshare Formation at  
 379 Qubu. Open circles represent occurrences based only on fragmentary or poorly  
 380 preserved material.

381

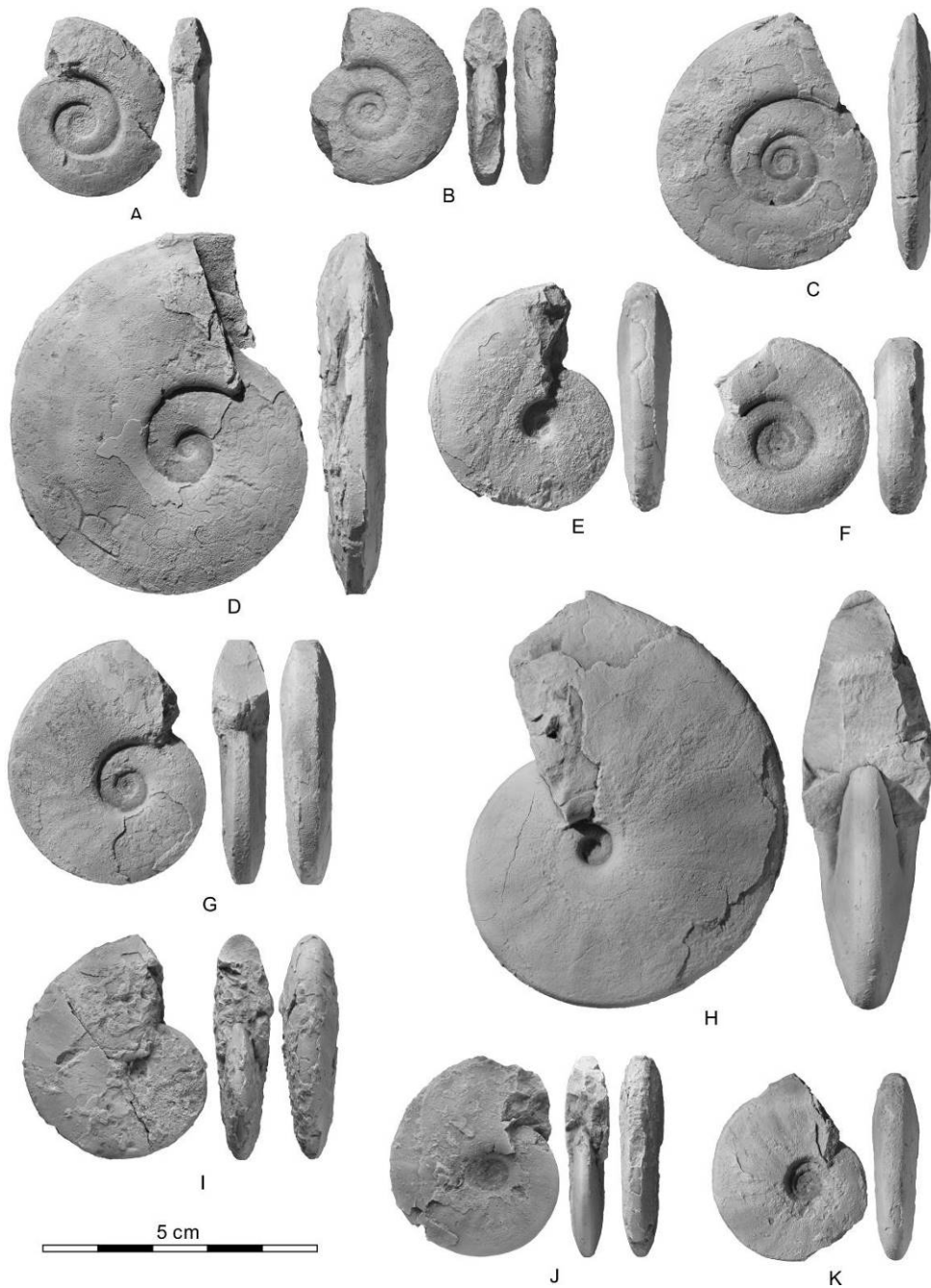


382

383 Figure 11. Ammonoid distribution in unit D of the Kangshare Formation at Xialong.

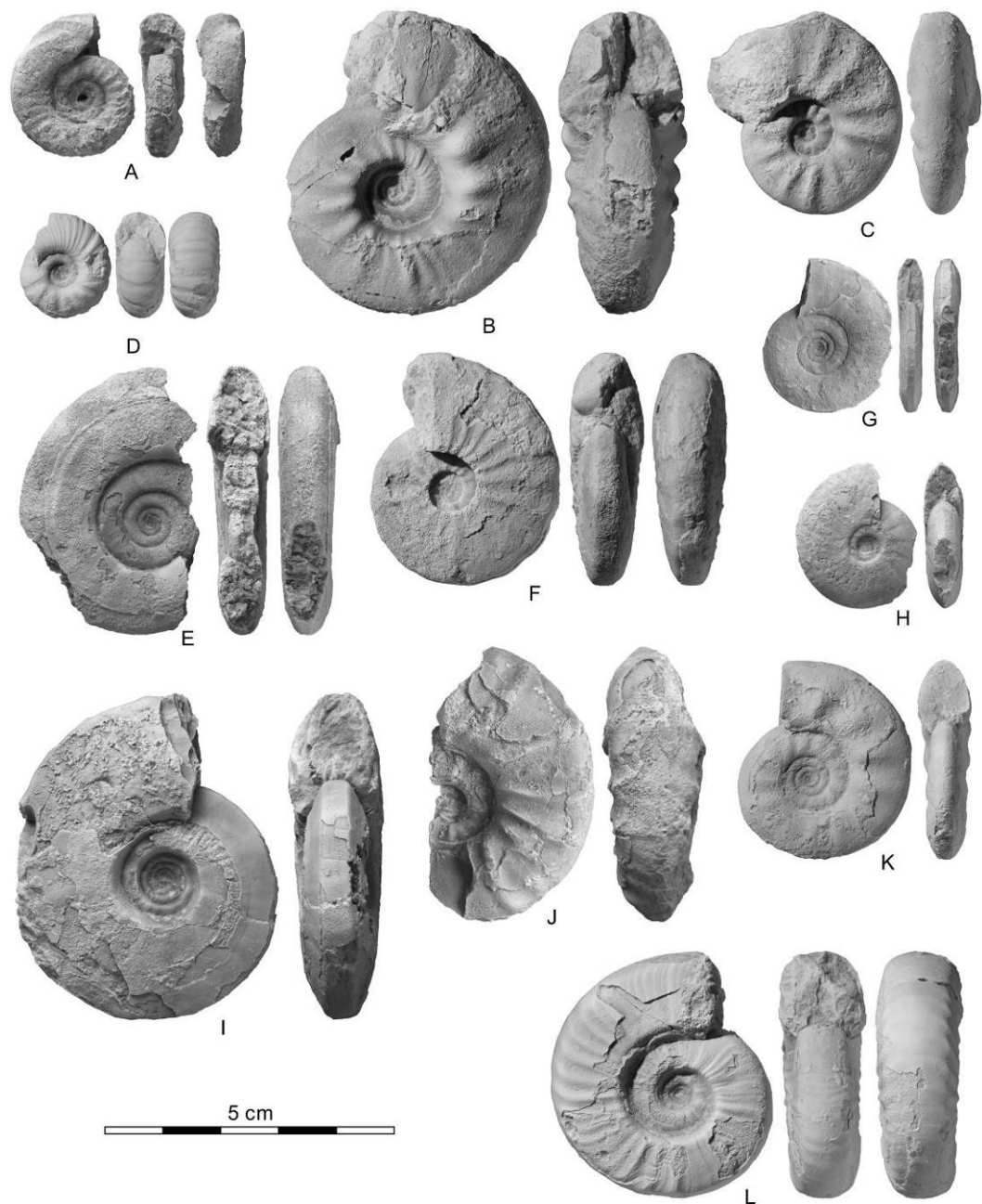


384  
 385 Figure 12. Representative Griesbachian ammonoids from South Tibet. (A) *Ophiceras*  
 386 *medium*, YFMCUG 00304, from sample SL-8, Selong. (B) *Otoceras* sp. indet.,  
 387 YFMCUG 00305, from sample SL-8, Selong. (C) *Metophiceras* cf. *demissum*,  
 388 YFMCUG 00306, from sample SL-3, Selong. (D) *Anotoceras nala*, YFMCUG 00307,  
 389 from sample SL-8, Selong. (E) *Ophiceras tibeticum*, YFMCUG 00308, from sample  
 390 SL-9, Selong. (F) *Ophiceras gibbosum*, YFMCUG 00309, from sample SL-8, Selong.  
 391  
 392

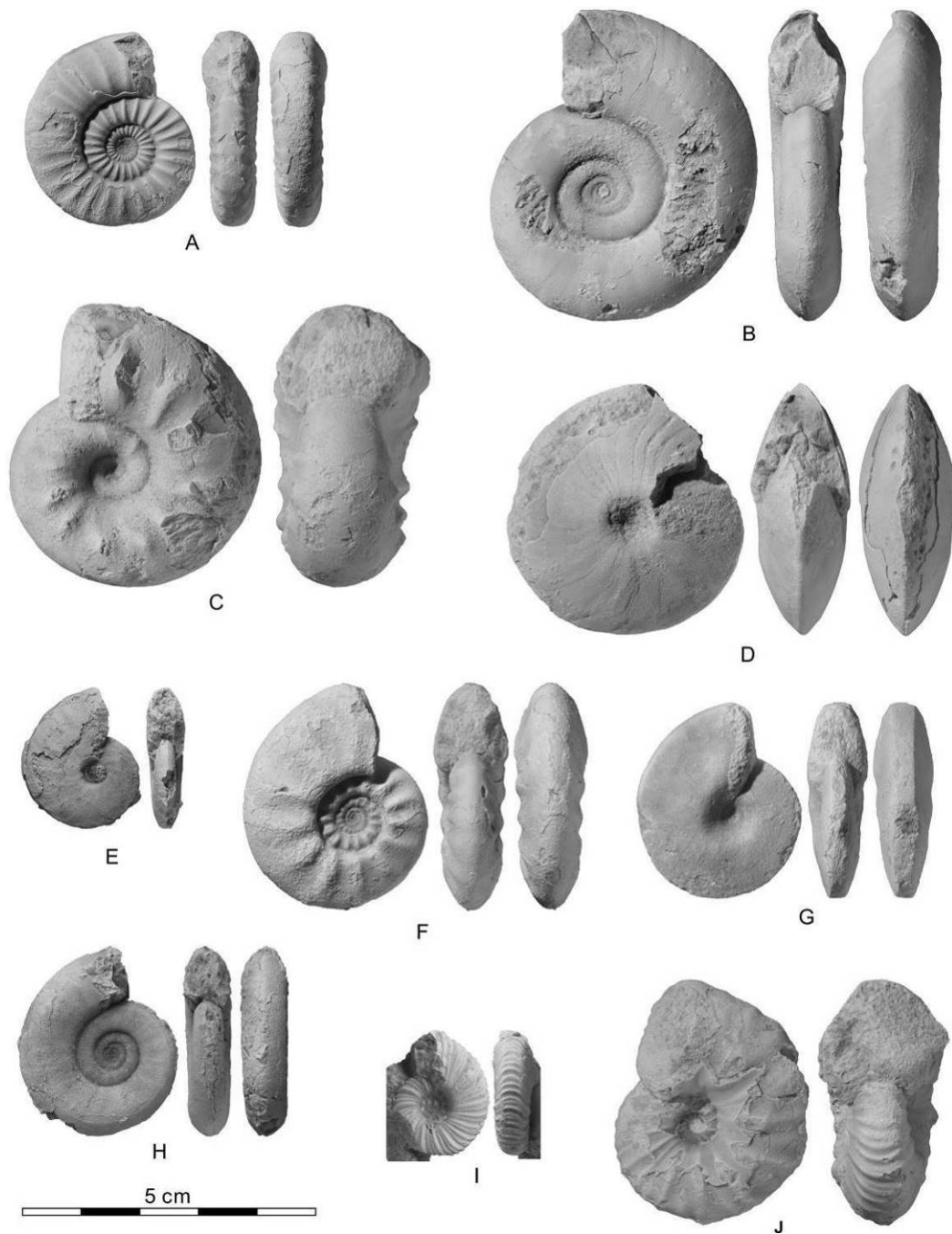


393  
 394 Figure 13. Representative Dienerian ammonoids from South Tibet. (A) *Gyronites*  
 395 *dubius*, YFMCUG 00310, from sample C20, Paizi. (B) *Gyronites plicosus*, YFMCUG  
 396 00311, from sample SL-16, Selong. (C) *Gyronites frequens*, YFMCUG 00312, from  
 397 sample C25, Paizi. (D) *Ambites discus*, YFMCUG 00313, from sample C28, Paizi. (E)  
 398 *Ambites lilangensis*, YFMCUG 00314, from sample C31, Paizi. (F) *Ambites bjerageri*,  
 399 YFMCUG 00315, from sample C27, Paizi. (G) *Ambites bojeseni*, YFMCUG 00316,  
 400 from sample C31, Paizi. (H) *Vavilovites meridialis*, YFMCUG 00317, from sample  
 401 C32, Paizi. (I) *Kingites davidsonianus*, YFMCUG 00318, from sample SL-27, Selong;  
 402 (J) *Koninckites vetustus*, YFMCUG 00319, from sample C33, Paizi. (K) *Koninckites*  
 403 *khoorensis*, YFMCUG 00320, from sample SL-29, Selong.





