Recurrent breakdown of Late Permian reef communities in response to episodic volcanic activities - evidence from southern Guizhou in South China

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Abstract

Reefs, both living and ancient, are extremely sensitive to environmental change. Recurrent breakdown of reef communities implies episodic occurrence of unfavourable marine conditions. An alternating sequence of reef limestone with algal-foraminiferal grainstone records frequent change of Late Permian shallow marine ecology in the Ziyun area of Guizhou Province, South China. The algal-foraminiferal grainstone interbedded in the marginal platform reef succession there has long been regarded as backreef lagoon deposits, indicating lateral facies changes as the sequence developed. However, our research reveals for the first time abundant pristine quartz crystals and volcanic glass scattered in the interbedded algal-foraminiferal layers but not in reef facies, suggesting temporal environmental change, not a simple facies shift. Many quartz crystals form overgrowths nucleated on smaller quartz crystals; the overgrowths are diagenetic, but the nuclei are good evidence of volcanic source. Therefore, the alternating formation of reef limestone with algal-foraminiferal limestone is interpreted as the result of episodic volcanic activity during the Late Permian. Temporary punctuations by nearby volcanic eruptions are suggested to have caused recurrent breakdown of reef communities and the occupation of reef ecological space by algal-foraminiferal fauna. The quartz crystals are evidence that this interpretation is more likely than other controls such as sea-level change. Cement-rich encrusted framestone (comprised of *Archaeolithoporella* encrusting sponges) at the top of the reef sequence, as well as abundant volcanic quartz, implies that both volcanism and increased temperature may be involved in leading to the complete collapse of the reef ecosystem flourishing in Changhsingian time in South China.

Keywords Reef - Sedimentary facies - Volcanism - Late Permian - South China

Introduction

Global marine mass extinction at the end of the Permian Period has been interpreted to be the result of multiple causes (Knoll et al. 1996; Wignall and Twichett

1996; Meyer et al. 2008; Meyer and Kump 2008; Heydari and Hassanzadeh 2003; Algeo et al. 2011). In South China, this global extinction event may be associated with disastrous volcanism (Yin et al. 1992) due to the widespread clay derived from volcanic ash near the Permo-Triassic boundary (PTB) (Yang et al. 1991). Currently, substantial evidence from oxygen isotopes from conodonts indicate volcano-induced lethally hot temperatures in the aftermath of the end-Permian event (Sun et al. 2012), strongly supporting the triggering role of volcanism (Wignall 2011).

Besides the thickest and widespread clay deposited just at the end-Permian mass extinction horizon, several other clay layers can also be found close to the PTB (Cao and Zheng 2007). The presence of other clay layers below the extinction boundary in many basinal sections as well as in terrestrial sections (Zhou et al. 1990; Wang and Yin, 2002) provides a reason to believe that the marine environment was frequently affected by volcanic activity throughout the entire Late Permian. However, volcanic clay is poorly preserved in shallow carbonate platforms including reef facies in most areas of South China because of the more turbulent conditions and high sedimentation rate of calcareous debris in shallow marine environments. Consequently, the impact of the Late Permian volcanic events on reef communities and shallow platform faunas is difficult to determine. Here we present the first record of volcanic glass and abundant pristine quartz crystals in carbonate sediments, which we interpret are derived from volcanic ash deposited on the marginal platform reef succession in Guizhou Province, South China. This work offers new insight into the impact of Late Permian volcanic events on the evolution of ancient reef ecosystems.

Extensive research on Late Permian reef-builders and facies of South China has been published (Fan et al. 1982; Li et al. 1985; Lin 1992; Li et al. 1993; Wang et al. 1996), with numerous studies on the eclipse of Late Permian reef communities (e.g. Stanley 1988; Flügel and Reinhardt 1989; Fan et al. 1990; Wignall 2001; Wu et al. 2007). However, the relationship between reef community evolution and geological events throughout the entire Changhsingian Stage remains unclear. Some studies show that communities in the reef succession underwent several replacements throughout the whole Changhsingian before reef-building disappeared completely (Lin 1992), reflecting the ecological response of Changhsingian reef communities to geological events occurring episodically before the end-Permian mass extinction. Previous studies suggest that the disappearance of the reef communities may be associated with end-Permian sea-level decline (Wu et al. 2003; Wu et al. 2010) or a hypoxia event (Wignall and Twitchett 1996; Weidlich et al. 2003). However, reports concerning the relationship between volcanic events and the evolution of reef communities are still lacking, despite the common interpretation that volcanism was one of the main triggering mechanisms for the end-Permian mass extinction (Yin et al. 1992). Reef communities are extremely sensitive to changes of environmental factors (Smith 1978; Wang 2004; Ruttimann 2006); if we assume that ancient and modern reef communities had similar sensitivities to environmental factors, Late Permian reefs in South China should have been seriously affected by the Late Permian volcanic activities occurring extensively in this region.

Geological setting

In South China, Permian reefs mainly developed during Middle Permian Capitanian and Late Permian Changhsingian, but largely decreased in other stages of the Permian because of enhanced volcanic activities in South China (Peng et al. 1997; Lai et al. 2009). Globally, Late Permian reef distribution is less widespread than Middle Permian reefs (Fan et al. 2005), but South China is exceptional because Late Permian Changhsingian reefs there have a wider distribution than the Middle Permian ones (Fan et al. 1982; Li et al. 1985; Fan et al. 1990; Xu et al. 1997). Late Permian Changhsingian reefs are palaeogeographically located in both the northern and southern margins of the Yangtze Platform, within the South China plate. In the southern margin, reefs crop out along a line from Xingyi, via Longlin, Ceheng, Zhenfeng, Ziyun, Wangmo, to Luodian, forming a zigzag reef belt along the carbonate platform margin within Guizhou Province (Fig. 1). South of the reef belt, facies pass laterally into a fore-platform slope and then the deep-water basin (ie. Nanpanjiang basin) where isolated carbonate platforms with Permian reefs are well developed.

Fig. 1

Palaeogeography and reef distribution of Late Permian Changhsingian (modified from Sang et al. 1986 and Feng et al. 1997).

The best reef outcrop is just south of Ziyun town, at Shitouzhai, where a clear stratigraphic sequence is exposed (Sang et al. 1986; Wang et al. 1996). The

Changhsingian marginal platform reef in Ziyun stretches from northwest to southeast, forming a topographically high carbonate belt, about 3 km long, adjacent to the town (Fig. 1). The reef core facies consists mainly of framestone, bafflestone and encrusted framestone formed by calcareous sponges, hydrozoans, bryozoans and calcareous algae. In addition to the reef limestone, several layers of algal-foraminiferal grainstone and packstone are preserved in the reef core. The restricted backreef lagoon facies occurs northeast of the reef belt, and characterized by dark thick-bedded packstone rich in calcareous algae and foraminifera (Wang et al. 1996). Southwest of the reef belt, the fore-reef slope deposit is composed of thick-bedded limestone talus with different types of packstone and granular limestone breccia transported from the marginal platform (Wang et al. 1996). The lithology passes southwards to fore-reef deep-basin sediments composed mainly of dark grey thin-bedded siliceous rocks and micrite, with radiolarians and sponge spicules.

