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Paleobiogeographic distribution of the Early Cretaceous radiolarian *Turbocapsula costata* and its correlation potential

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Abstract. ***Turbocapsula*, having three (or four) segments with a characteristic oval shape and a hemi-closed segmental end, is a radiolarian genus with a high stratigraphic value due to its phyletic evolution in the mid-Cretaceous period. An overview of lithology, depositional setting, associated fossil records, and paleomagnetic data from each locality of *Turbocapsula costata* (Wu) is summarized. All these data lead to the conclusion that locations of known *T. costata*-bearing strata are restricted to the low- to mid-latitude Mediterranean and eastern Tethys of the Tethyan realm. The results emphasize that the phyletic evolution of the genus *Turbocapsula* is significant in correlations within the Tethys. The zonation established by the phyletic evolution of the genus *Turbocapsula* cannot be utilized for Early Cretaceous zonal correlations beyond the *T. costata* territory.**

Key words: Atlantic, Mediterranean, Pacific, paleogeography, Tethys, *Turbocapsula*

Introduction

The genus *Turbocapsula*, the paleogeographic distribution of which is presented in this paper, was originally established by O'Dogherty (1994) using specimens from the northern Apennines (Italy) and the Betic Cordillera (Spain). The holotype (Figure 1.17) and paratype (Figure 1.18) of its type species, *Turbocapsula costata* (Wu), were obtained from the chert of the Congdu Formation, Xiagaze, southern Tibet. The range of this genus and its phyletic evolution at species level were well documented from the uppermost Barremian to Aptian pelagic sequence (section BB1) near Babazhadong, southern Tibet (Li *et al*., 2017). This comprehensive study concludes that *Turbocapsula* comprises four species, for one of which two subspecies are recognized: *Turbocapsula tetras* Li and Matsuoka, *T. fugitiva* O'Dogherty, *T. giennensis* O'Dogherty, *T. costata multicostata* Li and Matsuoka, and *T. costata costata* (Wu) (Figure 1). As discussed later, these species and subspecies were reported in marine sediments in the Indian Ocean (Renz, 1974; Sanfilippo and Riedel, 1985), Australia (Ellis, 1993), Spain (Riedel and Sanfilippo, 1974; Aguado *et al*., 1991, 1993, 2014), Tunisia (Elkhazri *et al*., 2015), Italy (O'Dogherty, 1994; Li *et al*., 2019), Slovakia (Ozvoldová, 1990; Bąk, 1999), Poland (Górka and Geroch, 1989), Montenegro (Goričan, 1994), Slovenia (Goričan and Šmuc, 2004; Šmuc *et al*., 2010; Rožič *et al*., 2014), southern Tibet (Wu, 1986; Matsuoka *et al*., 2002; Ziabrev *et al*., 2003, 2004; Li *et al*., 2017, 2019), Ladakh (Kojima *et al*., 2001; Zyabrev *et al*., 2008), and southwestern Japan (Ishida *et al*., 2008) (Figure 2). One *Turbocapsula* species was reported from the Middle Jurassic Akgöl Formation, northern Turkey as *Turbocapsula jurassica* Bragin and Tekin in Bragin *et al.* (2002), but later this was synonymized with the Jurassic *Unuma gordus* Hull by Suzuki and Gawlick (2003). Consequently, the phylogenetic and stratigraphic continuity indicates that *Turbocapsula* is a mid-Cretaceous genus so as to define the Turbocapsula Zone of O'Dogherty (1994). Based on the phyletic evolution of *Aurisaturnalis* and *Turbocapsula*, two radiolarian zones have been defined: the *Aurisaturnalis carinatus* Zone and the *Turbocapsula costata* Zone (Li *et al*., 2017) (Figure 3). The first appearance biohorizon (FAB) of *T. costata* was detected above the oceanic anoxic event (OAE) 1a interval, while the first representative of the genus *Turbocapsula* preceded the onset of the OAE 1a (Aguado *et al*., 2014).

Studies of Pessagno and Blome (1986), Pessagno *et al*. (1987, 1993), Baumgartner *et al*. (1992), Kiessling (1999), and Carter and Haggart (2006) indicated the existence of radiolarian biogeographic provinces in the Late Jurassic to Early Cretaceous. The Mesozoic radio-

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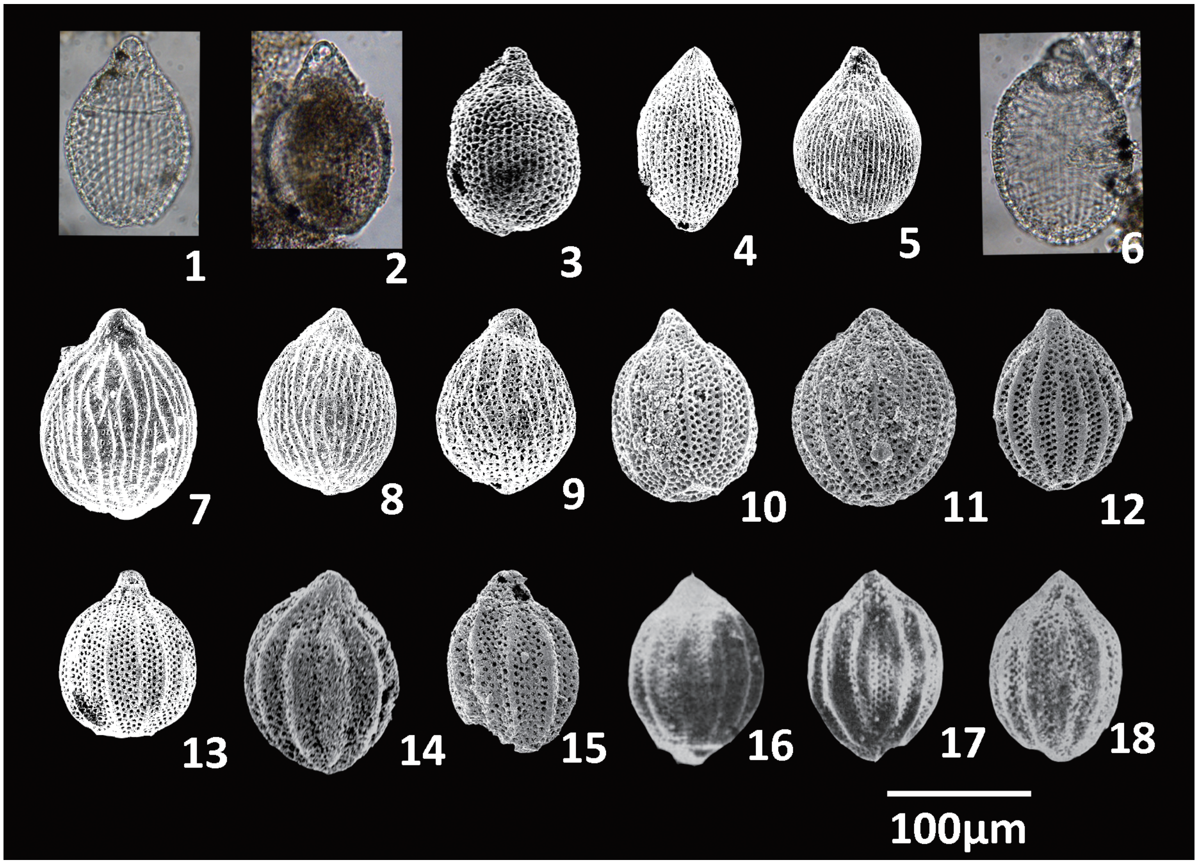