405  
 406 Figure 14. Representative early and middle Smithian ammonoids from South Tibet.  
 407 (A) *Kashmirites armatus*, YFMCUG 00321, from sample SL-38, Selong. (B)  
 408 *Brayardites compressus*, YFMCUG 00322, from sample A15, Paizi. (C) *Nammalites*  
 409 *pilatoides*, YFMCUG 00323, from sample A25, Paizi. (D) *Juvenites septentrionalis*,  
 410 YFMCUG 00324, from sample A28, Paizi. (E) *Baidites* sp. indet., YFMCUG 00325,  
 411 from sample SL-46, Selong. (F) *Truempyceras pluriformis*, YFMCUG 00326, from  
 412 sample A28, Paizi. (G) *Galfettites omani*, YFMCUG 00327, from sample SL-48,  
 413 Selong. (H) *Owenites simplex*, YFMCUG 00328, from sample SL-47, Selong. (I)  
 414 *Truempyceras compressum*, YFMCUG 00329, from sample SL-51, Selong. (J)  
 415 *Escarguelites spitiensis* YFMCUG 00330 from sample SL-48, Selong. (K)  
 416 *Anaxenaspis orientale*, YFMCUG 00331, from sample A41, Paizi. (L) *Pseudoceltites*  
 417 *multiplacatus*, YFMCUG 00332, from sample A40, Paizi.



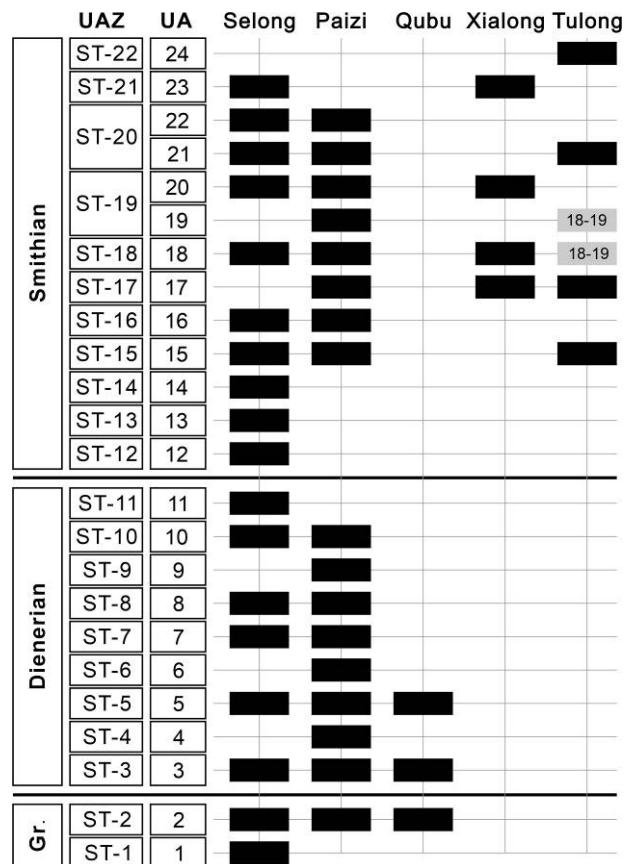
419

420 Figure 15. Representative middle and late Smithian ammonoids from South Tibet. (A)  
 421 *Nyalamites angustecostatus*, YFMCUG 00333, from sample A42, Paizi. (B)  
 422 *Subvishnuites welteri*, YFMCUG 00334, from sample A42, Paizi. (C) *Stephanites*  
 423 *superbus*, YFMCUG 00335, from sample A47, Paizi. (D) *Owenites koeneni*,  
 424 YFMCUG 00336, from sample A41, Paizi. (E) *Hemiprionites typus*, YFMCUG 00337,  
 425 from sample SL-57, Selong. (F) *Mianwaliites multiradiatus*, YFMCUG 00338, from  
 426 sample B6, Paizi. (G) *Prionites tuberculatus*, YFMCUG 00339, from sample A44,  
 427 Paizi. (H) *Subvishnuites posterus*, YFMCUG 00340, from sample SL-58b, Selong. (I)  
 428 *Anasibirites kingianus*, YFMCUG 00341, from sample SL-57, Selong. (J) *Wasatchites*  
 429 *distractus*, YFMCUG 00342, from sample B11, Paizi.

430

431 **2.5 A new ammonoid zonation for South Tibet**

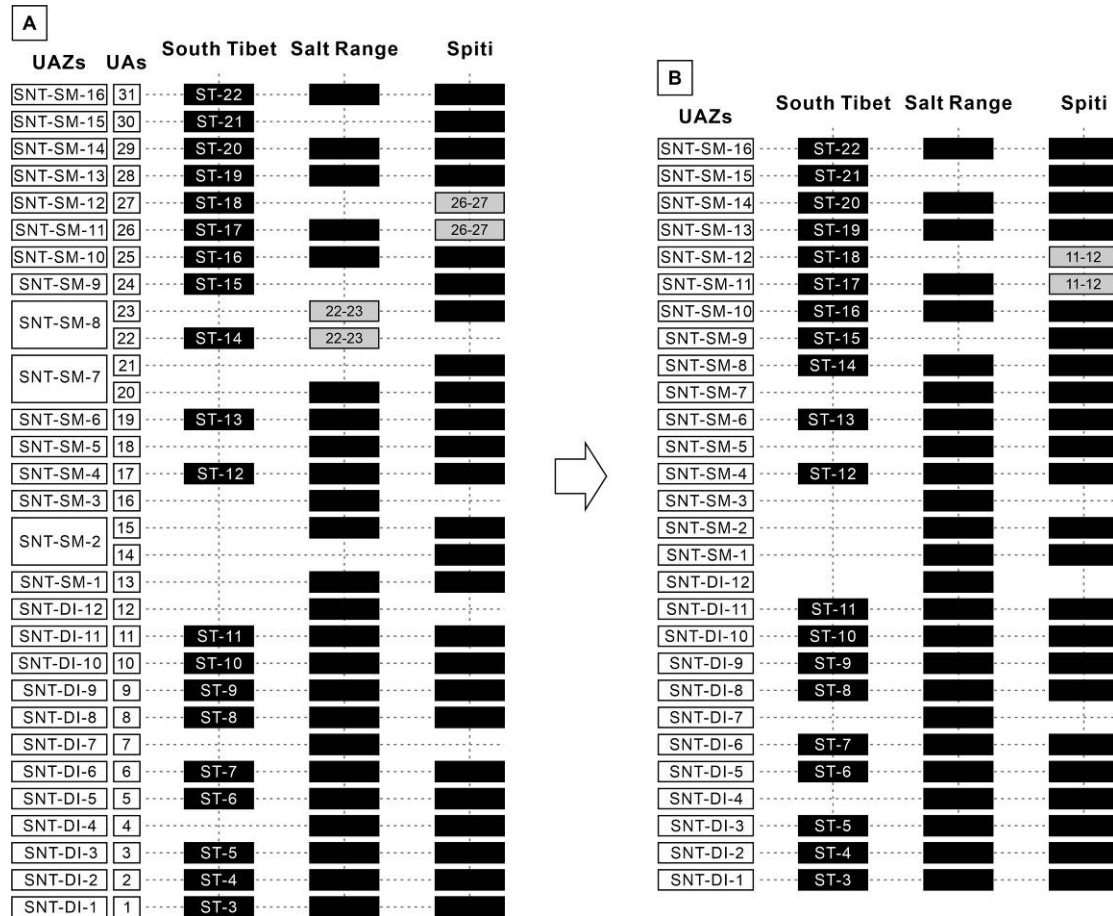
432 The first set of UA analyses based on the 59 species from South Tibet led to a  
 433 first UA ammonoid zonation comprising 24 associations for the  
 434 Griesbachian-Smithian interval without contradictions. UAs 19 and 20 were lumped  
 435 together, resulting from their low lateral reproducibility. UAs 21 and 22 were also  
 436 merged because they cannot be separated in adjacent regions, e.g., the Salt Range and  
 437 Spiti (Brühwiler et al., 2010a). The final UA zonation thus includes 22 ammonoid  
 438 UAZs: two for the Griesbachian, nine for the Dienerian, and 11 for the Smithian. The  
 439 lateral reproducibility of the UAZs is indicated in Fig. 16, and their faunal content in  
 440 Fig. 17.



441  
 442 Figure 16. Lateral reproducibility of the UAs and UAZs at the five analyzed sections  
 443 in South Tibet. Grey rectangles indicate uncertain UA assignment ranges.



454 constructed a synthetic Dienerian-Smithian ammonoid zonation. Twenty-eight UAZs  
 455 were identified, most of which showed strong lateral reproducibility (Figs. 18, 19).



456  
 457 Figure 18. Lateral reproducibility of UAs and UAZs within the SNT. Grey rectangles  
 458 indicate uncertain UA assignment ranges in (A) and uncertain UAZ assignment  
 459 ranges in (B).



463 placement of the Dienerian/Smithian boundary among different proposals (see section  
464 XXX).

465

### 466 **3.1 Griesbachian**

467 Griesbachian ammonoids are not well documented in the SNT. Thus, correlations  
468 with other basins for this time interval are rather rough (Fig. 20). Overall, SNT  
469 Griesbachian ammonoids can be divided into two successive assemblages, the older  
470 assemblage being dominated by xenodiscids and *Otoceras* and the younger  
471 assemblage being characterized by common occurrences of ophiceratids and a few  
472 *Otoceras* specimens.

473 In the seminal work of Griesbach (1880), the author introduced *Otoceras* and  
474 *Ophiceras* from the Shalshal Cliff in the central Himalayas, and coarsely grouped  
475 them into the *Otoceras* beds. Later, Diener (1897) published a more comprehensive  
476 taxonomic work based on Griesbach's specimens and his own new collections.  
477 However, Diener did not further subdivide the *Otoceras* beds. Wang and He (1976)  
478 initially established two zones in South Tibet: the *Otoceras latilobatum* and  
479 *Ophiceras sakuntala* Zones. The former zone contains *Otoceras latilobatum*,  
480 *Otoceras* sp. indet., and *Glyptophiceras* sp. (here, reassigned to *Metophiceras* sp.). It  
481 should be noted that the holotype of *Otoceras latilobatum* is a weathered fragment,  
482 without clear morphological details, thus questioning the taxonomic assignment of  
483 this species. Regardless of the taxonomic uncertainties, this zone most likely  
484 correlates with the newly defined ST-1, according to the association of *Otoceras* and  
485 *Metophiceras*. The *Ophiceras sakuntala* Zone of Wang and He (1976) undoubtedly  
486 correlates with ST-2.

487 At Qubu, Zhang et al. (2017) also distinguished the successive *Otoceras*  
488 *woodwardi* and *Ophiceras tibeticum* Zones. The former includes *Otoceras woodwardi*  
489 (the reader should note that the taxonomy of *Otoceras* in the Himalayas needs  
490 in-depth revisions) and *Ophiceras* sp. The latter contains *Ophiceras demisum*,  
491 *Ophiceras tibeticum* and *Discophiceras wordiei*. However, these two zones cannot be

492 distinguished at Selong (Fig. 6) and Shalshal Cliff (Griesbach, 1880; Diener, 1897).  
493 Thus, the two zones of Zhang et al. (2017) can be merged into one single zone and  
494 correlate with the ST-2.

495 Griesbachian ammonoid successions are almost identical between South Tibet  
496 and Spiti. Two distinct zones were recognized in Spiti (Krystyn and Orchard, 1996).  
497 The lower one is characterized by *Otoceras woodwardi* and “*Ophiceras bandoi*” (this  
498 taxon probably rather belongs to *Metophiceras*, because it is ribbed and more evolute).  
499 In the upper part of this zone, i.e., in bed E3 at Muth, *Ophiceras* cf. *tibeticum*  
500 co-occurs with *Otoceras woodwardi* and “*Ophiceras bandoi*”. Thus, the *Otoceras*  
501 *woodwardi* - “*Ophiceras bandoi*” Zone in Spiti probably correlates with the ST-1 plus  
502 the lower ST-2 in South Tibet (Fig. 20). The second zone established by Krystyn and  
503 Orchard (1996) is represented by an assemblage of *Ophiceras*, *Discophiceras* and  
504 *Bukkenites*. This zone correlates with the ST-2 in South Tibet (Fig. 20).

505 In the Manang district, Nepal, Waterhouse (1994) introduced two successive  
506 Griesbachian ammonoid zones. The lower one is the *Otoceras woodwardi* Zone,  
507 which can be correlated with the ST-1. The upper one is the *Ophiceras tibeticum* Zone,  
508 corresponding to the ST-2.

509 In the Salt Range, Griesbachian ammonoids can be divided into three regional  
510 zones (Ware et al., 2018b). The oldest is represented by a single specimen of  
511 *Hypophiceras* aff. *gracile*, which most likely correlates with the ST-1 in South Tibet  
512 and the *Otoceras woodwardi* - “*Ophiceras bandoi*” Zone in Spiti. The second zone is  
513 also characterized by a single species, *Ophiceras connectens*, and probably correlates  
514 with the lower ST-2 in South Tibet. The youngest zone is documented in a condensed  
515 bed, as indicated by the co-occurrence of *Ophiceras sakuntala* and the earliest  
516 Dienerian taxa, such as *Gyronites dubius*. This zone probably partly correlates with  
517 the upper ST-2 in South Tibet.

### 518 **3.2 Dienerian**

519 Integrated Dienerian ammonoid datasets from South Tibet, Spiti and the Salt



520 Range led to the construction of 12 UAZs without any contradiction, a resolution  
521 rather similar to the basinal UA zonation from Spiti and the Salt Range (Fig. 20).  
522 Most of these UAZs are documented in South Tibet, except SNT-DI-4, SNT-DI-7 and  
523 SNT-DI-12 (Figs. 18, 20). SNT-DI-4 (corresponding to sample C26) probably  
524 occurred at Paizi (Fig. 8) with several sampled fragments resembling *Ambites atavus*.  
525 The new resulting UAZs in this work is highly congruent with Ware et al. (2015).

526 Poorly preserved Dienerian ammonoids are reported from the Sabche and  
527 Jargeng members of the Khangsar Formation in the Manang district, Nepal  
528 (Waterhouse, 1996a). They may represent a complete Dienerian ammonoid succession  
529 similar to the synthetic SNT UAZs. However, precise correlation with this area  
530 require a bed-by-bed sampling and thorough taxonomic revisions of this material.

