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High-Precision Radioisotopic Ages for the Lower Midian (Upper Wordian) Stage of the Tethyan Time Scale, Shigeyasu Quarry, Yamaguchi Prefecture, Japan

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- High-precision radioisotopic ages for the lower Midian (upper Wordian) Stage of the Tethyan
 Time-time_Scalescale, Shigeyasu Quarry, Yamaguchi Prefecture, Japan.
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- 10 Abstract.
- 11

12 Global correlation of strata to the Guadalupian Series Epoch (Permian Period) of the International 13 Geologic Time Scale remains provisional due to a lack of many the sufficient biostratigraphically 14 constrained radioisotopic ages. Five new CA-IDTIMShigh-precision U-Pb radioisotopic ages were 15 obtained from tuffs in the lower Midian (upper Wordian) volcano-siliciclastic succession of the Akiyoshi 16 Plateau, southwestern -Japan. Two undisturbed and continuous tuffs occur within fusulinid-bearing 17 laminated limestone turbidites, that provide with precise biostratigraphic control. The Colania douvillei 18 and Lepidolina shiraiwensis fusulinid Zones in the Akiyoshi succession provide an early Midian age in 19 the Tethyan provincial Permian Timescale time scale. The range of ages (267.46 ± 0.04 Ma to 265.76 ± 20 0.03 Ma) over 25 m of section including the limestone turbiditic beds suggest that this early lower 21 Midian sequence Stage of the Tethyan time scale Scale is thus correlated with the upper Wordian Stage 22 of the International Geologic Time Scale. The sedimentologic, bio- and geochronologic data affirm 23 the effectively conformable nature of the siliciclastic-carbonate succession of the Tsunemori

24	Formation at the Shigeyasu Quarry, and the presence of acidic volcanic tuffs are consistent					
25	with a forearc basin or trench slope basin depocenter for the Tsunemori Formation.					
26	The sedimentologic, bio- and geochronologic data that are proving a normal sedimentary					
27	succession The obtained radioisotopic, sedimentologic and biostratigraphic data of the					
28	Tsunemori Formation at the Shigeyasu Quarry and the presence of acidic volcanic tuffs are					
29	consistent with the newly proposed model of the forearc basin or trench slope basin as					
30	sedimentation site for the entire Tsunemori Formation.					
31 32	Key words: Guadalupian (middle Permian); Tethyan Timescale; CA-IDITIMS, fusulinids biostratigraphy; correlation.					
33	2. <u>1.</u> Introduction.					
34	Significant progress has been made in the last decade on the radioisotopic calibration of the					
35	International Geologic Time Scale (IGTS) , (Gradstein et al., 2012; Cohen et al., 2013) but_yet					
36	some parts of the scale are still calibrated <u>only provisionally</u> . This is particularly true for the					
37	upper <u>late</u> Cisuralian (post early Artinskian) and Guadalupian Series <u>Epoch</u> of the Permian					
38	9280(280 -265 Ma), where just a few reliable high precision U-Pb ages exist (Henderson et al.,					
39	2012). This part of the Permian Time Scale that is calibrated-only with biostratigraphic scaling					
40	requires further geochronologic improvementThis part of the Permian Time Scale is thus					
41	calibrated with biostratigraphic scaling and requires further improvement. The					
42	paleobiogeographic provinciality and the lack of the radioisotopic calibration of this part of the					
43	scale make the correlation of Guadalupian Series and Stages in the type region with the rest of					
44	the world difficult. Besides the lack of the radioisotopic calibration, there is an issue of the					
45	paleobiogeographic provinciality, and correlation of the Stages stages of the Guadalupian Epoch					

46	Series in the type region with the marine Tethyan Scale time scale, as well as continental					
47	successions all over the world. The only TIMS calibrating radioisotopic age in the entire					
48	Guadalupian <u>in the type area came is f</u> rom a volcanic ash occurred between the Hegler and					
49	Pinery limestone members of the Bell Canyon Formation at Nipple Hill, Guadalupe Mountains					
50	National Park, Texas. The ash is 6 to 8 cm thick and lies 2 m above the top of the Hegler					
51	Member, within the undifferentiated Bell Canyon Formation, and 20 m below the base of the					
52	Jinogondolella postserrata conodont zone Zone and the base of the Capitanian Stage (Bowring					
53	et al., 1998). The original legacy age of 265.3 \pm 0.2 Ma for this volcanic tuff was recently revised					
54	using the chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-IDTIMS)					
55	method (Mattinson, 2005)-to 265.46 \pm 0.27 Ma (Ramezani and Bowring, 2018).					
56	Several CA-IDTIMS radioisotopic ages were recently published from the base of					
57	Kuhfengian in South China (Wu et al., 2017) and from the analogues of the Roadian (Russian-					
58	Omolonian and Olynian Regional Stages in N-E of Russian) and Capitanian (Gizhigian Regional					
59	Stage) in N-E of Russia (Davydov et al., 2016; Davydov et al., 2018). The latter publication					
60	suggests a new calibration of the entire Guadalupian <u>Epoch</u> and proposes the extension of the					
61	base of <u>the</u> Roadian down to 277 Ma and <u>the</u> Wordian down to 271 Ma. <u>The EARTHTIME</u>					
62	isotope dilution tracer has beenwas utilized in all of these studies, that aids which aids-directly					
63	comparein the direct comparison of the dates from Texas, Russia and South China.					
64	Nevertheless, the The correlation between the type section of the Guadalupian Series in					
65	Texas and the Tethyan Scale time scale remains quite controversial (Davydov et al., 2018).					
66	Specifically, we do not know the exact analogues of all three stages of the Guadalupian Series in					

the Tethyan <u>time</u> Scale. The <u>report in this study of new CA-IDTI high-precision</u> MS radioisotopic
U-Pb <u>zircon</u> ages <u>reported in this study fromfor</u> the lower Midian Stage of Japan is one <u>more</u>
step towards <u>that</u> correlation of the Tethyan to the International Geologic Time. The fusulinid
fauna within the limestone turbidites and limestone slump blocks intercalated with the dated
volcanic ashes are consistently early Midian in age and therefore can refine the maximum age
of <u>the that Stage stage</u> in the Tethyan <u>Geologic Time Scale (TTS time scale</u>) and <u>consequently</u>
its correlation to an <u>late-upper Wordian Stage in the International Geologic Time Scale (IGTS).</u>

74 3.2. Geological Setting setting.

The <u>Samples</u> for the present study were collected <u>in at</u> Shigeyasu Quarry, in rocks of the 75 76 Akiyoshi Belt, that which is distributed in across several isolated areas of the Inner Zone of 77 Southwestern Japan, extending into the western margin of the Hida Belt (Wakita, 2013). The 78 Akiyoshi Belt forms a Permian accretionary complex (Fig. 1) composed of sandstone, mudstone, 79 conglomerate, siliceous shale, felsic tuff, chert, limestone and basalt. The Permian Akiyoshi 80 accretionary complex is divided into two units, which show similar ages but distinctly different 81 dominant lithologies: a limestone-rich unit consisting of several large limestone plateaus that 82 belongs to the Akiyoshi Limestone Group Limestone. The, and a second unit that is composed 83 mainly of siliciclastic successions with minor volcanic components, named as the Tsunemori 84 Formation. Both units formed by continuous sedimentation through the same period (Sano and 85 Kanmera, 1991a; Tazawa et al., 2009). Many components of this belt are unmetamorphosed 86 and the limestone within the belt is famous for its well preserved and diverse fauna (Toriyama,

87 1967). The Tsunemori Formation is unconformably overlain by Triassic shallow marine to non88 marine sedimentary rocks of the Mine Group.

89 The Akiyoshi Limestone Group covers almost the whole area of the Akiyoshi Plateau in the central part of Yamaguchi Prefecture, southwest Japan. The Akiyoshi Limestone Group is a 90 91 reefal limestone on a seamount in the Panthalassan Ocean (Kanmera and Nishi, 1983), and is 92 one of the most complete and continuous carbonate successions in the Panthalassa region, 93 ranging from Early Carboniferous to Middle Permian in age (Toriyama, 1967). 94 The Tsunemori Formation along the marginal parts of the western Akiyoshi-dai 95 plateauPlateau, southwest Japan, <u>are-is</u> described as a sequence of broken limestone, 96 limestone breccia, and scaly mudstone (Sano and Kanmera, 1991b), designated as evidence of melange formation caused during subduction and accretion. The broken limestone is 97 98 characterized by penetrative and pervasive destruction of skeletal grains and primary 99 sedimentary fabrics. The Kasimovian, Gzhelian, Asselian, Sakmarian, and Artinskian Late Visean 100 to Midian foraminifera from the same depositional period as the entire Akiyoshi Limestone 101 Group are identified in the broken limestone, but with no orderly stratigraphic succession (Sano and Kanmera, 1991a; Tazawa et al., 2009; Kobayashi, 2012c). The Tsunemori Formation 102 103 according these the first authors is a trench deposit, with the Akiyoshi Limestone accreted as an 104 exotic block sometimes during Middle to Late Permian time, based upon radiolarian biostratigraphy (Sano and Kanmera, 1991c). 105

106 A<u>n alternative</u> new-model of <u>for</u> the_Tsunemori Formation sedimentation processes and 107 <u>depositional</u> setting has been proposed recently in the territory west from <u>of the</u> Akiyoshi-dai 108 plateau, that includes the area of our study (Wakita et al., 2018). The normal 109 stratigraphic stratified A comfortable succession of mudstone and mudstone-dominant 110 turbidite with very thin layers of sandstone or siltstone and rare horizons of calcarenite and limestone breccia is documented there. No fissility or and scaly cleavage are- is recognized in 111 112 the mudstone and pebbly mudstone of the Tsunemori Formation (Wakita et al., 2018). The deformation style of the rocks of the Tsunemori Formation are different fromlack of 113 114 penetrative deformations is inconsistent with sedimentary formations deposited at the trench 115 and accreted to form an accretionary wedge, and rather best fit with suggests a forearc basin or 116 trench slope basin as the sedimentation site for the Tsunemori Formation (Wakita et al., 2018). 117 Our brief field investigation of the Tsunemori Formation at Shigeyasu Quarry also suggests 118 documents that the formation generally stratified, although in places the rock is faulted and 119 bended folded overturned, but generally stratified (Fig. 2). We found three types of 120 sedimentation of the limestone within the Tsunemori Formation: 1) rare horizons of clastic 121 limestone within interbedded with the debris flows and turbidites; 2) fully isolated blocks (2x3 122 m) of limestone (10VD98), wholly embedded in mudstone, i.e. slump block; 3) laminated 123 limestone turbidite (10VD21, 22,23) that is laterally pinched out (Figs. 2-3). All fFusulinid 124 samples we collected from all these three types of the limestone possessed the same early Midian age fauna. 125

Acidic volcanism in the late Guadalupian and Lopingian of Japan in general, and specifically volcanic rocks in the Capitanian-upper Guadalupian of the Akyioshi Group have long been recognized (Kanmera, 1974). Recent provenance and petrologic studies confirm the presence of a volcanic arc system near by the Akiyoshi terrane during entire Permian time
(Okawa et al., 2013; Hara et al., 2018; Zhang et al., 2018).

