ELSEVIER

Palaeogeography, Palaeoclimatology, Palaeoecology 146 (1999) 1–18

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A ?microbialite carbonate crust at the Permian–Triassic boundary in South China, and its palaeoenvironmental significance

Stephen Kershaw [a,*], Tingshan Zhang [b], Guangzhi Lan [b]

[a] *Department of Geography and Earth Sciences, Brunel University, Uxbridge, Middlesex UB8 3PH, UK*
[b] *Carbonate Research Section, Southwest Petroleum Institute, Nanchong, Sichuan 637001, China*

Received 3 February 1998; revised version received 20 July 1998; accepted 5 August 1998

Abstract

A 1 m thick carbonate crust, layered and commonly domal, caps crinoidal limestones on reef complexes of the top Permian Changxing Formation in the Huaying Mountains, eastern Sichuan, China. The crust's stratigraphic level lies at a sharp change in facies, and is overlain by poorly fossiliferous laminated micrites and shales of the Lower Triassic Feixianguan Formation. The crust therefore appears to coincide with the end-Permian extinction event, although the dating of the strata is currently imprecise. The crust is composed mostly of digitate carbonate, locally thrombolitic, with remnant lobate fabric, and resembles microbialites, but is mostly recrystallised and a microbial origin is unconfirmed. It is enclosed in micrite with pyrite crystals, ostracode and other shell debris. The crust is absent from interreef areas. Previous interpretations of karstification and calcrete formation are not upheld, and the facies were deposited under water. Overlying sediments are low energy, with abundant ferroan calcite and pyrite, reflecting anoxia associated with rising sea level. Various interpretations of the crust are possible: (1) it was organic, and microbia grew preferentially on topographic highs of reef tops; (2) microbia were a disaster biota in the absence of grazers; (3) microbia took advantage of favourable conditions for calcification, associated with a rapidly rising environmental-CO_2 content during the Late Permian; (4) the crust was an inorganic precipitate associated with CO_2-rich water. Microbial crusts are rare after the Cambrian, but whether this crust is organic or not, its presence in these strata reinforces the view that oceanic-atmospheric conditions in the Permian–Triassic boundary interval were unusual.

Keywords: Permian–Triassic boundary; microbialites; anoxia; South China

1. Introduction

Controversy surrounds the interpretation of processes controlling palaeoenvironmental change during the Permian–Triassic boundary interval, highlighted in recent publications (Erwin, 1993; Hallam and Wignall, 1997). In the South China Block, disagreement includes the problem of whether sea level was rising (Wignall and Hallam, 1993; Wignall and Hallam, 1996), or at static lowstand with emergence (Reinhardt, 1988; Flügel and Reinhardt, 1989) during the extinction interval. This study describes a carbonate crust of possible microbialite origin capping reef complexes, at a critical horizon in the boundary interval, in the Huaying Mountains of southeastern Sichuan Province. Microbialites are sedimentary deposits generated or influenced by mi-

* Corresponding author. +44-1895-203217; E-mail: stephen.kershaw@brunel.ac.uk

0031-0182/99/$ – see front matter
PII: S0031-0182(98)00139-4

crobial processes in or on the sediment, and contain fabrics which may be interpreted as caused by organic processes. The example described here has a broad resemblance to early Palaeozoic dendrolites (branching microbialites) and thrombolites (clotted microbialites), but is unusual because not only is its outline different from those, but also because such microbialites are rare after the Cambrian Period. Furthermore, the crust describe here is recrystallised, so although it has characters like microbialite, its origin is unclear and may instead be inorganic. Examination of the crust and associated facies reveals none of the fabrics claimed by previous workers to indicate uplift in the boundary strata, and the crust provides another line of evidence in the interpretation of the enigmatic environmental conditions which occurred globally at this time. The overlying micritic facies contain beds with microgastropods, ostracodes, and curious sparitic microspheres, which are previously documented, but also contain beds with oncoids, which are not. Above these are undisputed transgressive micrites and shales of the Lower Triassic. This work aims to clarify interpretation of this unusual facies suite, to assist understanding of processes controlling palaeoenvironmental change during that time. The results strongly support a rising sea level, although the timing and rate of sea-level rise are unclear. The ?microbialite crust may have been influenced by a variety of processes, and promotes a critique of published models.

Recent prominence has been given to the large amount of precipitated $CaCO_3$ in Late Permian reef facies (Grotzinger and Knoll, 1995), including reinterpretation of the abundant problematic fossil organisms *Archaeolithoporella* and *Collenella* (Guo and Riding, 1992, for *Archaeolithoporella*) as inorganic, or at best microbially mediated structures. The amount of inorganic cement is particularly high, indicating the ocean composition of the Late Permian and the boundary facies to be unusual in Phanerozoic history. An oceanic upwelling model has been suggested (Grotzinger and Knoll, 1995; Knoll et al., 1996), with much inorganic $CaCO_3$ precipitating from CO_2-rich waters brought up from anoxic deep water, although this has sparked much controversy; the CO_2 may have been atmosphere-derived instead (see various authors in Science, 1996, vol. 274, pp. 1549–1552). The boundary-interval mass extinction in South China is part of this scenario, and contrary to the long-standing idea that the extinction was gradual, there is good evidence that it was sudden (Wignall and Hallam, 1996; Bowring et al., 1998). Reef cap facies of the Huaying Mountains, including the ?microbialite crust described here, have been interpreted as evaporites and dolomites, with dissolution and karst (Reinhardt, 1988, p. 254), or calcrete (Wang et al., 1994), in a Late Permian regression. Although a regression is mentioned in papers principally about sponges (Rigby et al., 1989, 1994, 1995), Late Permian reef evolution modelled by those authors invokes a sea-level rise leading to reef drowning instead. Sea-level rise is universally agreed for the Early Triassic deposits above the reef complexes, so the disagreement seems to be whether the boundary interval sediments on the South China Block contain a rise to drown the reefs, or whether this came later. Clarification of this discrepancy is needed in order to assess models of the extinction process itself in this region.

2. Localities and regional setting

Several well-exposed Permian–Triassic boundary interval sites in the Huaying Mountains show the ?microbialite crust, with good evidence that it was deposited in marine water at the end of the Permian. The Huaying Mountains exhibit strong lithology controlled topography, and comprise a series of subparallel ridges and valleys in a folded late Palaeozoic and Mesozoic succession (Fig. 1). The area is rich in Lower Permian and Middle Triassic coal, interspersed with limestones and clastics. The limestones represent part of the huge Late Permian carbonate platform bordering Tethys Ocean. Four reef complexes were examined, especially at Baizhuyuan and Laolongdong, but also Jianshuigou and Wenxingchang (Fig. 1). In most reef sections, the precise chronostratigraphic position of the Permian–Triassic boundary is not clear, but must lie either at the top, or within a short distance of the top, of reef-complexes. Recent work constraining the Permian–Triassic boundary in eastern China (Bowring et al., 1998) applies dating of volcanic ashes, which have not yet been recognised from the Huaying Mountains, although volcanic material (with a possible