### 531 **3.3 Smithian**

532 A total of 19 UAs were constructed for the SNT with no contradiction. Three can  
533 be merged with temporally close associations, according to poor lateral  
534 reproducibility or marked taxonomic similarities (Fig. 18). Finally, a new zonation  
535 with 16 UAZs is constructed for the entire Smithian.

536 Compared with the 14 UAZs established by Brühwiler et al. (2010b, 2011), we  
537 identified an additional middle Smithian UAZ, i.e., SNT-SM-12, located between the  
538 previously named *Pseudoceltites multiplicatus* and *Nyalamites angustecostatus* UAZs  
539 (i.e., S-10 and S-11 of Brühwiler et al., 2011, respectively). This UAZ (ST-18, see  
540 detailed assemblage description in section 2.5.18 and Fig. 17) is notably characterized  
541 by the co-occurrence of *Subvishnuites welteri*, *Pseudoceltites multiplicatus* and  
542 *Nyalamites angustecostatus*. *Subvishnuites welteri* was chosen as the index species of  
543 this zone, owing to its restricted occurrence within this zone in the SNT. This  
544 association was also found in Oman (Brühwiler et al., 2012a) and possibly in Timor  
545 (Jattiot et al., 2020). Another modification is that the UA 30, characterized by  
546 *Subvishnuites posterii*, is now considered as a UAZ because this UA can be recognized  
547 in both Spiti and South Tibet. Overall, the temporal resolution of the Smithian scale

548 has been improved from 14 to 16 UAZs.

549 At Paizi , we found an unusual association in upper Smithian beds B8 and B11  
550 (Fig 9), *Owenites koeneni* co-occurring with *Wasatchites distractus*. In other basins  
551 worldwide, *Wasatchites* distinctly overlies assemblages containing *Owenites*  
552 (Brühwiler et al., 2012b, 2012c; Jenks and Brayard, 2018). We interpret this  
553 uncommon association as a probable consequence of small condensation or reworking.  
554 Indeed, the Paizi section is somewhat condensed and some ammonoids from bed B11  
555 are inclined or even vertical to the bedding plane, possibly indicating a local weak  
556 reworking. Additionally, a superposition between *Wasatchites distractus* and  
557 *Anasibirites kingianus* is observed in the studied sections, although these two taxa  
558 occur together in other regions, e.g., Spiti and the Salt Range (Brühwiler et al., 2012a,  
559 2012b). This could be explained by a sampling or preservation bias. We therefore  
560 merged the UAs 21 and 22.

561 Successive Smithian ammonoid assemblages were also reported from the  
562 Manang Group, Manang district, Nepal, by Waterhouse (1996b, 1999). However, their  
563 very poor preservation and the near absence of any detailed superpositions prevent  
564 precise correlations with the SNT.

Age	South Tibet, China			Spiti, India			Salt Range, Pakistan			Amm. UAZs
	Previous works	This work	Conodont zones	Ammonoid zones	Conodont zones	Ammonoid zones	Conodont zones	Ammonoid zones	Conodont zones	
Early Triassic	late	<i>Glyptohiceras sinuatum</i>	ST-22: <i>Glyptohiceras sinuatum</i>	?	<i>Glyptohiceras sinuatum</i>	<i>Sc. milleri</i>	<i>Glyptohiceras sinuatum</i>	<i>Ns. pingdingshanensis</i>	SNT-SM-16	
		<i>Wasatchites distractus</i>	ST-21: <i>Subsushnites posterus</i>		<i>Subsushnites posterus</i>	<i>Wasatchites distractus</i>	<i>Sc. n. sp. F</i>	<i>Wasatchites distractus</i>	<i>Sc. milleri</i>	SNT-SM-15
		<i>Nyalamites angustecostatus</i>	ST-20: <i>Wasatchites distractus</i>		<i>Wasatchites distractus</i>	<i>Nyalamites angustecostatus</i>	<i>Spithicuspus n. sp. A</i>	<i>Nyalamites angustecostatus</i>	<i>Spithicuspus n. sp. A</i>	SNT-SM-14
	middle	<i>Pseudocerasites multiplicatus</i>	ST-19: <i>Stephanites superbus</i>	<i>Novispathodus waageni</i>	<i>Nyalamites angustecostatus</i>	<i>Novispathodus waageni</i>	<i>Parapachycladina</i>	<i>Novispathodus waageni</i>	<i>Pseudocerasites multiplicatus</i>	SNT-SM-13
		<i>Nammalites platoides</i>	ST-18: <i>Subsushnites welleri</i>		<i>Pseudocerasites multiplicatus</i>		SNT-SM-12			
		<i>Brayardites compressus</i>	ST-17: <i>Pungabites pungabensis</i>		<i>Pseudocerasites multiplicatus</i>		SNT-SM-11			
	early		ST-16: <i>Shigataceras dunajensis</i>		<i>Escarguallites horizon</i>		<i>Nammalites platoides</i>		SNT-SM-10	
			ST-15: <i>Nuetzella himalayica</i>		<i>Brayardites compressus</i>	<i>Ns. spitiensis</i>			SNT-SM-9	
			ST-14: <i>Brayardites compressus</i>		<i>Euflemingites cirratum</i>				SNT-SM-8	
			ST-13: <i>Kashmirites nivalis</i>		<i>Kashmirites nivalis</i>	<i>Eu. costatus</i>			SNT-SM-7	
			ST-12: <i>Kashmirites armatus</i>		<i>Rohillites rohilla</i>	<i>Bornella</i>			SNT-SM-6	
					<i>Flemingites nanus</i>				SNT-SM-5	
				<i>Kashmiritidae</i> gen. nov.				SNT-SM-4		
				<i>Flemingites bhargava</i>	<i>Novispathodus aff. waageni</i>			SNT-SM-3		
								SNT-SM-2		
Dienerian	late		ST-11: <i>Koninckites velustus</i>	<i>Neospathodus cristagalli</i>	<i>Koninckites velustus</i>	<i>Awanites awani</i>	<i>Neospathodus cristagalli</i>	SNT-DI-12		
			ST-10: <i>Kingites davidsonianus</i>		<i>Kingites davidsonianus</i>	<i>Kingites davidsonianus</i>	<i>Neospathodus dieneri</i>	SNT-DI-11		
			ST-9: <i>Vavilovites meridialis</i>		<i>Vavilovites meridialis</i>	<i>Vavilovites meridialis</i>	<i>Neospathodus dieneri</i>	SNT-DI-10		
	middle		ST-8: <i>Ambites biergeri</i>		<i>Ambites lilangensis</i>		<i>Ambites lilangensis</i>	<i>Neospathodus dieneri</i>	SNT-DI-9	
			<i>Ambites</i> sp. indet.		<i>Ambites discus</i>		<i>Ambites superior</i>	<i>Neospathodus dieneri</i>	SNT-DI-8	
			ST-7: <i>Ambites discus</i>	<i>Neospathodus dieneri</i>	<i>Ambites discus</i>		<i>Ambites discus</i>	<i>Neospathodus dieneri</i>	SNT-DI-7	
	early		ST-6: <i>Ambites bojeseni</i>		<i>Ambites bojeseni</i>		<i>Ambites radialis</i>	<i>Neospathodus dieneri</i>	SNT-DI-6	
			<i>Ambites alatus</i>		<i>Ambites alatus</i>		<i>Ambites alatus</i>	<i>Neospathodus dieneri</i>	SNT-DI-5	
			<i>Ambites alatus</i>		<i>Gyronites frequens</i>		<i>Ambites alatus</i>	<i>Neospathodus dieneri</i>	SNT-DI-4	
		<i>Gyronites psilogyrus</i>	ST-5: <i>Gyronites frequens</i>	<i>Sweetospathodus kummeli</i>	<i>Gyronites frequens</i>		<i>Gyronites frequens</i>	<i>Sweetospathodus kummeli</i>	SNT-DI-3	
			ST-4: <i>Gyronites pilosus</i>		<i>Gyronites pilosus</i>		<i>Gyronites pilosus</i>	<i>Sweetospathodus kummeli</i>	SNT-DI-2	
			ST-3: <i>Gyronites dubius</i>		<i>Gyronites dubius</i>		<i>Gyronites dubius</i>	<i>Sweetospathodus kummeli</i>	SNT-DI-1	
G.	I.	<i>Ophiceras sakuntala</i>	ST-2: <i>Ophiceras tibeticum</i>	<i>Clarkina carinata</i>	<i>Ophiceras tibeticum</i>	<i>Clarkina carinata</i>	<i>Ophiceras sakuntala</i>	SNT-DI-1		
				<i>Isarcicella staeschel</i>		<i>Isarcicella isarcica</i>	<i>Ophiceras connectens</i>			
		<i>Otoceras latlobatum</i>	ST-1: <i>Metopliceras cf. subdennissum</i>	<i>Hindeodus parvus</i>	<i>Otoceras woodwardi</i>	<i>Hindeodus parvus</i>	<i>Hypohiceras cf. gracile</i>			
Permian	e.			<i>Mesogoniatella sheni</i>						

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Figure 20. Correlation of Griesbachian-Smithian ammonoid and conodont zonation within the SNT. Previous works in South Tibet refer to Wang and He (1976), Brühwiler et al. (2010b), and Zhang et al. (2017). Spiti ammonoid data from Krystyn and Orchard (1996), Brühwiler et al. (2010c, 2012b), Ware et al. (2018a), and Krystyn et al. (2017). Salt Range ammonoid data from Brühwiler et al. (2011, 2012c) and

571 Ware et al. (2018b). South Tibet conodont data from Wang and Wang (1995); Salt  
572 Range conodont data from Romano et al. (2013) and Goudemand et al. (2019), Spiti  
573 conodont data from Krystyn and Orchard (1996), Krystyn et al. (2007, 2017),  
574 Goudemand (2014), and Sun et al. (2021). Grey area indicates an uncertain interval  
575 for the Dienerian/Smithian boundary among different proposals.

## 576 **4 Global correlations for the Griesbachian, Dienerian, and** 577 **Smithian ammonoid biostratigraphy**

578 The worldwide distribution (Fig. 21), fast evolutionary rates and abundant fossil  
579 record of Early Triassic ammonoids allow their use as ideal index fossils for  
580 large-scale stratigraphic correlations (Balini et al., 2010; Jenks et al., 2015). Thanks to  
581 the bed-rock-controlled extensive samplings and detailed taxonomic revisions in the  
582 past decades (e.g., Brayard and Bucher, 2008; Shigeta et al., 2009; Brühwiler et al.,  
583 2011), the resolution of the Early Triassic ammonoid biostratigraphical scales has  
584 been significantly improved, and their correlations have been strengthened. However,  
585 some uncertainties remain in large-scale correlations (Figs. 22–23).

### 586 **4.1 Griesbachian**

587 Generally, the Griesbachian can be subdivided into two parts (early and late)  
588 based on ammonoid assemblages from Arctic Canada (Tozer, 1965, 1967, 1994).  
589 Currently, Griesbachian ammonoid biostratigraphy is still rough with many  
590 uncertainties in long distance correlation and in need of revision and more detailed  
591 study. Sections with good Griesbachian ammonoid record are exceedingly rare,  
592 particularly for low latitudes.

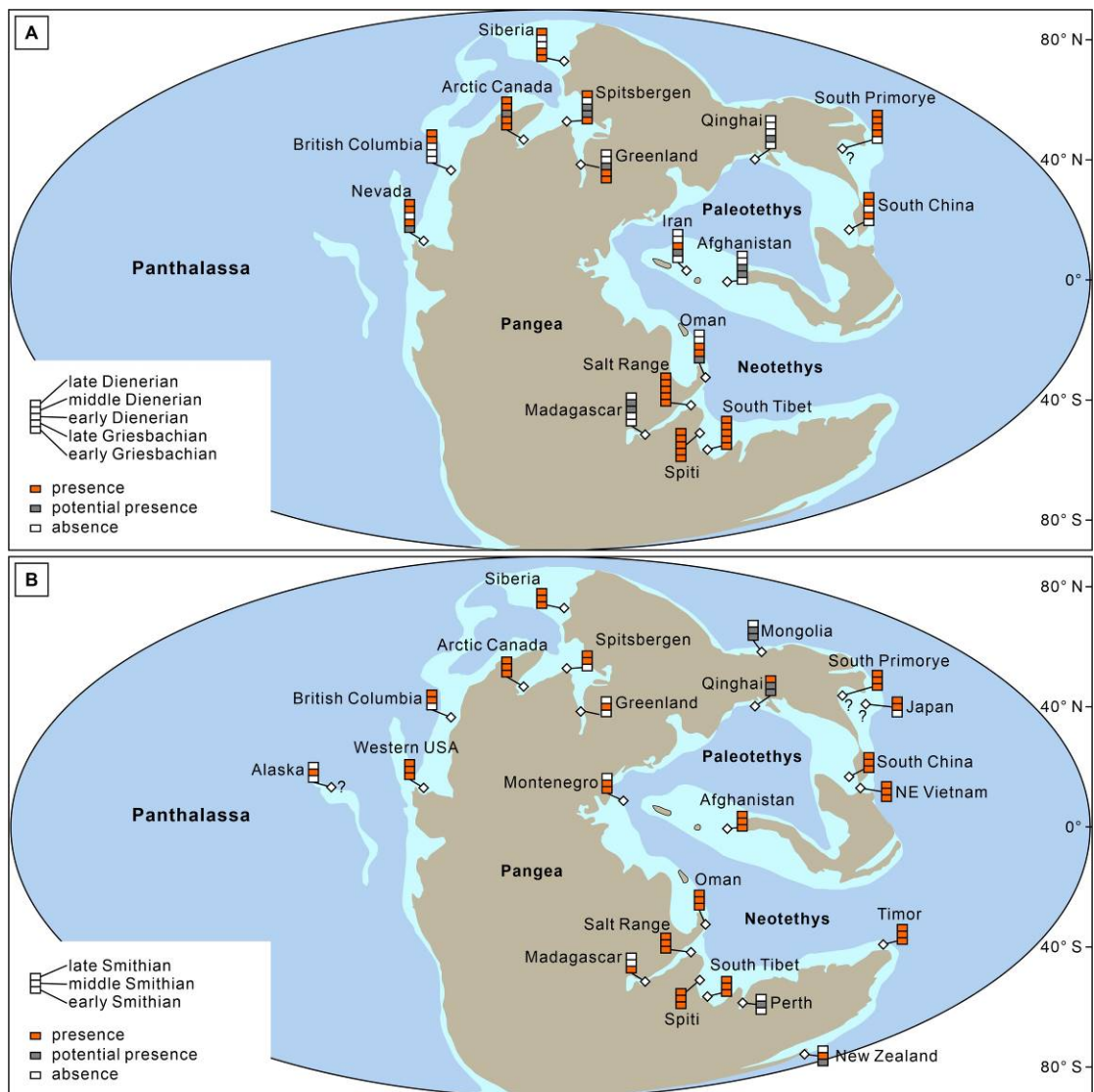
#### 593 **4.1.1 Oman**

594 Griesbachian ammonoids are sporadically reported from exotic limestone blocks  
595 (Krystyn et al., 2003; Brosse et al., 2019). These assemblages include *Ophiceras*,  
596 *Episageceras*, *Metophiceras*, *Aldanoceras*, *Anotoceras* and *Discophiceras*, correlating

597 with the late Griesbachian assemblages in other basins (Fig. 22). However, the  
 598 presence of *Metophiceras* could represent the late early Griesbachian, or an indication  
 599 of condensation.