131 4.3. Materials and Methodsmethods

132 Five samples of volcanic ash beds tuffs and four samples from of limestone turbidites 133 were collected in the succession of the lower Tsunemori Formation exposed along the north-134 east to south-west edge of Shigeyasu Quarry (Fig. 2). The samples for the radioisotopic studies 135 study were collected from completely altered to bentonite bentonitic volcanic tuff layers that frequently occur within the lower part of the succession (Fig. 3). Three horizons were sampled 136 137 from within siliciclastic beds 1.7, 5, and 20 meters below the base of a prominent bar of 138 laminated limestone turbidite beds (samples 10VD26, 10VD95, and 10VD96, respectively). Two 139 tuff samples were collected from- within the laminated limestone turbiditic bedses near their base and top (samples 10VD25 and 10VD20 respectively), thus bracketing several of the 140 141 fusulinids samples (Figs. 2-3). All tuffs are laterally traceable within the exposure of the 142 Tsunemori Formation at the quarry.

143 All tuffs were processed with standard procedures including ultrasonic disaggregation 144 and concentration (Hoke et al., 2014), Franz magnetic separation, heavy liquid separation, and 145 hand picking. All samples yielded hundreds of sharply facetted, prismatic zircon grains (Figs. 2-146 3). The procedure and approaches associated with chemical-abrasion isotope dilution thermal 147 ionization mass-spectrometry (CA-IDTIMS) method have been recently described in detail by 148 Davydov et al. (2018). <u>CA-IDTIMS dates are reported with weighted mean uncertainties given as</u> 149 $\pm X/Y/Z$, where X is the 2 σ analytical uncertainty, Y is the combined analytical and tracer uncertainty (value given in parentheses), and Z is the combined analytical, tracer, and decay
 constant uncertainty [value given in brackets]. All samples yield great amount several hundreds
 of excellent prismatic zircon grains (Figs.2-3). The limestone samples were sliced into plates and
 fifty-one thin-sections with oriented fusulinids sections were prepared.

- The field inclination of the rock suggests the younger rocks of Tsunbemori Formation
 <u>occur</u> in the north-eastern corner of the edge of the quarry (Fig. 2). However, it turns that CA IDTIMS radioisotopic ages a suggest the overturned position <u>orientation of the succession (Figs.</u>
 <u>3-4</u>), that <u>which is a common feature within the Tsunemori Formation (Wakita et al., 2018).</u>
- 158 159

5.4. Biostratigraphic results

160

161 We acknowledge that fusuilinid-bearing limestone turbidites (debris flows) are

allochthonous with respect to the deeper water syn-sedimentary siliciclastic rocks, the <u>and</u> thus

163 their biostratigraphic constraints would generally only constrain the maximum depositional age

164 of such a stratigraphic succession. In this case, however, the presence of volcanic ash beds at

the base and within the laminated turbiditic limestone directly date its deposition (Fig. 2c),

166 while the three volcanic tuffs stratigraphically below the limestone beds provide a check on the

167 conformable nature of sediment deposition across the sequence (Fig. 3).

168 Radiolaria belonging to the Pseudoalbaillella globosa Zone to the Follicucullus

scholasticus Zone of Wordian-Capitanian age were collected from the lower and middle parts of

170 <u>the Tsunemori Formation</u> (Sano and Kanmera, 1991b; Tazawa et al., 2009; Wakita et al., 2018).

171 ———The fusulinids in the turbidites and in the limestone slump block in the Tsunemori

172 Formation at the Shigeyasu Quarry are quite diverse and include schubertellids Schubertella,

173 Yangchienia, Codonofusiella, Kahlerina, and Rauserella, schwagerinids Parafusulina and 174 Chusenella and verbeekinaceans Lepidolina, Pseudodoliolina and Sumatrina (Table 1). The 175 taxonomic composition of fusulinids in the studied turbidites and slump block is generally consistent (Figs. 4-5) and therefore the age of the limestone turbidites/slump block and 176 volcanoclastics in the quarry is the same within the resolution of fusulinids biostratigraphy, i.e. 177 178 around 1-one myrs-million years in this case (Davydov et al., 2018) (Table 1). The occurrence of 179 species Lepidolina shiraiwensis Ozawa in the turbidites undoubtedly suggests constrains the 180 and early Midian age of for the limestone turbidites and surrounding rocks (Leven, 1980; 181 Kotlyar et al., 1989a). In the nearby Kaerimizu area of the Akiyoshi plateau, the carbonate 182 succession ended ends within the Colania douvillei zone-Zone (Ueno, 1992), but in places 183 extended extends up to the Lepidolina shiraiwensis Zone, which is also defined in the area from 184 the limestone blocks and calcareous sandstone (Kobayashi, 2012b, 2012a).

185 6. <u>5.</u> U-Pb Geochronology geochronology

Sample 10VD96 was the stratigraphically lowest sampled volcanic tuff within siliciclastic rocks at the Shigeyasu quarry, where the succession <u>is</u> overturned. Eight grains selected for CA-IDTIMS yielded dates ranging from 267.65 to 267.01 Ma; five of these analyses are concordant and equivalent with a weighted mean 206 Pb/ 238 U date of 267.46 ± 0.04 (0.14) [0.31] Ma (2s; MSWD = 1.90), which is interpreted as estimating the volcanic depositional age (Table 2, Fig. 6). Two analyses yielded resolvably older dates with a modified Thompson tau test, and are interpreted as representing slightly older-inheritance, and a single analysis with an anomalously younger age is interpreted as the sole crystal in this study in which Pb-loss was not completelymitigated by chemical abrasion.

Sample 10VD95 from fifteen meters stratigraphically higher in the section was dated using ten single zircon grains; the five youngest analyses yielded a weighted mean 206 Pb/ 238 U date of 266.00 ± 0.04 (0.14) [0.31] Ma (2s; MSWD = 1.06), which is interpreted as estimating the volcanic depositional age (Table 2, Fig. 6). Another five grains produced older ages ranging from 266.25 to 269.85 Ma, and are attributed to inheritance.

200 **Sample 10VD26** collected from a volcanic tuff 3.3 meters stratigraphically above sample 10VD95, and 1.7 meters below the base of the laminated limestone turbidite beds. All ten 201 202 single zircons analyzed by CA-IDTIMS yielded concordant and equivalent isotope ratios ratios within their errors, with a weighted mean $^{206}Pb/^{238}U$ date of 265.81 ± 0.04 (0.13) [0.31] Ma (2s; 203 MSWD = 1.05), which is interpreted as estimating the volcanic depositional age (Table 2, Fig. 6). 204 205 Samples 10VD25 and 10VD20 from the base and top of the laminated limestone turbidite 206 bar in the Tsunemori Formation yielded indistinguishable radioisotopic ages. Ten single zircons 207 from sample 10VD25 produced concordant and equivalent isotope ratios with a weighted mean ²⁰⁶Pb/²³⁸U date of 265.77 ± ± 0.03 (0.13) [0.31] Ma (2s; MSWD = 0.39), and six of tenfour of 208 <u>seven</u> single grains from sample 10VD20 produced a weighted mean 206 Pb/ 238 U date of 265.76 ± 209 210 0.04(0.14)[0.31] Ma (2s; MSWD = 2.481.60) (Table 2, Fig. 6). These dates demonstrate the 211 expected increase in rock accumulation rate through the laminated limestone beds as 212 compared to the underlying siliciclastic succession and affirm the <u>effectively</u> conformable nature of the siliciclastic-carbonate transition. The sequence of CA-IDTIMS radioisotopic ages 213

- also affirm the overturned orientation of the succession (Figs. 2-3), which is a common feature
 within the Tsunemori Formation (Wakita et al., 2018).
- 216

217 7. <u>6.</u> Discussion

6.1 Radioisotopic ages and sedimentation processes in the Tsunemori Formation.

219 The Tsunemori Formation at the Shigeyasu Quarry possessed possesses all of the features 220 of a locally normal sedimentation sedimentary succession. Besides its overturned position in 221 the Quarryquarry, it is generally stratified throughout. The laterally traceable volcanic tuffs 222 that were found in the Shigeyasu Quarry are marker beds of stratigraphic integrity, and 223 could be preserved only in relatively the low energy environments. The presence of two volcanic tuff horizons of the same age (10VD20 and 10VD25) within the turbiditic limestone 224 225 suggests normal sedimentation therein (Wakita et al., 2018), rather than the <u>olistrosomal</u> 226 incorporation in a mélange formation-environment (Sano and Kanmera, 1991b). Consistent The consistent regular succession of radioisotopic ages from 267.46± 0.04 at the bottom of 227 228 the exposed part of the Tsunemori Formation (samples 10VD96) towards to 265.76 ± 0.04 Ma at the exposed top of the formation (Figs. 2-3), and combined with the consistent age 229 230 of all fusulinids collected from limestone fusulinids suggest the normal sedimentary 231 processes of provide the most compelling evidence for conformable sedimentation within the Tsunemori Formation at the Shigeyasu Quarry. 232 233 6.2 Midian Stage of the Tethyan provincial Scale time scale The Midian Stage possesses a complicated history of establishment. Being proposed as a 234