Facies evolution of the reef complex

The Changhsingian reef of the Shitouzhai section was developed on the underlying Wuchiapingian clastic sediments. Reef limestone began at the very beginning of the Changhsingian and gradually developed into three alternations of algal-foraminiferal grainstone/packstone and sponge bafflestone upward. After deposition of the third layer of algal-foraminiferal grainstone, a large framestone and bafflestone unit more than 80 m thick was formed in the reef core. The fourth non-reef layer consists of bioclastic calcareous algae and benthic foraminifera. The overlying final stage of reef-building is characterized by 16 m thick of encrusted framestone including abundant *Archaeolithoporella* as the main encrusting organism and partly overlain by 1 m thick unit of microcrystalline dolomitic limestone (Fig. 2), marking termination of the luxuriant Changhsingian reef ecosystem in South China. The PTB is a topographically undulating unconformity, representing typical karst topography due to sea level fall at the end of Permian (Wu et al. 2003). The Early Triassic grey-brown marl, with several layers of volcanic clay at the bottom, overlies the unconformity surface and the lithology shifts gradually to thin-bedded silty marl in the overlying sequence (Fig. 2).

Fig. 2

Facies evolution of the Changhsingian reef complex in Shitouzhai section of Ziyun.

In the Shitouzhai section, Late Permian framestone and bafflestone consists mainly of benthic calcareous sponges, hydrozoans, bryozoans, Tabulozoa and *Tubiphytes* (Fig. 3). This assemblage represents a typical Permian reef community inhabiting normal shallow marine environments. Thin sections show biogenic skeletal carbonate and calcite cement are the main components of these reef limestones, with little volcaniclastic or terrigenous siliciclastic sediment. Therefore the reef limestone is interpreted to have been constructed during comparatively stable periods with rare tectonic and/or volcanic activities.

Fig. 3

The Late Permian Changhsingian reef framestone from Shitouzhai section in Ziyun, Guizhou Province.

As mentioned above, several layers of grainstone/packstone rich in calcareous algae and foraminifera are also developed in the marginal platform and were previously considered to be the product of backreef lagoon conditions (Lin 1992). Our observations by both light microscope and scanning electron microscope (SEM) show abundant quartz crystals in these grainstones/packstones (Fig. 4). The quartz crystals are very small (mostly between 30-300μm) and most of them can not be distinguished under optical microscope, only the few larger ones are visible.

Fig. 4

The quartz grains and volcanic glass debris preserved in the grainstone interbedded in the Late Permian reef sequence in Ziyun, Guizhou Province.

Large quantities of quartz grains are preserved mostly in the matrix of the algal-foraminiferal limestone, with a few tiny particles far into the interior of the foraminiferan chambers. However, SEM reveals that many quartz grains are concentrated around foraminifera tests (Fig. 4b). Most quartz grains are well-formed crystals (Fig. 4c), but clearly contain nuclei of smaller quartz crystals (Fig. 4d). Additionally, much volcanic glass debris is present together with the quartz crystals in the grainstone (Fig. 4e).

Fig. 5

Abundant *Tubiphytes* in the grainstone/packstone deposited in the upper part of the Late Permian reef sequence in Ziyun, Guizhou Province. All photos are in plane-polarised light.

It is noteworthy that abundant *Tubiphytes* is present in some parts of algal-foraminiferal grainstones, with quartz crystals included inside the *Tubiphytes* body in some cases (Fig. 5). However, the quartz grains are much smaller (mostly between 30-50 μm) and less perfectly formed than those produced in the grainstone which are double-pointed.

Besides their occurrence in the algal-foraminiferal limestone, quartz crystals also occur in the *Archaeolithoporella*-encrusted framestone at the top of the reef succession, indicating another volcanic event at the end of Late Permian. Nevertheless, instead of algal-foraminiferal grainstone, encrusted framestone became the significant sedimentological feature during this period of volcanic eruption. The encrusted framestone comprises *Archaeolithoporella* encrusting Tabulozoa, hydrozoa or sponges (Fig. 6a, d), with binding laminate thickness of about 5 mm (Fig. 6a). *Archaeolithoporella*, consisting of alternating light and dark laminae, forms a thick covering around the surface of reef-building organisms, interpreted here to have enhanced reef resistance to waves. The phenomenon of *Archaeolithoporella* encrusting Tabulozoa or *Tubiphytes* is very common in many other Permian reefs (Yang 1987; Li 1993).

Of potential importance for interpretations of the Late Permian marine chemistry is the presence of large quantities of carbonate cements in the top parts of the Late Permian, commonly found in Permian reefs in South China. In the Shitouzhai section, cements are mainly concentrated within the 16 m-thick encrusted framestone of the top (Fig. 2). Carbonate cements are formed along the periphery of the laminated *Archaeolithoporella*, and they are composed mostly of fibrous calcite layers about 7 mm thick (Fig. 6c). This kind of fibrous calcite is reported to have altered from aragonite precursors (Sandberg 1985), and regarded as a product of early submarine diagenesis.

Fig. 6

The encrusted framestone formed in the topmost of Late Permian reef sequence in Shitouzhai section of Ziyun.

Discussion

Many crystals produced in the algal-foraminiferal grainstones have nuclei of small quartz crystals with overgrowths (Fig. 4) and are thus inferred to have a two-stage history. However, abundant volcanic glass preserved together with the well-formed crystals strongly supports a volcanic origin for the nuclei, which may be interpreted as volcanic airfall crystals that have subsequently acquired overgrowths in diagenesis. The fact that many quartz crystals are concentrated around the foraminifera tests implies that the quartz crystals' distribution might have been affected by diagenesis. Diagenetic pore water rich in dissolved silica may have migrated to the nearby sites around the fossil shells because of the higher porosity there. The distribution of the quartz crystals as individual crystals with double-pointed terminations could be interpreted as diagenetic too.

Terrigenous clastics are unlikely to have been carried by aqueous media to the marginal reef settings because of the trap provided by the backreef lagoon, but volcaniclastic material could have been transported there via airfall (Fig. 7) and result in the deposition of volcanic ash in the reef facies. However, the volcano-related quartz crystals are not evenly distributed through the geological section at Ziyun. The restriction of quartz crystals to the algal-foraminiferal grainstone, and absence in the reefs, is strong evidence of the external influence of volcanism, consistent with intermittent deposition of layers of volcanic clays in deeper facies (Zhang et al. 1996; Shen et al. 2013) as well as in terrestrial sections (Zhou et al. 1990; Wang and Yin 2002).

Fig. 7

Deposition model of reef-related facies of Late Permian in Ziyun, Guizhou.

The algal-foraminiferal grainstones from the marginal platform reef in Shitouzhai generally lack micritic matrix, indicating an agitated environment rather than quiet conditions normally associated with lagoons. Grainstones in the reef succession may have formed at the top of reef cores after the temporary disappearance of reef-building organisms caused by volcanic activities rather than a lagoon deposit.