#### 600 4.1.2 Afghanistan

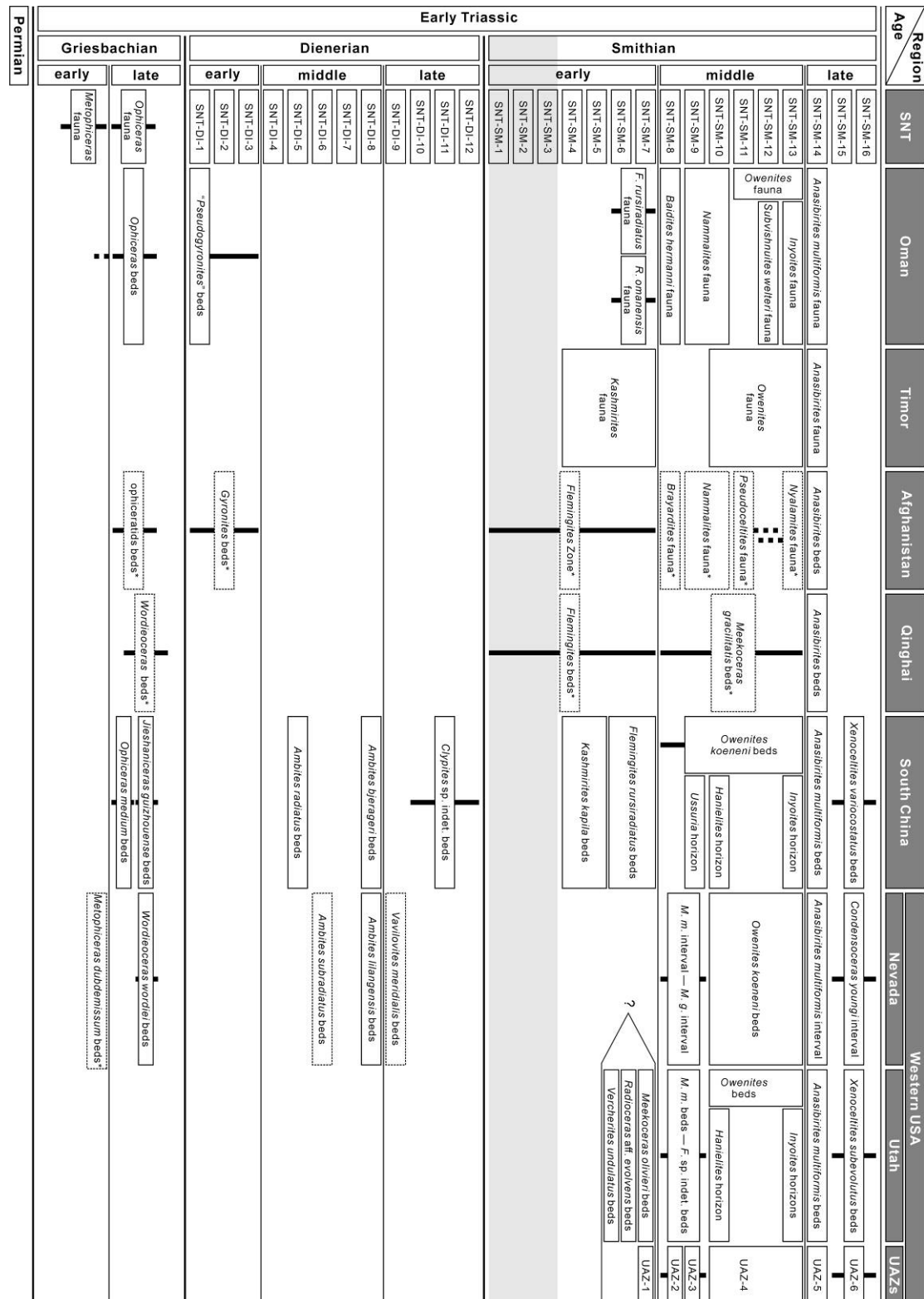
601 Griesbachian ammonoids have been poorly documented from Afghanistan thus  
 602 far. Some highly recrystallized, poorly preserved ophiceratid ammonoids were  
 603 reported at Khojia Ghare Wali, approximately 30 km east of Kabul (Ishii et al., 1971).  
 604 This ophiceratid assemblage could be of late Griesbachian age, but with many  
 605 uncertainties (Fig. 22).



606  
 607 Figure 21. Main localities of Griesbachian, Dienerian (A) and Smithian (B)  
 608 ammonoids. The paleogeographic maps were modified from Scotese (2014). Note that

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the paleopositions of South Primorye and Japan remains unclear (see e.g., Ehiro, 1998; Brayard et al., 2009).



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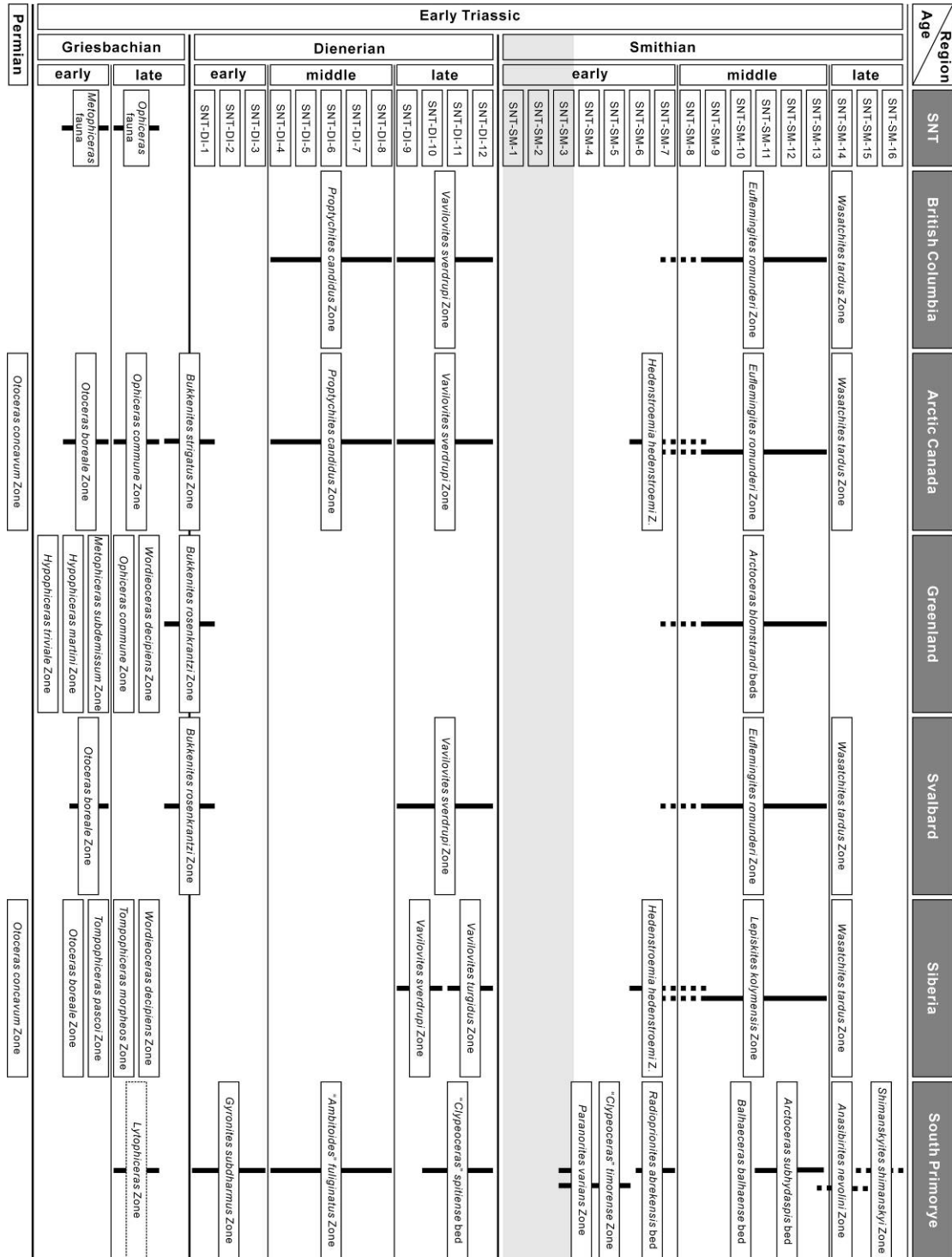
614

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Figure 22. Global correlations of Griesbachian-Smithian ammonoid biostratigraphic scales, part I, Tethys and low latitude regions. Asterisks indicate poorly documented assemblages/faunas/beds. Vertical solid and dotted lines represent uncertainties in correlation. Grey area indicates an uncertain interval for the Dienerian/Smithian

616 boundary among different proposals.

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618

619 Figure 23. Global correlations of Griesbachian-Smithian ammonoid biostratigraphic  
 620 scales, part II. Asterisks indicate poorly documented assemblages/faunas/beds.  
 621 Vertical solid and dotted lines represent uncertainties in correlation. The *Otcoceras*  
 622 *concavum* Zone is temporarily placed in the latest Permian, see discussion in section  
 623 4.1.6. Grey area indicates an uncertain interval for the Dienerian/Smithian boundary  
 624 among different proposals.

625

### 626 **4.1.3 Qinghai, China**

627 Qinghai Province is located in the center of the Qinghai-Tibet Plateau. Lower  
628 Triassic sediments are widely distributed within this area but are still poorly studied.  
629 Wang and Chen (1984) described an ammonoid assemblage near Maduo County,  
630 including *Cordillerites* sp., *Flemingites muthensis*, *Anotoceras costatum*,  
631 *Gyrophiceras vermiformis*, *Acanthopliceras* cf. *gibbosum*, and *Wordieoceras*  
632 *decipiens*. These identifications are highly questionable based on their poor  
633 preservation. In addition, this assemblage constitutes a mix of Griesbachian and  
634 Smithian taxa (Fig. 22). Further works are thus needed to fully decipher the exact  
635 taxonomic composition and stratigraphic superpositions of this assemblage.

### 636 **4.1.4 South China**

637 Griesbachian ammonoids have been rather well studied in South China (Fig. 22).  
638 However, many works are based on poorly preserved specimens (Wang, 1984; Tong  
639 et al., 2004). For instance, most Induan ammonoids are smooth without distinctive  
640 shell sculptures. Usually, flattened specimens cannot be confidently identified at the  
641 genus/species level and even at the family level. Therefore, biostratigraphic works  
642 based on poorly preserved flattened species were excluded in the following  
643 discussion.

644 Several works reported relatively well-preserved Griesbachian ammonoids (Mu  
645 et al., 2007; Brühwiler et al., 2008; Dai et al., 2019). Early Griesbachian ammonoids  
646 have not been reported thus far from South China. Late Griesbachian ammonoids,  
647 represented by the *Ophiceras* beds, have been described from Guangxi and Guizhou  
648 (Brühwiler et al., 2008; Dai et al., 2019). The overlying *Jieshaniceras guizhouense*  
649 beds were tentatively integrated into the latest Griesbachian since no typical  
650 Dienerian ammonoids have been found in these beds thus far (Dai et al., 2019).  
651 Conodont data from these beds also support a late Griesbachian age for these beds



652 (Mu et al., 2007).

#### 653 **4.1.5 Western USA basin**

654 Recently, a new Griesbachian ammonoid fauna was described at Crittenden  
655 Spring, Nevada (Jenks et al., 2021). It represents the first report of a late Griesbachian  
656 assemblage from the western USA basin (Fig. 22). This assemblage contains four  
657 species: *Wordieoceras wordiei*, *Wordieoceras mullenae*, *Kyokites* cf. *K. hebeiseni* and  
658 *Ophimullericeras paullae*.

659 Ammonoid specimens attributed to the early Griesbachian species *Metophipiceras*  
660 *subdemissum* and *Discophiceras subkyokiticum* were also briefly reported from the  
661 Dinwoody Formation of southeastern Idaho and Montana (Newell and Kummel,  
662 1942). However, their preservation is very poor and fragmentary. Thus, these  
663 taxonomic and age assignments are doubtful.

#### 664 **4.1.6 Arctic Canada**

665 Arctic Canada is one of the key regions for Griesbachian ammonoids, where the  
666 type section of this substage is located (Tozer, 1965). Tozer (1965, 1967) proposed 4  
667 successive ammonoid zones for the Griesbachian: *Otoceras concavum* Zone,  
668 *Otoceras boreale* Zone, *Ophiceras commune* Zone, and *Bukkenites strigatus* Zone, in  
669 ascending order (Fig. 23).