235 Stage stage equal to the Yabeina-Lepidolina fusulinids Genozone that is well known from Japan

236 (Toriyama, 1967), it was first named-referred as the "Capitanian" Stage in the Tethys (Leven, 237 1975). The However the Genozone and "Capitanian" Stage designation has mostly resulted 238 followed from compilation of the literature in Eastern Tethys without specific characterization 239 of the stage boundaries (Leven, 1975). Furthermore, strong provincialism Fthe lack of 240 verbeekinids in the Capitanian of the type area in Texas (Dunbar and Skinner, 1937) has caused difficulty in fusulinid correlation of the Capitanian Stage of Texas outside of this region. Because 241 242 of doubts on the exact correspondence of the Yabeina-Lepidolina fusulinids Genozone of the 243 Tethys with the Capitanian Stage of Texas (Leven, 1980), a new Midian Stage equal to the 244 Genozone was established with the potential type section in Transcaucasia. The base of the 245 Midian Stage was first drawn at the base of the Arpa Formation in Transcaucasia without 246 specific type section (Leven, 1980). An alternative type section The stratotype of the Stage was later proposed and the boundary defined at the base of bed-Bed 33 in the Dzhagadzur section, 247 248 Armenia, which coincided with the bottom of the Arpa Formation and with the base of the 249 Yangchienia thompsoni local fusulinids zone (Kotlyar et al., 1989a). The Midian Stage in 250 Transcaucasia is composed of massive limestone of the Arpa and Khachik Formations, totaling 251 350-450 m in thickness. Both the base of the Arpa and the top of Khachik Formations possess 252 transitional contacts with the limestones below and above the Midian Stage (Kotlyar et al., 253 1989a). The Midian Stage in Transcaucasia comprises three fusulinids zones. The Arpa 254 Formation is divided into the Yangchienia thompsoni (lower) and Chusenella abichi (upper) 255 zones-Zones (Kotlyar et al., 1989a). Small fusulinids Reichelina, Dunbarula, Codonofusiella, 256 Minojapanella (Wutuella), Kahlerina and Pseudokahlerina appear from the beginning of the 257 Arpa Formation. No specific zone is proposed for the Khachik Formation, but in accordance with 258 the fusulinids biota content in the formation (Kotlyar et al., 1989a) it could be named as the 259 Pseudofusulina solita -Neoschwagerina pinguis zoneZone. The latterse two species have been 260 described from Turkey in associated with typical upper Midian fusulinids Yabeina opima and small fusulinids such as Reichelina, Dunbarula, Codonofusiella, Rauserella and Kahlerina 261 262 (Skinner, 1969; Kotlyar et al., 1989b). The Khachik Formation in Transcaucasia is conformably 263 overlayingin by the Chanakhchi beds of Wuchiapingian age (Sahakyan et al., 2017). The most confusing aspect in the designation of the Midian Stage is that no Yabeina or 264 265 Lepidolina that originally were used for the concept of the stage designation (Leven, 1975) are occurring in the type area in Transcaucasia. Rare Neoschwagerina cheni Sheng, 1956, 266 267 Verbeekina verbeeki (Geinitz) and V. furnishi Skinner and Wilde are found in the underlying 268 Gnishik Formation. A single specimen of Neoschwagerina pinguis Skinner has been found in bed 269 13 of the Khachik Formation at the type section of the Midian Stage, 122 meters above the base 270 of the Stage (Kotlyar et al., 1989a). Similarly, a narrow bed with Sumatrina vediensis (Leven) has 271 been reported approximately 70 m above the base of the Arpa Formation in the Vedi section 272 (Leven, 1998). Although the type-section of the Midian Stage is lacking the indices Yabeina and 273 Lepidolina, it is reasonably well correlated with sections in the East Tethys thanks to its 274 stratigraphic position below the well-defined Wuchiapingian Stage of the IGTS (Kozur, 2005) in 275 Transcaucasia, and to the abundant assemblage of small fusulinids ozawainellids and 276 schubertellids, such as Kahlerina, Pseudokahlerina, Dunbarula, Reichelina, Rauserella and 277 numerous species of advanced schwagerinids Chusenella that are-occur within the entire 278 Midian Stage (Kotlyar et al., 1989a; Leven, 1998). These genera and the species of the latter 279 genus are very characteristic for the Midian deposits in Peri-Gondwana (Leven, 1998; Huang et

280 al., 2009; Leven, 2009; Davydov and Arefifard, 2013) and Cathaysian blocks including South 281 China (Sheng, 1963; Xiao et al., 1986). However, we cannot exclude that the lowermost part of 282 the Midian Stage corresponds with the underlying Yabeina and Lepidolina zZones in Japan and 283 South China. 284 Nevertheless, tThe problem of precise correlation the base of the Midian Stage in 285 Transcaucasia with the Capitanian Stage in Texas and elsewhere still exists, because of the 286 limited characteristics of the Midian Stage in the type area, i.e. the lack of additional correlation 287 tools, including geochemistry, paleomagnetism, and geochronology. 288 The Midian Stage in- of Japan that equates to the well-studied fusulinids of Genozone 289 Yabeina-Lepidolina Genozone (Toriyama, 1967), has become widely used since the Stage 290 designation, although the position of its lower boundary in Japan was not certain. It was 291 proposed (Leven, 1996) to include the Neoschwagerina margaritae zone-Zone of Japan into the 292 Midian Stage because of the appearance of small fusulinids Reichelina, Codonofusiella, 293 Kahlerina in this zone, whereas the majority of Japanese micropaleontologists follow the strict 294 definition of the stage in the sense as of First Appearance Datum (FAD) and Last Appearance 295 Datum (LAD) of Yabeina and Lepidolina genera including Lepidolina shiraiwensis, L. multiseptata 296 and L. kumaensis zones-Zones (Ozawa, 1975; Ozawa et al., 1991; Kobayashi, 2012a) and Yabeina globosa zZone in the Jurassic terrane of Japan (Kobayashi, 2011b). Some Japanese 297 298 paleontologists follow the suggestion of Leven (1996) and include the underlying Yabeina-299 Lepidolina Genozone, and the Colania douvillei zone-Zone in the Akiyoshi Limestone into the 300 Midian Stage (Nakazawa and Ueno, 2009).

301 **6.3 Capitanian <u>Stage</u> in the type area in Texas**

302 The Capitanian Stage in the traditional chronostratigraphic sense has been proposed in 303 West Texas as an equivalent of the ammonoid Timorites Zone of earlier American literature 304 (Glenister and Furnish, 1961). The lower boundary of the Capitanian Stage has conventionally been drawn at the base of the Hegler Member of the Bell Canyon Formation that is marking the 305 306 base of the Timorites Zone. Genus The genus Timorites though has also been recovered from the preceding Manzanita Member of the upper Cherry Canyon Formation (Glenister et al., 307 308 1999). The Capitanian was also equated with the fusulinids *Polydiexodina zoneZone*, which 309 includes the provincial endemic genus Polydiexodina, advanced Parafusulina, and an abundant 310 assemblage of small fusulinids such as Rauserella, Reichelina, Parareichelina, Codonofusiella, 311 Paradoxiella, Lantschichites, and Pseudokahlerina (Dunbar and Skinner, 1937; Yang and Yancey, 312 2000; Nestell et al., 2006; Nestell and Nestell, 2006). The Polydiexodina zone-Zone in the Glass 313 Mountain of Texas is equated with the Vidrio and Altuda Formations (Dunbar and Skinner, 314 1937; Yang and Yancey, 2000) and with the Bell Canyon Formation (pre-Lamar Limestone) in 315 the Guadalupe Mountains (Wilde, 1990). 316 The Capitanian (sensu lato) in this traditional sense seems to corresponds with the entire Midian Stage of the Tethyan Scale (Wardlaw, 2000; Menning et al., 2006) (Fig. 7). However the 317 318 base of the International Capitanian Stage (sensu stricto), is defined in the upper part of the Pinery Limestone Member of the Bell Canyon Formation near the top of Nipple Hill 319 320 (southeastern Guadalupe Mountains), at 4.5 meters in the outcrop section on the south side of 321 the hill and coinciding with the FAD of the conodont Jinogondolella postserrata (Glenister et al., 322 1999). This newly defined base of the International Capitanian (sensu stricto) therefore, occurs 323 much higher in the Guadalupian succession of West Texas than the traditional base of the

Capitanian (*sensu lato*). The Capitanian <u>lower</u> boundary is similarly shifted upwards from the
base of Vidrio Fm-Formation into the lower third of <u>the</u> Altuda Formation in the Glass
Mountains: (Fig. 7) (Rohr et al., 2000). In the latter region this is approximately **100 meters above** the traditional boundary (estimated here as 3 Myrs), whereas the total thickness of <u>the</u>
entire Guadalupian in the Glass and Del Norte mountains-Mountains is slightly over 300 meters
(Wardlaw, 2000).

Once As the newly defined current base of the International Capitanian Stage (s. s.) appears 330 331 within the <u>regional</u> Midian Stage of the Tethyan <u>Scale time scale</u> (Fig. 7), the lower part of the 332 Midian Stage in Tethys become the part of equites to the International Wordian Stage. This was 333 quickly recognized by the fusulinids workers who found <u>a</u> typical assemblage of small fusulinids 334 Reichelina, Codonofusiella, Kahlerina and Pseudokahlerina along with advanced Neoschwagerina and some Yabeina in the re-defined International upper Wordian Stage 335 336 (Davydov, 1994; Stevens et al., 1997; Leven, 2001)., Nonetheless, -but most of the Japanese and 337 Chinese fusulinids workers still consider the Midian Stage in Eastern eastern Tethys in the traditional sense, i.e. Capitanian (s. l.) (Ozawa and Kobayashi, 1990; Ozawa et al., 1991; 338 339 Kobayashi, 2012a; Kofukuda et al., 2014; Zhang and Wang, 2018). Ammonoid workers also 340 consider the Capitanian Stage in the traditional sense as the equivalent of *Timorites* ammonoid Genozone, because there is no opportunity to separate upper Wordian and lower Capitanian 341 342 parts of the Genozone (Bogoslovskaya et al., 1995; Ehiro and Misaki, 2005; Leonova, 2018). 343 6.4 Biotic and radioisotopic correlation of <u>the</u> Midian Stage of the Tethyan Scale and the Capitanian Stages of the International Geologic Time Scale. 344

345 Correlation of Midian Stage of the Tethyan Scale-time scale with the IGTS has been difficult 346 and controversial. Since its definition (Leven, 1980), and through the mid-1990s the Midian 347 Stage utilizing fusulinids and ammonoids was correlated utilizing fusulinids and ammonoids 348 with the Capitanian Stage (s. l.) Stage of Texas (Jin et al., 1997). Once the Capitanian was 349 redefined and its lower boundary in Texas shifted upwards (Glenister et al., 1999), the 350 fusulinids assemblages from the lower Capitanian (s.l.) now characterize the upper Wordian of 351 the IGTS (Davydov, 1994; Kozur and Davydov, 1996; Stevens et al., 1997). 352 Nevertheless, in some regions this part of the successions has remained equated with the 353 Capitanian (Menning et al., 2006; Nakazawa and Ueno, 2009; Kobayashi, 2011a, 2012a; 354 Kofukuda et al., 2014). In Japan, the Guadalupian succession Series is divided into a 355 seriesseveral of fusulinids zones (Fig. 7). The lower Midian Stage in the Akiyoshi area in our opinion correlates with the upper part of Colania douvelei-Neoschwagerina haydeni zoneZone, 356 357 where the first Kahlerina appear (Nakazawa and Ueno, 2009; Kobayashi, 2012a). We suggesting 358 naming this part of the Colania douvelei-Neoschwagerina haydeni zZ one as the Kahlerina beds. Following upwards, the Lepidolina shiraiwensis zone Zone together with the Kahlerina zone 359 Beds thus correlates with the upper Wordian of the IGTS (Fig. 7). The radioisotopic ages from 360 the Manzanita bed of Texas (Bowring et al., 1998; Ramezani and Bowring, 2018) and from the 361 362 Lepidolina shiraiwensis zone-Zone of Akasaka Akiyoshi (this study) support such a correlation. 363 This contrasts with and requires revision of the recent assignment of an uppermost Capitanian 364 age for the Lepidolina shiraiwensis Zone in some recent publications (Zhang and Wang, 2018). 365 The Kahlerina beds and Lepidolina shiraiwensis zone-Zone of Japan-Akiyoshi and Yabeina globosa Zone of Akasaka consequently correlate with the Arpa Formation (lower Midian) 366

367 of Transcaucasia (Kotlyar et al., 1988) (Kobayashi, 2011b), the lower Karasin Beds of S-E 368 southeast Pamir (Chediya et al., 1986), and the Yabeina inoyei fusulinid zone Zone of South-369 China (Mei et al., 1998). The Capitanian Stage (s. s.) of the IGTS correlates with the Lepidolina 370 multiseptata and L. kumaensis zones-Zones of Japan, the upper Midian Stage of the Tethyan 371 Scaletime scale, the Khachik Formation of Transcaucasia, the upper Karasin Beds in the Pamirs 372 where Lepidolina ex gr. multiseptata and Yabeina opima are found (Chediya et al., 1986; Kotlyar et al., 1989a), and the Metadoliolina multivoluta-Lepidolina multiseptata fusulinid zone-Zone of 373 374 South- China (Fig. 7).