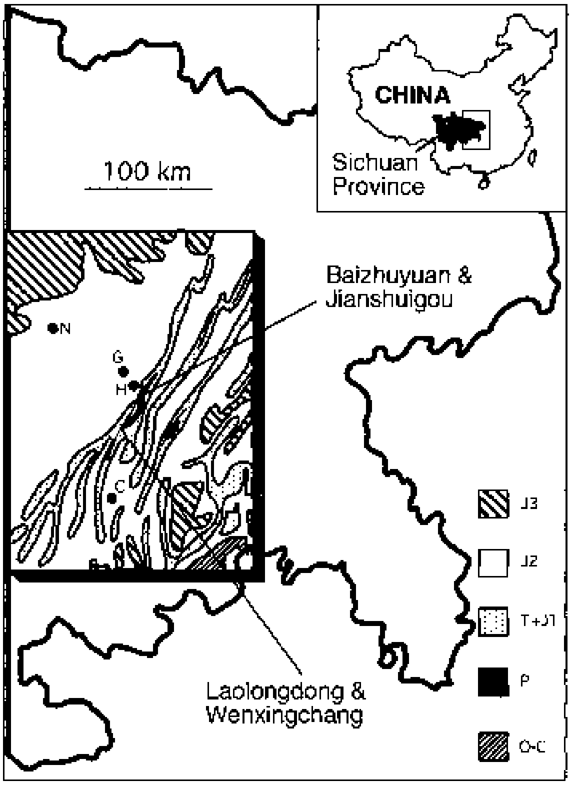


Fig. 1. Location and regional geology of the study area, eastern Sichuan Province, and PTBI localities used in this study. Only the geology relevant to study area is shown, as a raised surface in the map. Inset shows location of Sichuan Province within China. *N* = Nanchong; *G* = Guan'an; *H* = Huaying; *C* = Chongqing. Stratigraphic divisions use the informal scheme of regional maps: *O–C* = Ordovician–Carboniferous; *P* = Permian; *T* + *J1* = Triassic + Lower Jurassic; *J2* = Middle Jurassic; *J3* = Upper Jurassic.

extraterrestrial content) has been described from the boundary further south, near Chongqing (Sijing, 1993).

3. Permian–Triassic boundary interval sections

Not all sections show the same information, although there is much similarity between sites. Because the time available for field work was limited, our results are based on four sites, the facies and strata of which are described here; the detailed fabric of the crust is given in Section 4.

3.1. Laolongdong

Laolongdong is well known as a prime site for Permian reef study in China (Reinhardt, 1988; Fan et al., 1996). Here, the sponge-dominated reef core is overlain by several metres of partially dolomitised crinoidal limestone, capped by the prominent ?microbialite crust (Fig. 2). The reef may be as much as 2 km in diameter and 160 m thick (Qiang et al., 1985). Wignall and Hallam (1996) presented a log of this site, but did not encounter the crust; their log was located off the reef flank, in an interreef site close to the reef. They also described the Permian–Triassic boundary interval in a more fully interreef site near Chongqing, ca. 45 km to the south, likewise lacking the crust.

The crust sharply overlies partially dolomitised crinoidal wackestones and packstone shoals on the reef complex, and is largely bed-parallel, but in places domes upwards and superficially resembles the form of stromatolites (Fig. 2).

The upper (Fig. 2) and lower contacts of the crust represent sharp facies changes, but the crust's top surface is stylolitised in places, which superficially resembles erosion. If there *is* any erosion of the crust top, it is minor, because the undulating crust surface topography seen in vertical section is matched by undulation of layering within the crust (Fig. 2a). The crust base is bed-parallel with the underlying crinoidal grainstones, suggesting, again, that any erosion is minimal. Uplift into meteoric phreatic and vadose settings has been proposed for the underlying reef, on the basis of syntaxial cements on crinoids and possible vadose silt in reef cavities (Qiang et al., 1985). Crinoid syntaxial cements are, however, no longer regarded as diagnostic meteoric indicators (e.g. Tucker and Wright, 1990, p. 336), but even if there has been uplift at one stage in the development of the reef complex, sea-level rise to drown the reefs in the boundary interval is not incompatible with this.

Overlying the crust at Laolongdong is a unit of thin-bedded micrite (Fig. 2a), referred to as 'blue limestone' by Reinhardt (1988). Each bed is ca. 5 cm thick, interspersed with clay partings. Thin sections show the micrite is rich in recrystallised microgastropods, but lacks the diversity of the marine Changxing Formation crinoidal limestones only

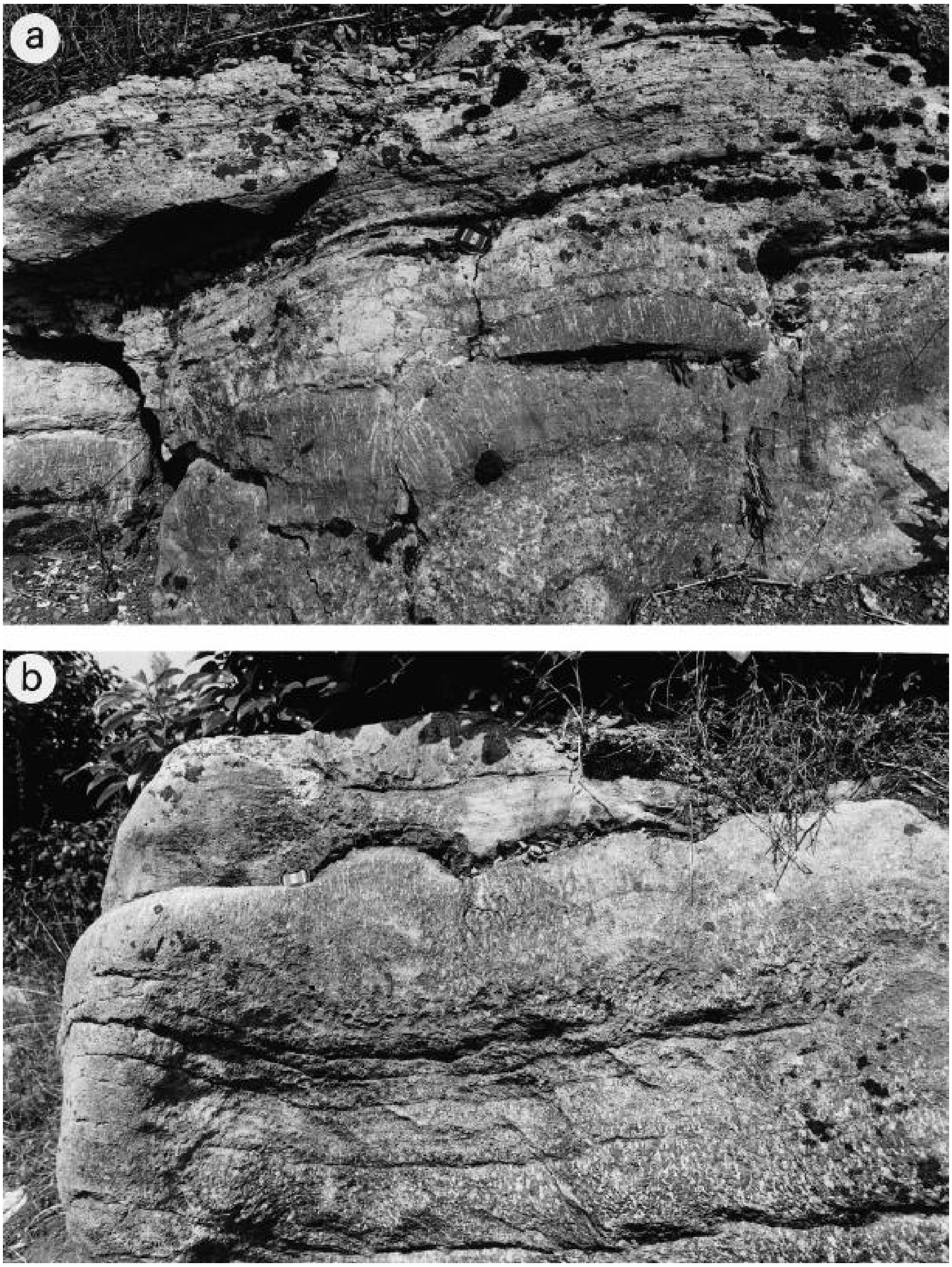


Fig. 2. (a, b) Photographs of the ?microbialite crust in the Permian–Triassic boundary interval at Laolongdong, showing the dominantly digitate structure, and minor thrombolitic texture in places. Note the sharp contact with the overlying Feixianguan Formation (marked by the lens cap).