Because most reef-building organisms are filter-feeding benthos, clastics derived from volcanoes or terrigenous weathering will certainly affect the growth of reef-building organisms. Although the intensity of volcanism in the Changhsingian had reduced a lot compared with earlier in the Late Permian, eruptions are interpreted to have still occurred frequently, indicated by the many horizons of volcanic clay. Episodic volcanic activities during the Late Permian Changhsingian are therefore expected to punctuate the developing process of reefs, leading to formation of algal-foraminiferal grainstone. However, once each episode of volcanism stopped, the reef ecosystem recovered rapidly. Although previous work suggests that volcanic activity could be the key factor for the biotic extinction, small volcanic events seem not to have been able to cause the complete disappearance of Changhsingian reefs in Ziyun. A similar interpretation was made by Reuter and Piller (2011) in their analysis of volcaniclastic impact on the Middle Miocene coral reef and seagrass environments in the Styrian Basin of Austria. Their work shows recurrent breakdowns of the carbonate producers (i.e. coralline red algae and zooxanthellate corals) in response to ashfalls from nearby volcanic island sources. However, the fact that the facies below and above these Miocene ash beds are almost identical suggests that volcaniclastic events had no long-lasting effects on the structure of the carbonate-producing benthic communities (Reuter and Piller 2011); we infer a similar situation for the later

Permian setting, during repeated events of volcanism before the final reef collapse in the extinction.

Algal-foraminiferal limestones are often deposited during volcanic periods, suggesting volcanism has less influence on algal-foraminiferal biota. Although volcanic ash may kill reef-building animals, nutrients released from the dissolution of ash particles may favour the development of some species of foraminifera and calcareous algae, as is the case in Miocene Styrian Basin of Austria (Reuter and Piller 2011). According to Wilson and Lokier (2002), the Neogene reef carbonate sequence in Indonesia contains tuffaceous bioclastic packstone that has abundant benthic foraminifera, but reef-building coral is significantly reduced. Foraminifera may adapt to more pyroclastic material, because they can still crawl to the surface even if buried by up to 1cm of sediment (Myers 1943).

Tubiphytes occurs abundantly in some part of the algal-foraminiferal limestones in the Ziyun reef succession, with some quartz crystals even included inside the *Tubiphytes* body. Similar features have also been observed by the Chinese authors of this paper in an isolated Permian reef island situated in the Tibetan Plateau where abundant *Tubiphytes* dwelled in some part of the island-reef carbonate environment; a large number of authigenic quartz crystals were found inside the *Tubiphytes* body. Although those quartz crystals are authigenic, their nuclei are here explained to be volcanic in origin because terrigenous sediments could find no way to get to the isolated reef island due to the deep ocean trap around it (Wang 2005). *Tubiphytes* is a problematic microfossil, with a strong ability to adapt to varied environments. As is the case with most other shallow marine benthos, *Tubiphytes* disappeared completely, although temporarily, from this region after the end-Permian mass extinction, but it was one of the pioneering taxa during biotic recovery in the Early Triassic (Song et al. 2011) and continued from Middle Triassic to form large reef carbonate buildups in South China, implying its adaptability to environmental events. For this reason, the possibility exists that the abundance of *Tubiphytes* in the Ziyun reef complex may indicate temporary deterioration of the ecology of reef environments, which might have resulted from episodic volcanic eruptions during the Late Permian.

At the top of the reef sequence in Ziyun, abundant volcanic quartz grains are also found in the matrix between fossil skeletons, which are encrusted by *Archaeolithoporella*. Although the existence of volcanic quartz indicates volcanic influence at the top of the reef, only *Archaeolithoporella*-encrusted framestone rich in carbonate cements was formed this time. The reason for the lack of algal-foraminiferal grainstone is probably due to the multiple influences of volcanic activities as well as the increased temperature in the latest Permian. A rapid temperature rise indicated by oxygen isotopes of conodont apatite was recently proposed from the beginning of the end of Late Permian time (Sun et al. 2012). However, their temperature values near the Permian and Triassic boundary are mainly based on the conodont fossils from basinal sections (such as Shangsi and Meishan). The Shitouzhai section of Ziyun was located in an epicontinental setting, likely to be affected by air temperature because of its shallow water environment. High temperature may induce higher saturation conditions with respect to calcium carbonate in shallow marine environment, leading to a large amount of fibrous carbonate cementation. Although upwelling of hypoxic seawater could bring abundant light carbon bicarbonate ions (Knoll et al. 1996) and lead to the formation of aragonite cement too, the Shitouzhai section of Ziyun was unlikely affected by the upwelling of bottom water because of its epicontinental setting. While high temperature induced higher carbonate saturation and the widespread formation of cement, lethally hot temperature may also have resulted in the loss of calcareous algae, which well explains why no algal-foraminiferal grainstone formed at the top of the reef sequence near the Permian-Triassic boundary but only *Archaeolithoporella*-encrusted framestone rich in carbonate cements is present there.

Conclusion

Several layers of algal-foraminiferal grainstone and packstone rich in quartz crystals were deposited in the marginal platform reef succession of the Late Permian Changhsingian Stage, at Shitouzhai, near Ziyun County in Guizhou Province, South China. Because the backreef lagoon located between the reef belt and ancient land could act as an effective sediment trap for the sediments carried by water, terrigenous-derived clastics are assumed unable to have been transported across the lagoon to the topographically high seafloor of the marginal platform reef. Therefore, airfall of volcaniclastics is suggested for the origin of those quartz grains. The alternative explanation, that the quartz is diagenetic, applies to part of the quartz crystalline material, but two aspects support the interpretation of a volcanic origin:

1) restriction of quartz crystals to the algal-foraminiferal limestone, coinciding with absence of reef facies; and
2) presence of quartz crystal nuclei (that were locations of later diagenetic overgrowth) show that many quartz crystals have two phases of growth, providing good reason to interpret the nuclei of two-phase quartz crystals as derived from airborne volcanic clasts.

The algal-foraminiferal limestone layers preserved in the reef succession are considered as deposits within the top of reef core after the temporary disappearance of reef-building organisms caused by volcanic activities, rather than a deposit of the backreef lagoon.

The frequent alternation of reef limestone and algal-foraminiferal grainstone in the marginal platform reef is interpreted here to reflect episodic volcanic activity during the Late Permian in South China. However, regional volcanism did not lead to complete disappearance of reef ecosystem, but resulted in repeated alternation of reef community and algal-foraminiferal biota until final reef extinction in the latest Permian. Thus the cause of final reef collapse is unlikely due to regional volcanism, but of course may be related to the much larger scale of Siberian volcanics.

Despite the existence of volcanic quartz grains in the topmost part of the reef sequence, encrusted framestone rich in abundant fibrous cements developed at the same time, implying that volcanism was only one of the environmental controls at the top of the sequence. Increased temperature may have been involved for the complete collapse of the reef ecosystem flourishing in Late Permian in South China.