- 375 8. <u>7. Conclusions</u>.
- 376

The successionsequence of radioisotopic ages and consistent age of all collected from limestone fusulinids suggest the normala conformable sedimentary processes succession of within the Tsunemori Formation at the Shigeyasu Quarry._-The obtained radioisotopic, sedimentologic and biostratigraphic data of the Tsunemori Formation at the Shigeyasu Quarry and the presence of acidic volcanic tuffs <u>isare</u> consistent with the newly proposed model of the <u>a</u> forearc basin or trench slope basin as <u>the site of deposition sedimentation site</u> for the entire Tsunemori Formation. (Wakita et al., 2018).

The <u>siliclastic mixed volcano-siliciclastic-carbonate</u> succession with limestone turbidites and slump blocks in the Tsunemori Formation at Shigeyasu Quarry, Japan, contain<u>s</u> both fusulinids and tuffs with U-Pb zircon CA-IDTIMS radioisotopic ages that allow a robust correlation of the *Kahlerina* and *Lepidolina shiraiwensis* <u>zones-Zones</u> of Japan to the lower Midian Stage of the Tethyan <u>time</u> scale, and to the upper Wordian Stage of the International Geologic Time Scale.

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Figure 1. Paleogeographic and tectonic maps. (A) Middle Permian global paleogeography with
the main regions discussed in this paper; (B) Regional tectonic map<u>of</u> southern Japan, modified
from (Wakita, (2013).

Figure 2. Shigeyasu Quarry: a, Google Earth image of Shigeyasu Quarry, red line shows
collection site; b, general panorama of studied site; c, volcanic ash (10VD20) within the
laminated limestone. Stratification is well expressed at the of within the Shigeyasu Quarry cut.

605 Figure 3. Stratigraphic log of the succession in Shigeyasu Quarry and position of the collected

samples. Note, that the succession there is overturned. <u>-All scale bars on fusulinids are 1mm.</u>
 <u>The entire set of the radioisotopic ages attributes can be seen in Table 2.</u>

608 Figure 4. Fusulinid assemblage from turbiditic bed (samples 10VD20-10VD23). 1, Schubertella

ovalis Kobayashi; 2, Yangchienia? sp.; 3, Kahlerina sp.; 4-5, Chusenella altinensis Ross; 6,

610 Chusenella otai (Nogami); 7-12, Lepidolina shiraiwensis (Ozawa); 13, Sumatrina longissima

611 Deprat. <u>All scale bars are 1mm.</u>

Figure 5. Fusulinid assemblage from slump block (sample 10VD98). 1, Codonofusiella sp.; 2,

- boultoniids; Kahlerina ampla Han; 4-7, Kahlerina nautiloidea Sosnina; 8, Kahlerina sp.; 9,
- 614 Rauserella ex gr. ellipsoidalis Sosnina; 10, Chusenella altinensis Ross; 11, Chusenella otai
- 615 (Nogami); 12-15, Lepidolina shiraiwensis (Ozawa); 16, Sumatrina longissima Deprat; 17,

616 Pseudodoliolina ozawai Yabe and Hanzawa. <u>All scale bars are 1mm.</u>

Figure 6. U-Pb concordia diagrams illustrating results of single grain chemical abrasion ID-TIMS analysis for each dated tuff samples from Shigeyasu Quarry, volcano-siliciclastic succession of the Akiyoshi Plateau, southwest Japan. Grey band represents the error envelope on the concordia curve based upon the decay constants and errors of Jaffey et al. (1975). Analyses accepted in weighted mean calculations are illustrated by filled translucent ellipses; analyses discarded as influenced by inheritance or Pb-loss are illustrated as open ellipses. All accepted analyses are concordant within the decay constant uncertainties.

Figure 7. Biostratigraphic and radioisotopic correlation of the Guadalupian of Shigeyasu Quarry
with the global major global sections. Data in: Texas – from (Glenister et al., 1999; Wardlaw,
2000; Yang and Yancey, 2000; Nestell et al., 2006; Nestell and Nestell, 2006); in Japan from
(Ueno, 1992; Nakazawa and Ueno, 2009; Kobayashi, 2012a); in Transcaucasia from (Kotlyar et
al., 1989a; Leven, 1998); in Pamirs from (Leven, 1967; Chediya et al., 1986; Kozur et al., 1994;
Angiolini et al., 2015) and our own data; in S.South China from (Mei et al., 1998; Wu et al.,
2017).

Table 1. Fusulinids taxonomic composition of the studied limestone samples.

632 Table 2. Zircon IDTIMS U-Pb isotopic data

Highlights

New CA-IDTIMS radioisotopic ages were obtained from the lower Midian Stage of the Akiyoshi Plateau, Japan

Tuffs occur within limestone turbidite beds containing Early Midian fusulinids of the Tethyan province

The lower Midian correlates with upper Wordian of the Permian International Geologic Time Scale.

The obtained data from the Tsunemori Fm consistent with the newly proposed model of the forearc basin

- High-precision radioisotopic ages for the lower Midian (upper Wordian) Stage of the Tethyan
 time scale, Shigeyasu Quarry, Yamaguchi Prefecture, Japan
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- 8 Abstract.

9 Global correlation of strata to the Guadalupian Series (Permian Period) of the International Geologic Time Scale remains provisional due to a lack of the sufficient biostratigraphically 10 11 constrained radioisotopic ages. Five new high-precision U-Pb radioisotopic ages were obtained from tuffs in the lower Midian (upper Wordian) volcano-siliciclastic succession of the Akiyoshi 12 Plateau, southwestern Japan. Two undisturbed and continuous tuffs occur within fusulinid-13 bearing laminated limestone turbidites with precise biostratigraphic control. The Colania 14 15 douvillei and Lepidolina shiraiwensis fusulinid Zones in the Akiyoshi succession provide an early Midian age in the Tethyan provincial time scale. The range of ages (267.46 ± 0.04 Ma to 265.7616 17 \pm 0.03 Ma) over 25 m of section including the limestone turbiditic beds suggest that this lower Midian Stage of the Tethyan time scale is correlated with the upper Wordian Stage of the 18 International Geologic Time Scale. The sedimentologic, bio- and geochronologic data affirm 19 the effectively conformable nature of the siliciclastic-carbonate succession of the Tsunemori 20 21 Formation at the Shigeyasu Quarry, and the presence of acidic volcanic tuffs are consistent 22 with a forearc basin or trench slope basin depocenter for the Tsunemori Formation.

23 Key words: Guadalupian; Permian; zircon; CA-IDTIMS, fusulinid; biostratigraphy

24 **1. Introduction**

Significant progress has been made in the last decade on the radioisotopic calibration of 25 the International Geologic Time Scale (IGTS) (Gradstein et al., 2012; Cohen et al., 2013), yet 26 27 some parts of the time scale are still calibrated only provisionally. This is particularly true for 28 the late Cisuralian (post Artinskian) and Guadalupian Epochs of the Permian (280-265 Ma), 29 where just a few reliable high-precision U-Pb ages exist (Henderson et al., 2012). This part of the Permian Time Scale that is calibrated only with biostratigraphic scaling requires further 30 geochronologic improvement. The paleobiogeographic provinciality and the lack of the 31 32 radioisotopic calibration of this part of the scale make the correlation of Guadalupian Series 33 and Stages in the type region with the rest of the world difficult. The only calibrating radioisotopic age in the entire Guadalupian in the type area is from a volcanic ash between the 34 Hegler and Pinery limestone members of the Bell Canyon Formation at Nipple Hill, Guadalupe 35 36 Mountains National Park, Texas. The ash is 6 to 8 cm thick and lies 2 m above the top of the Hegler Member, within the undifferentiated Bell Canyon Formation, and 20 m below the base 37 of the Jinogondolella postserrata conodont Zone and the base of the Capitanian Stage (Bowring 38 et al., 1998). The original legacy age of 265.3 ± 0.2 Ma for this volcanic tuff was recently revised 39 using the chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-IDTIMS) 40 method to 265.46 ± 0.27 Ma (Ramezani and Bowring, 2018). 41

Several CA-IDTIMS radioisotopic ages were recently published from the base of
Kuhfengian in South China (Wu et al., 2017) and from the analogues of the Roadian (RussianOmolonian and Olynian Regional Stages in N-E of Russian) and Capitanian (Gizhigian Regional
Stage) in N-E of Russia (Davydov et al., 2016; Davydov et al., 2018). The latter publication

suggests a new calibration of the entire Guadalupian Epoch and proposes the extension of the
base of the Roadian down to 277 Ma and the Wordian down to 271 Ma. The EARTHTIME
isotope dilution tracer was utilized in all of these studies, which aids in the direct comparison of
the dates from Texas, Russia and South China.

50 The correlation between the type section of the Guadalupian Epoch in Texas and the 51 Tethyan time scale remains quite controversial (Davydov et al., 2018). Specifically, we do not 52 know the exact analogues of all three stages of the Guadalupian in the Tethyan time scale. The report in this study of new high-precision U-Pb zircon ages for the lower Midian Stage of Japan 53 is one step towards that correlation. The fusulinid fauna within the limestone turbidites and 54 55 limestone slump blocks intercalated with the dated volcanic ashes are consistently early Midian in age and therefore can refine the maximum age of that stage in the Tethyan time scale and its 56 57 correlation to an upper Wordian Stage in the IGTS.

58 2. Geological setting

Samples for the present study were collected at Shigeyasu Quarry, in rocks of the 59 Akiyoshi Belt, which is distributed across several isolated areas of the Inner Zone of 60 61 Southwestern Japan, extending into the western margin of the Hida Belt (Wakita, 2013). The 62 Akiyoshi Belt forms a Permian accretionary complex (Fig. 1) composed of sandstone, mudstone, conglomerate, siliceous shale, felsic tuff, chert, limestone and basalt. The Permian Akiyoshi 63 64 accretionary complex is divided into two units, which show similar ages but distinctly different dominant lithologies: a limestone-rich unit consisting of several large limestone plateaus that 65 belong to the Akiyoshi Limestone Group, and a second unit that is composed mainly of 66

siliciclastic successions with minor volcanic components, named the Tsunemori Formation. Both
units formed by continuous sedimentation through the same period (Sano and Kanmera,
1991a; Tazawa et al., 2009). Many components of this belt are unmetamorphosed and the
limestone within the belt is famous for its well preserved and diverse fauna (Toriyama, 1967).
The Tsunemori Formation is unconformably overlain by Triassic shallow marine to non-marine
sedimentary rocks of the Mine Group.

The Akiyoshi Limestone Group covers almost the whole area of the Akiyoshi Plateau in the central part of Yamaguchi Prefecture, southwest Japan. The Akiyoshi Limestone Group is a reefal limestone on a seamount in the Panthalassan Ocean (Kanmera and Nishi, 1983), and is one of the most complete and continuous carbonate successions in the Panthalassa region, ranging from Early Carboniferous to Middle Permian in age (Toriyama, 1967).