one metre below. An unusual rock is also present at this level, containing microspheres (Fig. 3; Wignall and Hallam, 1996): micrite containing abundant sparitic ovoidal-spherical objects, some of which are presumably fossils, but the nature of the rest is unclear. Beneath the microsphere bed in their log is

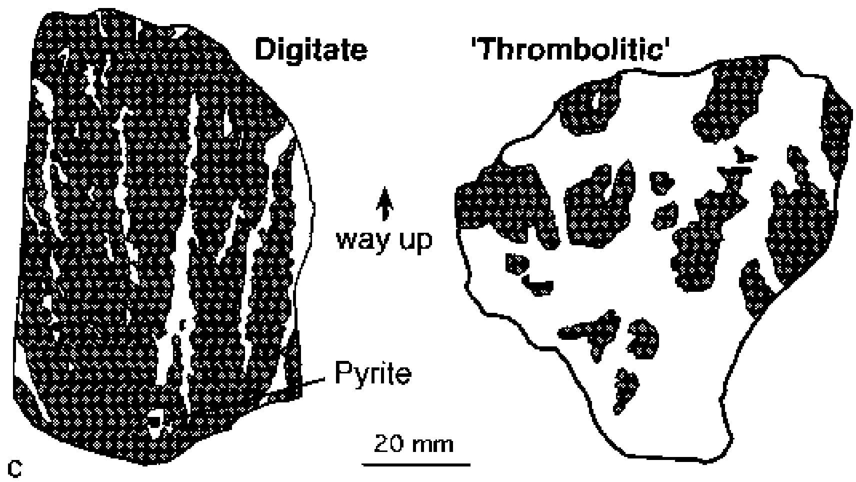


Fig. 2 (continued). (c) Difference between digitate and thrombolitic portions of crust fabric. ?Microbialite is shaded; white areas are micrite.

a micritic mudstone with crinoids, *Crurithyris* and *Claraia*. This is apparently a lateral equivalent of the crust; therefore we suggest that the crust thins to nothing down the reef flank (see Fig. 7). Unfortunately, although the crust forms a veneer visible for at least 100 m of hillside at Laolongdong, its location in privately owned farmland precluded verifying its relationship with the Wignall and Hallam (1996) log; given the proportions of the reef noted above, the crust may cover a considerable area of reef surface. The remainder of the section above the micrite unit is obscured by vegetation in the section we examined, but laterally equivalent exposure a few metres away shows the overlying beds have the characteristic brown micrite and shales typical of the Feixianguan Formation.

3.2. Baizhuyuan

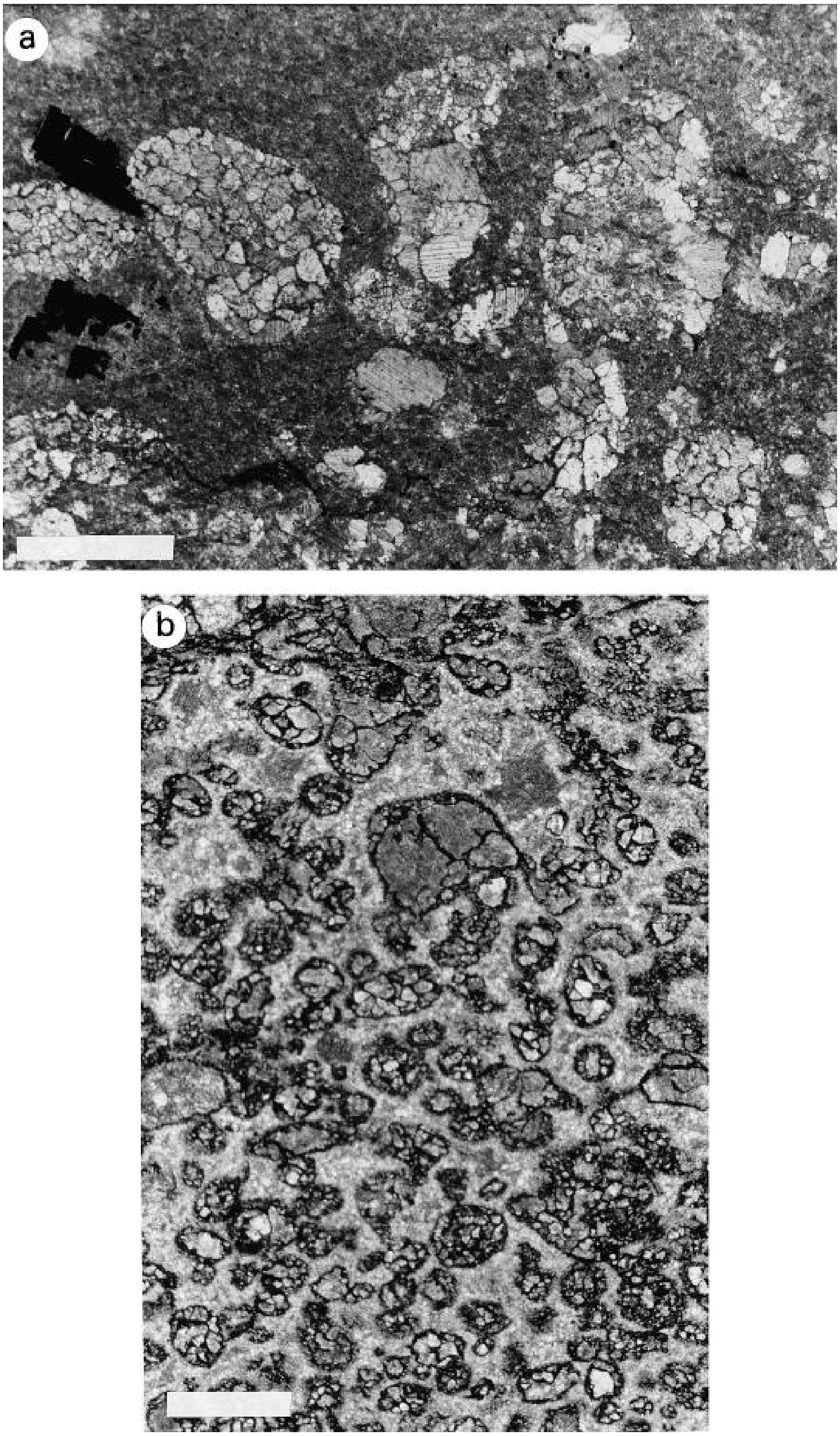
This new road section excavated near the top of a hill adjacent to fields of Baizhuyuan village exposes ca. 220 m of Upper Permian and Lower Triassic strata, including almost complete exposure of the boundary interval, from Changxing Formation to basal Feixianguan Formation. Fig. 4 shows a general log, and a detailed log of the boundary portion, indicating the prominent crust, ca. 1 m thick, overlying crinoidal grainstones with a sharp contact, and overlain (also sharply) by micritic limestones rich in microgastropods, as elsewhere. The crust was partially obscured by foliage, so its thickness in Fig. 4B is an estimate.

Above the crust, poorly fossiliferous laminated micrites are interbedded with shales. These beds contain abundant pyrite cubes and framboids, locally in layers, and the calcitic sediments are dominated by ferroan calcite.

