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Late Triassic bivalves associated with a hydrothermal vent system in the Yidun Island Arc (SW China) of the eastern Tethys

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The Yidun Island Arc in the Three Rivers (Jinsha River, Lancang River, Nujiang River) region of southwestern China is one of the most important Kuroko-type volcanogenic massive sulfide deposits (VMS) in China. Intra-arc rifting of Yidun Island occurred during the Late Carnian-Norian when VMS deposits such as the Gacun Pb-Zn-Cu deposit were formed. A bivalve fauna was found in fine-grained tuffaceous slate and in mineralized tuffaceous siltstone containing very high contents of Pb (45.01–103.37 ppm) and Zn (135.78–300.03 ppm) of the upper Tumugou Formation in the Changtai-Gacun volcanic-sedimentary rift basin. Stratigraphically, the bivalve-bearing beds are equivalents of the Gacun Pb-Zn-Cu deposits. The diversity of this bivalve fauna is very low. It consists mainly of the thin-shelled, epibyssate suspension-feeding bivalves *Pergamidia eumenea* and *Parapergamidia changtaiensis*, the burrowing large, elongated, suspension-feeding *Trigonodus keuperinus* and *Unionites*? sp., and occasional specimens of the endobyssate suspension-feeding *Trigonodus*? sp. and the deep burrowing suspension-feeding *Pleuromya markiamensis*. Individuals of the first four taxa are so abundant that the specimens are sometimes concentrated in shell beds, probably indicating a gregarious habit. This bivalve fauna is associated with internal moulds of cylindrical, slightly conical tubes most likely produced by a worm-shaped organism. Composition, morphology, diversity, and high abundance of this fauna, chemical features of the surrounding sediment, and the tectonic setting all suggest that this bivalve fauna lived in a deep-water environment in or around a hydrothermal vent system.

Late Triassic, hydrothermal vents, bivalves, Yidun Island Arc of the eastern Tethys

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Hydrothermal vent communities at seafloor-spreading centers are one of the most important research fields in connection with hydrothermal mineralization since they were first discovered in the Galapagos Rift at 2500 m depth [1, 2]. Hydrothermal vent communities were subsequently found at mid-ocean ridge settings in the east Pacific [3–5], Atlantic [6–9], Indian Ocean [10], and in the island arc basins of the west Pacific [11–13]. Vent communities are unique in that they live under conditions of high temperature, low pH, toxicity, high levels of hydrogen sulfide and methane, high metal levels (especially Fe, Mn, Zn, and Cu), and anoxia [14, 15] or in the mixing zone between ambient seawater and vent fluid. Only some taxa such as large bivalves and vestimentiferan tube worms are dominant around vents be-

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sides shrimps and limpets [16]. The metabolism of these large organisms depends entirely on internal symbiotic chemosynthetic bacteria [17–20] .

The discovery of hydrothermal vent communities on modern sea floors also has attracted research interests in ancient hydrothermal vent communities. A number of hydrothermal vent fossils in tectonic settings and volcanic sulfide deposits similar to modern hydrothermal vent communities have been found, for example, in the Early Carboniferous Ballynoe barite deposits [21–23] and Tynagh lead-zinc deposits of Ireland [24], the Cretaceous sulfide ores of the Samail Ophiolite of Oman [25, 26], the Late Cretaceous Troodos Ophiolite of Cyprus [27, 28], the Paleozoic Sibay and Yaman Kasy massive sulfide deposits from the southern Urals [29–36], the Early Jurassic Franciscan Complex of California [37, 38], the Late Cretaceous to Paleocene New Caledonia [39], and in the base of Cambrian barite of western China [40].

The vent rocks from southern Urals contain bivalves, gastropods and monoplacophorans, the Cyprus vents gastropods, and the Californian ophiolites brachiopods and gastropods. All vent fossils are dominated by vestimentiferan tube worms. In these ancient vents, communities composed of bivalves are only known from Paleozoic rocks of the southern Urals [35].