Figure 1. Scanning electron microscopic images (3–5, 7–18) and light microscopic images (1–2, 6) of the genus *Turbocapsula*. **1–3,** *Turbocapsula tetras* Li and Matsuoka; 1, = text-fig. 5.1b in Li *et al*., 2017, holotype; 2, = text-fig. 5.3 in Li *et al*., 2017, paratype; 3, = text-fig. 4.1a in Li *et al*., 2017; **4–6,** *Turbocapsula fugitiva* O'Dogherty; 4, =pl. 37, fig. 14 in O'Dogherty, 1994, holotype; 5, = pl. 37, fig. 12 in O'Dogherty, 1994; 6, = text-fig. 5.10 in Li *et al*., 2017; **7–9,** *Turbocapsula giennensis* O'Dogherty; 7, = pl. 37, fig. 23 in O'Dogherty, 1994, holotype; 8, = pl. 37, fig. 22 in O'Dogherty, 1994; 9, = pl. 37, fig. 21 in O'Dogherty, 1994; **10–18,** *Turbocapsula costata* (Wu); 10–13, *Turbocapsula costata* (Wu) *multicostata* Li and Matsuoka; 10, = text-fig. 4.21 in Li *et al*., 2017, holotype; 11, = text-fig. 4.18a in Li *et al*., 2017, paratype; 12, = text-fig. 4.14b in Li *et al*., 2017; 13, = pl. 37, fig. 27 in O'Dogherty, 1994; 14–18, *Turbocapsula costata* (Wu) *costata*; 14, = text-fig. 4.28a in Li *et al*., 2017; 15, = text-fig. 4.29 in Li *et al*., 2017; 16, =pl. 3, fig. 6 in Wu, 1986; 17, =pl. 3, fig. 16 in Wu, 1986, holotype; 18, = pl. 3, fig. 17 in Wu, 1986, paratype.

larian provinces are differentiated by latitude and include the Austral, Tethyan, and Boreal realms (Pessagno and Blome, 1986; Kiessling, 1999; Pessagno and Hull, 2002; Carter and Haggart, 2006). The bioprovinces are characterized by distinct changes in species abundance and the presence or absence of certain species.

This paper extends the topic of the paleogeographic distribution of the genus *Turbocapsula*, because the occurrence of this genus seems to be geographically limited based on preliminary examination. The present study mainly focuses on published occurrence locations of *Turbocapsula costata* in order to constrain the scope of application of the *Turbocapsula costata* Zone of Li *et al*. (2017) and the Turbocapsula Zone of O'Dogherty (1994) (Figure 3). Other *Turbocapsula* species like *T. tetras* and *T. fugitiva* were in fear of being overlooked in some previous literature, because these species were first distinguished in 2017 (Li *et al*., 2017). These two species are referred to but are not discussed in detail here. The occurrence of *Turbocapsula* is reviewed with stratigraphic positions, depositional age, and radiolarian assemblages from published reports. In reconstructing the paleolocation on a paleomap, the determination of the original location is important. Paleomagnetic data for *T. costata*-bearing strata or associated volcanic rocks are provided where available. The relationship between the *T. costata* territory and Mesozoic radiolarian provincialism is proposed. The adaptability of the zonation established by the bio-horizons of the genus *Turbocapsula* is discussed.

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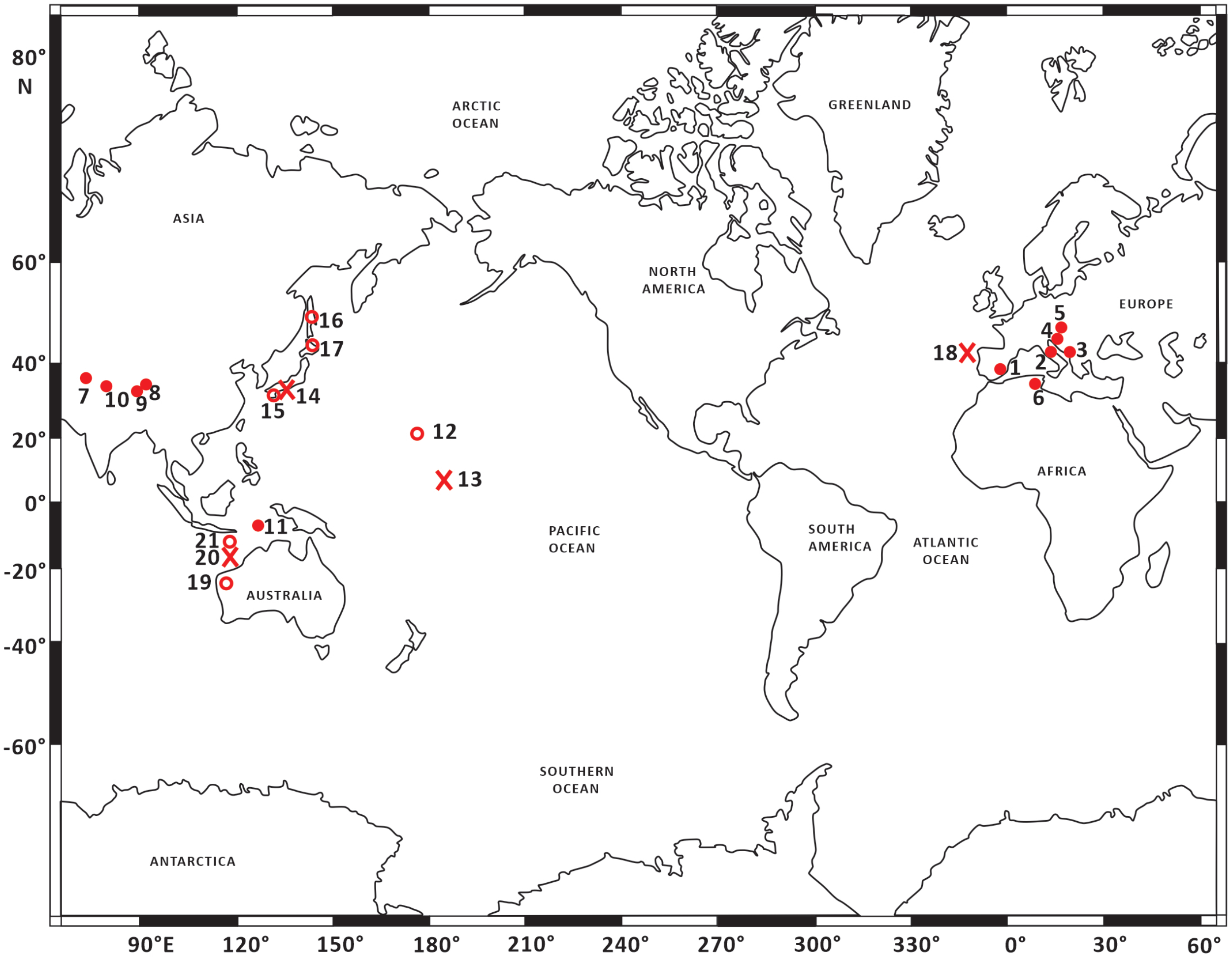