1.5 m above the crust is a 1 m thick unit of non-bioturbated thin-bedded clay-rich micrite with abundant ovoidal oncoids, ca. 5 mm diameter (Fig. 6), plus some small articulated brachiopods, all matrix supported. Some oncoids show evidence of geotrophic growth, such as that seen in oncoids which have stabilised. The oncoids are largely recrystallised to aggraded spar, and contain relict concentric laminae of micrite (Fig. 6b).

3.3. Jianshuigou

Exposed on a hillside close to Huaying City, this reef is patchily revealed through vegetation cover, and the crust is partly exposed, again forming the top bed of the Changxing Formation limestones, and at this site the domed structure and digitate architecture are well developed. The overlying Feixianguan Formation is poorly exposed. Crust thickness apparently varies across the hillside; (Wang et al., 1994) showed logs with no crust in nearby interreef areas, but up to 5 m in parts of the reef complex. Wang et al. (1994) recorded breccia in the succession; we did not see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breccia at any of the sites, but note that the limestone is commonly traversed by calcite veins in places, infilling tectonic fractures induced during folding.

3.4. Wenxingchang

The Wenxingchang reef is poorly exposed on farmland, with the top Changxing Formation forming the border of a field. Nevertheless, the hardness of the Changxing Formation limestones always forms prominent exposure, and, according to local geologists, this is the only reef in the region which lacks a crust, limestone at this position being a dark grey micrite. The poor outcrop precluded examination of the nature of the contact between the Changxing and Feixianguan formations.

4. ?Microbialite crust architecture and fabric

The crust is predominantly composed of a digitate structure. Although locally resembling thrombolites (Fig. 2), the structure of upward-branching columns is different from the clotted fabrics of thrombolites (Kennard and James, 1986; Aitken and Narbonne, 1989), and neither thrombolite nor dendrolite (Riding, 1991; Braga et al., 1995) adequately describe it. External morphology of the microbialite columns also resembles the external digitate form of modern silica microstromatolites in hot springs of New Zealand (Jones et al., 1997, figs. 3 and 5); both have finely lobate margins and are of similar size. The crust rather more distantly resembles the upward-branching habit of Quaternary travertine shrubs (Guo and Riding, 1994), which are somewhat smaller than the digitate fabric of the crust. There are no published records of Permian–Triassic boundary interval microbial deposits with a similar digitate architecture, although microbial fabrics do exist in the interval, in Japan (Sano and Nakashima, 1997), which was located near the South China Block at that time (Windley, 1995, p. 25).

The outline structure of the crust's architecture is also similar to Precambrian microdigitate stromatolites figured by Grotzinger and Knoll (1995, p. 582), although the crust is largely recrystallised; the radiating crystal fibres and layered microstructure present in Precambrian examples are not visible in the Huaying Mountains material. In thin section, the ?microbialite crust shows poor preservation at all sites.

The 1 m thick crust at Laolongdong is composed of 6 major layers, some of which have subsiduary layering (Fig. 2b). The lower 5 major layers are separated by thin layers of pale micritic limestone, with a thicker micrite bed between layers 5 and 6. Each layer displays the digitate architecture of largely recrystallised columns (Fig. 2). At Laolongdong the microfabric comprises mostly sparite with patchy micritic texture and scattered dolomite rhombs, and is presumably recrystallised from an unknown, but probably aragonitic precursor. Better fabric preservation was found in the other sites. Narrow spaces between the columns of the crust contain micrite with a macrofauna consisting of ostracodes and thin-shelled gastropods, as in the overlying sediments. Horizontal stylolitisation is common in all localities studied, but minor vertical stylolitisation at Laolongdong *within* the crust modified the margins of some columns.

At Baizhuyuan, the crust contains 4 layers in the lowermost 46 cm, and may well have more than the 6 layers recorded at Laolongdong. The crust's lobate fabric is clearly displayed in calcite, although preservation of microfabric is poor (Fig. 5b, d). The fabric has superficial similarity to *Renalcis* (Roux, 1991, p. 364), but it is not *Renalcis*, or any other named microbial structure (Riding, 1991). The microfabric has some similarity with modern microbialites in hypersaline settings of Bonaire (Kobluk and Crawford, 1990, figs. 7 and 8); however, although of lobate form, it lacks the strongly lobate structure of *Wetheredella* (Kazmierczak and Kempe, 1992), nor does it consist of tubes (Knoll et al., 1993).

At Jianshuigou the crust consists of at least a dozen layers; the schematic diagrams of Wang et al.

Fig. 3. Photomicrographs of the microsphere bed at Baizhuyuan (similar in all sites). (a) Varying size and shape of microspheres, plus pyrite cubes; microspheres are normally sharp-edged and some resemble fossil, especially ostracode, outlines. (b) Grainstone with microspheres preserved as ferroan calcite, surrounded by non-ferroan isopachous cements, and ferroan later cement occluding remaining pore space (stained peel). This picture demonstrates that microspheres are depositional objects, not a recrystallisation texture. Scales 1 mm.

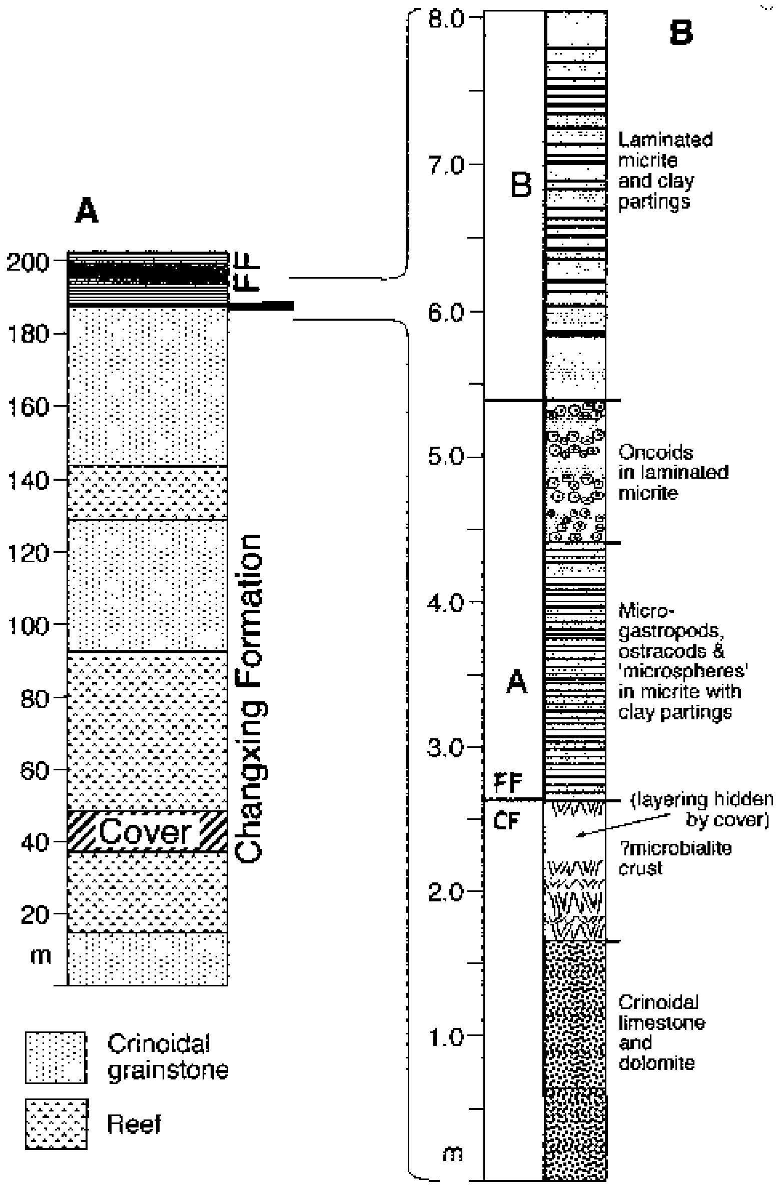


Fig. 4. (A) General log of the Upper Permian and Lower Triassic sequence and Baizhuyuan. The boundary between Changxing Formation and Feixianguan Formation (*FF*) is taken as the lithological Permian–Triassic boundary, but the chronostratigraphic boundary may differ from site to site. (B) Detailed log of the boundary interval. The top of the ?microbialite crust is taken as the top of the Changxing Formation (*CF*). Partial coverage by vegetation obscures details of layering in the upper part. Units A and B are discussed in the text.