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References

Algeo TJ, Chen ZQ, Fraiser ML, Twitchett RJ (2011) Terrestrial-marine teleconnections in the collapse and rebuilding of Early Triassic marine ecosystems. Palaeogeography Palaeoclimatology Palaeoecology 308(1-2): 1-11

Cao CQ, Zheng QF (2007) High-resolution lithostratigraphy of the Changhsingian stage in Meishan section D, Zhejiang. Journal of stratigraphy 31(1): 14-22 (in Chinese with English abstract)

Fan JS, Zhang W, Ma X, Zhang YB, Liu HB (1982) The upper Permian reefs in Lichuan distrect, west Hubei. Scientia Geologica Sinica (3): 274-282 (in Chinese with English abstract)

Fan JS, Qi JW, Zhou TM, Zhang XL, Zhang W (1990) Permian reefs in Longlin, Guangxi. Geological Publishing House, Beijing, pp 4-15 (in Chinese)

Feng ZZ, Yang YQ, Jin ZK, Li SW, Bao ZD et al (1997) Lithofacies paleogeography of Permian of South China. Petroleum University Press, Dongying, pp 79-88 (in Chinese)

Flügel E, Reinhardt J (1989) Uppermost Permian Reefs in Skyros (Greece) and Sichuan (China): Implications for the Late Permian Extinction Event. Palaios 4(6): 502-518

Heydari E, Hassanzadeh J (2003) Deev Jahi Model of the Permian-Triassic boundary mass extinction: A case for gas hydrates as the main cause of biological crisis on Earth. Sedimentary Geology 163(1-2): 147-163

Kershaw S, Crasquin S, Li Y, Collin P-Y, Forel M-B, Mu X, Baud A, Wang Y, Xie S, Maurer F, Guo L (2012) Microbialites and global environmental change across the Permian-Triassic boundary: a synthesis. Geobiology 10(1): 25–47

Knoll AH, Bambach RK, Canfield DE, Grotzinger JP (1996) Comparative earth history and late Permian mass extinction. Science 273(5274): 452-457

Lai XL, Sun YD, Jiang HS (2009) The relationship between volcanism of Emeishan large igneous province and mass extinction during Middle-Late Permian transition.

Bulletin of National Natural Science Foundation of China (6): 353-356 (in Chinese with English abstract)

Li SS, Liu DC, Gu SH (1985) Characteristics of the Honghua reef in Kai county of Sichuan and its significance in finding natrural gas. Natrural Gas Industry 5(2): 24-28 (in Chinese with English abstract)

Li XJ, Chen LZ, Luo XM (1993) The reefs of Changxing Formation in the southern Hunan province. Scientia Geologica Sinica 28(4): 317-326 (in Chinese with English abstract)

Lin QX (1992) Nature and evolution of Late Permian reef in Ziyun, Guizhou province. Earth Science-Journal of China University of Geosciences 17(3): 301-307 (in Chinese with English abstract)

Meyer KM, Kump LR (2008) Oceanic euxinia in Earth history: Causes and consequences. Annual Review of Earth and Planetary Sciences 36: 251-288

Meyer KM, Kump LR, Ridgwell A (2008) Biogeochemical controls on photic-zone euxinia during the end-Permian mass extinction. Geology 36(9): 747-750

Myers EH (1943) Life activities of Foraminifera in relation to marine ecology.

Proceedings of the American Philosophical Society 86: 439-458

Peng ZQ, Wang T, Gong YH (1997) New ideas on the study of Permian period coal-bearing strata in Hunan. Hunan Geology 16(1): 20-23 (in Chinese with English abstract)

Reuter M, Piller WE (2011) Volcaniclastic events in coral reef and seagrass environments: evidence for disturbance and recovery (Middle Miocene, Styrian Basin, Austria). Coral reefs 30(4): 889-899

Ruttimann J (2006) Oceanography: Sick seas. Nature 442: 978-980

Sandberg P (1985) Aragonite cements and their occurrence in ancient limestone. In: Schneidermann N, Harris PM (eds) Carbonate Cements: Society of Economic Paleontologists and Mineralogists. Special Publication, no 36, pp 33-57

Sang T, Wang LT, Ye NZ (1986) The characteristics of lithofacies and palaeogeography in Late Permian, Guizhou. Guizhou Geology (2): 105-151 (in Chinese with English abstract)

Shen J, Lei Y, Algeo TJ, Feng QL, Sercais T, Yu JX, Zhou L (2013) Volcanic effects on microplankton during the Permian-Triassic transition (Shangsi and Xinmin, South China). Palaios 28: 552-567

Smith SV (1978) Coral-reef area and contributions of reefs to processes and resources of the world's ocean. Nature 273(5659): 225-226

Song HJ, Wignall PB, Chen ZQ, Tong JN, Bond DPG, Lai XL, Zhao XM, Jiang HS, Yan CB, Niu ZJ, Chen J, Yang H, Wang YB (2011) Recovery tempo and pattern of marine ecosystems after the end-Permian mass extinction. Geology 39(8): 739-742

Stanley SM (1988) Climatic Cooling and Mass Extinction of Paleozoic Reef Communities. Palaios 3(2): 228-232

Su YD, Joachimski MM, Wignall PB, Yan CB, Chen YL, Jiang HS, Wang LN, Lai XL (2012) Lethally Hot Temperatures During the Early Triassic Greenhouse. Science 338(6105): 366-370

Wang GZ (2004) Global climatic changes and coral reefs. Marine Geology Letters 20(1): 8-13 (in Chinese with English abstract)

Wang SH, Fan JS, Rigby JK (1996) The characteristics and development of the Permian reefs in Ziyun county, South Guizhou, China. Acta Sedimentologica Sinica 14(2): 66-74 (in Chinese with English abstract)

Wang SY, Yin HF (2002) Characteristics of claystone at the continental Permian-Triassic boundary in the eastern Yunnan-western Guizhou region. Geology in China 29(2):155-160 (in Chinese with English abstract)

Wang YB (2005) Structure and evolution of Middle Permian palaeo-seamounts in Bayan Har and its adjacent area. Science in China (D) 48(11): 1848-1858

Weidlich O, Kiessling W, Flügel E (2003) Permian-Triassic boundary interval as a model for forcing marine ecosystem collapse by long-term atmospheric oxygen drop. Geology 31(11): 961-964

Wignall PB, Twitchett RJ (1996) Oceanic anoxia and the end Permian mass extinction. Science 272(5265): 1155-1158

Wignall PB (2001) Large igneous provinces and mass extinctions. Earth-Science Reviews 53(1-2): 1-33

Wignall PB (2011) Lethal volcanism. Nature 477(7364): 285-286

Wilson MEJ, Lokier SW (2002) Siliciclastic and volcaniclastic influences on equatorial carbonates: insights from the Neogene of Indonesia. Sedimentology 49(3): 583-601

Wu YS, Fan JS, Jin YG (2003) Emergence of the Late Permian Changhsingian reefs at the end of the Permian. Acta Geologica Sinica 77(3): 289-296 (in Chinese with English abstract)

Wu YS, Fan JS, Jiang HX, Yang W (2007) The pattern of reef ecosystem extinction at the end of Permian. Chinese Science Bulletin 52(2): 207-214 (in Chinese with English abstract)

Wu YS, Jiang HX, Fan JS (2010) Evidence for sea-level falls in the Permian-Triassic transition in the Ziyun area, South China. Geological Journal 45(2-3): 170-185

Xu GR, Luo XM, Wang YB, et al (1997) The formation model of Late Permian reefs in the middle reach of Yangtze river. China University of Geosciences Press, Wuhan, pp 2-3 (in Chinese)