78 The Tsunemori Formation along the marginal parts of the western Akiyoshi-dai Plateau, southwest Japan, is described as a sequence of broken limestone, limestone breccia, and scaly 79 80 mudstone (Sano and Kanmera, 1991b), designated as evidence of melange formation caused 81 during subduction and accretion. The broken limestone is characterized by penetrative and 82 pervasive destruction of skeletal grains and primary sedimentary fabrics. Late Visean to Midian 83 foraminifera from the same depositional period as the entire Akiyoshi Limestone Group are 84 identified in the broken limestone, but with no orderly stratigraphic succession (Sano and 85 Kanmera, 1991a; Tazawa et al., 2009; Kobayashi, 2012a). The Tsunemori Formation according 86 the first authors is a trench deposit, with the Akiyoshi Limestone accreted as an exotic block

sometime during Middle to Late Permian time, based upon radiolarian biostratigraphy (Sano
and Kanmera, 1991c).

89 An alternative model for Tsunemori Formation sedimentation and depositional setting has been proposed recently in the territory west of the Akiyoshi-dai Plateau, that includes the 90 91 area of our study (Wakita et al., 2018). A conformable succession of mudstone and mudstone-92 dominant turbidite with very thin layers of sandstone or siltstone and rare horizons of 93 calcarenite and limestone breccia is documented there. No fissility or scaly cleavage is recognized in the mudstone and pebbly mudstone of the Tsunemori Formation (Wakita et al., 94 2018). The lack of penetrative deformation is inconsistent with sedimentary formations 95 96 deposited at the trench, and rather suggests a forearc basin or trench slope basin as the 97 sedimentation site for the Tsunemori Formation (Wakita et al., 2018). Our brief field 98 investigation of the Tsunemori Formation at Shigeyasu Quarry documents that the formation is 99 faulted and overturned, but generally stratified (Fig. 2). We found three types of limestone within the Tsunemori Formation: 1) rare horizons of clastic limestone interbedded with debris 100 101 flows and turbidites; 2) fully isolated blocks (2x3 m) of limestone (10VD98), wholly embedded in 102 mudstone, i.e. slump block; 3) laminated limestone turbidite (10VD21, 22,23) (Figs. 2-3). 103 Fusulinid samples from all three types of the limestone possessed the same early Midian Stage 104 fauna.

Acidic volcanism in the late Guadalupian and Lopingian of Japan in general, and specifically volcanic rocks in the upper Guadalupian of the Akyioshi Group have long been recognized (Kanmera, 1974). Recent provenance and petrologic studies confirm the presence of

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a volcanic arc system near the Akiyoshi terrane during the entire Permian (Okawa et al., 2013;
Hara et al., 2018; Zhang et al., 2018).

110 **3. Materials and methods**

Five samples of volcanic tuff and four samples of limestone were collected in the 111 112 succession of the lower Tsunemori Formation exposed along the north-east to south-west edge 113 of Shigeyasu Quarry (Fig. 2). The samples for radioisotopic study were collected from bentonitic 114 volcanic tuff layers that occur within the lower part of the succession (Fig. 3). Three horizons 115 were sampled from within siliciclastic beds 1.7, 5, and 20 meters below the base of a prominent 116 bar of laminated limestone turbidite beds (samples 10VD26, 10VD95, and 10VD96, 117 respectively). Two tuff samples were collected from within the laminated limestone turbidite 118 beds near their base and top (samples 10VD25 and 10VD20 respectively), thus bracketing several of the fusulinid samples (Figs. 2-3). All tuffs are laterally traceable within the exposure 119 120 of the Tsunemori Formation at the quarry. 121 All tuffs were processed with standard procedures including ultrasonic disaggregation 122 and concentration (Hoke et al., 2014), Franz magnetic separation, heavy liquid separation, and 123 hand picking. All samples yielded hundreds of sharply facetted, prismatic zircon grains (Figs. 2-124 3). The procedure and approaches associated with chemical-abrasion isotope dilution thermal 125 ionization mass-spectrometry (CA-IDTIMS) method have been recently described in detail by Davydov et al. (2018). CA-IDTIMS dates are reported with weighted mean uncertainties given as 126 127 \pm X/Y/Z, where X is the 2 σ analytical uncertainty, Y is the combined analytical and tracer 128 uncertainty (value given in parentheses), and Z is the combined analytical, tracer, and decay

129	constant uncertainty [value given in brackets]. The limestone samples were sliced into plates						
130	and fifty-one thin-sections with oriented fusulinid sections were prepared.						
131 132	4. Biostratigraphic results						
133	We acknowledge that fusuilinid-bearing limestone turbidites (debris flows) are						
135	allochthonous with respect to the deeper water syn-sedimentary siliciclastic rocks, and thus						
136	their biostratigraphic constraints would generally only constrain the maximum depositional age						
137	of such a stratigraphic succession. In this case, however, volcanic ash beds at the base and						
138	within the laminated turbiditic limestone directly date its deposition (Fig. 2c), while the three						
139	volcanic tuffs stratigraphically below the limestone beds provide a check on the conformable						
140	nature of sediment deposition across the sequence (Fig. 3).						
141	Radiolaria belonging to the Pseudoalbaillella globosa Zone to the Follicucullus						
142	scholasticus Zone of Wordian-Capitanian age were collected from the lower and middle parts of						
143	the Tsunemori Formation (Sano and Kanmera, 1991b; Tazawa et al., 2009; Wakita et al., 2018).						
144	The fusulinids in the turbidites and in the limestone slump block in the Tsunemori Formation at						
145	the Shigeyasu Quarry are quite diverse and include schubertellids Schubertella, Yangchienia,						
146	Codonofusiella, Kahlerina and Rauserella, schwagerinids Parafusulina and Chusenella and						
147	verbeekinaceans Lepidolina, Pseudodoliolina and Sumatrina (Table 1). The taxonomic						
148	composition of fusulinids in the studied turbidites and slump block is generally consistent (Figs.						
149	4-5) and therefore the age of the limestone turbidites/slump block and volcanoclastics in the						
150	quarry is the same within the resolution of fusulinid biostratigraphy, i.e. around one million						
151	years in this case (Davydov et al., 2018) (Table 1). The occurrence of species Lepidolina						

shiraiwensis Ozawa in the turbidites undoubtedly constrains an early Midian age for the
limestone turbidites and surrounding rocks (Leven, 1980; Kotlyar et al., 1989). In the nearby
Kaerimizu area of the Akiyoshi plateau, the carbonate succession ends within the *Colania douvillei* Zone (Ueno, 1992), but in places extends up to the *Lepidolina shiraiwensis* Zone, which
is also defined in the area from the limestone blocks and calcareous sandstone (Kobayashi,
2012a).

158 **5. U-Pb geochronology**

159 **Sample 10VD96** was the stratigraphically lowest sampled volcanic tuff within siliciclastic 160 rocks at the Shigeyasu quarry, where the succession is overturned. Eight grains selected for CA-161 IDTIMS yielded dates ranging from 267.65 to 267.01 Ma; five of these analyses are concordant and equivalent with a weighted mean $^{206}Pb/^{238}U$ date of 267.46 ± 0.04 (0.14) [0.31] Ma (2s; 162 163 MSWD = 1.90), which is interpreted as estimating the volcanic depositional age (Table 2, Fig. 6). 164 Two analyses yielded resolvably older dates with a modified Thompson tau test, and are interpreted as representing inheritance, and a single analysis with an anomalously younger age 165 166 is interpreted as the sole crystal in this study in which Pb-loss was not completely mitigated by 167 chemical abrasion.

Sample 10VD95 from fifteen meters stratigraphically higher in the section was dated using ten single zircon grains; the five youngest analyses yielded a weighted mean ${}^{206}Pb/{}^{238}U$ date of 266.00 ± 0.04 (0.14) [0.31] Ma (2s; MSWD = 1.06), which is interpreted as estimating the volcanic depositional age (Table 2, Fig. 6). Another five grains produced older ages ranging from 266.25 to 269.85 Ma, and are attributed to inheritance. Sample 10VD26 collected from a volcanic tuff 3.3 meters stratigraphically above sample
10VD95, and 1.7 meters below the base of the laminated limestone turbidite beds. All ten
single zircons analyzed by CA-IDTIMS yielded concordant and equivalent isotope ratios within
their errors, with a weighted mean ²⁰⁶Pb/²³⁸U date of 265.81 ± 0.04 (0.13) [0.31] Ma (2s; MSWD

177 = 1.05), which is interpreted as the volcanic depositional age (Table 2, Fig. 6).

178 Samples 10VD25 and 10VD20 from the base and top of the laminated limestone 179 turbidite bar in the Tsunemori Formation yielded indistinguishable radioisotopic ages. Ten 180 single zircons from sample 10VD25 produced concordant and equivalent isotope ratios with a weighted mean ²⁰⁶Pb/²³⁸U date of 265.77 ± ± 0.03 (0.13) [0.31] Ma (2s; MSWD = 0.39), and four 181 of seven single grains from sample 10VD20 produced a weighted mean ²⁰⁶Pb/²³⁸U date of 182 183 265.76 ± 0.04(0.14)[0.31] Ma (2s; MSWD = 1.60) (Table 2, Fig. 6). These dates demonstrate the expected increase in rock accumulation rate through the laminated limestone beds as 184 185 compared to the underlying siliciclastic succession and affirm the effectively conformable 186 nature of the siliciclastic-carbonate transition. The sequence of CA-IDTIMS radioisotopic ages also affirm the overturned orientation of the succession (Figs. 2-3), which is a common feature 187 188 within the Tsunemori Formation (Wakita et al., 2018).

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190 **6.** Discussion

191 **6.1** Radioisotopic ages and sedimentation processes in the Tsunemori Formation.

192 The Tsunemori Formation at the Shigeyasu Quarry possesses all of the features of a 193 locally normal sedimentary succession. Besides its overturned position in the quarry, it is 194 generally stratified throughout. The laterally traceable volcanic tuffs that were found in the 195 Shigeyasu Quarry are marker beds of stratigraphic integrity, and could be preserved only in 196 relatively low energy environments. The presence of two volcanic tuff horizons of the same age 197 (10VD20 and 10VD25) within the turbiditic limestone suggests normal sedimentation therein 198 (Wakita et al., 2018), rather than olistrosomal incorporation in a mélange environment (Sano 199 and Kanmera, 1991b). The regular succession of radioisotopic ages from 267.46 ± 0.04 at the 200 bottom of the exposed part of the Tsunemori Formation (samples 10VD96) to 265.76 ± 0.04 Ma at the exposed top of the formation (Figs. 2-3), combined with the consistent age of all 201 202 fusulinids collected from limestone provide the most compelling evidence for conformable 203 sedimentation within the Tsunemori Formation at the Shigeyasu Quarry. 204 205 6.2 Midian Stage of the Tethyan provincial time scale The Midian Stage possesses a complicated history of establishment. Being proposed as a 206 stage equal to the Yabeina-Lepidolina fusulinid Genozone that is well known from Japan 207 208 (Toriyama, 1967), it was first referred to as the "Capitanian" Stage in the Tethys (Leven, 1975). However the Genozone and "Capitanian" Stage designation followed from compilation of the 209 210 literature in Eastern Tethys without specific characterization of the stage boundaries (Leven, 211 1975). Furthermore strong provincialism and the lack of verbeekinids in the Capitanian of the 212 type area in Texas (Dunbar and Skinner, 1937) has caused difficulty in fusulinid correlation of 213 the Capitanian Stage of Texas outside of this region. Because of doubts on the exact correspondence of the Yabeina-Lepidolina fusulinids Genozone of the Tethys with the 214 215 Capitanian Stage of Texas (Leven, 1980), a new Midian Stage equal to the Genozone was established with the potential type section in Transcaucasia. The base of the Midian Stage was 216 217 first drawn at the base of the Arpa Formation in Transcaucasia without specific type sections