(1994) suggest up to 35 layers at Jianshuigou, but this is unconfirmed. The crust's fabric (Fig. 5a, c) is apparently better preserved than at Laolongdong, although in our samples it is completely dolomitised, in contrast to both Laolongdong and Baizhuyuan, where it is calcite. At Jianshuigou it contains areas of lobate micritic structure and the remainder is a clotted micrite in spar. Some of the lobate structure lies on the margins of the columns, and in places is encrusted by fibrous cement, also seen in

Baizhuyuan (Fig. 5d). It is possible that the lobate portions are similar to the original fabric, and the clotted micrite in spar is mostly, if not completely, recrystallised. Wang et al. (1994) figured alveolar texture in the crust at Jianshuigou, as part of their evidence that the crust represents a calcrete; their photograph is similar to our lobate fabric and does not resemble alveolar texture.

5. Discussion

5.1. Comparison of the crust with other fabrics

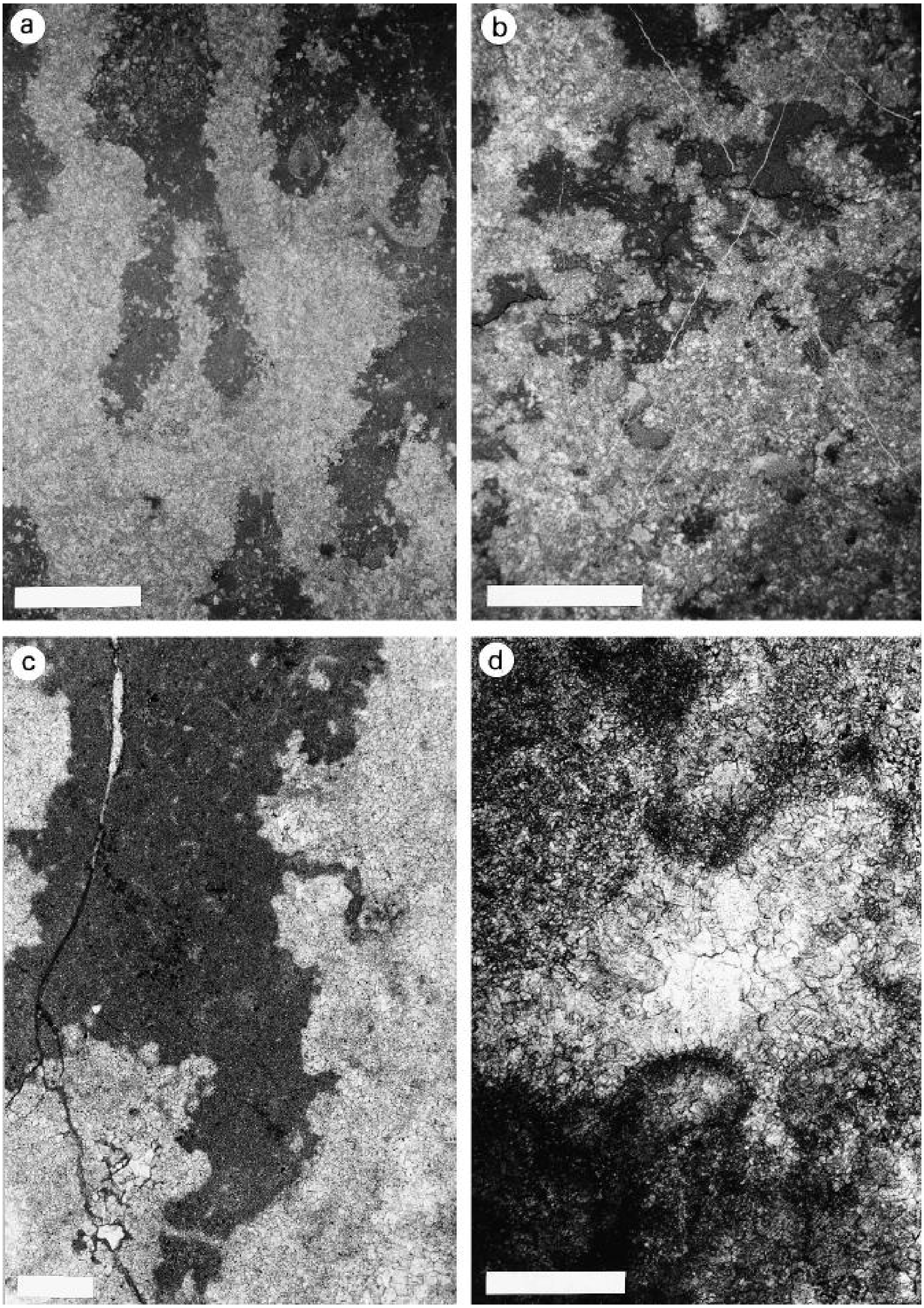
The domed form of the crust observed by us at Laolongdong, is identical to that of published photographs of the nearby Tudiya complex, where it has been interpreted as 'embryonic tepees' (Reinhardt, 1988, pl. 38, 3), but the dissimilarity of this structure with tepees was noted by Wignall and Hallam (1996). In fact none of the crust structure in this, or the other sites resembles calcrete or palaeosol fabrics (Adams, 1980; Riding and Wright, 1981; Wright, 1982a; Demicco and Hardie, 1994; Garces and Aguilar, 1994), including rendzinas (Wright, 1983) or palaeokarst (Wright, 1982b; Jones and Kahle, 1985). They lack pedogenic features of nodules, circumgranular cracks, fenestrae and rhizoliths; nor are any filaments present. Reinhardt (1988) figured from Tudiya a grain with features resembling circumgranular cracks, and a crystal fan which he interpreted as evaporite; also he figured a pyrite crystal interpreted as a pseudomorph after halite or anhydrite. However, it is odd that other evidence of evaporites is not present, and coincidental that halite and pyrite are both cubic! Pyrite in the crust does not show the diamond shapes described from Lower Carboniferous palaeosols (Wright, 1986) as replacement of gypsum, and we concur with Wignall and Hallam (1996) that the pyrite is simply crystal growth in sediment, and not a replacement of evaporite. In summary, we found nothing diagnostic for emergence in the sites we studied.

5.2. Formation of oncoids

Oncoids observed by us at Baizhuyuan are also recorded at Jianshuigou (Wang et al., 1994), and interpreted by them as vadose pisoliths. However, the oncoids do not resemble vadose pisoliths or any calcrete fabric (Donahue, 1969; Braithwaite, 1979; Chafetz and Butler, 1980; Tandon and Narayan, 1981; Folk and Chafetz, 1983; Wright, 1989). Some of the relict layering is superficially similar to terrestrial oncoids (Jones, 1991), but the overall facies setting is not terrestrial, and neither does the fabric resemble palustrine facies (Platt, 1989). At Jianshuigou, Wang et al. (1994) recorded these directly above the crust in some places, while our observations at Baizhuyuan show them 1.5 m above it. The possibility that they have been rolled into position from nearby shallower water is not supported, because present evidence indicates that facies are similar above the reef complexes, and the reefs appear to be the topographically highest sites. Furthermore, the oncoid-rich beds are matrix supported, not lags, and in the absence of other evidence, we interpret them as formed in situ. Nevertheless, although the oncoids may have been formed in shallow waters, evidence from the relatively deep shelf in Florida (35–65 m) (Prager and Ginsburg, 1989) shows that biological activity on, and storms affecting, the sea floor causes physical disturbance and therefore repositioning of nodules growing at those depths. The quiet water setting of the oncoids in this study may have been the result of deepening water as sea level rose, so relative water depth cannot be determined on the basis of these oncoids.