Yang WR (1987) Bioherm of Wujiaping Formation in Laibin, Guangxi. Oil and Gas Geology 8(4): 424-428 (in Chinese with English abstract)

Yang ZY, Wu SB, Yin HF, Xu GR, Zhang KX, Bi XM (1991) Permo-Triassic events of South China. Geological Publishing House, Beijing, pp 39-53 (in Chinese)

Yin HF, Huang SJ, Zhang KX, Hansen HJ, Yang FQ, Ding MH, Bie XM (1992) The effects of volcanism on the Permo-Triassic mass extinction in South China. In: Sweet WC, Yang ZY, Dickins JM, Yin HF (eds) Permo-Triassic Events in the Eastern Tethys. Cambridge Universiy Press, Cambridge, pp 169-174

Zhang KX, Tong JN, Yin HF and Wu SB (1996) Sequence stratigraphy of the Permian-Triassic boundary section of Changxing, Zhejiang. Acta Geologic Sinica 70(3): 270-281 (in Chinese with English abstract)

Zhou YP, Tang DZ, Burger K (1990) Synsedimentary volcanic ash-derived illite tonsteins in Late Permian coal-bearing deposits of southwestern China. Acta Sedimentalogica Sinica 8(4): 85-92 (in Chinese with English abstract)

Figure captions

Fig. 1

Palaeogeography and reef distribution of Late Permian Changhsingian (modified from Sang et al. 1986 and Feng et al. 1997). Note the location of the study area marked by a yellow cross south of Ziyun in the centre of the map. (a) Flood alluvial facies. (b)

Shallow-water siliciclastic deposit. (c) Carbonate platform. (d) Slope. (e) Basin. (f) Reef. (g) Location of reef section in Ziyun.

Fig. 2

Facies evolution of the Changhsingian reef complex in Shitouzhai section of Ziyun. (a) Argillaceous mudstone. (b) Silty marl. (c) Volcanic clay. (d) Bioclastic limestone. (e) Encrusted framestone composed of mainly sponge framework encrusted by *Archaeolithoporella*. (f) Bafflestone composed mainly of sphinctozoans baffling crinoid fragments, foraminifera and calcareous algae debris. (g) Framestone composed mainly of inozoans, sphinctozoans, hydrozoans, Tabulozoa and *Tubiphytes*.

Fig. 3

The Late Permian Changhsingian reef framestone from Shitouzhai section in Ziyun, Guizhou Province. Am (*Amblysiphonella* of Sphinctozoa), Gl (*Glomocystospongia* of Sphinctozoa), Mi (Micrite matrix), Pa (*Parauvanella* of Sphinctozoa), Pe (*Peronidella* of Inozoa), So (*Sollasia* of Sphinctozoa), Ta (Tabulozoa), Tu (*Tubiphytes*).

Fig. 4

Quartz grains and volcanic glass debris preserved in grainstone interbedded with reef facies in the Late Permian reef sequence in Ziyun, Guizhou Province. (a) Bioclastic grainstones cemented by sparry calcite, with some foraminifera containing tiny quartz crystals in the chambers, under optical microscopy. (b) Backscatter scanning electron microscope image showing abundant quartz crystals (black particles) surrounding a foraminiferan shell in the bioclastic grainstones. (c) SEM secondary electron images showing double-pointed quartz crystal. (d) Detail of individual quartz crystal in transmitted light, showing that the well-formed crystal is nucleated on smaller volcano-origin quartz fragments with grey-brown outer-ring. (e) Stereomicroscope image of volcanic glass debris.

Fig. 5

Abundant *Tubiphytes* in grainstone/packstone deposited in the upper part of the Late Permian reef sequence in Ziyun, Guizhou Province. All photos are in plane-polarised light view (a) Oriented arrangement of *Tubiphytes* in the grainstone, reflecting relatively more turbulent marine conditions. (b) Packstone containing abundant *Tubiphytes*. (c) Enlargement of one of the *Tubiphytes* from image b. The white box emphasises one quartz crystal contained in the fossil body. (d) Enlargement of the white box in image c.

Fig. 6

The encrusted framestone formed in the topmost of Late Permian reef sequence in Shitouzhai section of Ziyun. (a) Polished sample of encrusted framestone formed by *Archaeolithoporella* encrusting Tabulozoa. White arrows indicate Tabulozoa, green arrows indicate a 2-4 mm thick layer of encrusting *Archaeolithoporella*. (b) Backscatter scanning electron microscope image showing abundant quartz grains (dark spots) preserved in the matrix between reef-building organisms. (c) Fibrous calcite cement (marked with yellow arrows) precipitated along the periphery of encrusting *Archaeolithoporella* (marked with green arrows), outcrop view. (d) Microscope image showing the alternation of dark and light laminae in encrusting *Archaeolithoporella*.

Fig. 7

Deposition model of reef-related facies of the Late Permian in Ziyun, Guizhou. (a) Magma. (b) Volcanic rock. (c) Volcaniclasts. (d) Tidal flat siliciclastic deposits. (e) Backreef lagoon limestone. (f) Reef limestone. (g) Fore-reef slope deposits. (h) Basin mudstone. Ⅰ. Model of different depositions in reef-related environment during tectonically stable periods. Ⅱ. Deposition model showing breakdown of the reef community affected by volcanic activities and the invasion of algal-foraminiferal fauna to the marginal platform settings. Ⅲ. Deposition model showing recovery of the reef community when volcanic eruption ceased and the environment returned to normal conditions.