670 As the formal definition of the Permian-Triassic boundary is based on the first  
671 occurrence of the conodont *Hindeodus parvus* at the Meishan section, China (Yin et  
672 al., 2001), part of the initially early Griesbachian beds defined by Tozer is  
673 consequently assumed to be of late Permian age. The *Otoceras concavum* Zone and  
674 probably the lower part of the *Otoceras boreale* Zone were thus attributed to the Late  
675 Permian (Henderson and Baud, 1997). However, this age assignment is still debated  
676 (Shevyrev, 2006; Jenks et al., 2021). Baud and Beauchamp (2001) proposed a revised  
677 definition of the Griesbachian for Arctic Canada, which only includes the *Ophiceras*  
678 *commune* and *Bukkenites strigatus* Zones. This definition is not followed here because

679 *H. parvus* occurs within the *Otoceras boreale* Zone at Otto Fiord South (Henderson  
680 and Baud, 1997), and whether it represents the first appearance datum of *H. parvus* is  
681 unclear (Orchard, 1996; Orchard and Tozer, 1997). In any case, at least the upper part  
682 of the *Otoceras boreale* Zone belongs to the Early Triassic. At the same site, *Otoceras*  
683 *concauum* co-occurs with the latest Changhsingian conodont assemblage (Henderson  
684 and Baud, 1997). We thus here tentatively consider that the *Otoceras concauum* Zone  
685 corresponds to the latest Permian in Arctic Canada. It should nevertheless be noted  
686 that correlations between Griesbachian conodont and ammonoid biostratigraphical  
687 scales in Arctic Canada remain blurred with many uncertainties. This results from the  
688 scarce occurrences of conodonts at the Griesbach Creek section, the type area of the  
689 Griesbachian substage (Henderson and Baud, 1997; Orchard and Tozer, 1997).

690 To our knowledge, there is no coeval ammonoid fauna to the *Otoceras concauum*  
691 Zone within the Tethys. The *Otoceras boreale* Zone can be roughly correlated with  
692 the *Otoceras-Metophipiceras* associations of the SNT. The *Ophiceras commune* Zone  
693 correlates with the *Ophiceras* fauna in the SNT. The *Bukkenites strigatus* Zone was  
694 thought to represent the latest Griesbachian in Arctic Canada. However, conodonts  
695 from the upper part of this zone indicate a Dienerian age (Orchard and Tozer, 1997).  
696 Thus, the *Bukkenites strigatus* Zone most likely straddles the Griesbachian/Dienerian  
697 boundary. This age assignment is also supported by ammonoid data from the SNT, as  
698 *Bukkenites* occurs in the upper *Ophiceras* fauna in South Tibet (this work) and in the  
699 early Dienerian at the Salt Range and Spiti (Ware et al., 2018a, 2018b).

#### 700 **4.1.7 Greenland**

701 Greenland is another key region for Griesbachian ammonoid faunas. Indeed, it  
702 probably represents the most complete Griesbachian ammonoid succession worldwide  
703 (Spath, 1930, 1935; Trümpy, 1969). Six ammonoid zones were recognized from the  
704 Wordie Creek Formation (Bjerager et al., 2006). These are the *Hypophiceras triviale*,  
705 *Hypophiceras martini*, *Metophipiceras subdemissum*, *Ophiceras commune*,  
706 *Wordieoceras decipiens* and *Bukkenites rosenkrantzi* Zones, in ascending order (Fig.

707 23).

708 The *Hypophiceras triviale* Zone was considered latest Permian in age (Bjerager  
709 et al., 2006). However, this interpretation should be taken with caution since the  
710 correlation between conodont and ammonoid biostratigraphical scales in eastern  
711 Greenland is still crude (Bjerager et al., 2006). For instance, the base of the  
712 *Hypophiceras triviale* Zone is 7 m above the base of the Wordie Creek Formation at  
713 Oksedal, northern Jameson Land, while the first occurrence (FO) of *Hindeodus*  
714 *parvus* occurs 23.5 m above the base of the Wordie Creek Formation (Bjerager et al.,  
715 2006). In addition, the globally reported negative  $\delta^{13}\text{C}$  spike for PTB occurs at the  
716 base of the Wordie Creek Formation, predating the FO of *Hindeodus parvus* in  
717 Jameson Land (Stemmerik et al., 2001). Consequently, it is likely that the FO of  
718 *Hindeodus parvus* in Jameson Land is younger than its FO at the Meishan GSSP  
719 (Bjerager et al., 2006). We thus consider the *Hypophiceras triviale* Zone to belong to  
720 the early Griesbachian instead of the latest Permian.

721 The *Hypophiceras martini* and *Metophiceras subdemissum* Zones are also early  
722 Griesbachian in age. The *Ophiceras commune* and *Wordieoceras decipiens* Zones  
723 correspond to the late Griesbachian. As in Arctic Canada, the *Bukkenites rosenkrantzi*  
724 Zone probably straddles the Griesbachian/Dienerian boundary. A thorough revision of  
725 Griesbachian ammonoids in eastern Greenland is ongoing by one of the authors  
726 (D.W.).

#### 727 **4.1.8 Svalbard**

728 Griesbachian ammonoids are represented by two successive zones in Svalbard:  
729 the *Otoceras boreale* and *Bukkenites rosenkrantzi* Zones (Weitschat and Dagys, 1989).  
730 The *Otoceras boreale* Zone contains *Otoceras boreale*, *Paravishnuites oxynotus*, and  
731 *Ophiceras spathi*. This association correlates with the upper part of the *Otoceras*  
732 *boreale* Zone from Arctic Canada (Fig. 23). As in Arctic Canada and Greenland, the  
733 age of the *Bukkenites rosenkrantzi* Zone is unclear. This zone in Svalbard represents  
734 the latest Griesbachian or the early Dienerian.

#### 735 **4.1.9 Siberia**

736 Five latest Permian-Griesbachian ammonoid zones were established in Siberia  
737 (Dagys and Ermakova, 1996). These are the *Otoceras concavum*, *Otoceras boreale*,  
738 *Tompophiceras pascoi*, *Tompophiceras morpheos*, and *Wordieoceras decipiens* zones,  
739 in ascending order (Fig. 23). The *Otoceras concavum* Zone is here assigned to the  
740 latest Permian (see discussion in section 4.1.6). The *Otoceras boreale* and  
741 *Tompophiceras pascoi* Zones represent the early Griesbachian. Zakharov (1994)  
742 reported that *Otoceras concavum* co-occurs with *Otoceras boreale*, and thus merged  
743 these two zones. However, Dagys (1994b) argued that this co-occurrence was a  
744 consequence of incorrect interpretation on the taxonomy of *Otoceras concavum*. In a  
745 recent paper, Zakharov et al. (2020) admitted this misinterpretation and adopted the  
746 scheme with two distinct zones.

747 *Ophiceras commune* occurs within the overlying *Tompophiceras morpheos* Zone,  
748 thus allowing correlation of this zone with the *Ophiceras commune* Zone in eastern  
749 Greenland and Arctic Canada. The *Wordieoceras decipiens* Zone was hypothesized to  
750 correlate with the *Bukkenites strigatus* Zone in Arctic Canada (Dagys, 1994a). This is  
751 rejected here. Indeed, the *Wordieoceras decipiens* Zone in Siberia is a monospecific  
752 assemblage, and this species is not found within the *Bukkenites strigatus* Zone. In  
753 addition, *Wordieoceras decipiens* occurs below *Bukkenites* in eastern Greenland  
754 (Bjerager et al., 2006). Therefore, the *Wordieoceras decipiens* Zone in Siberia  
755 correlates with the *Wordieoceras decipiens* Zone in eastern Greenland and is older  
756 than the *Bukkenites strigatus* Zone in Arctic Canada.

#### 757 **4.1.10 South Primorye**

758 A single Griesbachian zone was defined from South Primorye, the *Lytophiceras*  
759 sp. indet. Zone (Shigeta et al., 2009). It is expected to be of late Griesbachian age (Fig.  
760 23), but the sampled specimens are somewhat poorly preserved, preventing further  
761 in-depth comparisons and correlation with other basins.

#### 762 **4.1.11 Iran**

763 Griesbachian ammonoids in Iran are poorly documented and are mainly  
764 composed of ophiceratids (Bando, 1979; Korn et al., 2021), which likely indicates a  
765 late Griesbachian age. However, their general poor preservation prevents robust  
766 identifications and correlations.

### 767 **4.2 Dienerian**

768 Well-preserved Dienerian ammonoid faunas and successions are restricted to a  
769 few regions, such as the SNT. Other regions only show sporadic records of Dienerian  
770 ammonoids.

#### 771 **4.2.1 Oman**

772 Only a few Dienerian ammonoids have been described from Oman. A small  
773 ammonoid fauna was reported from an exotic block at Wadi Wasit (Krystyn et al.,  
774 2003). This fauna contains *Bukkenites? scheibleri*, “*Proptychites*” *markhami*,  
775 “*Kymatites*” *hodgsoni*, and “*Pseudogyronites*”, which is similar to the early Dienerian  
776 ammonoids in the SNT (Fig. 22). However, the co-occurring conodont taxa suggest a  
777 late Griesbachian age for beds including this ammonoid assemblage (Krystyn et al.,  
778 2003). Further correlations thus need a more detailed taxonomic revision of this fauna.  
779 Another block from the Batain Plain, eastern Oman, contains rich Dienerian-Smithian  
780 ammonoids and conodonts (Souquet and Goudemand, 2020). However, the detailed  
781 ammonoid content of this block has not yet been published.

#### 782 **4.2.2 Afghanistan**

783 Ishii et al. (1971) described a *Gyronites* fauna at Khoja Ghare Wali, ca. 30 km  
784 east of Kabul. This fauna most likely indicates an early Dienerian age (Fig. 22).  
785 However, the poor preservation of this material prevents further in-depth correlation.  
786 Collignon (1973) also illustrated a specimen (pl. 5, fig. 1) from the Azrao Valley (S.E.

787 of Kabul) and assigned it to *Clypites typicus*, which is an iconic late Dienerian species.  
788 However, after observation of this specimen (UBGD 277233) in Collignon's  
789 collection housed at the Université de Bourgogne, France, we can reassign this  
790 specimen to *Pseudosageceras*, which ranges from the late Dienerian to the Spathian  
791 and has therefore a low biostratigraphic value.

#### 792 **4.2.3 South China**

793 Occurrences of Dienerian ammonoids are scarce in South China (Fig. 22). Early  
794 Dienerian ammonoids have not been found thus far. The middle Dienerian *Ambites*  
795 *radiatus* and *A. bjerageri* Zones were documented in Guizhou and Guangxi  
796 (Brühwiler et al., 2008; Dai et al., 2019). The late Dienerian genus *Clypites* was found  
797 only in Guangxi (Brayard and Bucher, 2008). One specimen identified as *Proptychites*  
798 sp. indet. by Brühwiler et al. (2008) was later synonymized with *Koninckites*  
799 *khoorensis* by Ware et al. (2018), which adds one more occurrence of the late  
800 Dienerian ammonoid in South China.

#### 801 **4.2.4 Nevada**

802 Middle and late Dienerian ammonoids are documented only from the Candelaria  
803 Hills, Nevada (Ware et al., 2011). Most of these come from float concretions and lack  
804 stratigraphic information. However, the ages of these middle and late Dienerian  
805 assemblages (Fig. 22) can be confirmed based on the occurrences of *Ambites*,  
806 *Mullericeras*, *Protychites* and *Vavilovites*. These assemblages have strong affinities  
807 with SNT faunas, suggesting frequent faunal exchanges between the Neotethys and  
808 the opposite side of the Panthalassa during that time (see also Brayard et al., 2007,  
809 2009; Jenks et al., 2010; Monnet et al., 2013; Jenks and Brayard, 2018, for discussion  
810 of such faunal exchanges during the Early Triassic).

#### 811 **4.2.5 British Columbia**

812 Two Dienerian ammonoid zones were established in British Columbia, i.e., the

813 *Proptychites candidus* and *Vavilovites sverdrupi* Zones (Tozer, 1994). The former  
814 generally indicates a middle Dienerian age (Fig. 23), while the latter corresponds to  
815 the late Dienerian (Ware et al., 2018b). The *Vavilovites sverdrupi* Zone can also be  
816 subdivided into three subzones: *Koninckites dimidiatus*, *Vavilovites obtusus*, and  
817 “*Kingites*” *discoidalis* Subzones. However, precise correlation with the SNT is  
818 difficult.

819 According to our observations of Tozer’s collection at the Geological Survey of  
820 Canada in Vancouver, many of the Dienerian taxa in British Columbia are not the  
821 same as those found in Arctic Canada but have SNT affinities. For instance, the  
822 specimens identified by Tozer (1994) as *Proptychites candidus* and *Vavilovites*  
823 *sverdrupi* in British Columbia do not belong to these species found in Arctic Canada,  
824 but rather to species with SNT affinities (*Proptychites candidus* is close to  
825 *Proptychites ammonoides* and *Koninckites khoorensis*, and *Vavilovites sverdrupi*  
826 resembles *Vavilovites meridialis*). *Ambites fuliginatus* initially described by Tozer  
827 (1994) was synonymized with *Ambites lilangensis* by Ware et al. (2018a), thus  
828 suggesting the existence of a latest middle Dienerian ammonoid fauna.

#### 829 **4.2.6 Arctic Canada**

830 Tozer (1965, 1967, 1994) distinguished two Dienerian ammonoid zones in Arctic  
831 Canada (Fig. 23). The lower zone is the *Proptychites candidus* Zone, which roughly  
832 corresponds to the middle Dienerian based on the occurrence of *Ambites* (Ware et al.,  
833 2018b). The upper zone is the *Vavilovites sverdrupi* Zone, roughly corresponding to  
834 the late Dienerian (Ware et al., 2018b).