5.3. Significance of the crust

Because the crust seems always to be found capping crinoidal limestones on reef complexes, it most likely formed simultaneously across the region. The sharp change in facies from the top of the Changxing Formation reef complexes to the micrites of the lower Feixianguan Formation, separated across the reef complexes by the crust, provides a compelling argument that the environment changed rapidly and drastically at this level, which coincides with sharp diversity decrease of the end-Permian extinction (Wignall and Hallam, 1996; Bowring et al., 1998). As a consequence of the poor state of preservation of microfabric, an organic formation of the crust cannot be confirmed. Blue-light fluorescence has not revealed any bright responses normally associated with the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presence of organic matter trapped within the crust fabric. Preliminary CL work indicates well-developed orange luminescence typical of calcite, but no remnant structure is revealed. Nevertheless, if the crust is an organically controlled microbial structure, then its environmental significance may well be different from a purely inorganic precipitate.

Organic or not, the crust was initiated rapidly, marking a change from high energy crinoidal shoals to low energy micrites and clay, then ended just as abruptly. Therefore we first assess evidence for sea-level trends in the boundary interval, then the nature of the crust.

5.4. Sea level during the Permian–Triassic boundary interval

Our field and thin-section study concurs with the lack of emergence features, and there is no unequivocal evidence that these strata were above sea level at any time during the Permian–Triassic boundary interval. Terrestrial sediments elsewhere indicate that both plants and vertebrates suffered rapid extinction at the boundary (Retallack et al., 1996), followed by a fungal spike (Eshet et al., 1995). Although a controversial viewpoint that global tectonic uplift around the margins of Pangaea caused oxidation of plant matter, not extinction (Faure et al., 1995), evidence from acritarchs in non-marine environments indicates a global sea-level rise, and it is notable that the marine extinctions and the beginning of the Early Triassic coal hiatus (i.e. lack of coal) coincide (Retallack et al., 1996). The relevance of these observations is that apparent coincidence of the crust with extinction events in marine and terrestrial realms means that its presence is presumed to be closely linked to the extinction process. Nevertheless, a more tightly constrained dating of these features is required, as recently emphasised by work on dating the boundary (Bowring et al., 1998).

Strata overlying the Huaying Mountains crust do not reveal contemporaneous erosion, and the well-preserved laminated micrite is undisturbed. These strata may be broadly divided into two units (see Fig. 4B): unit A includes beds up to the top of the oncoids, and are more variable than higher beds of unit B, which are rhythmic micrites (containing some clay, and the top few millimetres of individual beds may be burrowed) and shales. Unit B rhythmites suggest a stability of the system, consistent with a deeper water setting. Unit A strata, with a more variable facies suite containing microgastropods, microspheres and oncoids suggest, but do not prove (as noted in Section 5.2 for oncoids), shallower water in a low sedimentation rate with winnowing of fines. The fine-grained succession implies some sea-level rise above the crust in contrast to the underlying grainstones, because there seems to be no evidence of a barrier structure on the platform. However, if future work reveals a barrier, then unit A could be reinterpreted as some form of restricted-circulation platform limestone. Because the accommodation space on top of crinoidal shoals in shallow water is presumably limited, the micrites of unit A might therefore indicate that sea-level rise was initially slow, or even delayed.

Rapid rise after the top of unit A may thus have been responsible for the uniformity of the rhythmites of unit B, and conditions of rapid sea-level rise ought to lead to condensation of strata. An Ir anomaly in boundary sediments of the Meishan section (Xu and Yan, 1993) is probably not of sufficient magnitude to demonstrate an extraterrestrial impact, but may represent decreased sedimentation due to rapid sea level rise, as proposed for the end-Ordovician rapid sea-level rise following collapse of the Hirnantian ice sheet (Wang et al., 1992, 1993). The impact hypothesis is, however, still a contender for the extinction (Bowring et al., 1998). Wignall and Hallam (1996) noted the decline in burrow diameters in extinction-level strata, and interpreted this as due to dysoxia consistent with a sea-level rise. Nevertheless, geochemical data in the boundary interval of South China are equivocal; it is well known that sub-

Fig. 5. Details of the ?microbialite crust. (a) Vertical section at Jianshuigou, showing upward-branching structure with irregular to lobate margins, enclosed in micrite with some shell debris; scale 5 mm. (b) Transverse section at Baizhuyuan, showing irregular nature of the columns; scale 5 mm. (c) Vertical section at Jianshuigou, showing lobate margins of columns, and recrystallised texture; scale 1 mm. (d) Transverse section at Baizhuyuan, showing lobate and clotted texture, enclosing a cavity, with cement fringe; scale 0.5 mm.

stantial volcanic activity occurred at that time (Yin et al., 1992), and analysis of a range of major and trace elements (Chai et al., 1992) reveals results that could be related to volcanism, but with an unknown component of enrichment due either to condensation of strata or diagenetic alteration. Isopachs and palaeogeographic reconstructions (Reinhardt, 1988) suggest a westerly terrestrial source for clay in the micritic beds, supplying an irregular shelf containing platform and basin subareas, the Huaying Mountain area representing the platform.

Widespread pyrite in the crust and overlying sediments, while rare in strata underlying the crust, strongly suggest a change to anoxic conditions. Pyrite framboids in Holocene Black Sea sediments have been interpreted as indicating formation within the water column, rather than on the sea floor (Wilkin et al., 1997). Although pyrite in the Huaying Mountains crust and overlying sediments is present mostly as large cubes and crystal complexes, presumably formed in the sediment, tiny framboids are also abundant, but whether they grew within anoxic seawater cannot be determined on present evidence.

5.5. Controls on crust formation

The Huaying Mountains crust formed as either an organic microbial deposit, or an inorganic (possibly microbially mediated) precipitate. The detailed profile of individual portions of crust is unclear. Normally, microbial mats are surface phenomena with little capacity for growing much above the substrate surface; but if the crust was an inorganic crystalline mass, it may have been a more prominent feature. In Fig. 7, it is portrayed as protruding only slightly above the substrate. For its distribution, we consider a substrate-composition control on the crust's distribution unlikely; the boundary facies recorded by Wignall and Hallam (1996) at Laolongdong show Changxing Formation packstones typical of the reef-capping facies, overlain by typical Feixianguan Formation micritic facies but without the microbialite crust, in contrast to the sites we examined. Therefore we consider four possible origins of the crust (Fig. 7), and acknowledge that there may be others:

(1) The environment could simply have been a shallower setting on the winnowed tops of reef complexes, suitable for microbia to grow under conditions of low sedimentation, while the surrounding deeper interreef sea bed was unsuitable. In this interpretation, the crust may have been photoresponsive. Macrofossils were excluded either because of a stressful environment, or because the strata were deposited following the extinction [see (2)].