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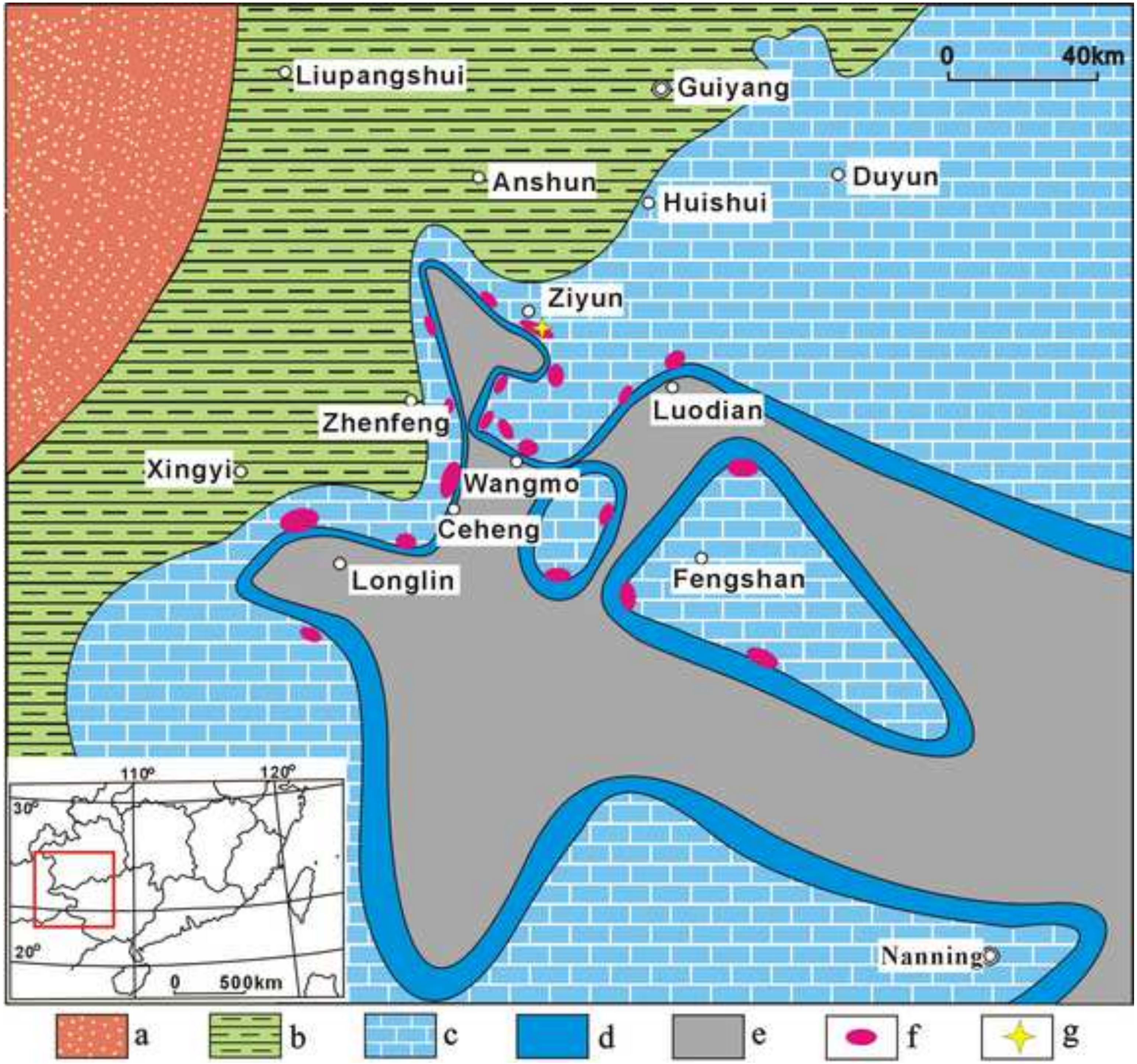

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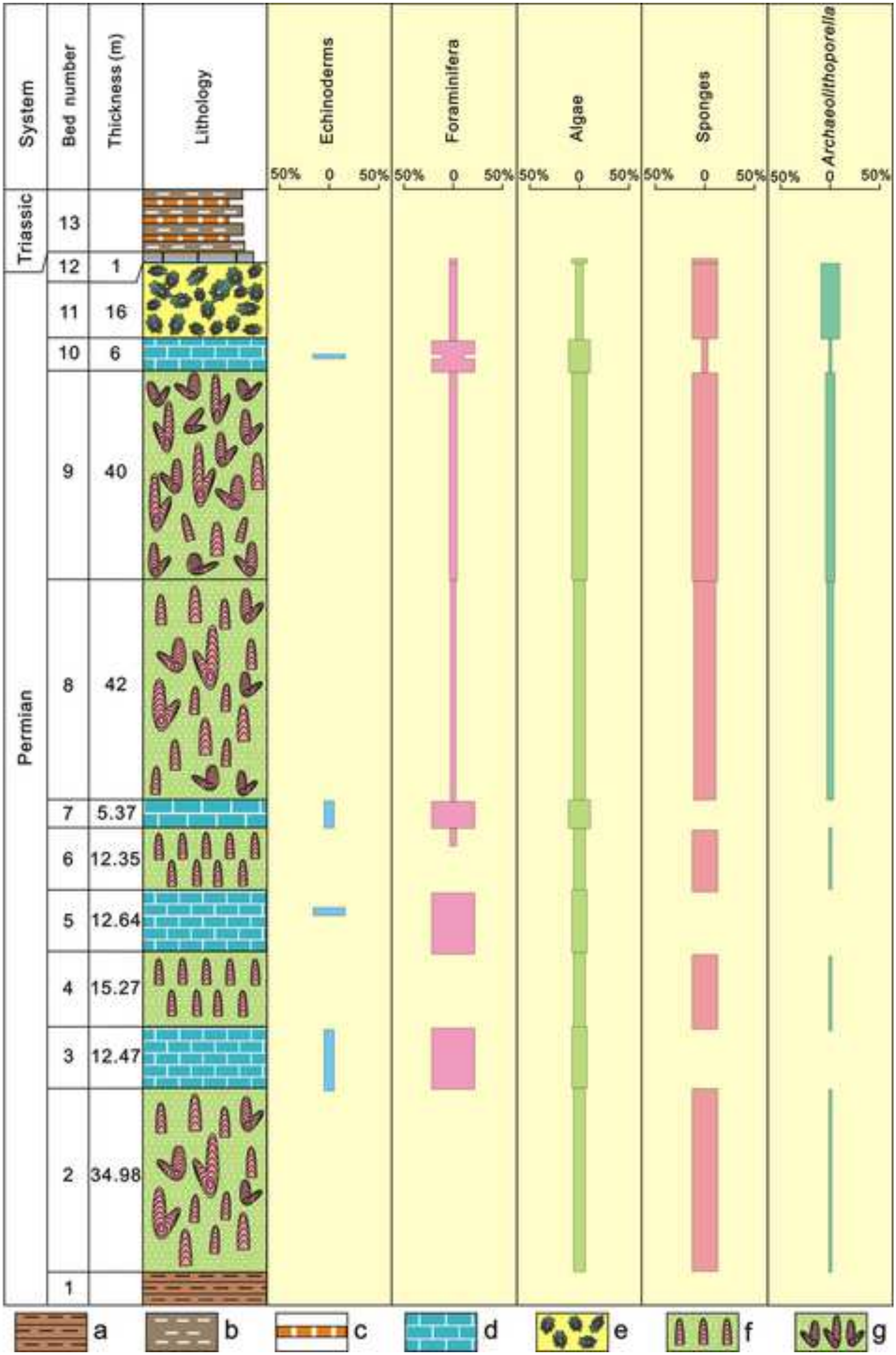