Figure 2. World map showing localities of the Barremian–Aptian radiolarian-bearing deposits. *Turbocapsula costata*-present localities are indicated by closed circles. *Turbocapsula costata*-absent localities are indicated by crosses (genus *Turbocapsula*-absent localities) and open circles (locations without *Turbocapsula costata* but with other species of *Turbocapsula*). **1,** Betic Cordillera (Riedel and Sanfilippo, 1974; Aguado *et al*., 1991, 1993, 2014; O'Dogherty, 1994); **2,** northern Apennines (O'Dogherty, 1994; Li *et al*., 2019); **3,** Budva Zone, Montenegro (Goričan, 1994); **4,** Slovenian Basin (Rožič *et al*., 2014); **5,** Vienna Basin (Ozvoldová, 1990); **6,** northeastern Tunisia (Elkhazri *et al*., 2015); **7,** mid-Cretaceous cover sediments on the ophiolite in Ladakh (Kojima *et al*., 2001; Zyabrev *et al*., 2008); **8,** mid-Cretaceous cover sediments on the ophiolite in southern Tibet (Wu, 1986; Ziabrev *et al*., 2003); **9,** hemipelagic part of Jurassic–Early Cretaceous chert represented by the Xialu Chert and the Bainang terrane in southern Tibet (Matsuoka *et al*., 2002; Ziabrev *et al*., 2004); **10,** passive margin sediments off the Indian continent (Li *et al*., 2017, 2019); **11,** Rotti Island (Sanfilippo and Riedel, 1985); **12,** DSDP Site 463 at Mid-Pacific Mountains (Schaaf, 1981); **13,** DSDP Site 167 at Magellan Rise (Moore, 1973); **14,** Shimanto Belt, Southwest Japan (Nakaseko *et al*., 1979; Nakaseko and Nishimura, 1981; Matsuyama *et al*., 1982; Kumon *et al*., 1986; Okamura, 1992); **15,** Kagoshima Prefecture, Japan (Ishida *et al*., 2008); **16,** East Sakhalin (Kurilov and Vishnevskaya, 2011; Zyabrev, 2011); **17,** northern Hokkaido, Japan (Tumanda, 1989); **18,** ODP Sites 638 and 641 in the North Atlantic (Thurow, 1988); **19,** western Australia (Ellis, 1993); **20,** ODP Site 765, Leg 123 off northwestern Australia (Baumgartner, 1992, 1993); **21,** DSDP Site 261, Leg 27 off northwestern Australia (Renz, 1974; Sanfilippo and Riedel, 1985).

Occurrence of *Turbocapsula costata* (Wu)

Localities where *Turbocapsula costata* (Wu) has been reported are briefly summarized below (Figure 2). They are categorized into three regions: Mediterranean realm, Indus–Yarlung–Tsangpo Suture Zone, and Rotti, Indonesia. Information on lithology, depositional setting, associated fossil records, and paleomagnetic data is also included where available. Locations of known Barremian–Aptian radiolarite deposits on an Early Cretaceous paleogeographic map are illustrated in Figure 4. The paleogeographic map follows the ODSN Plate Tectonic Reconstruction Service (http://www.odsn.de). The map is made from the datafiles used for Hay *et al*. (1999)

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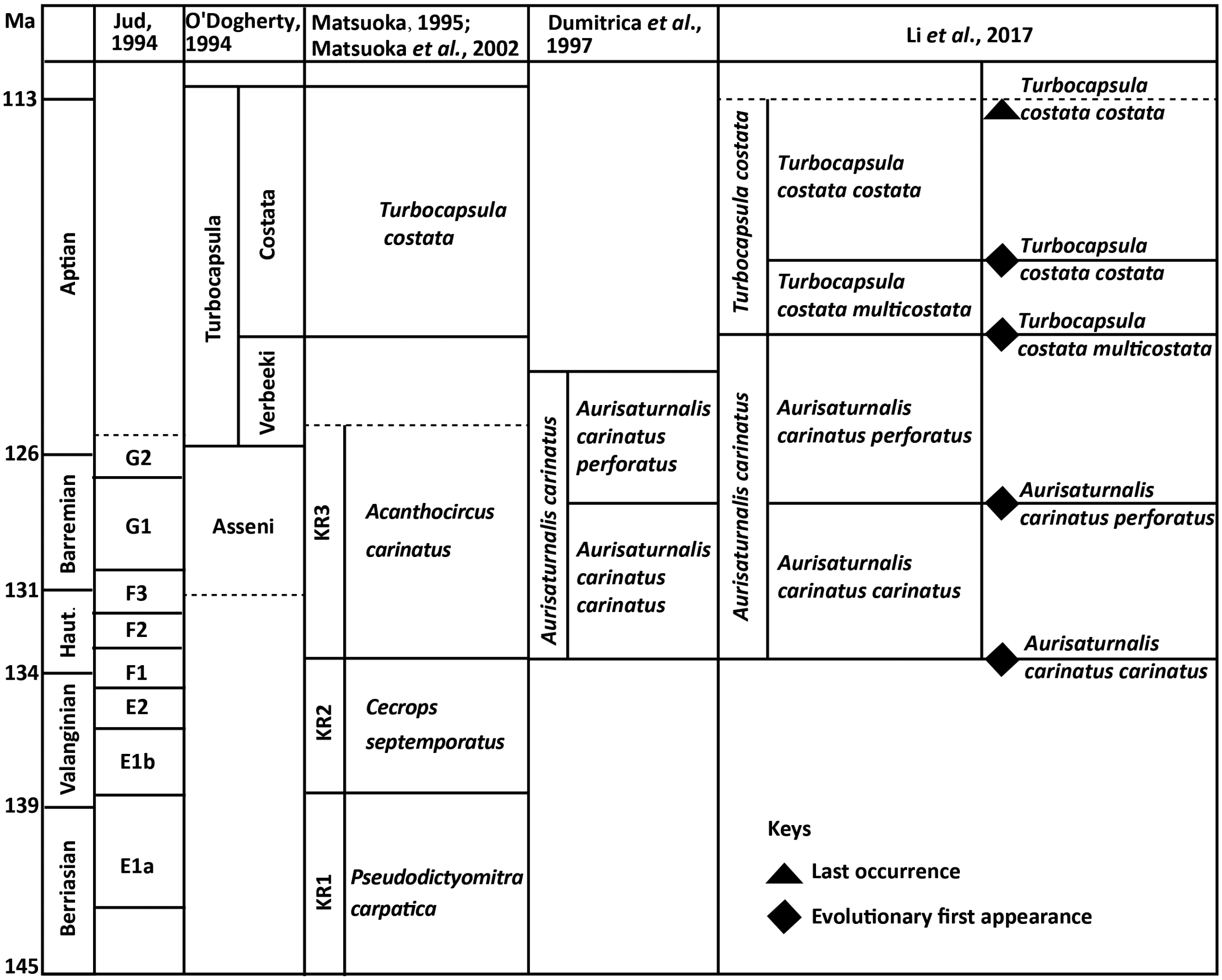

Figure 3. Comparison of Early Cretaceous radiolarian zonations by Jud (1994), O'Dogherty (1994), Matsuoka (1995), Matsuoka *et al.* (2002), Dumitrica *et al.* (1997), and Li *et al.* (2017).

and uses the paleomagnetic reference frame for North America of Harrison and Lindh (1982) as the standard.

The Mediterranean realm

Betic Cordillera.—The Betic Cordillera (location 1 in Figure 2) of southern Spain is divided into three major zones: a central part, the Middle Subbetic, and two marginal areas (the Internal and the External Subbetic). *Turbocapsula costata* was found from the Internal Subbetic Zone (Riedel and Sanfilippo, 1974; Aguado *et al.*, 1991; O'Dogherty, 1994) and the transition between the External Subbetic and the Middle Subbetic zones (Aguado *et al.*, 1993, 2014).