In the Yidun Island Arc of the eastern Paleotethys, southwestern China (Figure 1), a Late Triassic (Late Carnian-Early Norian) bivalve fauna dominated by fairly large epibyssate mussels such as pergamidiids and reclining forms such as pachycardiids was recently found in deposits with very high Pb (45.01–103.37 ppm) and Zn (135.78–300.03 ppm) of the upper Tumugou Formation of the Changtai-Gacun volcanic-sedimentary rift basin [42]. The bivalve-bearing strata are sandwiched between basalts, andesites, and rhyolites below and andesites and rhyolites above. No organisms except those adapted to hydrothermal vent environments could have tolerated the environments with such high Pb and Zn concentrations. This bivalve fauna, therefore, probably represents a hydrothermal community.

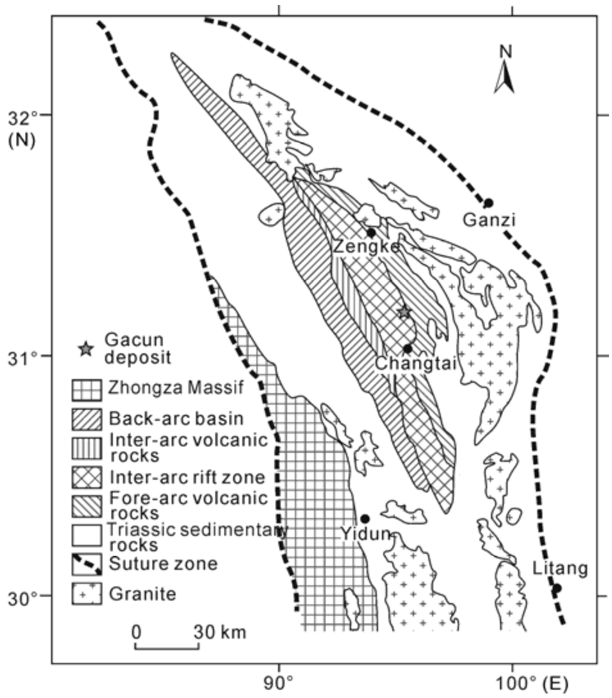

Figure 1 Geologic map of the Changtai-Gacun area and volcanic-sedimentary rift basin (after Figures 2–10 in ref. [41]).

1 Geologic setting

The Yidun Island Arc is situated in the eastern part of the Tethys orogenic belt. It underwent an evolution from early arc construction, intra-arc rifting, late arc construction to back-arc spreading. The complete trench-arc-basin system was not formed until intra-arc rifting occurred during the Late Carnian-Norian. In the intra-arc rift, four separate rift basins differing in dimensions and depth developed [43] i.e., the Zenke, Changtai-Gacun, Xiangcheng, and Zhongdian basins. The Changtai-Gacun rift basin had a water depth of about 800–1200 m by the fluid inclusions from the Gacun deposit and sedimentary analysis of Tumugou Formation [43]. A bimodal calc-alkaline volcanic suite at the seafloor and abyssal sedimentary rocks characterized the intra-arc rift zone. Tectonically, the rock succession resembles that of the back-arc Okinawa Trough spreading zone [44] and the Miocene back-arc sequence of northwestern Japan [45]. Volcanic massive sulfide (VMS) deposits and ore spots formed in the Late Carnian-Norian intra-arc rift zone. The Gacun Pb-Zn-Cu-Ag deposit is the biggest of the VMS deposits of the Changtai-Gacun volcanic-sedimentary basin [43]. The formation process of the VMS deposits is thought to have been similar to that of the Kuroko-type VMS deposits on the modern sea floor [41].

The bivalve fossils come from the upper Tumugou Formation (= Gacun Formation, Figure 2) of the Changtai-Gacun volcanic-sedimentary basin (Figure 1). In the Gacun area, the fossils occur in fine-grained tuffaceous slate, and in the Changtai area in a lens within limonitic mineralized tuffaceous siltstones containing Pb-Zn-Cu-Ag ores. In both areas, the fossiliferous strata are underlain by basalts, andesites and rhyolites, and overlain by andesites and rhyolites. This sequence represents the slow process from spreading to closure and from closure to stretching of the intra-arc rift of the Yidun Arc.