218 (Leven, 1980). The stratotype of the Stage was later proposed and the boundary defined at the 219 base of Bed 33 in the Dzhagadzur section, Armenia, which coincided with the bottom of the 220 Arpa Formation and with the base of the Yangchienia thompsoni local fusulinid Zone (Kotlyar et 221 al., 1989). The Midian Stage in Transcaucasia is composed of massive limestone of the Arpa and 222 Khachik Formations, totaling 350-450 m in thickness. Both the base of the Arpa and the top of 223 Khachik Formations possess transitional contacts with the limestones below and above the Midian Stage (Kotlyar et al., 1989). The Midian Stage in Transcaucasia comprises three fusulinid 224 225 zones. The Arpa Formation is divided into the Yangchienia thompsoni (lower) and Chusenella 226 abichi (upper) Zones (Kotlyar et al., 1989). Small fusulinids Reichelina, Dunbarula, 227 Codonofusiella, Minojapanella (Wutuella), Kahlerina and Pseudokahlerina appear from the 228 beginning of the Arpa Formation. No specific zone is proposed for the Khachik Formation, but in accordance with the fusulinid biota in the formation (Kotlyar et al., 1989) it could be named as 229 230 the Pseudofusulina solita -Neoschwagerina pinguis Zone. The latter two species have been 231 described from Turkey in associated with typical upper Midian fusulinids Yabeina opima and small fusulinids such as Reichelina, Dunbarula, Codonofusiella, Rauserella and Kahlerina 232 233 (Skinner, 1969; Kotlyar et al., 1989). The Khachik Formation in Transcaucasia is conformably 234 overlain by the Chanakhchi beds of Wuchiapingian age (Sahakyan et al., 2017). The most confusing aspect in the designation of the Midian Stage is that no Yabeina or 235 236 Lepidolina that originally were used for the concept of the stage designation (Leven, 1975) 237 occur in the type area in Transcaucasia. Rare Neoschwagerina cheni Sheng, 1956, Verbeekina 238 verbeeki (Geinitz) and V. furnishi Skinner and Wilde are found in the underlying Gnishik 239 Formation. A single specimen of Neoschwagerina pinguis Skinner has been found in bed 13 of

240 the Khachik Formation at the type section of the Midian Stage, 122 meters above the base of 241 the Stage (Kotlyar et al., 1989). Similarly, a narrow bed with Sumatrina vediensis (Leven) has 242 been reported approximately 70 meters above the base of the Arpa Formation in the Vedi 243 section (Leven, 1998). Although the type-section of the Midian Stage is lacking the indices 244 Yabeina and Lepidolina, it is reasonably well correlated with sections in the East Tethys thanks to its stratigraphic position below the well-defined Wuchiapingian Stage of the IGTS (Kozur, 245 246 2005) in Transcaucasia, and to the abundant assemblage of small fusulinids ozawainellids and 247 schubertellids, such as Kahlerina, Pseudokahlerina, Dunbarula, Reichelina, Rauserella and numerous species of advanced schwagerinids Chusenella that occur within the entire Midian 248 249 Stage (Kotlyar et al., 1989; Leven, 1998). These genera and the species of the latter genus are 250 very characteristic for the Midian deposits in Peri-Gondwana (Leven, 1998; Huang et al., 2009; Leven, 2009; Davydov and Arefifard, 2013), and Cathaysian blocks including South China 251 252 (Sheng, 1963; Xiao et al., 1986). However, we cannot exclude that the lowermost part of the 253 Midian Stage corresponds with the underlying Yabeina and Lepidolina Zones in Japan and South 254 China. The problem of precise correlation the base of the Midian Stage in Transcaucasia with 255 the Capitanian Stage in Texas and elsewhere still exists, because of the limited characteristics of 256 the Midian Stage in the type area, i.e. the lack of additional correlation tools, including 257 geochemistry, paleomagnetism, and geochronology. 258 The Midian Stage of Japan that equates to the well-studied fusulinid Yabeina-Lepidolina

260 position of its lower boundary in Japan was not certain. It was proposed (Leven, 1996) to

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261 include the Neoschwagerina margaritae Zone of Japan into the Midian Stage because of the

Genozone (Toriyama, 1967), has become widely used since the Stage designation, although the

262 appearance of small fusulinids Reichelina, Codonofusiella, Kahlerina in this zone, whereas the 263 majority of Japanese micropaleontologists follow the strict definition of the stage in the sense 264 of First Appearance Datum (FAD) and Last Appearance Datum (LAD) of Yabeina and Lepidolina genera including Lepidolina shiraiwensis, L. multiseptata and L. kumaensis Zones (Ozawa, 1975; 265 Kobayashi, 2012a,b) and Yabeina globosa Zone in the Jurassic terrane of Japan (Kobayashi, 266 267 2011). Some Japanese paleontologists follow the suggestion of Leven (1996) and include the 268 underlying Yabeina-Lepidolina Genozone, and the Colania douvillei Zone in the Akiyoshi 269 Limestone into the Midian Stage (Nakazawa and Ueno, 2009).

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- 271

6.3 Capitanian Stage in the type area in Texas

272 The Capitanian Stage in the traditional chronostratigraphic sense has been proposed in 273 West Texas as an equivalent of the ammonoid Timorites Zone of earlier American literature 274 (Glenister and Furnish, 1961). The lower boundary of the Capitanian Stage has conventionally 275 been drawn at the base of the Hegler Member of the Bell Canyon Formation that is marking the base of the Timorites Zone. The genus Timorites though has also been recovered from the 276 277 preceding Manzanita Member of the upper Cherry Canyon Formation (Glenister et al., 1999). 278 The Capitanian was also equated with the fusulinids Polydiexodina Zone, which includes the 279 provincial endemic genus Polydiexodina, advanced Parafusulina, and an abundant assemblage 280 of small fusulinids such as Rauserella, Reichelina, Parareichelina, Codonofusiella, Paradoxiella, Lantschichites, and Pseudokahlerina (Dunbar and Skinner, 1937; Yang and Yancey, 2000; Nestell 281 282 et al., 2006; Nestell and Nestell, 2006). The Polydiexodina Zone in the Glass Mountain of Texas 283 is equated with the Vidrio and Altuda Formations (Dunbar and Skinner, 1937; Yang and Yancey,

284 2000) and with the Bell Canyon Formation (pre-Lamar Limestone) in the Guadalupe Mountains
285 (Wilde, 1990).

286 The Capitanian (sensu lato) in this traditional sense seems to correspond with the entire Midian Stage of the Tethyan Scale (Wardlaw, 2000; Menning et al., 2006) (Fig. 7). However the 287 288 base of the International Capitanian Stage (sensu stricto), is defined in the upper part of the 289 Pinery Limestone Member of the Bell Canyon Formation near the top of Nipple Hill (southeastern Guadalupe Mountains), at 4.5 meters in the outcrop section on the south side of 290 291 the hill and coinciding with the FAD of the conodont Jinogondolella postserrata (Glenister et al., 292 1999). This base of the International Capitanian (sensu stricto) therefore, occurs much higher in 293 the Guadalupian succession of West Texas than the traditional base of the Capitanian (sensu 294 *lato*). The Capitanian boundary is similarly shifted upwards from the base of the Vidrio Formation into the lower third of the Altuda Formation in the Glass Mountains. (Fig. 7) (Rohr et 295 296 al., 2000). In the latter region this is approximately 100 meters above the traditional boundary, 297 whereas the total thickness of the entire Guadalupian in the Glass and Del Norte Mountains is 298 slightly over 300 meters (Wardlaw, 2000).

As the current base of the global Capitanian Stage (*s. s.*) appears within the regional Midian Stage of the Tethyan time scale (Fig. 7), the lower part of the Midian Stage in Tethys equates to the global Wordian Stage. This was quickly recognized by fusulinids workers who found a typical assemblage of small fusulinids *Reichelina*, *Codonofusiella*, Kahlerina and *Pseudokahlerina* along with advanced *Neoschwagerina* and some *Yabeina* in the re-defined upper Wordian Stage (Davydov, 1994; Stevens et al., 1997; Leven, 2001). Nonetheless, most Japanese and Chinese fusulinid workers still consider the Midian Stage in eastern Tethys in the traditional sense, i.e. Capitanian (s. l.) (Ozawa and Kobayashi, 1990; Kobayashi, 2012a,b;

Kofukuda et al., 2014; Zhang and Wang, 2018). Ammonoid workers also consider the Capitanian
Stage in the traditional sense as the equivalent of the *Timorites* ammonoid Genozone, because
there is no opportunity to separate upper Wordian and lower Capitanian parts of the Genozone
(Bogoslovskaya et al., 1995; Ehiro and Misaki, 2005; Leonova, 2018).

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6.4 Biotic and radioisotopic correlation of the Midian and Capitanian Stages.

Correlation of Midian Stage of the Tethyan time scale with the IGTS has been difficult and controversial. Since its definition (Leven, 1980), and through the mid-1990s the Midian Stage was correlated utilizing fusulinids and ammonoids with the Capitanian Stage (*s. l.*) of Texas (Jin et al., 1997). Once the Capitanian was redefined and its lower boundary in Texas shifted upwards (Glenister et al., 1999), the fusulinid assemblages from the lower Capitanian (*s.l.*) now characterize the upper Wordian of the IGTS (Davydov, 1994; Kozur and Davydov, 1996; Stevens et al., 1997).