Riedel and Sanfilippo (1974) illustrated *Turbocapsula costata* as "*Theocorys antiqua* Squinabol" (p. 781, pl. 10, fig. 9 in Riedel and Sanfilippo, 1974) from east of Velez Blanco, Southeast Spain (location 1 in Figure 2). The depositional age is assigned as late Barremian by calcareous nannofossils listed in Riedel and Sanfilippo (1974): *Biscutum supracretaceum* (Reinhardt), *Braarudosphaera bigelowi* (Gran and Braarud), *Lithraphidites carniolensis* Deflandre, *Manivitella pemmatoidea* (Deflandre), *Micrantholithus hoschulzi* (Reinhardt), *Nannoconus bucheri* Brönnimann, *N. colomi* de Lapparent, *N. elongatus* Brönnimann, *N. truitti* Brönnimann, *Parhabdolithus embergeri* (Noel), *Parhabdolithus splendens* (Deflandre), *Rhagodiscus asper* (Stradner), and *Watznaueria barnesae* (Black).

Aguado *et al.* (1991) reported the occurrence of *Turbocapsula costata* as "*Cyrtophormis*? *costata* Squinabol" (text-fig. 7.15 in Aguado *et al.*, 1991) from the Fardes Formation in the north of Velez Blanco (Internal Subbetic) (location 1 in Figure 2). The Fardes Formation is a pelagic facies and in many places has intercalations of

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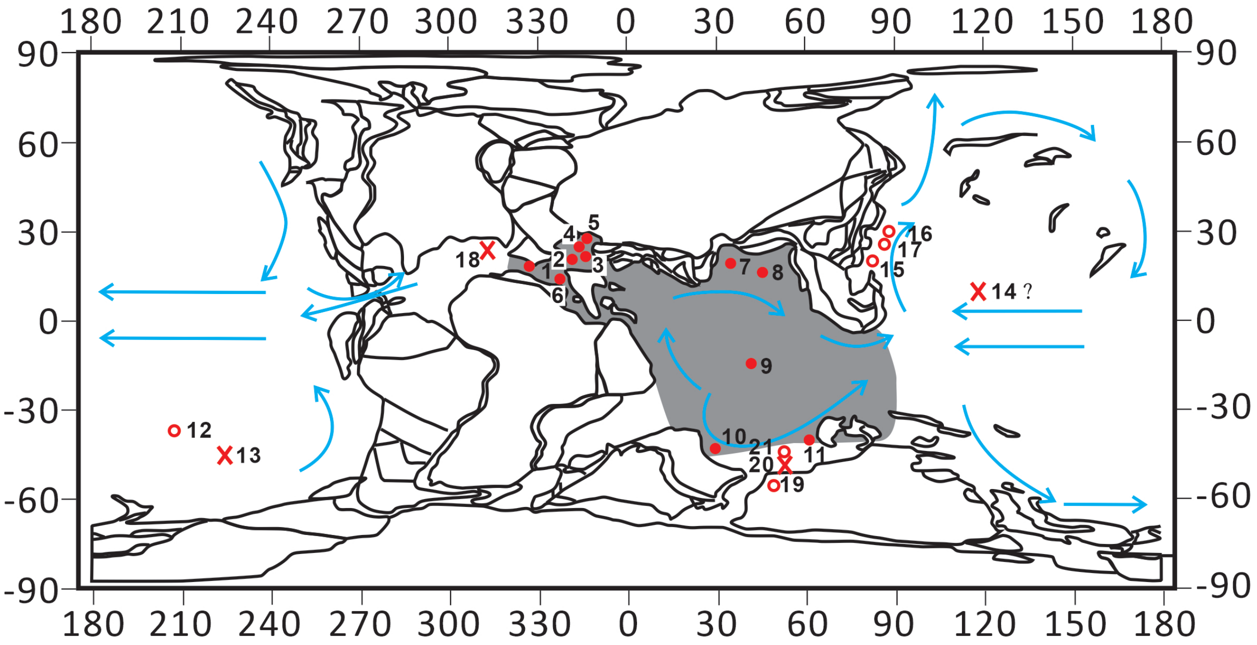

Figure 4. Locations of known Barremian–Aptian radiolarite deposits on Early Cretaceous paleogeographic map (ODSN Plate Tectonic Reconstruction Service http://www.odsn.de/odsn/services/paleomap/paleomap.html). Arrows indicate ocean currents modified from Hay (2009). Gray area indicates the *Turbocapsula costata* territory. *Turbocapsula costata*-present localities are indicated by closed circles. *Turbocapsula costata*-absent localities are indicated by crosses (genus *Turbocapsula*-absent localities) and open circles (locations without *Turbocapsula costata* but with other species of *Turbocapsula*). **1,** Betic Cordillera (Riedel and Sanfilippo, 1974; Aguado *et al.*, 1991, 1993, 2014; O'Dogherty, 1994); **2,** northern Apennines (O'Dogherty, 1994; Li *et al.*, 2019); **3,** Budva Zone, Montenegro (Goričan, 1994); **4,** Slovenian Basin (Rožič *et al.*, 2014); **5,** Vienna Basin (Ozvoldová, 1990); **6,** northeastern Tunisia (Elkhazri *et al.*, 2015); **7,** mid-Cretaceous cover sediments on the ophiolite in Ladakh (Kojima *et al.*, 2001; Zyabrev *et al.*, 2008); **8,** mid-Cretaceous cover sediments on the ophiolite in southern Tibet (Wu, 1986; Ziabrev *et al.*, 2003); **9,** hemipelagic part of Jurassic–Early Cretaceous chert represented by the Xialu Chert and the Bainang terrane in southern Tibet (Matsuoka *et al.*, 2002; Ziabrev *et al.*, 2004); **10,** passive margin sediments off the Indian continent (Li *et al.*, 2017, 2019); **11,** Rotti Island (Sanfilippo and Riedel, 1985); **12,** DSDP Site 463 at Mid-Pacific Mountains (Schaaf, 1981); **13,** DSDP Site 167 at Magellan Rise (Moore, 1973); **14,** Shimanto Belt, Southwest Japan (Nakaseko *et al.*, 1979; Nakaseko and Nishimura, 1981; Matsuyama *et al.*, 1982; Kumon *et al.*, 1986; Okamura, 1992); **15,** Kagoshima Prefecture, Japan (Ishida *et al.*, 2008); **16,** East Sakhalin (Kurilov and Vishnevskaya, 2011; Zyabrev, 2011); **17,** northern Hokkaido, Japan (Tumanda, 1989); **18,** ODP Sites 638 and 641 in the North Atlantic (Thurow, 1988); **19,** western Australia (Ellis, 1993); **20,** ODP Site 765, Leg 123 off northwestern Australia (Baumgartner, 1992, 1993); **21,** DSDP Site 261, Leg 27 off northwestern Australia (Renz, 1974; Sanfilippo and Riedel, 1985).

carbonate turbidite deposits, oolitic turbidites, and breccias. The illustrated specimen was obtained from the upper Aptian. The radiolarian assemblage is low in diversity and includes *Hexapyramis pantanellii* Squinabol and *Zifondium* sp.

Aguado *et al*. (1993) reported *Turbocapsula costata* as "*Tricolocapsa* sp." (pl. 3, fig. 7 in Aguado *et al.*, 1993) from "Membro II" of the Carbonero Formation in the transition between the External Subbetic and the Middle Subbetic (location 1 in Figure 2). The "Membro II" is correlated with the lower member of the Fardes Formation. Coexisting species include: *Archaeodictyomitra lacrimula* (Foreman), *Dibolachras tytthopora* Foreman, *Pantanellium lanceola* (Parona), and *Williriedellum gilkeyi* Dumitrica. The radiolarian association is characteristic of the early Aptian.