Lin et al. [42] demonstrated, by means of ammonoids such as *Juvanites* and *Griesbachites*, and by bivalves such as *Halobia dilatata* and *Pergamidia eumenea*, that the Tumugou Formation is mainly Early Norian in age, but probably extends back to the Late Carnian. Thus, the present bivalve assemblage can be placed in the Late Carnian-Norian.

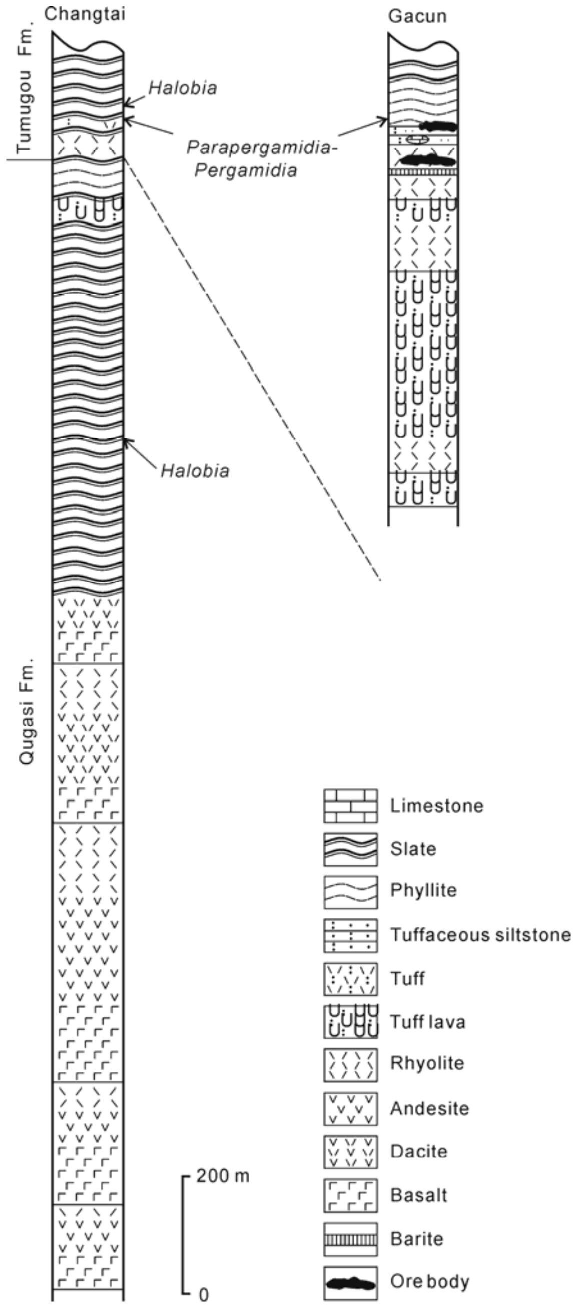

Figure 2 Lithologs of the Tumugou Formation at Changtai (a) and Gacun (b) with positions of the bivalve fauna.

2 The bivalve assemblage

2.1 Bivalve assemblage

The bivalve assemblage of the upper Tumugou Formation in the Gacun-Changtai area is dominated by abundant, large (maximum length >100 mm), thin-shelled (maximum thickness <1 mm), epibyssate, suspension-feeding, *Mytilus*- to *Modiolus*-like bivalves of the family Pergamidiidae, i.e., *Pergamidia eumenea* (Figure 3(c), (d)) and *Parapergamidia changtaiensis* (Figure 3(e)-3). These are associated with many elongated, suspension-feeding pachycardiid bivalves including *Trigonodus keuperinus* (Figure 3(a)), some of which are quite large (length about 240 mm), and *Unionites*? sp. (Figure 3(f)). Additional taxa are occasional specimens of the probably endobyssate suspension-feeding *Triaphorus*? sp. (Figure 3(e)-2) and the deep-burrowing suspension-feeding *Pleuromya markiamensis* (Figure 3(e)-1). Fragments or very poorly preserved specimens of the thin-shelled, byssate, suspension-feeding bivalve *Halobia* and pelagic ammonoids also occur. Associated fossils include internal moulds of straight to slightly curved cylindrical tubes with a maximum diameter of 4 mm (Figure 3(b)).