(2) Because the crust developed in the extinction interval, it may represent a disaster biota, a term used to denote a community developed in the aftermath of an extinction, as interpreted for Early Triassic stromatolites in several places (Schubert and Bottjer, 1992), for example western Turkey (Baud et al., 1997). An alternative view is that the occurrence of stromatolite layers is related to environmental control facilitating calcification and not requiring a disaster to create those conditions (Riding, 1997). This issue is difficult to resolve, and of potential relevance is that the boundary interval facies and biotic changes took place in a world of increasing environmental CO_2 (Berner, 1991; Graham et al., 1995). If CO_2-induced anoxia was the cause of the disaster, then the CO_2 may have also facilitated crust growth on a poorly populated sea bed. Although this notion is attractive, it may be seen by some as too simplistic to provide a satisfactory solution, and the timescale over which CO_2 was increasing may have been too long to account for the rapid facies changes seen in the Huaying Mountains.

(3) The Huaying Mountains crust may have an inorganic origin, and its location in the extinction interval nevertheless draws attention to CO_2 as the agent of extinction through anoxia (Wignall, 1992). An extreme case of environmental facilitation of crust growth is that the crust potentially represents the result of upwelled anoxic CO_2-rich water, leading to chemical precipitation on the sea floor, as in the alkalinity model for the modern Black Sea (Kempe, 1990), whereby CO_2-rich water upwelled from ocean floor mixed with oxic shallow waters and precipitated $CaCO_3$. Modelling of the modern North Atlantic indicates that rapid rise of atmospheric CO_2 could trigger disruption of ocean circulation, whereas a slower rise of the same amount of CO_2 would not (Stocker and Schmitter, 1997). The upwelling model was used as a possible explanation for abundant inorganic cement well known in Late Permian reefs (Grotzinger and Knoll, 1995; Knoll et

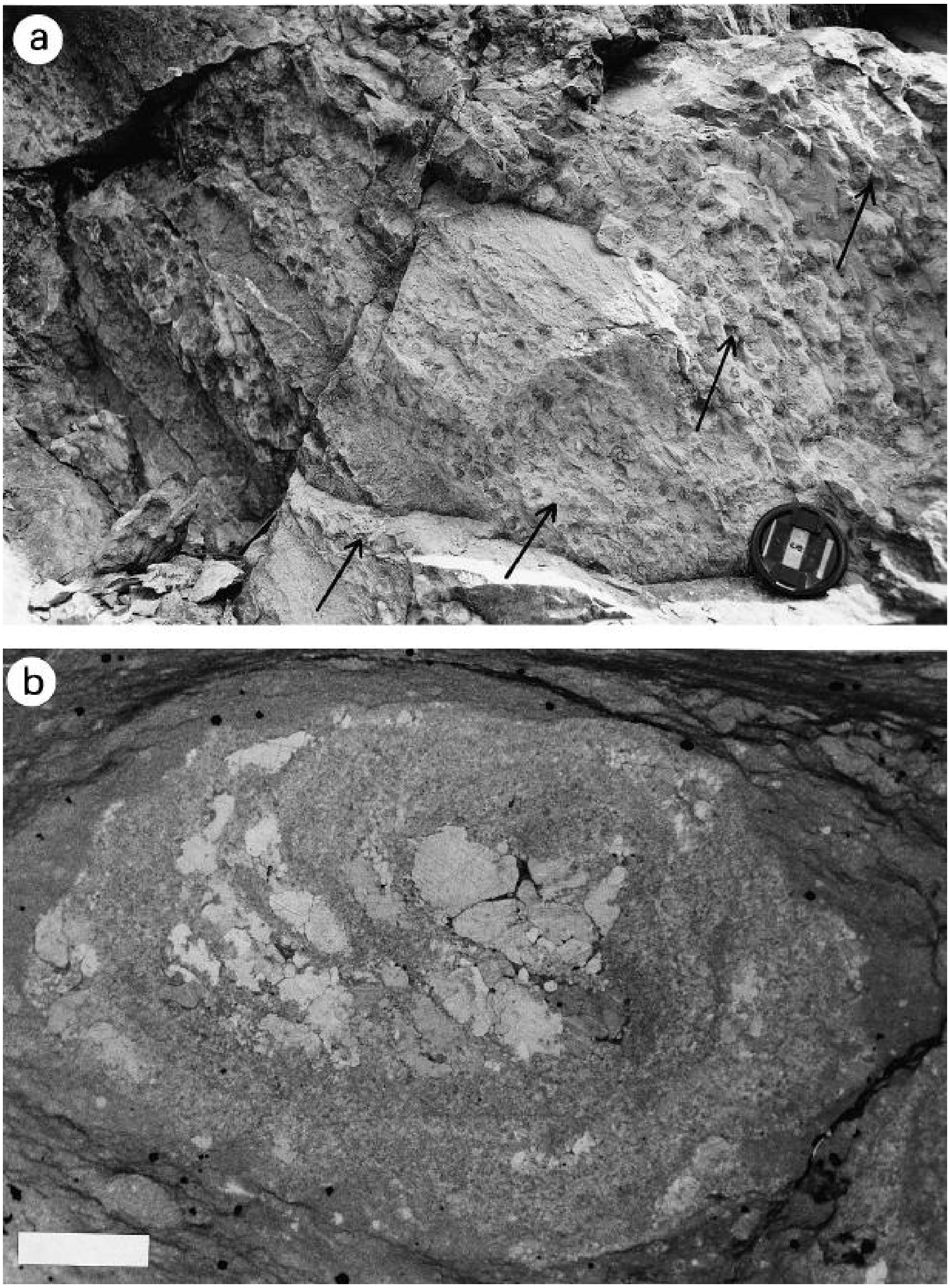

Fig. 6. Oncoid beds at Baizhuyuan. (a) Field view, showing several oncoid beds (arrows), interspersed with laminated micrites. (b) Oncoid in clay-rich micrite. Note prominent pressure dissolution and abundant tiny pyrite cubes and framboids; scale 2 mm.

al., 1996), but those cements comprise crystal fans and layers filling cavities, and do not resemble the lobate structure of the crust. However, reinterpretation of the abundant Permian reef microbial structures such as *Archaeolithoporella* as inorganic (Grotzinger and Knoll, 1995) coupled with the lack of proof of