Aguado *et al*. (2014) integrated the biostratigraphies of calcareous nannofossils, planktonic foraminifera, and radiolarians for the uppermost Barremian–lower Aptian succession in the La Frontera area, which is located in the Subbetic Zone of the Betic Cordillera (location 1 in Figure 2). The stratigraphy is characterized by the pelagic rhythmite succession of the Carretero Formation (Barremian) and the dark marls, radiolaritic claystones, and green marls of the Carbonero Formation (lower Aptian). The first appearance biohorizon (FAB) of *Turbocapsula costata* (text-fig. 10.5 in Aguado *et al.*, 2014) was detected above the OAE 1a interval. As *T. costata* phyletically evolved from *T. fugitiva*, and *T. fugitiva* came from *T. tetras* according to Li *et al.* (2017), the *Turbocapsula* lineage apparently crossed the onset of the OAE 1a.

Northern Apennines.—O'Dogherty (1994) carried out mid-Cretaceous radiolarian biostratigraphic analyses of the Pantano section in the Betic Cordillera of Spain

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(location 1 in Figure 2) and the Gorgo a Cerbara and Monte Casalini sections in the northern Apennines of Italy (location 2 in Figure 2). A new genus *Turbocapsula* was defined from the Carretero and Fardes formations in the External Subbetic and the Scisti a Fucoidi Formation in the Umbria–Marche Apennines. The Carretero Formation consists of limestones and marls rhythmite. The Fardes Formation is characterized by predominant marly constituents. The Scisti a Fucoidi Formation consists of thinly interbedded red and green marlstone and calcareous mudstone, marly claystone, and marly limestone. Two species, *T. fugitiva* and *T. giennensis*, were described under the genus *Turbocapsula*.

A paleolatitude of 20–25°N has been inferred for the Aptian position of sections in the Subbetic Basin (southern Spain) (Masse *et al*., 1993). The 125–150 Ma high-resolution Apparent Polar Wander Path for Adria from magnetostratigraphic sections in the Umbria–Marche (northern Apennines, Italy) indicates a paleolatitude of 20–25°N in the Early Cretaceous (Satolli *et al*., 2007) (Figure 4).

Budva Zone.—Goričan (1994) reported Jurassic and Cretaceous radiolarite sedimentation in the Budva Zone in the Dinarides, Montenegro (location 3 in Figure 2). *Turbocapsula costata* (p. 93, pl. 10, figs. 3, 4 in Goričan, 1994) was recovered from the upper part of the Bijela Radiolarite, corresponding to the Aptian.

Slovenian Basin.—The Slovenian Basin is a Mesozoic deep-water paleogeographic unit located between the south-lying Dinaric Carbonate Platform and the north-lying Julian Carbonate Platform (Buser, 1996) (location 4 in Figure 2). Two samples from Cretaceous cherts and siliceous mudstones of the lower flyschoid formation contain *Turbocapsula costata* (pl. 4, figs. 7–10 in Rožič *et al*., 2014). Based on the co-occurrence with *Xitus clava* (Parona) and *Pantanellium* sp., one sample is restricted to the Costata Subzone of O'Dogherty (1994), indicating an age of late Aptian. Based on the occurrence of *Archaeodictyomitra montisserei* (Squinabol), the other sample is correlated with the Romanus Subzone of O'Dogherty (1994), indicating an age of middle Albian. As Rožič *et al.* (2014) pointed out, *Turbocapsula costata* (Wu) extending above the Costata Subzone may correspond to the missing early Albian interval in O'Dogherty (1994). Specimens of Goričan and Šmuc (2004, pl. 2, fig. 3) and Šmuc *et al.* (2010, text-fig. 19.14) were reported as *Turbocapsula costata* (Wu). However, these specimens should be *T. giennensis* O'Dogherty because of their discontinuous costae.

Carpathian Klippen Belt.—Ozvoldová (1990) showed two specimens of *Turbocapsula costata* as "*Protunuma* sp." (p. 143, pl. 2, figs. 4, 5 in Ozvoldová, 1990) from the green to gray limestones at 1498–1499 m depth in the drillhole Smolinske 17, in the Slovakian part of the Vienna Basin (location 5 in Figure 2). The composition of the pyritized radiolarians includes: *Acanthocircus amissus* (Squinabol), *Amphipyndax stocki* (Campbell and Clark), *Archaeodictyomitra puga* Schaaf, *Cryptamphorella dumitricai* Schaaf, *C. macropora* Dumitrica, *Cyrtocapsa grutterinki* Tan Sin Hok, *Halesium*? *sexangulum* Pessagno, *Hemicryptocapsa tuberosa* Dumitrica, *Holocryptocanium barbui* Dumitrica, *Holocryptocapsa*? *cryptodon* (Dumitrica), *Praeconocaryomma lipmanae* Pessagno, *Pseudodictyomitra leptoconica* (Foreman), *Thanarla conica* (Aliev), and *Xitus spicularius* (Aliev). The assemblage suggests the middle to late Albian by Ozvoldová (1990).

Turbocapsula costata (p. 191, pl. 2, fig. 3 in Górka and Geroch, 1989) was reported from the Outer Carpathians, Poland. Although we cannot provide a precise location according to the limited information in their reports. It should be located in the Mediterranean realm.

North Africa.—Elkhazri *et al*. (2015) showed one specimen of *Turbocapsula costata* (text-fig. 12.31 in Elkhazri *et al*., 2015) from northeastern Tunisia (location 6 in Figure 2). The co-occurrence of *Turbocapsula costata* and planktonic foraminifera with radially elongated chambers belonging to the genus "*Leupoldina*" indicates an age of early Aptian. The studied section belongs to the South Tethyan margin (Bodin *et al*., 2010).

The Indus–Yarlung–Tsangpo Suture Zone

The Indus–Yarlung–Tsangpo Suture Zone (IYTSZ), which is traced from Pakistan in the west to Tibet in the east, marks where the previously vast Tethys eventually closed with the India-Asia collision. Ophiolitic massifs and mélanges, which form an ophiolitic belt, are distributed along the IYTSZ (e.g. Ding *et al*., 2005; Guilmette *et al*., 2009).

Indus Suture Zone.—The Nidar ophiolite is a large fragment of oceanic lithosphere preserved along the western continuance of the suture, the Indus Suture Zone, in the Ladakh Himalaya, northern India (Kojima *et al.*, 2001; Sachan, 2001). The occurrence of *Turbocapsula costata* (text-fig. 5.35, 5.36 in Zyabrev *et al.*, 2008) was reported from the marine sedimentary sections of the Nidar ophiolite in the Indus Suture Zone (location 7 in Figure 2). Based on radiolarian biostratigraphic correlation, the marine sedimentary succession is upper Barremian to upper Aptian. Kojima *et al.* (2001) illustrated *T. costata* (pl. 5, fig. 11 in Kojima *et al.*, 2001) as *Turbocapsula* sp. from the sedimentary-volcanic member of the Nidar ophiolite.

Yarlung–Tsangpo Suture Zone.—*Turbocapsula costata* was repeatedly reported from the ophiolite belt along the Yarlung–Tsangpo Suture Zone (YTZS), southern Tibet.