This characteristic assemblage exhibits low species diversity but very high individual abundance. Epifaunal suspension-feeders dominate, whereas deposit-/detritus-feeders appear to have been absent.

2.2 Preservation of fossils

These bivalves' fossil assemblages show a patchy spatial distribution. As their shells have been fairly thin, most of the specimens, including the very large individuals, are moulds of complete single valves, which are occasionally concentrated in beds (Figure 3(f)). This implies extensive time-averaging and a residence time on the sea floor long enough for the valves to become separated before final burial. Given that the environment was quite deep, quiet, and toxic for most organisms, physical and biological reworking appears to have been absent. Processes responsible for the formation of the shell concentrations most likely were, apart from the low rate of sedimentation, a gregarious settling behavior of the bivalves and comparatively high population densities. In addition, compaction of the sediments may have accentuated the shell density.

The bivalve *Halobia* and ammonoids are scarce, fragmentary or very poorly preserved. The latter clearly dropped from the water column to the sea floor. The same may have been true also of specimens of *Halobia*, which apart from their normal benthic mode of life probably might have adopted a pseudoplanktonic life style.

Except for a few specimens with remains of shell, the bivalves are preserved as external and internal moulds, the original shell material having been dissolved during diagenesis.

3 Geochemistry of fossiliferous deposits

In all fossils collected, only one has a calcareous crust and others are moulds (like the fossils in Figure 3(f)). All moulds are coated with pyrite, limonite, and oxidized manganese. The veins in the rock bearing fossils are filled by pyrite, limonite, and oxidized manganese, which are similar to coated moulds of fossils. In some cases, the cavities between the internal and external moulds are completely filled

