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RESEARCH ARTICLE

Geobiological interpretation of the oxygen-deficient deposits of the Middle Permian marine source rocks in South China: A working hypothesis

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Abstract To decipher the origin of oxygen-deficient shelfal deposits is significant for tracing the distribution of marine source rocks and interpreting the evolution of depositional environment. The origin of the Middle Permian Chihsia Formation in South China remains a puzzle for long with its evident oxygen-deficient features but diverse benthos. This paper shows a typical Chihsian depositional rhythm composed of the massive and the laminated limestones with ecological and geochemical features. Massive bioclastic limestone from the rhythm was aerobic in paleoxygenation condition indicated by both the ecological and geochemical features. However, a contradictory oxygenation was inferred for the "laminated" counterpart from the rhythm, with the ecological signal being aerobic and the geochemical one being anoxic. The difference in ecological and geochemical indications was interpreted as the instability of paleoxygenation condition in shelf environments, caused by an enhanced paleoproductivity. Rhythmic occurrence of the oxygen-deficient condition might have been stemmed from paleo-Tethyan paleocurrents flowing across South China.

Keywords South China, Middle Permian, oxygen-deficient, paleoxygenation condition, model

1 Introduction

The discovery of the Puguang gas field in carbonate rocks in northeastern Sichuan Province indicates that further exploration in the marine carbonate succession of South China is of great promise. Middle Permian black argillaceous limestone and shales rich in organic matter in the region were believed to be one of main source rocks (Cai et al., 2005; Ma et al., 2005). Constraining the origin and the distributions in temporal and spatial framework of those deposits would be of great implications in promoting the further exploration and in evaluating the contribution of the Permian marine source rocks.

The marine Middle Permian in South China includes the Chihsia and Maokou formations in Chinese literatures, which are well exposed and soundly investigated in the region. However, the origin of the organic-rich succession is still open, especially about the sedimentary environment and its paleoxygenation condition. This paper emphasizes on a typical Chihsian succession with available sedimentary, ecological and geochemical features, and end up with a working hypothesis about the origin of the oxygen-deficient environment in light of geobiology.

2 Sedimentary features and depositional environments of the Permian Chihsia Formation

The Chihsia Formation of South China is commonly about 150 m in thickness. If completely developed, this formation accommodates five fusulinid zones: namely *Schwagerina tschernyschewi*, *Misellina claudiae*, *Nankinella orbicularia*, *Schwagerina chihsiaensis* and *Parafusulina multiseptata* in an ascending order, correlating with the late Artinskian to Roadian stages (Jin et al., 1994; 1997). In the upper valley of the Yangtze River, the basal interval beneath the carbonate succession additionally develops littoral coal-bearing clastics commonly less than 10 m thick (known as the Liangshan Member), as a result of the regression before the Chihsian time.

The South China region during the Chihsian stage was a carbonate platform characterized lithologically by homogeneous sublittoral lime mudstone, bioclastic wackestone

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and packstone interbedded with thin-bedded argillaceous limestone. In the northwestern Guangxi and southern Guizhou area (Qian–Gui carbonate basin), equivalent carbonates are intercalated with carbonate turbidites, thin-bedded black shales and siliceous rocks yielding ammonites and sponge spicules (Feng et al., 1994; Wang et al., 1994). In southeastern Guangxi (Qinzhou–Fangcheng Trough), the Chihsian strata are replaced by radiolarian-rich siliceous sediments that are surrounded by a narrow belt of carbonate shoals.

The Chihsian carbonate succession is unique in its great lateral persistence in both thickness and lithofacies, and its widespread enrichment in organic matter and chert nodules. In the shallow carbonate platform succession, no intertidal and supratidal sediments have been reported. Except the aforesaid shoals, few grainstones occur, connoting a low-energy depositional environment. It is widely accepted that the ambient salinity was normal as indicated by a diverse stenohaline benthic fauna. Additionally, carbonate ooids, whose development is strongly dependent on salinity (Lees, 1975), are absent in the broad area (Yan and Du, 1994; Yan et al., 2005).