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The Xigaze ophiolite, which is the best known ophiolite in southern Tibet, stretches for ~150 km between Dazhuqu to the east and Sangsang to the west (location 8 in Figure 2). Wu (1986) mentioned the occurrence of *Turbocapsula costata* (p. 359, pl. 3, figs. 6, 16 in Wu, 1986) as *Tricapsula costata* Wu from the red chert just above the boundary between chert and pillow basalt in the Xigaze ophiolite. A specimen of *Turbocapsula costata* (p. 359, pl. 3, fig. 17 in Wu, 1986) was reported as *Tricapsula costata* Wu from the siliceous mudstone 30 m above the boundary between chert and pillow basalt. Ziabrev *et al*. (2003) reported *Turbocapsula costata* (text-fig. 5.50 in Ziabrev *et al*., 2003) from siliceous mudstone in mid-Cretaceous cover sediments on the Xigaze ophiolite. The siliceous mudstone yielded *Acaeniotyle diaphorogona* Foreman, *A. umbilicata* (Rüst), *Becus gemmatus* Wu, *Crolanium puga* (Schaaf), *Crucella euganea* (Squinabol), *Dictyomitra communis* (Squinabol), *Pseudodictyomitra hornatissima* (Squinabol), *Pseudoeucyrtis hanni* (Tan Sin Hok), *Thanarla brouweri* (Tan Sin Hok), and *Xitus clava* (Parona).

The existence of a northward dipping equatorial intra-oceanic subduction zone and island arc system within the Neo-Tethys is supported by seismic tomographic images of subducted lithosphere below the Indian plate, where high-velocity mantle anomalies appear to exist at equatorial latitudes (e.g. anomaly III of Van der Voo *et al.* (1999), see also van Hinsbergen *et al.* (2012)). The Xigaze ophiolite was viewed as a geological archive of near-equatorial subduction within the Neo-Tethys. New paleomagnetic data, after correction of the inclination shallow bias of the sedimentary rocks, yielded a robust paleolatitude of the Xigaze ophiolite at −16.5°N. Available Early Cretaceous paleomagnetic results obtained from volcanic rocks provide paleolatitudes of 14.7±5.5°N and 18.6±2.1°N for the Lhasa terrane (Chen *et al*., 2012; Ma *et al*., 2014; Yang *et al*., 2015). These data indicate that the distribution of the cover sediment of the Xigaze ophiolite occurred in the Gangdese forearc, and formed the basement of the Xigaze forearc strata (Huang *et al.*, 2015) (location 8 in Figure 4). Both the Nidar and Xigaze ophiolites contain similar arc volcanism and equivalent upper Barremian to upper Aptian sedimentary successions. The Nidar and Xigaze ophiolites were interpreted as distant chronological equivalents (Zyabrev *et al*., 2008).

Ziabrev *et al*. (2004) reported *Turbocapsula costata* (text-fig. 3.51 in Ziabrev *et al*., 2004) from a siliceous mudstone, which indicates the hemipelagic part of the Jurassic–Lower Cretaceous siliceous sequence in the Bainang terrane (location 9 in Figure 2). Matsuoka *et al*. (2002) reported the occurrence of *T. costata* (text-fig. 7.12 in Matsuoka *et al*., 2002) from siliceous mudstone and mudstone samples in the Xialu-E section. The *Turbocapsula costata* Zone, which can be assigned to the Aptian, was introduced.

Radiolarites from the Bainang sections yield low paleomagnetic inclinations that would suggest a subequatorial paleolatitude, but the distribution of the paleomagnetic directions in these rocks strongly suggests a low inclination bias by compaction (Huang *et al*., 2015). The Xialu fauna of the *Pseudodictyomitra carpatica* Zone (KR 1) of Tithonian–early Valanginian age contains many taxa common to the Torinosu fauna that inhabited northern hemisphere middle-latitude (temperate) locations and is less similar to low-latitude (tropical) assemblages represented by the coeval Mariana fauna (Matsuoka *et al*., 2005). The middle-latitude (temperate) fauna from the Xialu Chert suggests that Xialu radiolarians were deposited in middle latitudes of the southern hemisphere. Aptian *Turbocapsula*-bearing hemipelagic siliceous mudstone above the Xialu Chert must have accumulated in locations north to the Tithonian–early Valanginian (KR 1) chert. The existence of terrigenous components in the siliceous mudstone indicates the sediments were accumulated close to a subduction zone (location 9 in Figure 4).

Li *et al*. (2017) reported specimens of *Turbocapsula costata* (text-figs. 4.14–4.30, 5.13–5.22 in Li *et al*., 2017) and discussed its phyletic relationship with other species of the genus *Turbocapsula* based on radiolarian biostratigraphic analyses on passive margin sediments off the Indian continent (“Greater India”) near Babazhadong (location 10 in Figure 2). Paleomagnetic investigation was conducted on the Xiare and Weimei formations (Jurassic) and Chuangde Formation (Cretaceous) in the Chuangde area of southern Tibet. The paleomagnetic results were interpreted to represent remanence of a normal polarity based on geological constraints and thus indicate that the Tethyan Himalaya was located at 33.1±5.6°S in the Late Cretaceous (80.1±6.2 Ma) (Zhang *et al*., 2017). The paleolatitude of the Tethyan Himalaya is similar to the coeval paleolatitude of India (reference site: 28.0°N, 88.5°E), suggesting that the Tethyan Himalaya and India were not separated by oceans, but likely formed a single crustal block in the Campanian. A section studied by Li *et al*. (2017), which is located 600 km west of the Chuangde area, belongs to the Tethyan Himalaya. Therefore, the *T. costata*-bearing strata near Babazhadong should be close to the north margin of the Indian continent during the Early Cretaceous.

Rotti Island, Indonesia

Rotti Island is situated off the southwestern tip of West Timor, Indonesia. The island of Timor and adjacent small islands belong to the Outer Banda arc, part of the Australian continental margin (Audley-Charles, 2011). From the chalks on the Indonesian island of Rotti (loca-

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tion 11 in Figure 2), a specimen of *Turbocapsula costata* (p. 623, fig. 14.6d in Sanfilippo and Riedel, 1985) was reported as *Theocorys antiqua* Squinabol.

Regions without *Turbocapsula costata* (Wu)

Although Barremian to Aptian radiolarian assemblages were discovered from the Pacific, the North Atlantic, and northwestern Australia, no *Turbocapsula costata* has been reported from these regions (Figures 2, 4).

The Pacific

Site 463 of Deep Sea Drilling Project (DSDP) Leg 62 was drilled at the Mid-Pacific Mountains (location 12 in Figure 2). Remarkable amounts of well preserved radiolarians were recovered in the upper Lower Cretaceous sediments (Schaaf, 1981). Radiolarian faunas of the *Dibolachras tytthopora* Zone, the *Crolanium pythiae* Zone, the *Archicapsa similis* Zone, the *Acaeniotyle umbilicata* Zone, and the *Obesacapsula somphedia* Zone range from the late Barremian to the Cenomanian. *Turbocapsula fugitiva* (Schaaf, 1981, p. 440, pl. 24, fig. 10a, b) was reported as *Theocorys antiqua* Squinabol. However, no *T. costata* has been reported. A four-segmented closed nassellarian, *Theocorys renzae* Schaaf (Schaaf, 1981, p. 440, pl. 27, fig. 1a, b) was reported from Lower Cretaceous strata. It differs from *T. tetras* in having pores aligned horizontally and diagonally instead of longitudinally. These specimens are not included in the genus *Turbocapsula* because of the lack of longitudinal costae.

The Jurassic and Cretaceous materials recovered from DSDP Leg 17 in the Pacific are commonly neither well preserved nor abundant. Early Cretaceous radiolarians were found only from Site 167 on the Magellan Rise (location 13 in Figure 2). Material of early Aptian age was not found. The radiolarian association of Zone RK3, which ranges from Hauterivian to early Albian, contains no *Turbocapsula costata* (Moore, 1973).