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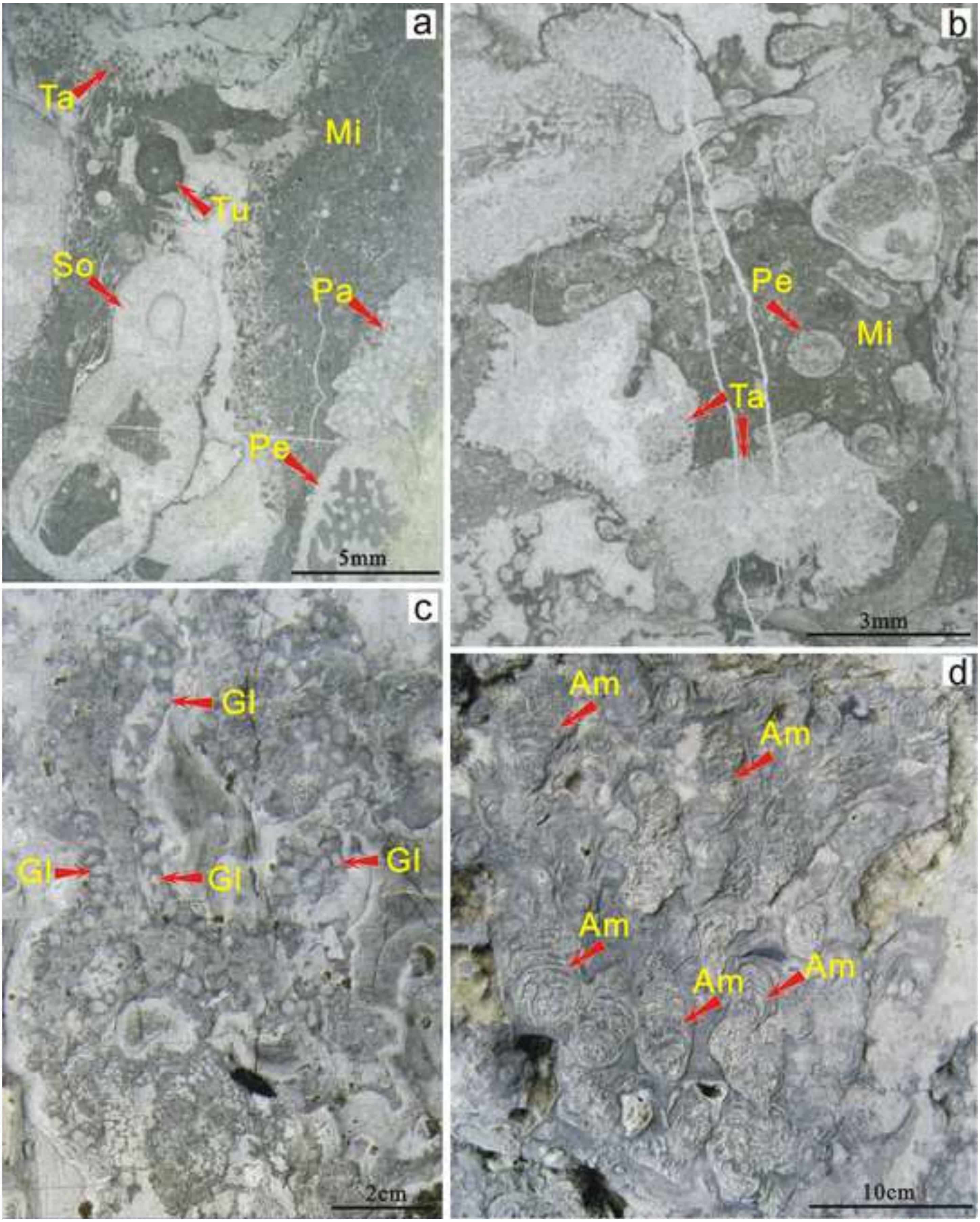

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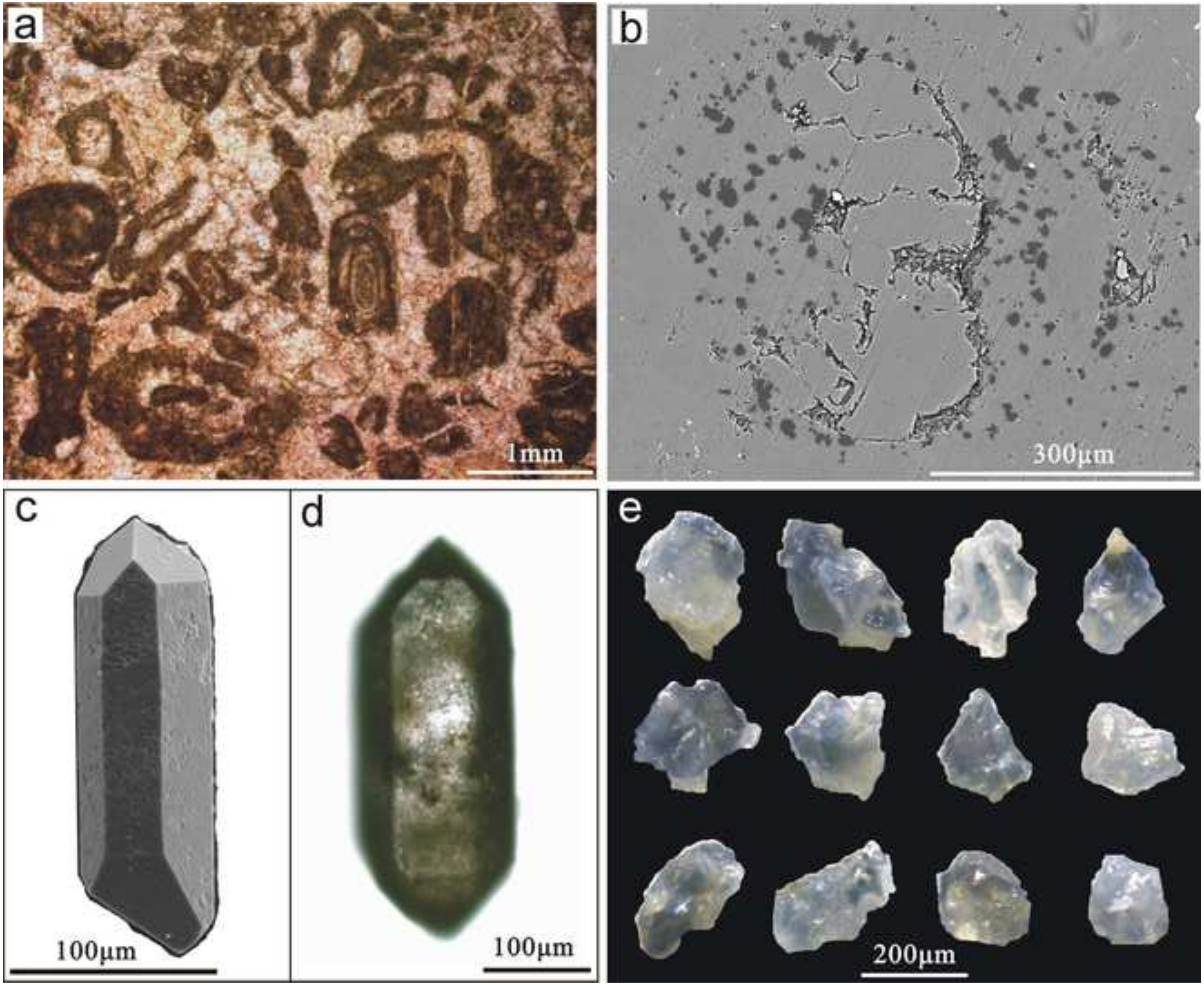