There are plenty of sedimentary features, which were thought as indicators of oxygen deficient environments in the Permian Chihsia Formation, including (1) cyclic occurrence of black argillaceous limestone and nodular chert, (2) organic sedimentary facies, (3) ecological features such as some ichinofabrics, (4) sedimentary background of low energy without grainstone, and (5) trace element ratios such as Ni/Co and V/(V + Ni) (Yan, 2004). In striking contrast, the diverse shallow benthos from the Chihsia Formation indicate the carbonate succession accumulated in an environment of aerobic conditions. Thus, the paleoxygenation condition for the succession is still controversial.

3 Geochemical analysis on a typical Chihsian rhythm

In outcrops, the Chihsian carbonates consist mainly of shelfal sublittoral lime mudstones and bioclastic wackestones (hard and massive) alternating with thin-bedded, soft, sepiolite-bearing ("argillaceous") limestones, resulting in a special rhythm (Fig. 1). In mudstone, the kinds of skeletal detritus are limited, including ostracods, foraminifera, brachiopod fragments and spines, and rare bryozoans and trilobites. Wackestones are rich in skeletal detritus, dominated by algae, foraminifers, and mollusks with subordinate amounts of brachiopods, echinoderms, and ostracods, and minor bryozoans and trilobites. Fragile skeletons such as calcareous algae are well preserved, indicating that cementation took place during early diagenesis with little diagenetic compaction (Fig. 2(b)) (Yan et al., 2005). Total organic matter (TOC) content is low in the massive limestone.

The soft intercalated Chihsian sepiolite-bearing limestone is locally termed as "calc-magnesium shale" if sepiolite content is high (Liu, 1985). The sepiolite-bearing limestone is gray to dark gray on weathered surfaces, and dark gray to black on fresh surfaces. Common benthic organisms are brachiopod fragment, ostracod and foraminifera. Bioclastic flakes are oriented parallel to bedding planes, and thin-shelled fragments, e.g. ostracods, are broken due to compaction of the unlithified sediment (Fig. 2(d)) (Yan et al., 2005). The TOC content is relatively high in the soft limestone.

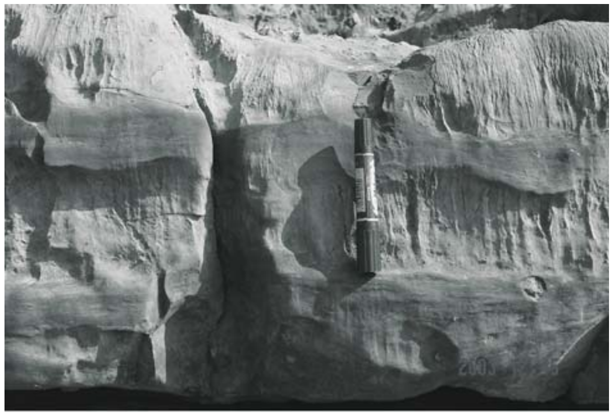

Fig. 1 Field photo of Chihsian rhythm consisting of massive limestone and sepiolite-bearing limestone (with faint lamination) (Yan, 2004)

Variations in the thickness of the sepiolite-bearing interlayers follow a pattern of sea-level changes. In intervals near maximum flooding surfaces, beds are dominated by sepiolite-bearing limestone (Yan et al., 1997). As the relative sea level falls, soft sepiolite-bearing limestone decreases in the relative content, and massive bioclastic limestone increases in the rhythm. This alternation forms sedimentary cycles, with 10 to 15 m thick each (Fig. 3).

Samples for this study were collected from the middle of the Chihsian Formation at the Cihua Section, Pingxiang of Jiangxi Province. There occur four beds of (fusulinid) bioclastic limestone. Eight samples were collected continuously from the third bed about 30 cm thick. Fusulinid is present in the whole bed but condensed in the lower and upper parts (Fig. 2(a)). The appearance of the sampled bed is similar to the common rhythm observed in the Chihsian carbonates (Fig. 1).

In the light of fusulinid ecology, the limestone bed seems to have been accumulated in aerobic conditions. However, the fusulinid was mainly preserved in the black and laminated limesotne at the lower and the topmost parts of the rhythm. The laminated limestone is characterized by diagenetic compaction such as suture and crush observed between fusulinid (Fig. 2(c)). The lamination was generally thought as an original sedimentary record, but further enhanced by the diagenetic compaction. If original laminations were preserved, the lower part and the uppermost part where the lamination develops were formed in an oxygen-deficient environment, which would conflict with the reference from fusulinid ecology.