Age-equivalent Early Cretaceous radiolarian assemblages have also been reported from Southwest Japan (location 14 in Figure 2). An *Acaeoniotyle umbilicata* assemblage, a *Holocryptocanium barbui* assemblage (Kumon *et al*., 1986), and a *Thanarla conica–Ultranapora* sp. assemblage (Matsuyama *et al*., 1982) were reported from the Hidakagawa Group in the Shimanto Belt, Kii Peninsula. An Early Cretaceous *Acaeniotyle umbilicata–Ultranapora praespinifera* assemblage and a *Holocryptocanium barbui–H. geysersensis* assemblage were reported from the Shimanto Belt, Southwest Japan (Nakaseko *et al*., 1979; Nakaseko and Nishimura, 1981). Okamura (1992) also reported Cretaceous radiolarians from the Shimanto Belt in Shikoku, Southwest Japan. No *Turbocapsula costata* has been reported from the Barremian–Aptian radiolarian assemblages in Southwest Japan, which were deposited in the Proto-Pacific. An Early Cretaceous radiolarian assemblage was found in mudstone samples from the Gumizaki Formation in the northwestern part of Kagoshima Prefecture, Japan (location 15 in Figure 2). *Turbocapsula fugitiva* (p. 533, fig. 2.32 in Ishida *et al*., 2008) was reported together with *Crolanium puga* (Schaaf), *Dictyomitra communis* (Squinabol), *Gangylothorax verbeeki* (Tan Sin Hok), *Godia decora* (Li and Wu), *Hiscocapsa grutterinki* (Tan Sin Hok), *Pseudodictyomitra carpatica* (Lozyniak), *P. hornatissima* (Squinabol), *P. lodogaensis* Pessagno, *Pseudoeucyrtis hanni* (Tan Sin Hok), *Stichomitra simplex* (Smirnova and Aliev), *Thanarla conica* (Aliev) sensu Taketani (1982), *T. brouweri* (Tan Sin Hok), and *T. lacrimula* (Foreman). The assemblage indicates the late early to middle Aptian in age.

The East Sakhalin accretionary wedge is a part of the Cretaceous–Paleogene accretionary system, which developed in eastern Asia first as an island arc and then as a continental margin structure in response to subduction of the oceanic plates of the Northwest Pacific (Parfenov, 1984). The accretionary wedge represents a scaly–thrust structure composed of intensely deformed volcanogenic–siliceous, terrigenous, and metamorphic rocks with ophiolitic massifs. Berriasian–Valanginian, Barremian, and Aptian radiolarians were reported from the East Sakhalin Mountains (Kurilov and Vishnevskaya, 2011; Zyabrev, 2011) (location 16 in Figure 2). Specimens (pl. 3, fig. 10, pl. 4, figs. 2, 3 in Kurilov and Vishnevskaya, 2011) morphologically similar to *Turbocapsula costata* were reported as *T. costata* in the Aptian–Albian radiolarian assemblage from tuffaceous cherty rocks of the Khoe Formation, which are exposed in the Pravyi Nabil River Basin. One specimen (pl. 6, fig. 10 in Kurilov and Vishnevskaya, 2011) morphologically similar to *Turbocapsula costata* was reported as *Turbocapsula* aff. *costata*. A similar specimen was reported as *T. costata* (pl. 3, fig. 34 in Zyabrev, 2011) from lower Aptian to middle Albian hemipelagic siliceous mudstones in the Nabil zone of the East Sakhalin accretionary wedge. A similar specimen was reported as *Protunuma* sp. (pl. 6, fig. 19 in Tumanda, 1989) from one black chert from the Poronupuri Formation in the Nakanogawa section, Hokkaido, Japan (location 17 in Figure 2). The sample yielded abundant radiolarian species belonging to the *Staurosphaera septemporata–Parvicingula usotanensis* Assemblage Zone. However, according to the phyletic evolution of *Turbocapsula*, specimens with fewer than 5 obvious costae (*T. costata costata*) in lateral view bear an inflated spherical abdomen (Li *et al*., 2017). *Turbocapsula* aff. *costata*, *T. costata*, and *Protunuma* sp. reported by Kurilov and Vishnevskaya (2011), Tumanda (1989),

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and Zyabrev (2011), which bear a slender abdomen and are probably four-segmented, are not *T. costata* with three segments.

Paleolatitudes of 18±5°N and 28±5°N are estimated for the Kiselevka-Manoma terrane and West Sakhalin Basin using the data sets of Abrajevitch *et al.* (2012) and Didenko *et al.* (2014), respectively. The Zhuravlevka-Amur terrane, the Kiselevka-Manoma terrane, and the East Sakhalin accretionary wedge were extended in an east–west direction during the Early Cretaceous, while their declinations were directed toward the north. Based on the schematic reconstructions of these three terranes in the Late Jurassic to Early Cretaceous, the East Sakhalin accretionary wedge was located in low latitudes of the northern hemisphere (Ichihashi *et al.*, 2015).

The North Atlantic

Cretaceous radiolarians in the North Atlantic deep-sea sequences are not well documented. Radiolarian associations at ODP Sites 638 and 641 in the North Atlantic (Thurow, 1988) (location 18 in Figure 2), which are assigned to the *Crolanium pythiae* Zone, the *Stichocapsa euganea* Zone, and the *Acaeniotyle umbilicata* Zone, indicate an age range of Barremian to Aptian. However, no *Turbocapsula costata* has been reported from the Cretaceous sediments.

Western Australia

Mid- to high-latitude Austral faunas were reported from the Windalia Radiolarite in the Carnarvon Basin of western Australia (location 19 in Figure 2). The Windalia Radiolarite is late (latest) Aptian to Albian in age as indicated by ammonites and belemnites. *Turbocapsula fugitiva* (p. 974, pl. 4, figs. 17, 22 in Ellis, 1993) is present in the Austral faunas. However, no *Turbocapsula costata* (Wu) has been reported.

Abundant and well-preserved Barremian to Albian radiolarian faunas were also reported from ODP Site 765, Leg 123 (location 20 in Figure 2) and DSDP Site 261, Leg 27 (location 21 in Figure 2), off northwestern Australia. Radiolarians from ODP Site 765 are characterized by the dominance of non-Tethyan forms and by the scarcity of Tethyan taxa. No species of *Turbocapsula* was reported from Site 765 (Baumgartner, 1992, 1993). *Turbocapsula tetras* (p. 623, fig. 14.6c in Sanfilippo and Riedel, 1985) and *T. fugitiva* (p. 798, pl. 6, figs. 4–7 and pl. 11, fig. 4 in Renz, 1974; p. 623, figs. 14.6a,b in Sanfilippo and Riedel, 1985) were present at Site 261. However, no *T. costata* (Wu) was reported off northwestern Australia.

Discussion

The distribution of the *Turbocapsula costata* territory

Turbocapsula costata (Wu) has been discovered at many localities in the world (Figure 2). The localities are distributed in the present northern hemisphere except one scattered record from the southern hemisphere locality in the Indonesian island of Rotti. Possible depositional sites of *T. costata*-bearing rocks during the Early Cretaceous are shown in Figure 4. The occurrences of *T. costata* show a latitudinal spread of 30°N to 40°S. They are concentrated in low latitudes of the Mediterranean and the eastern Tethys. The occurrences of *T. costata* are also located in the middle latitude of the southern margin of the eastern Tethys (north of the Indian and Australian continents). No *T. costata* has been reported from mid- to high-latitudes off northwestern Australia. On the basis of the occurrences of *T. costata*, we propose the term, *Turbocapsula costata* territory, for the water mass that *T. costata* inhabited. The northern and southern limits of the *Turbocapsula costata* territory are drawn based on the land masses around the Mediterranean and eastern Tethys. However, the latitude, width, location, and depth of sills in the Tethys seaway vary in different paleogeographic reconstructions (Hay, 2009).