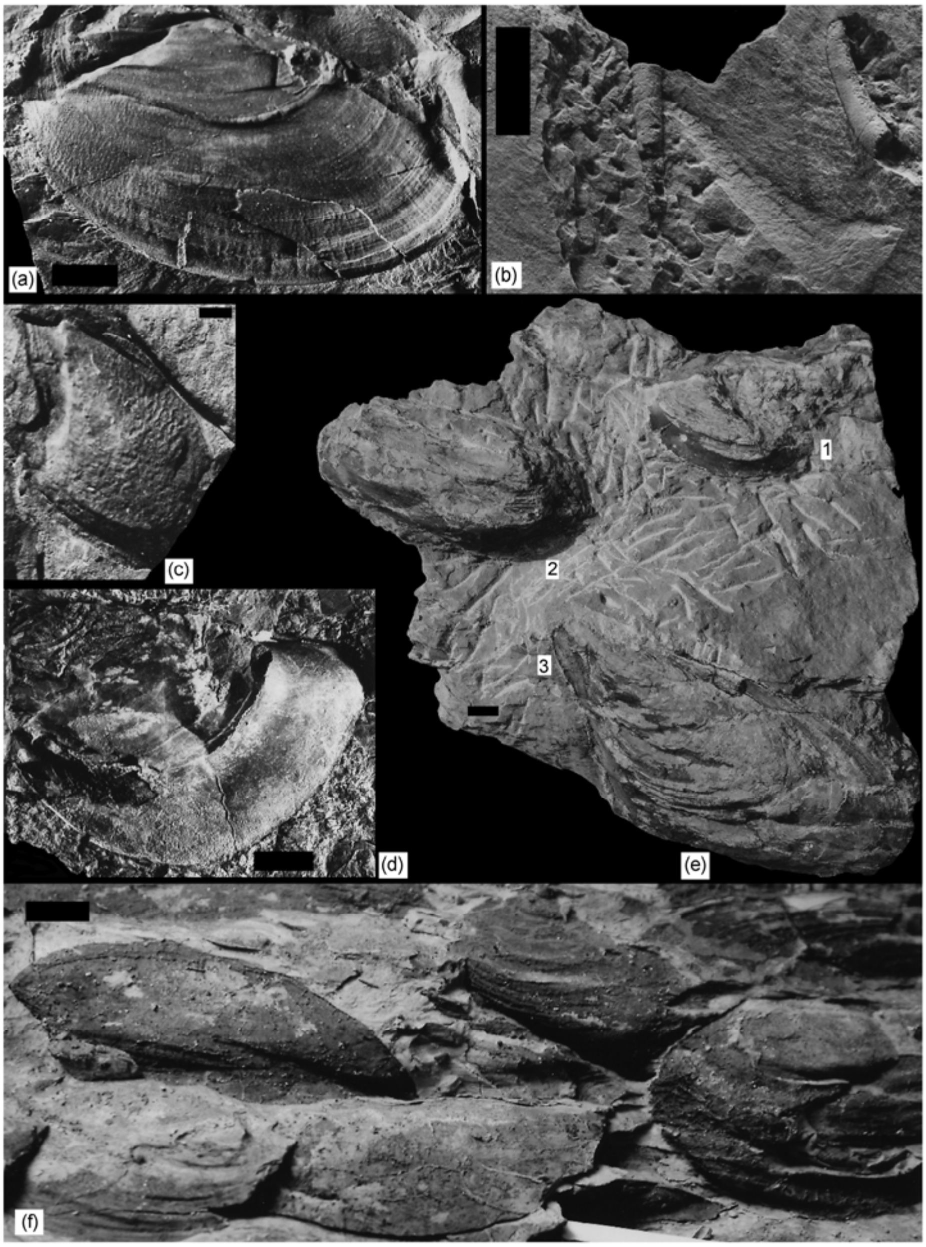

Figure 3 Late Triassic fossils in rocks of the upper Tumugou Formation containing very high contents of lead and zinc. Scale bar: 1 cm. (a) *Trigonodus keuperinus* (Berger, 1854), left internal mould; (b) internal moulds of cylindrical, slightly conical tubes; (c) and (d) *Pergamidia eumenea* Bittner, 1891, right internal mould (c) and left internal mould (d). (e) *Pleuromya markamensis* Zhang, 1985 (1, left internal mould with remains of shell, *Triaphorus* ? sp.; 2, right internal mould with remains of shell, and *Parapergamidia changtaiensis* Lin, Zhu, Pang et Sha, 2007; 3, left valve. F, Concentration of *Unionites*? sp., internal moulds).

with mixture materials of bearing the elements of Mn, Fe, Zn, Pb, Cu, and Ba. These elements are also highly concentrated in the rocks enclosing the bivalves, but the concentrations of the metallic elements in the film coating the bivalve moulds are much higher. In the Gacun area, manganese and iron contents are 1.98% and 7.04% respectively in the film coating internal moulds, but 0.2%–0.45% and 3.78%–4.40% in the matrix. Zn, Pb and Cu contents in films covering the internal moulds and in the matrix reach up to 1172, 202, and 78.5 ppm, respectively. In three samples of the matrix, the average contents of Zn, Pb and Cu are 133.438, 62.920, and 56.289 ppm, respectively. In the Changtai area, the manganese and iron contents in the film covering internal moulds range from 0.35% to 9.24%. In three samples of matrix, the average contents of Zn, Pb, Cu and Ba are 135.885, 41.679, 46.45 and 743.611 ppm, respectively, and the maximum values 161.448, 63.278, 66.134, and 804.101 ppm, respectively (Table 1).