In geochemistry, the degree of pyritization (DOP), trace elemental ratios, such as Ni/Co, V/(V + Ni) and U/Th are commonly used to determine the paleoxygenation condition

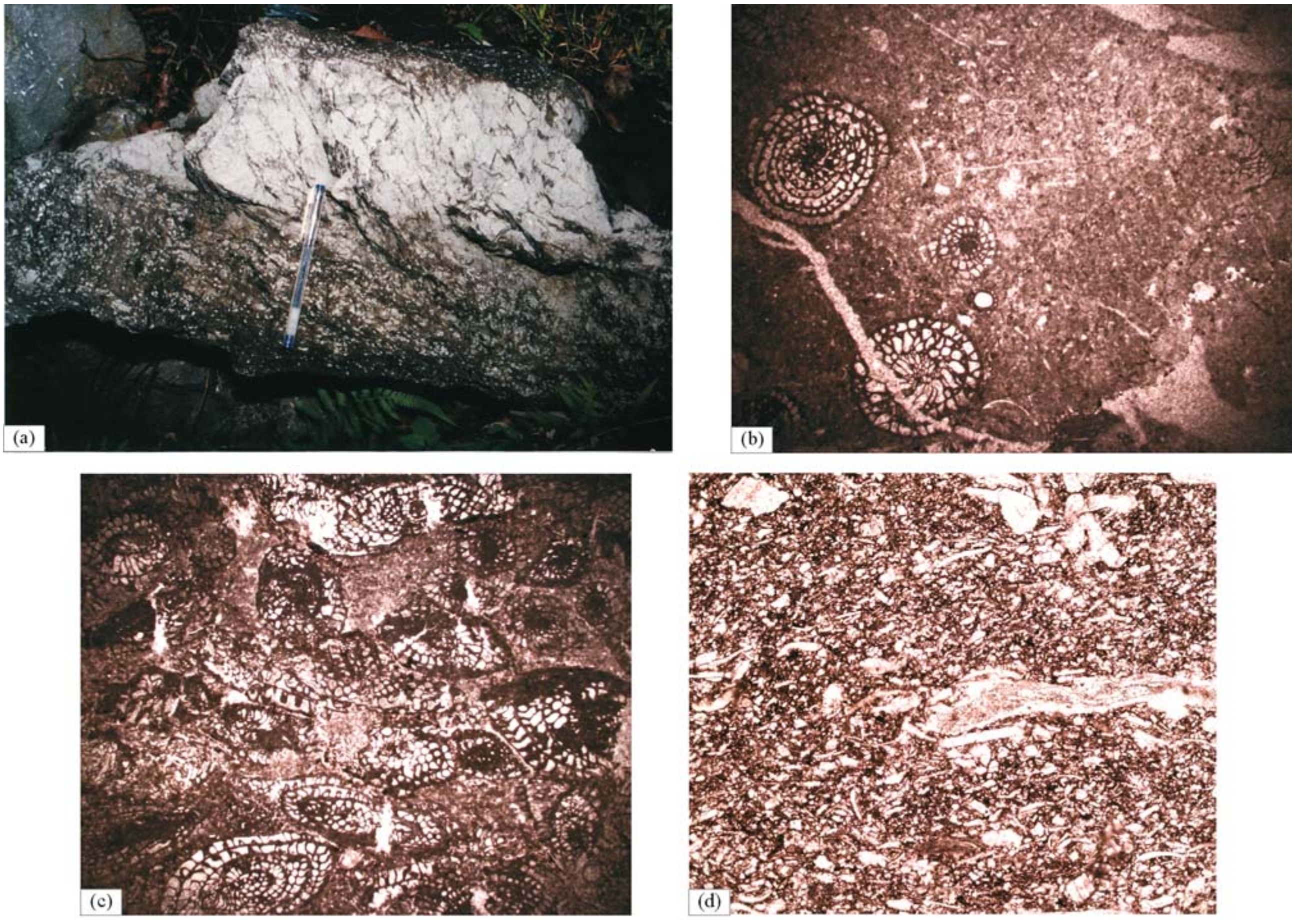

Fig. 2 Photography of Chihsian limestone
(a) Exposure of a typical Chisian limestone bed with plenty fusulinid in its lower and topmost parts. Cihua, Jiangxi; (b) microphotography of sample CH-10 from the middle of the sampled bed (X5); (c) microphotography of sample CH-13 from the top part of the sampled bed (X5); (d) microphotography of Chihsian laminated limestone from the Tieqiao Section (X5), Laibin of Guangxi