Nevertheless, in some regions this part of the succession has remained equated with the 320 321 Capitanian (Menning et al., 2006; Nakazawa and Ueno, 2009; Kobayashi, 2011, 2012a,b; 322 Kofukuda et al., 2014). In Japan, the Guadalupian Series is divided into a several fusulinid zones (Fig. 7). The lower Midian Stage in the Akiyoshi area in our opinion correlates with the upper 323 324 part of Colania douvelei-Neoschwagerina haydeni Zone, where the first Kahlerina appear 325 (Nakazawa and Ueno, 2009; Kobayashi, 2012a,b). We suggest naming this part of the Colania 326 douvelei-Neoschwagerina haydeni Zone as the Kahlerina beds. Following upwards, the 327 Lepidolina shiraiwensis Zone together with the Kahlerina Beds thus correlates with the upper 328 Wordian of the IGTS (Fig. 7). The radioisotopic ages from the Manzanita bed of Texas (Bowring

329	et al., 1998; Ramezani and Bowring, 2018) and from the Lepidolina shiraiwensis Zone of					
330	Akiyoshi (this study) support such a correlation. This contrasts with and requires revision of the					
331	recent assignment of an uppermost Capitanian age for the Lepidolina shiraiwensis Zone in some					
332	recent publications (Zhang and Wang, 2018).					
333	The Kahlerina Beds and Lepidolina shiraiwensis Zone of Akiyoshi and Yabeina globosa					
334	Zone of Akasaka consequently correlate with the Arpa Formation (lower Midian) of					
335	Transcaucasia (Kotlyar et al., 1988; Kobayashi, 2011), the lower Karasin Beds of the southeast					
336	Pamir (Chediya et al., 1986), and the Yabeina inoyei fusulinid Zone of South China (Mei et al.,					
337	1998). The Capitanian Stage (s. s.) of the IGTS correlates with the Lepidolina multiseptata and L.					
338	kumaensis Zones of Japan, the upper Midian Stage of the Tethyan time scale, the Khachik					
339	Formation of Transcaucasia, the upper Karasin Beds in the Pamirs where Lepidolina ex gr.					
340	<i>multiseptata</i> and <i>Yabeina opima</i> are found (Chediya et al., 1986; Kotlyar et al., 1989), and the					
341	Metadoliolina multivoluta-Lepidolina multiseptata fusulinid Zone of South China (Fig. 7).					
342	7 Conclusions					
343 344	The sequence of radioisotopic ages and consistent age of all fusulinids suggest a					
345	conformable sedimentary succession within the Tsunemori Formation at the Shigeyasu Quarry.					
346	The obtained radioisotopic, sedimentologic and biostratigraphic data of the Tsunemori					
347	Formation at the Shigeyasu Quarry and the presence of acidic volcanic tuffs are consistent with					
348	a forearc basin or trench slope basin as the site of deposition for the Tsunemori Formation.					
349	The mixed volcano-siliciclastic-carbonate succession in the Tsunemori Formation at					
350	Shigeyasu Quarry, Japan, contains both fusulinids and tuffs with U-Pb zircon CA-IDTIMS					
351	radioisotopic ages that allow a robust correlation of the Kahlerina Beds and Lepidolina					

shiraiwensis Zones of Japan to the lower Midian Stage of the Tethyan time scale, and to the
upper Wordian Stage of the International Geologic Time Scale.

354

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568

570 Figure 1. Paleogeographic and tectonic maps. (A) Middle Permian global paleogeography with

- the main regions discussed in this paper; (B) Regional tectonic map of southern Japan, modified
 from Wakita (2013).
- 573 Figure 2. Shigeyasu Quarry: a, Google Earth image of Shigeyasu Quarry, red line shows
- 574 collection site; **b**, general panorama of studied site; **c**, volcanic ash (10VD20) within the
- 575 laminated limestone. Stratification is well expressed within the Shigeyasu Quarry cut.
- 576 Figure 3. Stratigraphic log of the succession in Shigeyasu Quarry and position of the collected
- 577 samples. Note that the succession is overturned. All scale bars of the fusulinid images are 1
- 578 mm. The entire set of the radioisotopic age attributes can be seen in Table 2.
- 579 Figure 4. Fusulinid assemblage from turbiditic bed (samples 10VD20-10VD23). 1, Schubertella
- 580 ovalis Kobayashi; 2, Yangchienia? sp.; 3, Kahlerina sp.; 4-5, Chusenella altinensis Ross; 6,
- 581 Chusenella otai (Nogami); 7-12, Lepidolina shiraiwensis (Ozawa); 13, Sumatrina longissima
- 582 Deprat. All scale bars are 1 mm.
- 583 Figure 5. Fusulinid assemblage from slump block (sample 10VD98). 1, Codonofusiella sp.; 2,
- 584 boultoniids; Kahlerina ampla Han; 4-7, Kahlerina nautiloidea Sosnina; 8, Kahlerina sp.; 9,
- 585 Rauserella ex gr. ellipsoidalis Sosnina; 10, Chusenella altinensis Ross; 11, Chusenella otai
- 586 (Nogami); 12-15, Lepidolina shiraiwensis (Ozawa); 16, Sumatrina longissima Deprat; 17,
- 587 Pseudodoliolina ozawai Yabe and Hanzawa. All scale bars are 1mm.

Figure 6. U-Pb concordia diagrams illustrating results of single grain chemical abrasion ID-TIMS analysis for each dated tuff samples from Shigeyasu Quarry, volcano-siliciclastic succession of the Akiyoshi Plateau, southwest Japan. Grey band represents the error envelope on the concordia curve based upon the decay constants and errors of Jaffey et al. (1975). Analyses accepted in weighted mean calculations are illustrated by filled translucent ellipses; analyses discarded as influenced by inheritance or Pb-loss are illustrated as open ellipses. All accepted analyses are concordant within the decay constant uncertainties.

595 Figure 7. Biostratigraphic and radioisotopic correlation of the Guadalupian of Shigeyasu Quarry

596 with major global sections: Texas (Glenister et al., 1999; Wardlaw, 2000; Yang and Yancey,

597 2000; Nestell et al., 2006; Nestell and Nestell, 2006); Japan (Ueno, 1992; Nakazawa and Ueno,

598 2009; Kobayashi, 2012a); Transcaucasia (Kotlyar et al., 1989a; Leven, 1998); Pamirs (Leven,

1967; Chediya et al., 1986; Kozur et al., 1994; Angiolini et al., 2015) and our own data; South

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600 China from (Mei et al., 1998; Wu et al., 2017).
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Table 1. Fusulinid taxonomic composition of the studied limestone samples.

602 Table 2. Zircon IDTIMS U-Pb isotopic data



1, Akiyoshi atoll; 2, West Texas Basin; 3, Transcaucasia; 4, S-E Pamirs; 5, S. China









Fig. 5. Davydov and Schmitz



Fig. 5. Davydov and Schmitz



Fig. 6 Davydov and Schmitz

		IGTS	West Texas					Japan Transcaucasia						South - East P	South China			
	SERIES		Formation Member		Conodont zonation	Fusulinids	Ammonoids	Fusulinids		Fusulinids		Formation	Member	Fusulinids	Conodonts		Fusulinids	Conodonts
255 - - - - 260 -	LOPINGIAN (part)	Wuchiapingian	Castile					Nanlingella suzukii Codonofusiella kwangsiana	Akhura	Codonofusiella kwangsiana			Kutal	Paradunbarula Reichelina Codonofusiella			Gallowayinella meitiensis Nanlingella simplex Codonofusiella kwangsiana	Not discusssed C. asymmetrica C. dukouensis C. postbitteri
200 - - - - 2065	PIAN (part)	Capitanian	Bell Canyon	Altuda	C. hongshuiensis / J. granti J. xuanhanensis J. altudaensis J. shannoni J. postserrata	Lantchechites Pseudokahlerina Yabeina texana Reichelina Paradoxiella	Timorites	Yabeina Lepidolina kumaensis Lepidolina multiseptata	Khachik	Neoschwagerina pinguis	n stage	Gan	Karasin	Lepidolina ex gr. multiseptata Yabeina ex gr. opima	Jinogondolella altudaensis	gwuan	Metadoliolina multivoluta	C. hongshuiensis J. granti J. xuanhanensis J. prexuanhanensis J. altudaensis J. shannoni J. postserrata
200 - - -	UADALU	Wordian			Jinoqondolella	Codonofusiella, Le shumardi		Lepidolina shiraiwensis 25 5 Kahlerina beds	Arpa	Chusenella abichi Kahlerina Yang.thompsoni Sumatrina	Midian		-	Yabeina archaica Lantchechites Kahlerina	Jinogondolella	Lenç	Yabeina inoyei	Jinogondolella
270 -	G	- 271.0	ashy Car	Vord	aserrata	Parafusulina antimonioensis	es Waagenoceras	Colania douvillei Neosch. haydeni Neosch. craticulifera	shik	Neosch. cheni Verbeekina verbeeki			Izhamantal Deirin	Neosch. ex gr. margaritae Neosch. craticulifera Neosch. schuberti	aserrata Mesogongolella omaensis	Kuhfeng	Afghanella shencki	aserrata Jinogondolella
-		Roadian	B	>	Jinogondolella nankingensis	Parafusulina		Neosch. simplex	Gnis	Presumatrina		Ŀ	har D	Neosch. simplex Presumatrina	? J. nankingensis	L	Neosch. simplex	nankingensis
- Age (Ma) -	- (part) Ma) -				namangonolo	Schardol	Demarezit	Cancellina		Cancellina		Kubei	Agalk	Neosch. sp. Cancellina	Mesogongolella pingxiangensis	Loudinia	Cancellina	J. gracilis Mesogongolella pingxiangensis

1, 265.3 ± 0.2 Ma; 2, 265.79 ± 0.04 Ma; 3, 265.77 ± 0.03 Ma; 4, 265.81 ± 0.04 Ma; 5, 266.0 ± 0.04 Ma; 6, 267.46 ± 0.04 Ma; 7, 272.95 ± 0.11 Ma C. - Clarkina; J. - Jinogondolella; Neoschw. - Neoscwagerina; Kuber. - Kubergandy; Traditional base of the Capitanian Stage