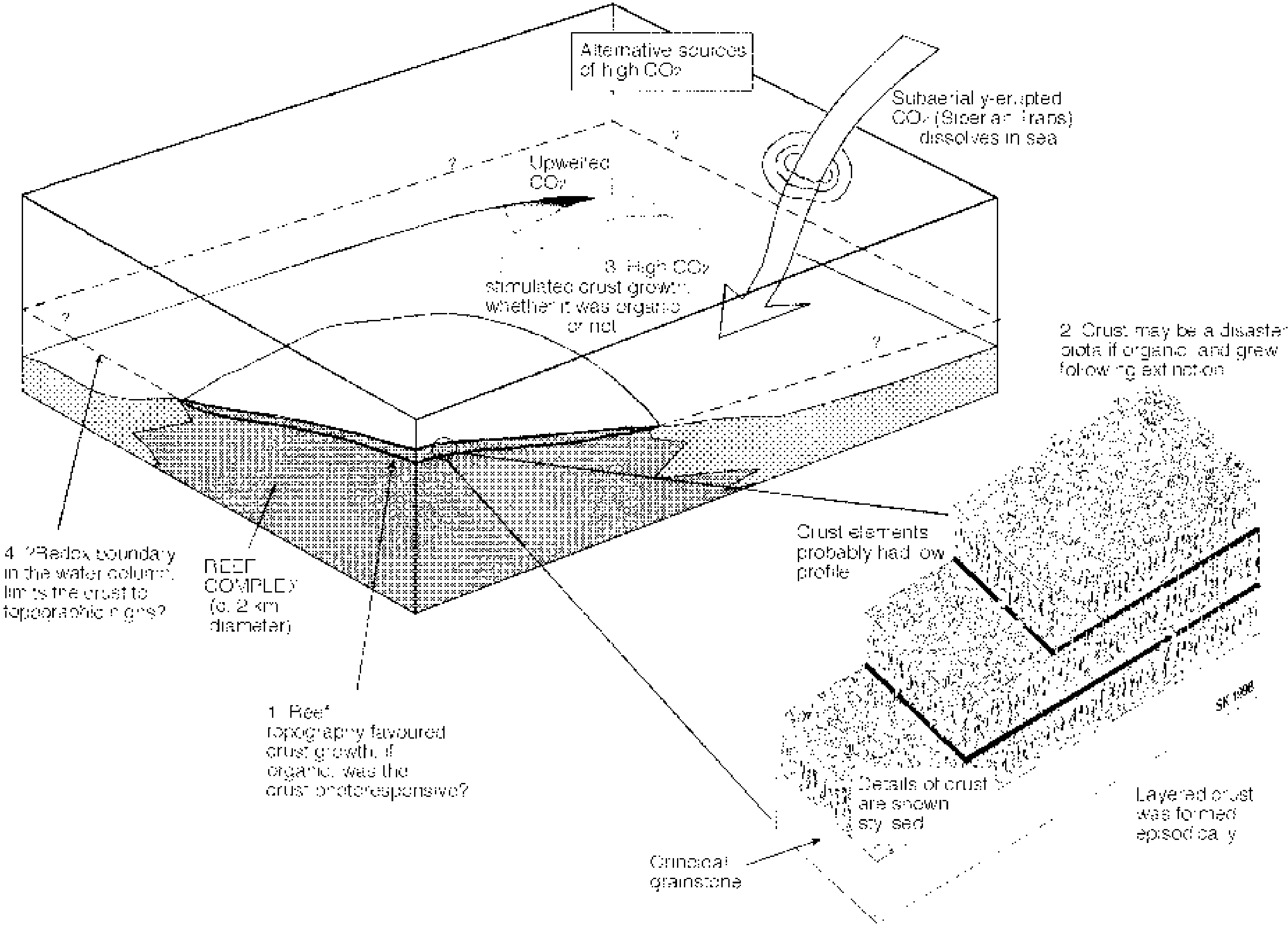

Fig. 7. Reconstruction of location of crust on hypothetical reef profile, and summary of alternative models to explain the crust. Note that branches of the crust are shown as protruding only slightly from the surface, but its true profile is unknown. See text for discussion.

organic origin of the crust of this study, raises the question as to whether the upwelling model is applicable. In this case, we consider that the upwelling model does *not* apply successfully to the Huaying Mountains crust, largely because of its restriction to tops of reef complexes. Had upwelled anoxic water spread across the area, the crust would be expected in the interreef areas too. In the upwelling model, carbonate precipitation occurs when the anoxic water reached oxidised surface water; the sea floor during latest Changxing Formation times was well oxygenated because of the abundant biotas, but the overlying sediments show anoxia/dysoxia.

(4) It might be argued that upwelled anoxic water displaced oxygenated water, so that the redox boundary moved into the water column, with the reef tops protruding through it into oxidised surface waters, where calcite precipitation could occur (Fig. 7). However, we feel that such an idea is rather tenuous, and of course depends on supply of anoxic water, and the topographic difference between reef tops and interreef areas; reconstruction diagrams (Fan et al., 1996, p. 233) imply considerable relief, but this has not been verified. Furthermore, some pyrite is found within the crust itself, but this may be diagenetic; thus it is difficult to be sure whether the crust formed in anoxic/dysoxic or oxic water.

The region is located in the inner platform, away from the open ocean margin and, therefore, sites of upwelling. Whether upwelled anoxic waters could have reached the Huaying Mountains area cannot be assessed in this study, but if sea level was rising sharply, we would not ignore that possibility.

The atmosphere is an alternative source of CO_2, for inorganic carbonate precipitation, especially in view of the rapidly increasing CO_2 levels interpreted for the Late Permian atmosphere (Berner, 1991; Graham et al., 1995). Potential sources are volcanic eruptions forming the huge volume of the Siberian Traps, and there is abundant volcanic material in the boundary strata of South China (although apparently not in the study area); also possible is release of CO_2 from previously assimilated carbon in the Upper Carboniferous. However, as in (3) there is a problem of why the interreef areas did not receive the precipitate, and there is insufficient precision of dating of the Siberian Traps eruptions in relation to the time of the extinction (Bowring et al., 1998).

Poor preservation of the crust's fabric makes its interpretation currently equivocal. The most likely explanation lies in environmental facilitation of carbonate precipitation, but we regard upwelled/atmosphere-derived CO_2-forcing of large-scale inorganic precipitation on the sea floor as the least satisfactory explanation of its origin, because of its apparent restriction to reef tops. A model applied to Quaternary travertines (Guo and Riding, 1994), whereby control is principally inorganic, but with possible microbial mediation, may have elements in common with controls on the Huaying Mountains crust. Layering of the crust suggests repeated events of crust growth, either environmentally stimulated or punctuated by sedimentation. Baud et al. (1997) suggested that stromatolites in the Lower Triassic of Turkey grew because of a drop in sedimentation rate. The sudden appearance and abrupt end of crust growth indicate a short episode of favourable conditions, which presumably ended as sea level rose. However, the gastropod-rich and oncoid-rich beds presumably also developed when sedimentation rate was low, so the crust may represent shallow water, and facies above were deeper. Furthermore, if the crust formed as a disaster biota following the extinction, then its presence as a thin layer is curious. Given the low diversity of fossils in the overlying beds, with abundant evidence of low oxygen, the crust would be expected to be much thicker, drawing attention to the view (Riding, 1997) that microbial calcification responds principally to supply of bicarbonate, and that there may have been only a short time during which the sea water was super-enriched with CO_2. A sharp negative $\delta^{13}C$ excursion (Bowring et al., 1998) in the boundary interval near Nanjing, may be relevant.

6. Conclusions

A microbialite crust in facies capping reef complexes in the Permian–Triassic boundary interval of eastern Sichuan, South China Block, provides illustration of the complexities of environments in the interval. The evidence may be used to support alternative, but some overlapping, views:

(1) The crust was organic, and the microbia took advantage of topographic highs on reef tops.

(2) The microbia were a disaster biota following the extinction.

(3) The microbia took advantage of favourable conditions for calcification, associated with a rapidly rising environmental-CO_2 content.

(4) The crust was an inorganic precipitate associated with CO_2-rich water.

Microbial crusts are rare after the Cambrian, and emphasise that the prevailing oceanic-atmospheric conditions were unusual. Bowring et al. (1998) summarise the current position of knowledge of causes of the end-Permian extinction into three overlapping areas: CO_2 from volcanic eruptions, productivity collapse and bolide impact. The environmental consequences of any of these might apply to the Huaying Mountains ?microbialite crust.

Acknowledgements

We are grateful to the State Key Laboratories of China for supporting this work, and for providing facilities for the project. SK also thanks the Southwest Petroleum Institute, Nanchong, China, for its hospitality during visits to China in 1996 and 1997. The Royal Society supported his travel in 1997, and Brunel University provided facilities in UK, both of which were gratefully received. We thank Professor X. Zhou, Dai Zhongyan, Tan Xiucheng, Yang Jianghai (SWPI) for their assistance in the field. We are particularly grateful to Chen Xiaohui for her help in Nanchong. Robert Riding and Paul Wright (Cardiff, UK) gave valuable advice and Lindsey Axe (Cardiff) assisted with photography. Tony Dickson (Cambridge, UK) provided CL facilities. Paul Wignall (Leeds, UK) made helpful comments on an earlier draft, and we are grateful to Anthony Hallam, Maurice Tucker, Finn Surlyk and an anonymous reviewer for their invaluable comments.

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