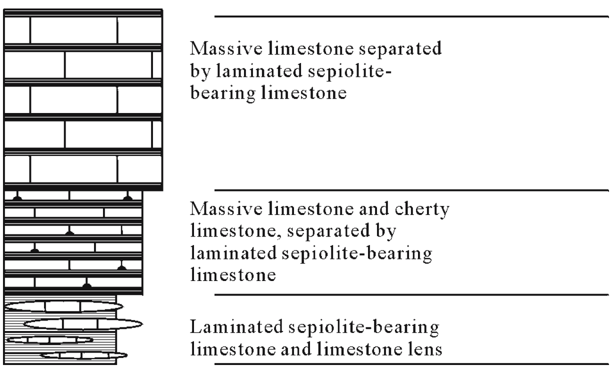

Fig. 3 Typical composite cycle in the Chihsia Formation (about 15 m thick) (Yan et al., 2005)

(Jones and Manning, 1994). Geochemical analytic results for the eight samples are plotted in Fig. 4. Based on the U/Th, Ni/Co and DOP, the paleoxygenation condition for the massive limestone from the middle part was aerobic, but oxygen deficient for the lower part and the topmost part. Similar record was observed in the V/(V+Ni) for the lower part, but different for the upper part.

Opposite to the results mentioned above is the Ce/La ratio, which was proposed by Bai et al. (1994). After comparing the rare earth element (REE) features with those of Ce abnormity from the upper Devonian of northeastern Guangxi, they thought that the Ce/La ratio positively correlated with Ce abnormity, and the ratio might be used as a proxy for the Ce abnormity. In addition, they suggested that values less than 1.5, between 1.5–1.8 and above 2.0 of the Ce/La ratio would correspond to respectively aerobic, dysaerobic and anaerobic conditions. If their notions were accepted, then all the samples analyzed in this study would belong to anaerobic sediments, and the lowest value in dissolved oxygen for ambient water would be for samples from the middle of the sampled interval. Such an inference conflicts obviously with the paleoecological interpretation of fusulinid. Thus, paleoxygenation implication of the Ce/La ratio should be revised.

Both of the Ce and La are REE, in which Ce is positive quadrivalence and La is positive trivalence. Under an aerobic condition, sedimentary organic matter tends to adsorb more Ce^{4+} than La^{3+}, resulting in the increase of the Ce/La ratio. Contrarily, the ratio would be relatively lower under an

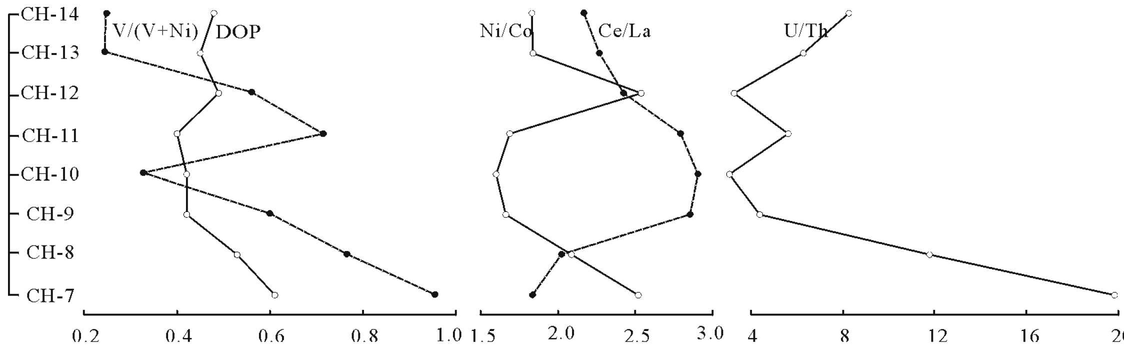

Fig. 4 Geochemical analysis on a typical limestone bed (Fig. 1)

anaerobic condition. If so, a positive shift of Ce/La ratio would indicate an oxygenation event, and a negative shift mean the deoxygenation event. Undoubtedly, the aerobic condition could be expected for samples from the middle part of the rhythm studied because their values are higher than those for the lower and topmost laminated parts. By this interpretation, the paleoxygenation implication of the Ce/La ratio is coincident with that of the DOP index.