Table 1 Concentrations of metallic elements in fossils and matrix in Gacun and Changtai a)

Deposits	Samples	Mn (%)	Fe (%)	Zn (ppm)	Pb (ppm)	Cu (ppm)	Ba (ppm)
Gacun	Fossil (internal moulds)	1.98	7.04	1172	202	78.5	
	matrix	0.2–0.45	3.78–4.40	133.438	62.920	56.289	395.617
Changtai	fossil	5.88	33.43	161.448	63.278	66.134	804.101
	matrix	0.35	9.24	135.885	41.679	46.45	743.611
21°N East Pacific Rise [46]	hydrothermal solutions	0.07–0.1	0.0750–0.2400	40–106	0.183–0.359		
Guaymas Basin [47]	hydrothermal solutions	0.0132–0.0236	0.0017–0.018	0.1–40	0.020–0.652	0.02–1.1	
11°–13°N East Pacific Rise [48]	sulfide-forming metals	0.0742–0.2932	0.164–1.0760	2–105	0.009–0.270		
Okinawa Trough [49]	hydrothermal sediment			7.6	0.036	0.003	

a) The moulds of fossils were peeled off and measured. The matrix is materials between fossils and did not mineralize. The elements of samples were analyzed by ICP-MS in Cardiff School of Earth, Ocean and Planetary Science, Cardiff University.

4 Discussion

Both the films covering the bivalve moulds and the matrix contain a great amount of metallic elements including Pb and Zn. The concentrations are even much higher than those recorded in hydrothermal solutions of the 21°N East Pacific Rise [46] (Table 1), in hydrothermal solutions of the Guayman Basin [47], in sulfide-forming metals of 11°–13°N East Pacific Rise [48] (Table 1), and in hydrothermal sediments of the Okinawa Trough [49] (Table 1), where only hydrothermal vent biota exist. How did this concentration of metallic elements originate?

Although the concentration of metallic elements in the films and/or matrix probably has been partially accentuated during diagenesis or weathering, the existence of time-equivalent volcanic massive sulfide (VMS) deposits and ore spots, such as the Pb-Zn-Cu-Ag deposit of Gacun, strongly suggests also a synsedimentary concentration process. Thus, the various abundant metallic elements might have come from the underlying volcanic massive sulfide (VMS) deposits, or from hydrothermal vents caused by tectonic activity in the island arc along the Tethys suture, around or in the area colonized by bivalve fauna.

An environment similar to modern hydrothermal vents is corroborated by the fact that the bivalve fauna contains unusually large individuals, given its bathymetric position, and is dominated by epibyssate taxa, which occasionally are densely packed. These features resemble those of modern hydrothermal vent bivalves, which are characterized by large *Bathymodiolus* and/or *Calyptogena* in the Okinawa Trough [50, 51], on the sea floor of the western Pacific [11, 13], on the Mid-Atlantic Ridge [6–9] and Indian Ocean Ridge [10], in the eastern Pacific [52, 53], and on the Galapagos Rift [1, 2, 54].

With respect to water depth, modern hydrothermal vent bivalves have been recorded from abyssal and bathyal regions to the continental slope, between 4200 m and 900 m [55, 56]. As for substrate, modern hydrothermal vent bivalves are able to live on or in various types of substrate including sandy substrates surrounding eruptive areas (e.g. in the Okinawa Trough) [49, 51, 56], and in vent cracks within basalt (e.g., in the Galapagos Rift vents) [5, 57]. However, the various types of substrates have in common that they are related to hydrothermal activity and/or influenced by hydrothermal waters.

The biomass of modern hydrothermal community exceeds by far that of normal marine epibenthic communities. The Late Triassic bivalves of Gacun and Changtai occasionally are concentrated in shell layers, as in modern vent settings [4, 5, 9, 11, 53, 57, 58]. Apart from a low rate of sedimentation, the high productivity was most likely responsible for it.

5 Conclusions

Paleontological, lithological and geochemical evidence suggest that the Late Triassic bivalve fauna, dominated by members of the Pergamidiidae and Pachycardiidae and occurring in highly metalliferous sediments of the Yidun Island Arc of the eastern Tethys, lived in a deep-sea environment subjected to tectonic activity and under the influence of hydrothermal waters [41]. It most probably represents a hydrothermal vent fauna.

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