835

#### 836 **4.2.7 Svalbard**

837 *Vavilovites* have been documented in Svalbard (Weitschat and Dagys, 1989).  
838 This taxon indicates a late Dienerian age (Fig. 23). Early and middle Dienerian  
839 ammonoids have not been documented in Svalbard to date.

#### 840 **4.2.8 Siberia**

841 Two Dienerian ammonoid zones were defined in Siberia, i.e., the *Vavilovites*  
842 *sverdrupi* and *Vavilovites turgidus* Zones (Dagys and Ermakova, 1996). The  
843 *Vavilovites sverdrupi* Zone is well correlated within the Boreal regions and is late  
844 Dienerian (Fig. 23). The *Vavilovites turgidus* Zone can be subdivided into two  
845 subzones: the *Vavilovites subtriangularis* and *Vavilovites umbonatus* Subzones.  
846 However, due to the strong endemicity of taxa occurring in this zone, accurate  
847 correlations are impossible. We tentatively assign this zone also to the late Dienerian  
848 since *Vavilovites* has not been documented in the early Smithian to date.

#### 849 **4.2.9 South Primorye**

850 The Dienerian ammonoid succession in South Primorye was described by  
851 Shigeta et al. (2009). It includes the *Gyronites subdharmus* Zone, the *Ambitoides*  
852 *fuliginatus* Zone, and the “*Clypeoceras spitiense*” bed, in ascending order (Fig. 23).  
853 The *Gyronites subdharmus* Zone was interpreted to be of late Griesbachian age by  
854 Shigeta et al. (2009). This zone was later reassigned to the early Dienerian (Ware et  
855 al., 2015; Ware et al., 2018b). The *Ambitoides fuliginatus* Zone (index marker  
856 reassigned to *Mullericeras* by Ware et al., 2018b) roughly corresponds to the middle  
857 Dienerian (Ware et al., 2018b). The “*Clypeoceras spitiense*” bed (reassigned to  
858 *Clypites typicus* by Ware et al., 2018b) correlates with SNT-DI-10 and SNT-DI-11  
859 (Fig. 22).

#### 860 **4.2.10 Iran**

861 An early Dienerian ammonoid fauna from Iran was recently mentioned (Korn et  
862 al., 2021). It contains *Ussuridiscus varaha* and *Gyronites* cf. *dubius*, thus  
863 corresponding to SNT-DI-1 in SNT (Fig. 22).



## 864 **4.3 Smithian**

865 Our present knowledge of the Smithian ammonoid biochronology is more  
866 detailed than for the Griesbachian and Dienerian. This results from several published  
867 works based on extensive bed-by-bed sampling and homogenized taxonomic  
868 treatment during the last two decades (e.g., Brayard and Bucher, 2008; Brühwiler et  
869 al., 2011; Shigeta et al., 2014; Jenks and Brayard, 2018). However, regarding  
870 high-resolution scales and global correlations, some uncertainties remain, owing to  
871 the presence of endemic assemblages at some sites and the absence of revised studies  
872 for some localities.

### 873 **4.3.1 Oman**

874 Smithian ammonoids in Oman were found in isolated exotic blocks, initially  
875 deposited on sea highs with low sedimentary rates (Krystyn et al., 2003; Brosse et al.,  
876 2019). These cm- to km-sized blocks (exhibiting a “Hallstatt” facies) were  
877 redeposited into younger sediments due to tectonic instability (Baud et al., 2012). A  
878 high-resolution ammonoid biostratigraphy is thus difficult to determine due to high  
879 levels of condensation and the often lack of stratigraphic superpositions. However,  
880 after careful and detailed sampling, it is possible to construct a rather highly resolved  
881 biostratigraphic scale for a large part of the Smithian, as done, for instance, by  
882 Brühwiler et al. (2012a). These authors have defined seven Smithian ammonoid  
883 faunas (Fig. 22).

884 The *Rohillites omanensis* and *Flemingites rursiradiatus* faunas correspond to the  
885 late early Smithian, but information on superposition is lacking to determine their  
886 exact succession (Fig. 22). Here, we follow former works (Brühwiler et al., 2012a;  
887 Jattiot et al., 2020) and correlate them with the late early Smithian.

888 The *Baidites hermanni* fauna was thought to be of early middle Smithian age but  
889 with some uncertainty (Brühwiler et al., 2012a). Here, we correlate the *Baidites*  
890 *hermanni* fauna with the *Brayardites compressus* Zone in the SNT, according to the

891 following evidences: (1) *Baidites* was found in SNT-SM-8 in South Tibet; (2)  
892 *Jinyaceras*, found in this fauna, is restricted to SNT-SM-7 and SNT-SM-8 in the SNT;  
893 and (3) the occurrence of “*Paranorites jenksi*” in the *Baidites hermanni* fauna is the  
894 main evidence of its early Smithian age assignment (Brühwiler et al., 2012a).  
895 However, this is questionable, owing to its poor preservation.

896 The overlying *Nammalites pilatoides* fauna correlates with SNT-SM-9 and  
897 SNT-SM-10 based on the range of *Nammalites pilatoides* (Fig. 22).

898 The *Owenites* fauna correlates with SNT-SM-11 to SNT-SM-13 UAZs. The  
899 *Owenites* fauna can be further subdivided into different faunas. Here, we differentiate  
900 a *Subvishnuites welteri* fauna (represented by samples HB 904 and HB 905 in  
901 Brühwiler et al., 2012a). This fauna is characterized by the co-occurrence of  
902 *Subvishnuites* and *Nyalamites*, which correlates with SNT-SM-12 (Fig. 22).

903 The late middle Smithian *Inyoites* fauna corresponds to SNT-SM-13. The  
904 *Anasibirites multiformis* fauna correlates with SNT-SM-14 (Fig. 22).

#### 905 **4.3.2 Timor**

906 Smithian ammonoids are also found in exotic blocks in Timor (Welter, 1922;  
907 Kummel, 1968b; Nakazawa and Bando, 1968; Jattiot et al., 2020). The specimens  
908 show an exquisite preservation, better than in other sampled localities worldwide.  
909 However, superposition information among blocks is sometimes lacking. Generally,  
910 blocks can be divided into three successive faunas: the *Kashmirites*, *Owenites* and  
911 *Anasibirites* faunas, corresponding to the early, middle and late Smithian, respectively  
912 (Jattiot et al., 2020). According to the taxonomic composition of each fauna, we can  
913 roughly correlate the *Kashmirites* fauna with SNT-SM-4 to SNT-SM-7 UAZs and the  
914 *Owenites* fauna with SNT-SM-8 to SNT-SM-13 UAZs (Fig. 22). The *Anasibirites*  
915 fauna correlates with SNT-SM-14.

#### 916 **4.3.3 Afghanistan**

917 Rare Smithian ammonoids were described from Afghanistan (Kummel and

918 Erben, 1968; Collignon, 1973). Based on the available data, we can confirm that all  
919 the early, middle and late Smithian ammonoid faunas occur (Fig. 22).

920 Studied collections of Collignon (1973) housed at the Université de Bourgogne,  
921 Dijon, France, were also revised. Although generally poorly preserved, some  
922 specimens can be identified at the genus and species levels. The occurrence of  
923 *Flemingites* sp. indet. (pl. 3, fig. 6 in Collignon, 1973, UBGD 277253) suggests the  
924 probable occurrence of an early Smithian ammonoid assemblage (Fig. 22).

925 Middle Smithian ammonoids were relatively well documented by Kummel and  
926 Erben (1968). They are generally grouped into the *Owenites* Zone. According to  
927 illustrations provided by Kummel and Erben (1968), we expect the occurrences of the  
928 *Nammalites*, *Pseudoceltites* and *Nyalamites* faunas but lack a detailed taxonomic  
929 composition and precise superposition (Fig. 22). One Collignon's specimen (pl. 3, fig.  
930 5 in Collignon, 1973, UBGD 277252), initially assigned to *Flemingites muthianus*, is  
931 actually a specimen of *Brayardites*. Thus, an almost complete middle Smithian  
932 succession is potentially present in Afghanistan. In addition, this succession appears  
933 identical to the SNT. However, this remains to be confirmed during future access on  
934 outcrops.

935 Kummel and Erben (1968) also described an unusual *Anasibirites* fauna, which  
936 contains a mixed assemblage of middle Smithian and late Smithian taxa. This  
937 probably results from a sampling, reworking, or condensation bias. Further work is  
938 therefore needed to clarify the exact composition of this fauna. We nevertheless  
939 consider in this work that part of this fauna correlates at least with other *Anasibirites*  
940 beds worldwide (Fig. 22).

#### 941 **4.3.4 Qinghai, China**

942 Smithian ammonoids have scarcely been documented in Qinghai Province,  
943 China (Fig. 22). A poorly preserved specimen of *Flemingites muthianus* was found  
944 near Maduo County (Wang and Chen, 1984). If this assignment is correct, it suggests  
945 an early Smithian age for beds containing this specimen. *Meekoceras gracilitatis* was

946 also reported from this area (Wang and Chen, 1984), which suggests the occurrence of  
947 middle Smithian beds. The late Smithian genus *Anasibirites* was found at the  
948 Naocangjiangou section (He et al., 1986) and indicates the presence of a late Smithian  
949 fauna (Fig. 22).

#### 950 **4.3.5 South China**

951 Smithian ammonoids have been well documented from Guangxi (Chao, 1959;  
952 Brayard and Bucher, 2008; Dai et al., 2021). Materials from other localities in South  
953 China are usually poorly preserved (Tong et al., 2004) and are thus excluded from the  
954 following discussion. To date, 5 intervals have been recognized (Brayard and Bucher,  
955 2008). They are the early Smithian *Kashmirites kapila* and *Flemingites rursiradiatus*  
956 beds, the middle Smithian *Owenites koeneni* beds and the late Smithian *Anasibirites*  
957 *multiformis* and *Xenoceltites variocostatus* beds (Fig. 22).

958 The *Kashmirites kapila* beds correlate with SNT-SM-4 and SNT-SM-5,  
959 according to the occurrence of *K. kapila* in both Guangxi and SNT (Fig. 22). The  
960 *Flemingites rursiradiatus* beds were assigned to the early middle Smithian in some  
961 previous works (Brayard et al., 2013; Jenks et al., 2015). However. According to the  
962 initial subdivisions of the Smithian (Brühwiler et al., 2010a), the age of these beds  
963 should be the late early Smithian (Fig. 22).

964 The *Owenites koeneni* beds are middle Smithian and can be subdivided into three  
965 horizons: the *Ussuria*, *Hanielites*, and *Inyoites* horizons. The *Inyoites* horizon  
966 correlates with SNT-SM-13 based on the occurrence of *Inyoites* in both regions, while  
967 precise correlations of the former two horizons with UAZs in the SNT remain  
968 uncertain (Fig. 22).

969 The early late Smithian *Anasibirites multiformis* beds correlate with SNT-SM-14.  
970 The *Xenoceltites variocostatus* beds correspond to SNT-SM-15 and SNT-SM-16 (Fig.  
971 22).

#### 972 4.3.6 Northeastern Vietnam

973 Four Smithian ammonoid beds have been recognized in northeastern Vietnam  
974 (Shigeta et al., 2014), which are rather similar to those found in South China. They  
975 are the early Smithian *Flemingites rursiradiatus* beds, the middle Smithian *Urdyceras*  
976 *tulongensis* beds and *Owenites koeneni* beds, and the late Smithian *Xenoceltites*  
977 *variocostatus* beds. *Urdyceras tulongensis* beds correlate with SNT-SM-8. The early  
978 late Smithian *Anasibirites* fauna has not yet been reported from northeastern Vietnam.

#### 979 4.3.7 Western USA basin

980 The western USA basin is one of the key regions for Smithian ammonoids. It has  
981 been studied since the beginning of the last century (Hyatt and Smith, 1905; Smith,  
982 1932; Kummel and Steele, 1962) and recently provided new ammonoid findings  
983 (Jenks et al., 2010; Brayard et al., 2013; Jattiot et al., 2017; Jenks and Brayard, 2018;  
984 Brayard et al., 2020, 2021). Middle and late Smithian ammonoid faunas are well  
985 documented, while early Smithian assemblages are less well-known owing to the lack  
986 of well-preserved specimens (Fig. 22).

987 Ten Smithian ammonoid beds are recognized in Utah (Brayard et al., 2013,  
988 2020, 2021). Brayard et al. (2013) initially tentatively assigned the six following beds  
989 to the early Smithian: *Vercherites undulatus* beds, *Radioceras* aff. *Evolvens* beds,  
990 *Meekoceras olivieri* beds, *Meekoceras millardense* beds, *Preflorianites-Kashmirites*  
991 beds, and *Inyoites beaverensis* beds. However, the material from these beds is often  
992 poorly preserved, leaving many uncertainties on age attribution (Fig. 22).

993 Based on recently sampled well-preserved material from Crittenden Spring,  
994 Nevada, and comparison with conodont occurrences, it appears that *Meekoceras*  
995 *millardense* is middle Smithian (Jenks and Brayard, 2018; Maekawa and Jenks, 2021).  
996 Co-occurring ammonoids (e.g., *Juvenites* and *Proharpoceras*) also suggest a middle  
997 Smithian age. Thus, the *Meekoceras millardense* beds are middle Smithian, but it is  
998 not certain that these beds represent the earliest middle Smithian in the western US  
999 basin (Fig. 22). The ammonoid content of the three beds below the *Meekoceras*

1000 *millardense* beds (*Vercherites undulatus*, *Radioceras* aff. *evolvens* and *Meekoceras*  
1001 *olivieri* beds), are dominated by paranoritids, and *Meekoceras olivieri* is potentially  
1002 closer to *Vercherites*. We thus leave them as early Smithian (Fig. 22). Additional  
1003 well-preserved material is mandatory to determine their exact superposition.