The rhythm analyzed above is of representative implications for the paleoxygenation interpretation of the Permian Chihsia Formation, in which the laminated limestone is aerobic in the light of ecological features, but anaerobic in light of geochemical features. The aerobic interpretation on massive limestone from the middle part of the rhythm appears in well agreement on the basis of different records.

Actually, disagreement of biofacies with geochemical features is common for paleoxygenation explanation of shallow shelf deposits. Several reasons for the disagreement in the paleoxygenation condition were proposed. (1) Biofacies and sedimentary features from a shelf environment span a long period and their records represent the average values of the deposition covering this period. (2) Dissolved oxygen in seawater of shelf environments may fluctuate rapidly and frequently between aerobic and anaerobic regime. (3) Short periods of the oxygenation event with intensive biodisturbation may eliminate the sedimentary signal of previous anaerobic conditions, but this might not affect the geochemical record (if the interval of aerobic condition is not too long, and deposition rate is not too low) (Tyson, Personal communication to LXY, 2007). Based on geochemical and ecological analysis on the Chihsian rhythm mentioned above, the frequent inversion of oxygen deficient conditions is feasible for the laminated limestone. But most of the massive limestones were formed in the period of oxygenation interval.

4 A working hypothesis for the Middle Permian Chihsia Formation

There exist three models about the origin of the Chihsian oxygen-deficient environment, i.e. the halo-stratification model, the upwelling current model and the transgression model. The first one might be of the least feasibility, because the Chihsian depositional environment was too shallow to sustain the stratification long enough (Yan, 2004). The upwelling model was a frequently cited one since its first proposal by Lu and Zhai (1989).

Widespread enrichment in organic matter and chert nodules in the Chihsia Formation might support the upwelling model. However, the Chihsia Formation differs from upwelling deposits in its great lateral persistence of thickness and lithofacies over the whole South China region. And contrast to upwelling deposits, the phosphorus content in the Chihsia Formation is low. Transgression approaches its maximum at the Chihsian time during the whole geological history of the region, judging from its greatest areal coverage. However, the sole transgression cannot count for the enrichment of organic matter in the whole succession.

On the other hand, the enhanced productivity would increase the consuming of dissolved oxygen, which, in turn, facilitates the accumulation and the preservation of organic matter. In addition, variations in productivity may result in a fluctuation of the dissolved oxygen in the environment, as recorded by the alternation of aerobic shelf carbonate deposits with the oxygen-deficient sediments. Such a scenario is supported by carbon isotopic analysis of bulk carbonate from the formation. $\delta^{13}C$ value for the Chihsia carbonates is the heaviest one in the Late Paleozoic succession of the South China region (Huang, 1997), and the $\delta^{13}C$ value from the laminated sepiolite-bearing limestone is much heavier than that from its counterpart massive limestone (Yan, 1996).

Paleoecologically, the biotic community from the massive limestone is highly diversified, with relatively large body-size and plenty of calcareous algae, while that from its counterpart laminated limestone is monotonous with relatively small body-size. The transition from massive limestone to laminated limestone is coincident with, and might be the record of, the following ecological processes, i.e. enhanced nutrition input and elevated primary productivity→ blooms of small body-size fauna and fresh algae → decrease of dissolved oxygen by bioloigcal consume → occurrence of an oxygen deficient condition (Hallock and Schlager, 1986). Sedimentary features of the Chihsian carbonates, such as the enrichment in organic matter and chert nodules as well as the great persistence in strata thickness and lithofacies, conform to the enhanced productivity mentioned above (Yan, 2004).

Based on following facts, paleoproductivity for the Chihsian environment was relatively high, but lower than those environments of the common upwelling areas. (1) The phosphorus content in the Chihsia Formation is low. (2) In upwelling areas, the eutrophic environment stimilates the flurishment of phytoplankton and fresh algae, resulting in deposits rich in organic matter and barren of carbonate deposits. The Chihsia Formation is however carbonate-dominated deposits. (3) Marine sepiolite seems to be of implications in the recognition of ambient trophic level. In the Tertiary phosphorous and sepiolite clay deposits in western Africa and southeastern USA, phosphorous clay layer and sepiolite clay layer border upon one another, but never associate in any layers (Yan et al., 2005). As commonly accepted, those phosphorous clay layers accumulated in the upwelling eutrophic environments. Thus, the mesotrophic level would support sepiolite deposits and the eutrophic upweling condition support phosphorous deposits. In another word, the trophic level for the Chihsian environment was relatively high, but not high enough for the phosphrous deposits (Yan, 2004).