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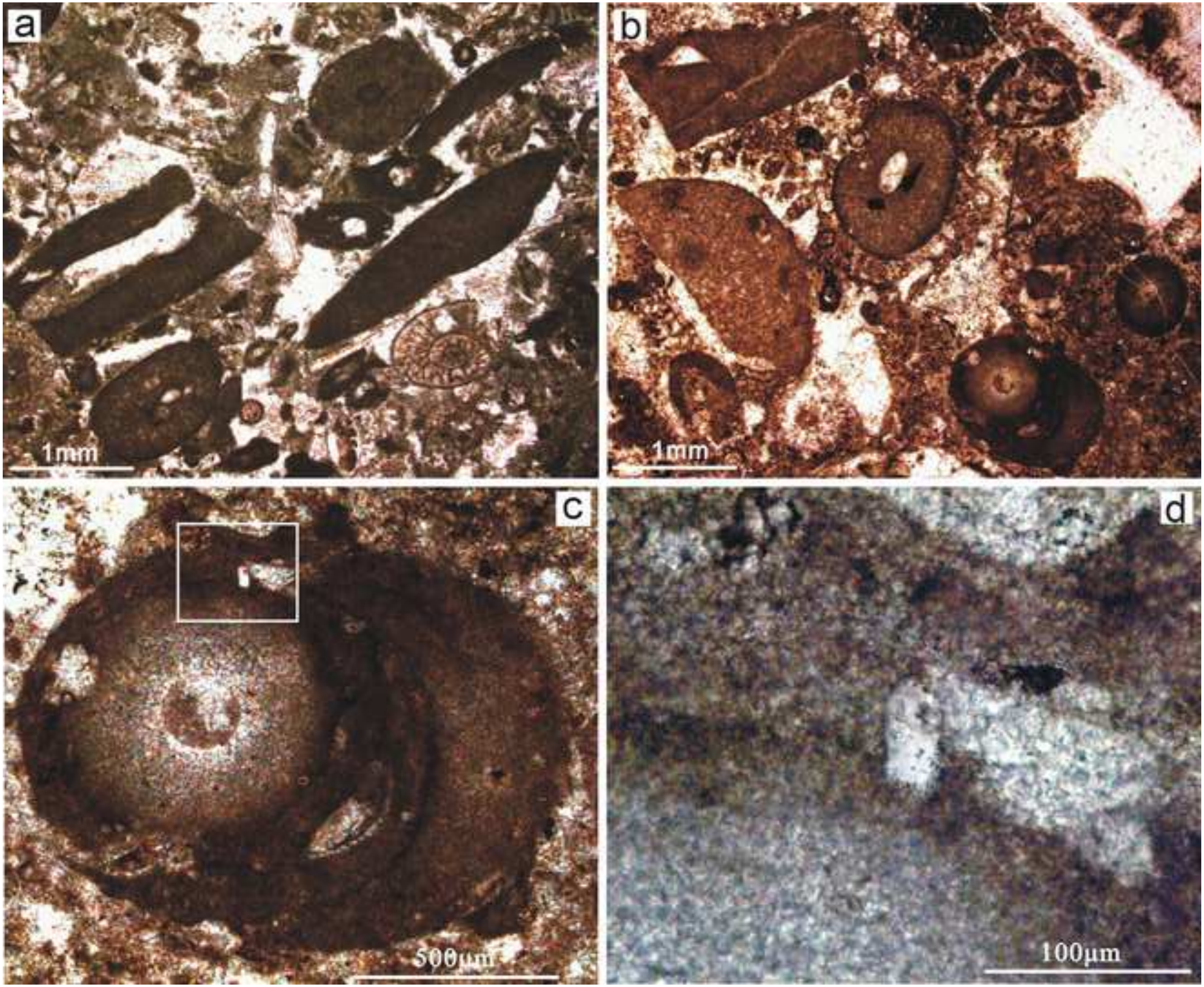

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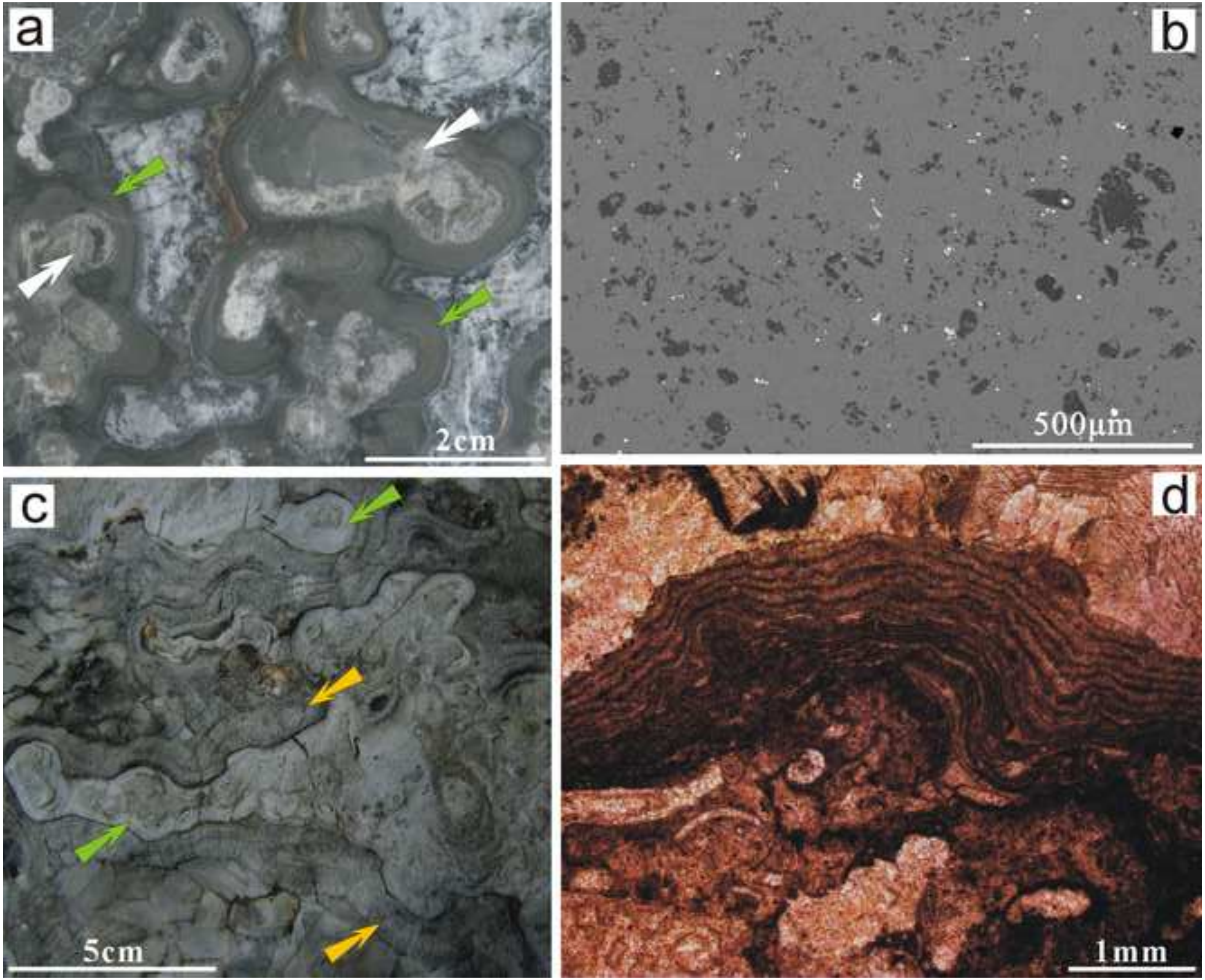

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