Study on living radiolarians shows a close relationship between some radiolarian taxa and worldwide water masses and circulation patterns (Gordon, 1973; Welling *et al.*, 1996; Ishitani *et al.*, 2008; Boltovskoy *et al.*, 2010). Early Cretaceous radiolarian assemblages can be recovered both in the Mediterranean and the eastern Tethys. The Mediterranean and the North Atlantic were connected through a strait. The strait was narrowed since the Aptian, and circulation in the North Atlantic has decreased, causing the North Atlantic to become a restricted basin (Thurow, 1988). The paleobathymetry of the Atlantic and Tethys would make it likely that each basin might have its own source for deep water, its own nutrient supply, and its own recycling system. It is unlikely that there were many unobstructed passages from the Tethys of dense water formation into the Pacific Basin. The absence of *Turbocapsula costata* in the North Atlantic and the Pacific may be explained by the supposition that this species inhabited a particular water mass within the Mediterranean and the Tethys. The radiolarian assemblage of the latest Barremian to the Aptian interval in the North Atlantic was only reported by Thurow (1988). Poor preservation and incomplete faunal description are also likely to explain the lack of *T. costata* in the North Atlantic. More research is needed to testify whether *T. costata* is an endemic species restricted to the Tethys.

A great number of specimens of *Turbocapsula costata* were reported from the Betic Cordillera (southern Spain),

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the Umbria–Marche (northern Apennines, Italy), the eastern Tethys (Ladakh Himalaya and southern Tibet), and Rotti Island. The presence of *T. costata* at the localities mentioned above indicates that this species has different tolerances on environmental parameters, including the latitudinal relative position and the water depth. The Betic Cordillera and the Umbria–Marche Basin were located in restricted marginal seas and at a water depth shallower than the calcium carbonate compensation depth (CCD). Radiolarites in the Bainang terrane were deposited in a hemipelagic setting and at a water depth deeper than the CCD. A *Turbocapsula costata*-bearing siliceous sequence occupied the latitudes between 30°N to 40°S. Although meridional and ocean-continent temperature gradients during the Cretaceous were lower than today, there was clearly a meridional climatic zonation, reflected in the modern use of the terms ''Boreal'' and ''Tethyan'', based on the biogeographic distribution of ammonites and other marine molluscs (Neumayr, 1883; Uhlig, 1911; Hay, 1995, 2008). However, their ''Boreal realm'' was in northern Europe, Greenland, and Alaska. On modern plate tectonic reconstructions the boundary between the Tethyan and Boreal realms plots at a latitude of about 40°N (Wagreich, 1992; Voigt *et al.*, 1999; Mutterlose *et al.*, 2003). The Mesozoic radiolarian provinces are differentiated by latitude and include the Austral, Tethyan, and Boreal realms (Pessagno and Blome, 1986; Kiessling, 1999; Pessagno and Hull, 2002; Carter and Haggart, 2006). Temperature is presumably a latitudinal component (Petrushevskaya, 1971). The fact that no *T. costata* was reported from middle to high latitudes off northwestern Australia indicates that *T. costata* could not survive in a cold water environment.

The *Turbocapsula costata* territory and correlation of radiolarian zonation

Turbocapsula costata (Wu) occurred in low and middle latitudes of the Mediterranean and eastern Tethys. No *T. costata* has been reported from the Atlantic and the Pacific so far. Pessagno and Hull (2002) placed the boundary between the Tethyan and Boreal realms at 30°N and the boundary between the Tethyan and Austral realms at 30°S. *Turbocapsula costata* (Wu) is concentrated in the Mediterranean and eastern Tethys of the Tethyan realm. The results indicate that the zonation provides useful correlations within the Tethys because of the rapid and easily recognizable phyletic evolution of the genus *Turbocapsula*. O'Dogherty (1994) reported mid-Cretaceous radiolarian biostratigraphic results in the Betic Cordillera (southern Spain) and the Apennines (Italy). The Asseni Zone and Turbocapsula Zone (Verbeeki Subzone and Costata Subzone) were defined for the Barremian to Aptian (Figure 3). The first appearance biohorizon (FAB) of the genus *Turbocapsula* was used to define the base of the Turbocapsula Zone. The total range of this genus defines the Turbocapsula Zone. The FAB of *T. costata* was used to define the base of the Costata Subzone. The rare occurrence and small size of *Turbocapsula* specimens during the primitive stage make it difficult to recognize the base of his Turbocapsula Zone. Matsuoka (1995), in a zonal scheme for the Jurassic to Lower Cretaceous in Japan and the western Pacific, introduced the *Acanthocircus carinatus* Zone for the interval above the *Cecrops septemporatus* Zone. Dumitrica *et al.* (1997) revised this zone as the *Aurisaturnalis carinatus* Zone and divided it into the *Aurisaturnalis carinatus carinatus* Subzone and the *Aurisaturnalis carinatus perforatus* Subzone. The base of the *Aurisaturnalis carinatus* Zone is marked by the evolutionary first appearance biohorizon (EFAB) of *Aurisaturnalis carinatus carinatus* (Foreman). The *Aurisaturnalis carinatus perforatus* Subzone was defined as the interval between the EFAB of *A. carinatus perforatus* Dumitrica and Dumitrica-Jud and the last appearance of this subspecies. Based on the phyletic evolution of *Aurisaturnalis* and *Turbocapsula*, two radiolarian zones have been defined: the *Aurisaturnalis carinatus* Zone and the *Turbocapsula costata* Zone (Li *et al*., 2017). The top of the *Aurisaturnalis carinatus* Zone of Dumitrica *et al.* (1997) was revised as the evolutionary first appearance biohorizon (EFAB) of *Turbocapsula costata multicostata* Li and Matsuoka. The Costata Subzone of O'Dogherty (1994) is correlative to the *Turbocapsula costata* Zone of Li *et al*. (2017). The EFAB of *T. costata costata*, which marks the evolution of *T. costata*, is used for subdividing the *Turbocapsula costata* Zone into two subzones: the *Turbocapsula costata multicostata* Subzone and the *Turbocapsula costata costata* Subzone (Li *et al*., 2017). The radiolarian zonations established by O'Dogherty (1994) and Li *et al*. (2017) are an important zonal scheme for the Barremian to Aptian interval (Figure 3). The EFAB of *T. costata costata* is a key horizon for these zonations. However, both of these zonations established based on the genus *Turbocapsula* cannot be utilized for Early Cretaceous zonal correlations beyond the *T. costata* territory. More detailed radiolarian biostratigraphic research is needed to establish an interregional correlation of zonal schemes.

Conclusion

The phyletic evolution of the genus *Turbocapsula* has a high stratigraphic value. Lithology, depositional setting, associated fossil records, and paleomagnetic data of *Turbocapsula costata*-bearing strata are overviewed. *Turbocapsula costata* (Wu) occurred in low and middle latitudes of the Mediterranean and eastern Tethys in

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Early Cretaceous time. No *T. costata* was reported from the Atlantic and the Pacific. This indicates *Turbocapsula costata* (Wu) is a paleobiogeographic indicator restricted to the Mediterranean and eastern Tethys of the Tethyan realm. The results emphasize that the phyletic evolution of the genus *Turbocapsula* is significant in correlations within the Tethys. The zonation established by the phyletic evolution of the genus *Turbocapsula* cannot be utilized for Early Cretaceous zonal correlations beyond the *T. costata* territory.

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Author contributions

X. L. collected data and is responsible for the distribution of *Turbocapsula costata* (Wu). A. M. contributed on checking the data and discussion. All authors contributed to the writing of the paper.

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