In a broad paleogeographic frame, the South China region comprised a group of isolated oceanic islands in the eastern Paleotethys during the Permian (Fig. 5(a)). Because the whole region submerged beneath the transgressional water during the middle and late parts of the Chihsian time, the enhanced nutritional supply that stimulated the relatively high Chihsian paleoproductivity would be solely of oceanic source, but

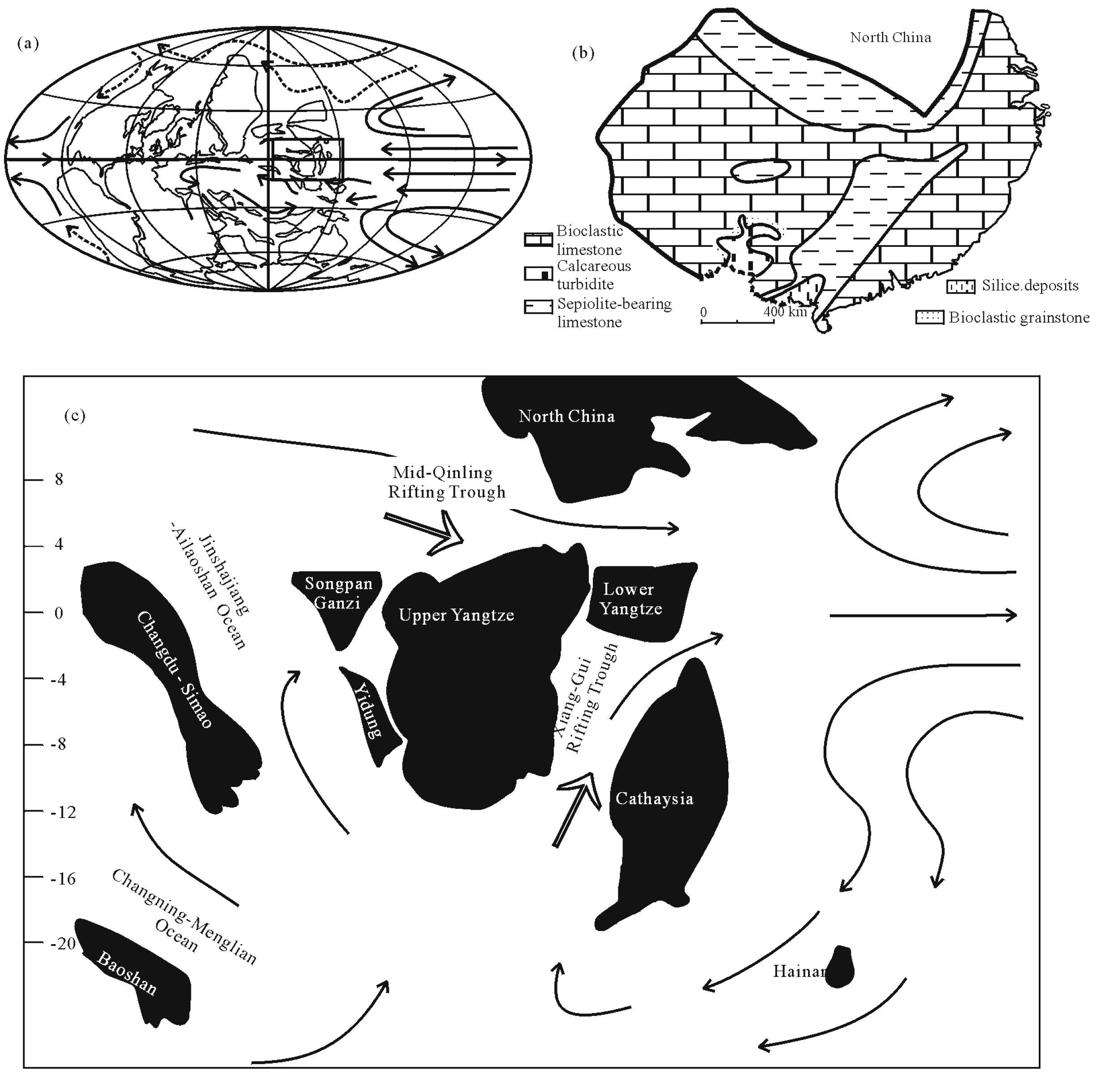

Fig. 5 (a) Configuration of Pangea and Paleotethys during the Chihsian stage (Yan and Zhao, 2001). The rectangle indicates the South China region; (b) Chihsian lithofacies in the South China region; (c) paleocurrent reconstruction of the Chihsian Stage in the South China region (terrain and their position after Yin H F unpublished data)