1004 Middle Smithian ammonoids are abundant in the western USA basin and were  
1005 most often included into a single interval, i.e., the *Meekoceras gracilitatis* Zone  
1006 (Kummel and Steele, 1962). However, it has been shown that this zone can be  
1007 subdivided into more horizons or subzones with different stratigraphic resolutions  
1008 depending on sampling effort and taxonomic revisions (Brayard et al., 2013; Jattiot et  
1009 al., 2017; Jenks and Brayard, 2018). Ten middle Smithian interval zones have, for  
1010 instance, been recognized from Crittenden Spring, northeastern Nevada (Jenks and  
1011 Brayard, 2018), with some uncertainties in correlating this high-resolution scale at a  
1012 global scale.

1013 Jattiot et al. (2017) postulated 6 UAZs for the Smithian of the western US basin,  
1014 which were recently confirmed at the basin scale (Brayard et al., 2021). UAZ 1 is  
1015 characterized by a single species, *Meekoceras olivieri*, resembling *Vercherites* (see  
1016 previous paragraph). Thus, UAZ 1 most likely represents the early Smithian. UAZs 2  
1017 and 3 were assigned to the early Smithian based on the occurrence of *Kashmirites*  
1018 *stepheni*. However, this material is rather poorly preserved, and its attribution may be  
1019 questionable. In addition, the co-occurring species *Meekoceras gracilitatis* suggests a  
1020 middle Smithian age. Overall, UAZs 2 and 3 can likely be included in the middle  
1021 Smithian. UAZ 4 is middle Smithian, and UAZs 5 and 6 are late Smithian.

1022 Late Smithian ammonoids were also commonly reported from the western USA  
1023 basin (e.g., Mathews, 1929; Jattiot et al., 2017; Brayard et al., 2021). Two successive  
1024 assemblages can be recognized. The lower one corresponds to the UAZ 5 of Jattiot et  
1025 al. (2017) and is dominated by prionitids, such as *Anasibirites*, *Wasatchites*,  
1026 *Hemiprionites*, and *Gurleyites*. The upper zone is equal to the UAZ 6 of Jattiot et al.  
1027 (2017) and is characterized by the co-occurrence of xenoceltitids and  
1028 *Pseudosageceras* (Brayard et al., 2021).

1029 Widmann et al. (2020) recently introduced a new latest Smithian zone above the

1030 xenoceltitids-*Pseudosageceras* assemblage and below the first Spathian ammonoid  
1031 assemblage. However, the detailed taxonomic composition of this new zone has not  
1032 yet been described, and no specimens have been illustrated. Based on present data,  
1033 this zone would have no equivalent worldwide.

#### 1034 **4.3.8 British Columbia**

1035 Two Smithian ammonoid zones have been recognized in British Columbia, i.e.,  
1036 the *Euflemingites romunderi* and *Anawasatchites tardus* Zones (Tozer, 1994). The  
1037 *Euflemingites romunderi* Zone roughly corresponds to the middle Smithian, while the  
1038 *Anawasatchites tardus* Zone correlates with the early late Smithian SNT-SM-14 and  
1039 worldwide (Fig. 23). A second late Smithian zone potentially exists in British  
1040 Columbia, as suggested by *Pseudosageceras plicatum*, which closely  
1041 resembles *?Pseudosageceras bullatum* from the late Smithian in Nevada (Jattiot et al.,  
1042 2017). Unfortunately, this specimen occurs in a floated block (Tozer, 1994),  
1043 preventing further age determination and correlation.

#### 1044 **4.3.9 Arctic Canada**

1045 Tozer (1965, 1967, 1994) identified 3 zones in Arctic Canada, i.e., the  
1046 *Hedenstroemia hedenstroemi*, *Euflemingites romunderi*, and *Anawasatchites tardus*  
1047 Zones, in ascending order (Fig. 23). The *Hedenstroemia hedenstroemi* Zone can be  
1048 tentatively roughly correlated with the late early Smithian to early middle Smithian  
1049 interval (see discussion in subsection 6.3.10). The *Euflemingites romunderi* and  
1050 *Anawasatchites tardus* Zones correspond to the middle and early late Smithian,  
1051 respectively.

#### 1052 **4.3.10 Siberia**

1053 Three Smithian ammonoid zones can be distinguished in Siberia (Fig. 23), i.e.,  
1054 the *Hedenstroemia hedenstroemi*, *Lepiskites kolymensis* and *Wasatchites tardus* Zones  
1055 (Dagys, 1994a). The *Hedenstroemia hedenstroemi* Zone was tentatively correlated

1056 with the early Smithian in several previous works but with very large uncertainty  
1057 (Brayard et al., 2013; Jenks et al., 2015; Jenks and Brayard, 2018). There is no firm  
1058 known occurrence of *Hedenstroemia* from the earliest Smithian of well-sampled  
1059 regions, such as the Salt Range (Brühwiler et al., 2011). In the SNT, the oldest  
1060 occurrence of *Hedenstroemia* is in SNT-SM-6. Although the *Hedenstroemia* species  
1061 from Siberia differ from the Salt Range species, we can therefore hypothesize that the  
1062 Boreal *Hedenstroemia hedenstroemi* Zone roughly correlates with the late early  
1063 Smithian in the SNT. This deserves more work to be confirmed. In addition, another  
1064 genus, *Anaxenaspis*, co-occurring in the *Hedenstroemia hedenstroemi* Zone, suggests  
1065 a middle Smithian age, as it occurs in the middle Smithian of, e.g., the Salt Range and  
1066 Spiti (Brühwiler et al., 2012b, 2012c). Overall, the *Hedenstroemia hedenstroemi* Zone  
1067 may span the late early Smithian to early middle Smithian interval (Fig. 23).

1068 The overlying *Lepiskites kolymensis* Zone is middle Smithian, as it contains  
1069 *Juvenites*, *Meekoceras*, *Arctoceras* and *Euflemingites*, but accurate correlations with  
1070 other basins are problematic. The *Wasatchites tardus* Zone corresponds to the early  
1071 late Smithian (Fig. 23).

#### 1072 **4.3.11 Greenland**

1073 Smithian ammonoids are scarcely reported from Greenland with the single  
1074 occurrence of *Arctoceras blomstrandii* (Lindström et al., 2020), suggesting a middle  
1075 Smithian age (Fig. 23).

#### 1076 **4.3.12 Svalbard**

1077 Middle and late Smithian ammonoids have been well documented from Svalbard  
1078 (Tozer and Parker, 1968; Korchinskaya, 1972; Weitschat and Hamburg, 1978;  
1079 Weitschat and Dagys, 1989; Piazza et al., 2017; Hansen et al., 2021). Two  
1080 assemblages can be distinguished. The lower one is characterized by the occurrences  
1081 of *Arctoceras* and *Euflemingites* and represents the middle Smithian (Fig. 23). This  
1082 interpretation is also supported by organic carbon isotopic values (Hansen et al.,



1083 2021). The upper assemblage is dominated by early late Smithian prionitids, such as  
1084 *Anasibirites* and *Wasatchites*, and thus correlates worldwide.

#### 1085 **4.3.13 South Primorye**

1086 Seven Smithian ammonoid zones/beds were established in South Primorye  
1087 (Shigeta et al., 2009; Smyshlyaeva and Zakharov, 2012, 2013, 2015; Zakharov et al.,  
1088 2013, 2021). The *Paranorites varians* Zone was interpreted to be of Dienerian age  
1089 (Shigeta et al., 2009). However, *Paranorites* occurs in the early Smithian from South  
1090 China and the Salt Range (Brayard and Bucher, 2008; Brühwiler et al., 2012c),  
1091 suggesting that the *Paranorites varians* Zone is potentially of Smithian age (Fig. 23).  
1092 In addition, the conodont *Eurygnathodus costatus*, co-occurring in this zone, also  
1093 suggests an early Smithian age, at least younger than SNT-SM-3 (see Krystyn et al.,  
1094 2017).

1095 The “*Clypeoceras*” *timorensis* Zone most likely correlates with SNT-SM-3 to  
1096 SNT-SM-5 interval in the SNT (Fig. 23), based on their faunal similarity. This  
1097 interpretation is based on: (1) “*Clypeoceras*” *timorensis* illustrated by Shigeta et al.  
1098 (2009) resembles *Radioceras evolvens* (found in SNT-SM-5), both in shell shape and  
1099 suture line. We thus consider them here as potential synonyms. (2) *Ussuriflemingites*  
1100 *primoriensis* found in the “*Clypeoceras*” *timorensis* Zone is close to *Vercherites*  
1101 *vercheri* (occurring in SNT-SM-3), except for fewer indentations on its suture lobes.  
1102 This taxon thus suggests a middle early Smithian age as well.

1103 The *Radioprionites abrekensis* bed is difficult to correlate with other regions.  
1104 *Radioprionites* is closer to early Smithian paranoritids than to prionitids. Its overall  
1105 shell shape resembles some paranoritids (e.g., *Paranorites*) found in the SNT, and its  
1106 suture lines show a somewhat long auxiliary series, also close to paranoritids (e.g.,  
1107 *Radioceras* and *Paranorites*). Based on the strong affinity of *Radioprionites*  
1108 *abrekensis* to paranoritids and the absence of typical middle Smithian taxa occurring  
1109 in this bed, we thus tentatively correlate it with the late early Smithian.

1110 The *Balhaeceras balhaense* bed was correlated to SNT-SM-10 by Brühwiler et al.

1111 (2012c). We agree with this interpretation as: (1) *Hemiprionites* sp. indet. occurring in  
1112 this bed was synonymized with *Shigetaceras* (occurring exclusively in SNT-SM-10)  
1113 by Brühwiler et al. (2012c). (2) *Balhaeceras balhaense* is close to *Galfettites omani*,  
1114 which has been found in SNT-SM-9 and SNT-SM-10 (Fig. 19). Overall, the  
1115 taxonomic composition similarity between the *Balhaeceras balhaense* bed and  
1116 SNT-SM-10 supports this correlation.

1117 The *Arctoceras subhydaspi* bed can be roughly constrained to SNT-SM-11 to  
1118 SNT-SM-13 (Fig. 23), since it is younger than the *Balhaeceras balhaense* bed, and no  
1119 typical late Smithian taxa were found in this bed. More precise correlation is not  
1120 possible based on present data.

1121 The *Anasibirites nevolini* Zone corresponds to the early late Smithian. However,  
1122 its content exhibits an unusual mixture of both typical middle Smithian and early late  
1123 Smithian taxa (Zakharov et al., 2013, 2021), which is not recorded in other basins.

1124 A recently described *Shimanskyites shimanskyi* Zone (Zakharov et al., 2013) can  
1125 be roughly assigned to the second part of the late Smithian (Fig. 23).

#### 1126 **4.3.14 Japan**

1127 A few Smithian ammonoids have been described from the Lower Triassic in  
1128 Kyushu, Japan. They can be grouped into two zones: the middle Smithian *Owenites*  
1129 and late Smithian *Anasibirites* Zones (Kummel and Sakagami, 1960; Bando, 1964).  
1130 Bando (1970) described two poorly preserved ammonoid assemblages from the  
1131 Osawa Formation in Kitakami Massif. He identified three genera, *Meekoceras*,  
1132 *Flemingites*, and *Euflemingites* in the lower assemblage. This assemblage could be  
1133 early-middle Smithian age, but with great uncertainty due to poor preservation of  
1134 these specimens. The upper assemblage is monospecific, containing “*Glyptopheroceras*  
1135 cf. *gracile*”, which was re-assigned to a Spathian ammonoid *Deweeveria kovalenkoi* by  
1136 Shigeta (2022). Therefore, whether Smithian ammonoids exist in Kitakami Massif  
1137 remains to be clarified.

#### 1138 **4.3.15 Montenegro**

1139 Montenegro represents one of the rare regions in western Tethys yielding  
1140 Smithian ammonoids. Đaković (2017) and Đaković et al. (2022) described a  
1141 moderately-rich ammonoid assemblage from screes.. These authors assigned it to the  
1142 middle Smithian. However, based on available data, this assemblage may encompass  
1143 the late Dienerian to the middle Smithian interval. Indeed, the presence of  
1144 *Parahedenstroemia* suggest a potential late Dienerian age. *Parahedenstroemia* was  
1145 indeed documented from the late Dienerian at South Primorye (Shigeta et al., 2009)  
1146 and the Candelaria Hills, Nevada (Ware et al., 2011). Other genera, such as  
1147 *Lingyunites*, *Owenites* and *Truempyceras*, occurring in this assemblage better suggest  
1148 an early to middle Smithian age. More specimens from *in situ* sampling are needed to  
1149 solve this conundrum.

#### 1150 **4.3.16 Northwestern Caucasus**

1151 A middle Smithian ammonoid assemblage was reported from the northwestern  
1152 Caucasus (Shevyrev, 1995). It includes *Inyoites*, *Dieneroceras*, *Meekoceras*,  
1153 *Arctoceras*, *Subvishnuites*, *Parussuria*, *Lanceolites*, *Juvenites*, and *Owenites*. Due to  
1154 the lack of stratigraphic information about their superpositions, more detailed  
1155 correlations are impossible. This fauna shows an apparent strong affinity with both the  
1156 SNT and the western USA basin, indicating frequent biotic exchanges between Tethys  
1157 and Panthalassa during the middle Smithian (Brayard et al., 2009).

#### 1158 **4.3.17 New Zealand**

1159 Kummel (1968a) described a small Smithian ammonoid assemblage from New  
1160 Zealand, which contains four species: *Owenites* cf. *koeneni*, *Flemingites* cf. *lidacensis*,  
1161 *Subvishnuites* *welteri*, and *Wyomingites* cf. *aplanatus*, suggesting an early to middle  
1162 Smithian age. However, the preservation of sampled specimens is very poor,  
1163 preventing further comparisons.

## 1164 **5 Correlations with conodont biostratigraphy**

1165         Apart from ammonoids, conodonts also play a significant role in Early Triassic  
1166 biochronology. For instance, the GSSP of the Permian/Triassic boundary was defined  
1167 by the first occurrence of conodont *Hindeodus parvus* (Yin et al., 2001). Generally,  
1168 ammonoids and conodonts are somewhat congruent for defining stage/substage  
1169 boundaries in the Early Triassic (Orchard and Tozer, 1997). Within the Southern  
1170 Neotethys, detailed correlations await similar high-resolution scales for conodonts  
1171 (Fig. 20).