Table 2. Zircon CA-IDTIMS U-Pb isotopic data

							Radiogenic Isotopic Ratios								Radiogenic Isotopic I			ic Dates		
	<u>Th</u>	²⁰⁶ Pb*	mol %	<u>Pb*</u>	Pbc	<u>206Pb</u>	²⁰⁸ Pb	207Pb		²⁰⁷ Pb		206Pb		corr.	207Pb		²⁰⁷ Pb		²⁰⁶ Pb	
Gra	in U	x10 ⁻¹³ mo	l ²⁰⁶ Pb*	Pbc	(pg)	²⁰⁴ Pb	²⁰⁶ Pb	²⁰⁶ Pb	% err	²³⁵ U	% err	²³⁸ U	% err	coef.	²⁰⁶ Pb	±	²³⁵ U	±	²³⁸ U	±
(a)	(b)	(c)	(c)	(c)	(c)	(d)	(e)	(e)	(f)	(e)	(f)	(e)	(f)		(g)	(f)	(g)	(f)	(g)	(f)
10VD-20																				
z1	0.747	0.9576	0.997	122	0.21	6865	0.237	0.05157	0.1	0.299481	0.1	0.042116	0.030	0.608	267	2	265.99	0.21	265.93	0.08
z7	0.572	0.3661	0.992	37	0.25	2179	0.181	0.05178	0.2	0.300602	0.2	0.042108	0.046	0.543	275	5	266.87	0.58	265.89	0.12
z6	0.504	0.6164	0.987	23	0.67	1408	0.160	0.05153	0.2	0.299162	0.2	0.042108	0.040	0.582	265	5	265.75	0.55	265.88	0.10
z5	0.693	0.9609	0.996	88	0.29	5036	0.220	0.05155	0.1	0.299221	0.1	0.042095	0.031	0.626	266	2	265.79	0.22	265.81	0.08
z4	0.730	1.3211	0.997	103	0.34	5864	0.231	0.05161	0.1	0.299542	0.1	0.042095	0.030	0.631	268	2	266.04	0.20	265.81	0.08
z2	0.730	0.9618	0.997	104	0.24	5915	0.231	0.05158	0.1	0.299260	0.1	0.042082	0.031	0.515	267	2	265.82	0.24	265.72	0.08
z3	0.705	1.6631	0.996	83	0.53	4736	0.224	0.05160	0.1	0.299384	0.1	0.042080	0.033	0.462	268	2	265.92	0.26	265.71	0.09
								1	weightee	d mean ²⁰⁶ l	Pb/238U	age = 265.7	6 ± 0.0	4 (0.14)	[0.31]	Ma N	Aa (2s);]	MSWI	D = 1.60 (1)	n=4)
10VD-25												0								,
z2	0.640	0.5062	0.992	39	0.33	2294	0.203	0.05164	0.2	0.299762	0.2	0.042099	0.044	0.560	270	5	266.21	0.55	265.83	0.11
z4	0.474	0.6459	0.996	81	0.20	4920	0.150	0.05165	0.1	0.299733	0.1	0.042093	0.034	0.601	270	2	266.19	0.28	265.79	0.09
z8	0.517	0.6167	0.996	85	0.18	5078	0.164	0.05153	0.1	0.299061	0.1	0.042092	0.038	0.515	265	3	265.67	0.32	265.79	0.10
z5	0.401	0.4466	0.994	51	0.21	3135	0.127	0.05165	0.2	0.299724	0.2	0.042091	0.036	0.588	270	4	266.18	0.41	265.78	0.09
z7	0.661	0.2318	0.989	29	0.21	1695	0.209	0.05152	0.3	0.298998	0.3	0.042091	0.045	0.672	264	7	265.62	0.76	265.78	0.12
z1	0.602	0.8236	0.996	83	0.25	4889	0.191	0.05161	0.1	0.299514	0.1	0.042089	0.033	0.657	268	2	266.02	0.24	265.77	0.09
z6	0.742	0.4629	0.993	44	0.28	2515	0.235	0.05162	0.2	0.299568	0.2	0.042088	0.039	0.582	269	5	266.06	0.54	265.76	0.10
z3	0.646	0.7450	0.996	85	0.23	4951	0.205	0.05158	0.1	0.299313	0.1	0.042087	0.036	0.771	267	2	265.86	0.26	265.76	0.09
z10	0.630	0.7297	0.997	96	0.20	5571	0.200	0.05159	0.1	0.299338	0.1	0.042086	0.031	0.660	267	2	265.88	0.24	265.75	0.08
z9	0.732	0.3427	0.992	41	0.22	2352	0.232	0.05168	0.2	0.299797	0.2	0.042076	0.050	0.567	271	5	266.24	0.56	265.69	0.13
								w	eighted	mean ²⁰⁶ P	b/ ²³⁸ U a	ge = 265.77	2 ± 0.03	(0.13) [0.31] N	la M	a (2s); N	ISWD	= 0.39 (n	=10)
10VD-26																				
z5	0.604	0.6881	0.996	80	0.22	4716	0.191	0.05145	0.1	0.298812	0.2	0.042120	0.077	0.564	261	3	265.47	0.42	265.96	0.20
z9	0.754	0.4084	0.992	39	0.28	2216	0.239	0.05162	0.2	0.299737	0.3	0.042114	0.053	0.440	269	5	266.19	0.59	265.92	0.14
z8	0.529	1.0216	0.997	117	0.22	7011	0.168	0.05162	0.1	0.299668	0.1	0.042104	0.045	0.696	269	2	266.14	0.22	265.86	0.12
z2	0.997	2.2386	0.998	170	0.37	9017	0.316	0.05163	0.1	0.299676	0.1	0.042101	0.031	0.724	269	1	266.15	0.16	265.84	0.08
z7	0.697	0.5274	0.995	64	0.22	3658	0.221	0.05169	0.2	0.300055	0.2	0.042100	0.051	0.328	272	5	266.44	0.55	265.84	0.13
z4	0.676	1.0657	0.998	126	0.22	7225	0.214	0.05159	0.1	0.299419	0.1	0.042096	0.035	0.541	267	2	265.95	0.25	265.81	0.09
z3	0.616	1.0260	0.997	106	0.25	6209	0.195	0.05162	0.1	0.299557	0.1	0.042090	0.033	0.576	269	2	266.05	0.23	265.78	0.09
z10	0.533	0.4149	0.994	50	0.21	2977	0.169	0.05164	0.2	0.299682	0.2	0.042088	0.041	0.514	270	4	266.15	0.45	265.76	0.11
z1	0.573	0.5362	0.994	53	0.26	3155	0.182	0.05174	0.2	0.300215	0.2	0.042086	0.054	0.405	274	4	266.57	0.46	265.75	0.14
z6	0.482	0.8388	0.988	24	0.88	1456	0.153	0.05146	0.2	0.298627	0.2	0.042086	0.044	0.490	262	4	265.33	0.50	265.75	0.11
										_										

weighted mean ${}^{206}Pb/{}^{238}U$ age = 265.81 ± 0.04 (0.13) [0.31] Ma (2s); MSWD = 1.05 (n=10)

Table 2 continued

							Radiogenic Isotopic Ratios								Radiogenic Isotopic Dates					
	<u>Th</u>	²⁰⁶ Pb*	mol %	<u>Pb*</u>	Pbc	206Pb	²⁰⁸ Pb	²⁰⁷ Pb		²⁰⁷ Pb		²⁰⁶ Pb		corr.	²⁰⁷ Pb		²⁰⁷ Pb		²⁰⁶ Pb	
Grai	in U :	x10 ⁻¹³ mc	ol 206Pb*	Pbc	(pg)	²⁰⁴ Pb	²⁰⁶ Pb	²⁰⁶ Pb	% err	²³⁵ U	% err	²³⁸ U	% err	coef.	²⁰⁶ Pb	±	²³⁵ U	±	²³⁸ U	±
(a)	(b)	(c)	(c)	(c)	(c)	(d)	(e)	(e)	(f)	(e)	(f)	(e)	(f)		(g)	(f)	(g)	(f)	(g)	(f)
10VD-95																				
z10	0.669	0.4608	0.995	60	0.20	3468	0.212	0.05162	0.1	0.304248	0.2	0.042749	0.061	0.557	269	3	269.71	0.39	269.85	0.16
z2	0.671	1.3504	0.996	81	0.43	4678	0.213	0.05163	0.1	0.300443	0.1	0.042203	0.033	0.525	269	2	266.75	0.27	266.47	0.09
z7	0.689	1.8592	0.999	251	0.19	14366	0.218	0.05159	0.1	0.300090	0.1	0.042189	0.033	0.543	267	2	266.47	0.19	266.38	0.09
z3	0.649	1.3590	0.998	145	0.24	8360	0.206	0.05160	0.1	0.300039	0.1	0.042170	0.031	0.600	268	1	266.43	0.18	266.27	0.08
z8	0.646	1.8276	0.999	241	0.20	13956	0.205	0.05158	0.0	0.299868	0.1	0.042166	0.028	0.763	267	1	266.30	0.13	266.25	0.07
z6	0.620	2.0705	0.998	160	0.33	9305	0.196	0.05158	0.1	0.299678	0.1	0.042136	0.028	0.699	267	1	266.15	0.17	266.06	0.07
z5	0.701	1.4384	0.998	185	0.20	10580	0.222	0.05158	0.1	0.299614	0.1	0.042127	0.032	0.700	267	1	266.10	0.16	266.00	0.08
z4	1.717	0.8942	0.998	165	0.18	7511	0.544	0.05157	0.1	0.299564	0.1	0.042127	0.033	0.621	267	2	266.06	0.20	266.00	0.09
z1	0.849	2.7419	0.999	278	0.27	15290	0.269	0.05154	0.1	0.299301	0.1	0.042120	0.033	0.434	265	2	265.85	0.20	265.96	0.09
z9	0.631	1.5792	0.998	172	0.24	9975	0.200	0.05160	0.0	0.299669	0.1	0.042120	0.032	0.758	268	1	266.14	0.16	265.96	0.08
	weighted mean ${}^{206}\text{Pb}/{}^{238}\text{U}$ age = 266.00 ± 0.04 (0.14) [0.31] Ma (2s); MSWD = 1.06 (n=4)															n=5)				
10VD-96																				
z4	0.443	2.2507	0.999	277	0.20	16893	0.140	0.05160	0.1	0.301623	0.1	0.042393	0.035	0.650	268	1	267.67	0.17	267.65	0.09
z6	0.434	2.8250	0.999	308	0.22	18843	0.137	0.05167	0.0	0.301935	0.0	0.042384	0.028	0.963	271	0	267.91	0.11	267.59	0.07
z10	0.516	1.6215	0.998	194	0.21	11586	0.164	0.05165	0.0	0.301777	0.1	0.042375	0.028	0.757	270	1	267.79	0.14	267.54	0.07
z3	0.383	3.1905	0.999	289	0.27	17917	0.121	0.05168	0.0	0.301871	0.0	0.042363	0.030	0.937	271	1	267.86	0.12	267.46	0.08
z5	0.453	2.5301	0.999	313	0.20	19058	0.143	0.05162	0.0	0.301495	0.1	0.042361	0.032	0.746	269	1	267.57	0.14	267.45	0.09
z8	0.556	3.4060	0.992	39	2.23	2340	0.176	0.05160	0.1	0.301371	0.1	0.042358	0.035	0.591	268	2	267.47	0.22	267.43	0.09
z7	0.475	1.4587	0.998	190	0.19	11488	0.151	0.05161	0.1	0.301384	0.1	0.042351	0.030	0.633	268	1	267.48	0.17	267.39	0.08
z1	0.506	8.4201	1.000	566	0.37	33925	0.160	0.05172	0.0	0.301565	0.0	0.042290	0.031	0.904	273	1	267.62	0.11	267.01	0.08
									weig	ghted mean	²⁰⁶ Pb/ ²	³⁸ U age = 2	67.46 ±	0.04 (0	.14) [0.	31] N	Ma (2s);]	MSWI	D = 1.90 (1)	n=5)

Notes:

(a) z1, z2 etc. are labels for single zircon crystals or fragments thereof, annealed and chemically abraded after Mattinson (2005).

(b) Model Th/U ratio calculated from radiogenic ²⁰⁸Pb/²⁰⁶Pb ratio and ²⁰⁷Pb/²³⁵U date.

(c) Pb* and Pbc are radiogenic and common Pb, respectively; mol % ²⁰⁶Pb* is with respect to radiogenic and blank Pb.

(d) Measured ratio corrected for spike and fractionation only. Most samples are spiked with the ET2535 tracer, with internal Pb and U fractionation correction using the measured ²⁰²Pb/²⁰⁵Pb and ²³³U/²³⁵U.

(e) Corrected for fractionation, spike, common Pb, and initial disequilibrium in 230 Th/ 238 U. Up to 0.3 pg of common Pb is assigned to procedural blank with composition of 206 Pb/ 204 Pb = 18.042 ± 0.61%; 207 Pb/ 204 Pb = 15.537 ± 0.52%; 208 Pb/ 204 Pb = 37.686 ± 0.63% (1-sigma). Excess over blank was assigned to initial common Pb, using the Stacey and Kramers (1975) two-stage Pb isotope evolution model at 266 Ma.

(f) Errors are 2-sigma, propagated using algorithms of Schmitz and Schoene (2007).

(g) Calculations based on the decay constants of Jaffey et al. (1971). ²⁰⁶Pb/²³⁸U and ²⁰⁷Pb/²⁰⁶Pb ratios and dates corrected for initial disequilibrium in ²³⁰Th/²³⁸U using Th/U [magma] = 3.