neither terrestrial input, nor dusts from the remote Pangea through the incipient megamonsoon circulation (Fig. 5(a)). Considering the frequent alternation of an aerobic with an oxygen-deficient condition recorded in the massive-laminated limestone rhythm, the relatively high paleoproductivity, as well as the Chihsian paleogeographic background worldwide, was proposed here as a tentatively hypothesis for the origin of the Chihsian paleoxygenation condition, which emphasizes the importance of the paleoland-ocean configuration and the paleocurrent pattern (Fig. 5(c)).

At that time, the Upper Yangtze, Lower Yangtze and Cathaysia terrene in the South China region were located in eastern Paleotethyan ocean, and in the southern lower latitudes near the paleoequator (Fig. 5(a)). The paleocurrent to the west of the region originates from Paleotethys, and to the east includes an equator warm current and a counter-equator current (Yan and Zhao, 2001). Interplay of those currents resulted in an intensive surface current flowing northeastward over the region through Hunan–Guangxi Rifting Trough. The surface current would possibly be involved with the component from the oxygen minimum zone with rich nutrition. As a result, the Hunan-Guangxi Rifting Trough was a belt rich in sepiolite deposits and dysaerobic deposits (Fig. 5(b)). Another current might have flowed through the Qinling Rifting Trough, resulting in the deposits rich in silica and sepiolite along the northern margin of the region (Fig. 5(b)).

Although lithofacies features of the Maokou Formation defers from those of the Chihsia Formation, similar paleocurrent pattern might be expected in the Maokou stage. During the Maokou stage, lateral variation in lithofacies is evident, including reef, siliceous and terrestrial deposits. However the distribution of Maokou chert fallows the distribution pattern of the Chihsian sepiolite-rich deposits (Liu and Xu, 1994; Wang et al., 1994). At the middle of the Maokou stage, chert deposits with phosphorous nodules replaced the previous sepiolite clay, indicating the paleoproductivity surpass of Maokou over Chihsian. Even so, the phosphorous content in the Maokou deposits is still less than those in the common upwelling deposits.

Because of the uplifting of the Kangdian Paleoland in the west and the Cathaysia Paleoland in the east during the Maokou stage, it is reasonable to expect an addition of the terrestrial nutrition, which in turn stimulates an enhanced coeval productivity. Intensive volcanic activity during the Maokou stage might have played a role but remains to be detailed. In addition, the uplifting of the two paleolands might confine the flowing path, facilitating the siliceous deposits with radiolarians. Thus, the features and the distribution pattern of the Maokou deposits are also coincident with the working hypothesis proposed above.

5 Conclusion remark

Comparing with traditional paleontology, geobiology emphasizes the interaction between the organisms and the associated environments, and between biosphere and geosphere. Although intensive investigations have been conducted on the paleontological and sedimentological features of the Chihsian carbonates, the paleoxygenation condition for the formation remains open. It seems difficult to puzzle out through the sole paleontological or sedimentological investigation for the dilemma, i.e. plenty of diversified benthos of shallow water with features indicative of an oxygen deficient environment. Compiling the depositional environment with organisms, as well as the paleogeographical and the paleoceanographical background, the key of the geobiological notion would be of particular significance while dealing with similar issues stated above.

It is worthwhile to differentiate the shelf oxygen deficient environment from the oceanic one, because in the former situation organisms are not commonly used to large and rapid variations in dissolved oxygen, which in turn recorded in sedimentological and geochemical features. The origin of Middle Permian oxygen deficient environment in the South China region might have been rooted in coeval paleogeographical evolution (e.g. the uplifting of the Kangdian and Cathaysia paleolands) as well as the paleoceanographical background. The proposed paleocurrent model differs from traditional upwelling ones, and remains to be detailed.

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