1172         At the base of the Griesbachian, the conodont *Hindeodus parvus* appears in the  
1173 same horizon as *Otoceras woodwardi* in Spiti (Krystyn and Orchard, 1996). At the  
1174 Selong section, *Hindeodus parvus* also co-occurs together with “*Otoceras*  
1175 *latilobatum*” (Wang and Wang, 1995). This suggests that *Hindeodus parvus* co-occurs  
1176 with *Otoceras* in the Southern Neotethys. However, in Boreal regions, *Otoceras*  
1177 apparently occurs slightly earlier than *Hindeodus parvus* (Henderson and Baud,  
1178 1997).

1179         The Griesbachian/Dienerian boundary corresponds to the first appearances of the  
1180 ammonoid *Gyronites* and the conodont *Sweetospathodus kummeli* in the Salt Range  
1181 (Romano et al., 2013; Ware et al., 2018b), Spiti (Ware et al., 2018a; Sun et al., 2021)  
1182 and South Tibet (Wang and Wang, 1995). The *Sweetospathodus kummeli* Zone  
1183 corresponds to the whole early Dienerian and correlates with SNT-DI-1, SNT-DI-2,  
1184 and SNT-DI-3. The first regional occurrence of the conodont *Neospathodus dieneri*  
1185 seems congruent with that of *Ambites*, but may be slightly younger in the Salt Range  
1186 (Romano et al., 2013).

1187         Regarding the base of the Smithian, the first appearance of the ammonoid  
1188 *Flemingites bhargavai* is coeval to that of the conodont *Novispathodus waageni* in the  
1189 Salt Range (Brühwiler et al., 2012c; Romano et al., 2013). However, Krystyn et al.  
1190 (2007, 2017) found in Spiti that *Novispathodus waageni* occurs ~60 cm higher than  
1191 *Flemingites bhargavai*, and corresponds to the base of the *Flemingites* gr. *nanus* Zone

1192 (=SNT-SM-4). If we adopt this conodont proposal, the Induan/Olenekian boundary  
1193 will be three ammonoid UAZs higher than the *Flemingites bhargavai* Zone (Figs. 19,  
1194 20, 22-24). Their correlation remains unclear in South Tibet, due to the lack of  
1195 fossiliferous limestones at the base of the Smithian in the studied sections. Thus far, a  
1196 single Smithian conodont zone has been defined in Selong, the *Novispathodus*  
1197 *waageni* Zone, roughly corresponding to the whole unit D of the Kangshare  
1198 Formation (Wang and Wang, 1995). Goudemand et al. (2019) mentioned several  
1199 regional Smithian conodont zones in the Salt Range, which can be easily correlated  
1200 with ammonoids according to their positions in the same sections. However, the  
1201 detailed taxonomic composition of these conodont zones is still unpublished. Another  
1202 difficulty in Smithian correlating ammonoid and conodont scales in the SNT is the  
1203 heterogeneous definitions of conodont zones. For instance, the compositions and  
1204 definitions of Smithian conodont zones in the Salt Range and Spiti are quite different  
1205 (Fig. 20). Similar to ammonoids, high-resolution biostratigraphical works on  
1206 conodonts in different regions using a standard quantitative method, such as the UA  
1207 method (e.g., Leu et al., 2022), are therefore necessary to propose robust correlations  
1208 between ammonoid and conodont zones.

## 1209 **6 Correlation with oxygen and carbon isotopic curves**

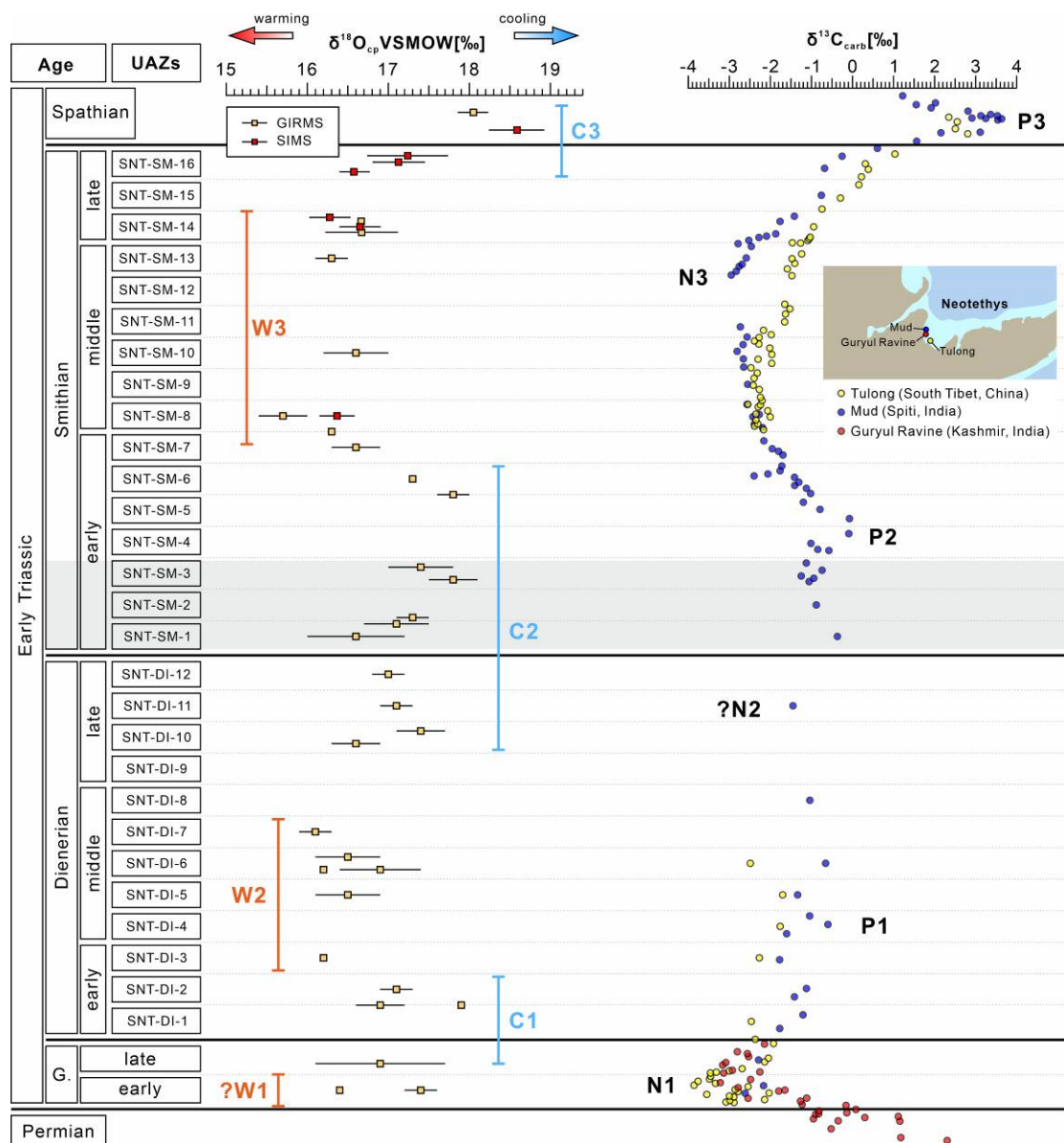
1210 The global average surface temperature during the Early Triassic was potentially  
1211 the highest in the Phanerozoic (Scotese et al., 2021), representing an extremely hot  
1212 climate. Early Triassic carbon cycle and sea surface temperature experienced large  
1213 fluctuations (Payne et al., 2004; Tong et al., 2007; Sun et al., 2012; Romano et al.,  
1214 2013; Song et al., 2013; Goudemand et al., 2019). However, the detailed tempo of  
1215 some of these perturbations remains poorly constrained. Here, we compiled the  
1216 published Early Triassic oxygen and carbon isotopic data from the southern Neotethys  
1217 and correlated them with the newly established high-resolution ammonoid UA zones  
1218 (Fig. 24).

1219 Four negative (N1–N4) and three positive (P1–P3) carbon isotopic excursions  
1220 have been reported in the Early Triassic (Song et al., 2013), of which three negative  
1221 (N1–N3) and two positive (P1–P2) excursions are encompassed in the studied interval.  
1222 In the absence of biostratigraphical scales, these excursions can be used as a  
1223 supplementary tool for global stratigraphic correlations (Song et al., 2013; Zhang et  
1224 al., 2019).

1225 In the SNT, N1 occurs during the early Griesbachian, and is followed by a  
1226 gradual increase from the early Griesbachian to the middle Dienerian SNT-DI-4. P1  
1227 potentially occurs in SNT-DI-4, followed by a possible N2 in SNT-DI-11. However,  
1228 the currently available isotopic data for this interval in the SNT are too scarce to be  
1229 certain. Carbon isotopes display a rapid increase across the Dienerian/Smithian  
1230 boundary and reach P2 during SNT-SM-4. After P2, carbon isotopes show a gradual  
1231 decrease until N3 at the end of the middle Smithian. From the late Smithian to the  
1232 Spathian, the carbon isotope curves exhibit a remarkable increase and reached P3  
1233 during the earliest Spathian. The Smithian/Spathian boundary (SSB) based on SNT  
1234 ammonoids is thus located close to the recent high-resolution proposal of Leu et al.  
1235 (2022) based on conodont AUs from South China.

1236 Similarly to the carbon isotopic oscillations, the Early Triassic oxygen isotopic  
1237 composition of conodont apatite also displays large fluctuations, reflecting sea surface  
1238 temperature changes (Sun et al., 2012; Romano et al., 2013; Goudemand et al., 2019).  
1239 Based on available data, three warm periods (W1–W3) and three relatively cooler  
1240 intervals (C1–C3) occur from the Griesbachian to the early Spathian (Romano et al.,  
1241 2013; Goudemand et al., 2019). Across the Permian/Triassic boundary, a rapid  
1242 increase (W1) in SST has been documented at many sites, such as South China  
1243 (Joachimski et al., 2012; Chen et al., 2016) and northwestern Iran (Schobben et al.,  
1244 2014). However, W1 has not been formally reported from southern Neotethys due to  
1245 the lack of data on the oxygen isotopes of the Changhsingian. C1 occurs during the  
1246 late Griesbachian to the early Dienerian UAZ SNT-DI-2. Thereafter, the second warm  
1247 period (W2) corresponds to SNT-DI-3 to SNT-DI-7. The transition from W2 to C2 has  
1248 not been well-documented due to the lack of conodont apatite oxygen isotopic data in

1249 SNT-DI-8 and SNT-DI-9. C2 begins roughly in SNT-DI-10 and persists until  
 1250 SNT-SM-6. From SNT-SM-6 to SNT-SM-7, oxygen isotopes exhibit a rapid and  
 1251 marked decrease, reflecting the beginning of the third warm period (W3). It persists  
 1252 until the early late Smithian SNT-SM-14. From the SNT-SM-15 to the early Spathian,  
 1253 oxygen isotope displays a remarkable increase, suggesting a cooling event (C3).  
 1254 Similar sea surface temperature changes have been reported in South China (Leu et al.  
 1255 2022).



1256  
 1257 Figure 24. Correlations of ammonoid biostratigraphy with oxygen and carbon isotopic  
 1258 records in the southern Neotethys. Oxygen isotopic data (mean values with one  
 1259 standard deviation) of conodont apatite from Romano et al. (2013) and Goudemand et  
 1260 al. (2019). Carbon isotopic records were compiled from four sections, Tulong  
 1261 (Brühwiler et al., 2009), Mud (Sun et al., 2021), and Guryul Ravine (Wang et al.,

1262 2019). Grey area indicates an uncertain interval for the Dienerian/Smithian boundary  
1263 among different proposals.

## 1264 **7. Conclusions**

1265 The main conclusions of this work are summarized as follows:

1266 (1) Based on exhaustive bed-by-bed sampling and a revised taxonomy, we  
1267 identified 140 species from the Kangshare Formation in South Tibet covering  
1268 the Griesbachian-Smithian interval. Twenty-two UAZs were recognized by  
1269 means of the UA method, largely improving the known resolution of the  
1270 Early Triassic ammonoid biostratigraphy in South Tibet.

1271 (2) The synthetic analysis of the new ammonoid data from South Tibet and two  
1272 other basins, i.e., Spiti (India) and the Salt Range (Pakistan), resulted in an  
1273 unprecedented high-resolution Dienerian and Smithian ammonoid  
1274 biostratigraphic scale, including 12 UAZs for the Dienerian and 16 UAZs for  
1275 the Smithian, including a new UAZ (ST-18 in South Tibet; SM-12 at the SNT  
1276 scale).

1277 (3) These new UAZs can be well correlated within the SNT and provide a robust  
1278 time calibration for carbon cycle and temperature fluctuations.

1279 (4) Within the SNT, ammonoids and conodont biostratigraphy are in relatively  
1280 good agreement to define stage/substage boundaries. However,  
1281 high-resolution analyses using quantitative biostratigraphical methods on  
1282 conodonts from this area await further work to achieve good correlation  
1283 between conodonts and ammonoid biostratigraphies.

1284 (5) Comprehensive global correlations for the Griesbachian, Dienerian, and  
1285 Smithian ammonoid biostratigraphy are discussed in depth. We found that the  
1286 originally suggested earliest Smithian *Hedenstroemia hedenstroemi* Zone in  
1287 Arctic regions can be correlated to the late early Smithian age.

1288 Despite the marked progresses of Early Triassic ammonoid biostratigraphy in  
1289 recent decades and in this work, many uncertainties remain in the detailed correlation



1290 of the zonal scheme from different basins and the definitions of the stage/substage  
1291 boundaries. Additional work with similarly extensive high-resolution sampling and  
1292 quantitative method in other basins is still needed to obtain comparable highly  
1293 resolved biostratigraphic scales and more robust correlations.

1294

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1326 **Haijun Song:** Conceptualization, Investigation, Supervision, Writing - review & editing

1327

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