Allogenic succession in Late Ordovician reefs from southeast China: a response to the Cathaysian orogeny

Qijian Li[a], Yue Li[b] and Wolfgang Kiessling[a,c]

[a] GeoZentrum Nordbayern, University of Erlangen-Nürnberg, Loewenichstr. 28, 91054 Erlangen, Germany; qijianli@hotmail.com, wolfgang.kiessling@fau.de
[b] Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences, 39 East Beijing Road, Nanjing 210008, China; yueli@nigpas.ac.cn
[c] Museum für Naturkunde, Invalidenstr. 43, 10115 Berlin, Germany

Received 1 July 2014, accepted 16 December 2014

Abstract. Several Late Ordovician (late Katian) reef complexes are known from the border area of Jiangxi and Zhejiang provinces in southeast China. We studied two coral–stromatoporoid reefs exposed in the Xiazhen Formation at Zhuzhai (Yushan, Jiangxi). The reefs have a combined thickness of 7.4 m and are metazoan-dominated with most reef-builders in growth position. Stromatoporoids and tabulate corals constitute the framework of the reefs. Stromatoporoids (mostly *Clathrodictyon*) dominate the first unit and show a vertical increase in proportion and dominance from the middle part to the top of the unit, whereas tabulate corals (dominated by *Catenipora* and *Agetolites*) are the main reef-builders in the second unit where stromatoporoids are rare. We attribute this change to a greater tolerance of tabulate corals to turbidity, allowing them to thrive in the muddy facies of the upper unit. This facies change is probably related to the increasing terrestrial input from the northwestward expansion of the Cathaysian Land during the late Katian. The Cathaysian orogeny also led to a short-term exposure of the sea floor in the study area, which terminated the reef growth.

Key words: Xiazhen Formation, coral–stromatoporoid reefs, late Katian, Cathaysian orogeny, allogenic succession.

INTRODUCTION

The Great Ordovician Biodiversification is manifested on the South China Plate by pulsed three main diversification phases and a Katian diversity climax (Zhan et al. 2013). During the Late Ordovician, reef ecosystems were completing their fundamental shift from microbial to metazoan-dominated reefs (Webby 2002). Stromatoporoids, corals and bryozoans became the major contributors to metazoan reefs. The complexity of reef communities also showed a steep rise in the Late Ordovician (Webby 2002). In South China, highly diverse Late Ordovician reef complexes only existed on an isolated platform in the Jiangshan–Changshan–Yushan area of southeast China (Bian et al. 1996; Li et al. 2004; Wang et al. 2012). Late Katian reefs on this platform provide the opportunity to trace the trajectory of reef development. The best-known example of coral–stromatoporoid reefs is exposed in the lower part of the Xiazhen Formation at Zhuzhai (Yushan County, Jiangxi Province). These reefs are well studied (Chen et al. 1987; Bian & Zhou 1990; Bian et al. 1996) but little is known about the relative abundances and the dynamics of the reef-building communities. Based on detailed line transects we here provide the first quantitative assessment of framework density and palaeontological data. This allowed us to assess how the reef communities responded to palaeoenvironmental change in the context of the Cathaysian orogeny.

GEOLOGICAL SETTING AND CHARACTERISTICS OF REEFS

The South China Plate comprises three depositional settings, which are arranged in WSW–ENE trending belts: Yangtze Platform, Jiangnan Slope and Zhujiang Basin. To the southeast of the Zhujiang Basin, the Cathaysian Land (or Oldland) has existed, as part of the South China Plate during the Ordovician and Silurian (Chen & Rong 1992; Chen et al. 1995). Since the late Katian, the southeastern part of South China had been uplifted due to the northwestward expansion of the Cathaysian Land. This resulted in an uplift of the former slope and basin areas and led to the development of Zhe-Gan Platform in the Jiangshan–Changshan–Yushan area (Zhang et al. 2007) with shallow-water carbonates and reefs. The Zhuzhai section (28°34′28.65″N, 118°20′05.45″E) is located near Sanxuesi village, some 15 km to the southeast of Yushan. In the 205 m thick section the Xiazhen Formation is exposed, which consists of interbedded deposits of siliciclastics and limestones. The base of the section is in fault contact with Jurassic deposits; the top is unconformably overlain by Carboniferous rocks (Fig. 1). Based mostly on the shelly faunas, the age of the Xiazhen Formation is constrained to the late Katian, probably corresponding to the *Dicellograptus complexus* Biozone (Zhang et al. 2007).

Coral–stromatoporoid-bearing reefs occur in the lower part of the formation. They consist of stacked bioherms (varying from 0.4 to 1.6 m in thickness individually), which are 7.4 m thick and over 20 m wide. The reef complex contains two main reefal units (Fig. 1). Below the first unit, there is a thick layer (around 1.1 m) of micritic limestones containing a monospecific assemblage of large brachiopods (*Tcherskidium*), often in growth position. The overlying 2.3 m thick in situ reef framework of the first reef unit is chiefly constructed by tabulate corals and massive stromatoporoids (*Clathrodictyon*), which are partly silicified. Scattered dendritic stromatoporoids (*Thamnobeatricea*), solitary rugose and brachiopod fragments are also visible on weathered surfaces. A 2.6 m thick interval of nodular, muddy limestone separates the lower unit from the upper unit. The upper reef unit is 2.5 m thick. Massive corals (*Plasmoporella*, *Agetolites* and *Catenipora*) dominate the reef framework, whereas stromatoporoids are scarce. Three-dimensionally preserved *Catenipora* are conspicuous. These are composed of several layers of fence-shaped structures as already observed by other authors (Bian et al. 1996). Terrigenous clastics are more prevalent in this unit than below and reefs are covered by muddy limestone with a low proportion of corals. The succession is disconformably overlain by the yellow shale of the Xiazhen Formation. Mud cracks on the top of the muddy limestone and large-scale erosional features (Fig. 2) suggest a palaeokarst surface.

METHODS

We quantified the framework density and main constructional biota by line transects. Four to six 1-m linear transects with 20 points were taken from each of three transect targets (Fig. 1): (1) the vertical surface of the middle part of the first reef unit (U1-V), (2) the horizontal surface of the top of the first reef unit (U1-H) and (3) the vertical surface of the middle part of the second reef unit (U2-V). There was no suitable surface (well-weathered and at least 1 m × 1 m flat surface) for horizontal line transects in the second unit. We distinguished nine components in the field: massive stromatoporoids (*Clathrodictyon*), other stromatoporoids, four types of tabulate corals (*Plasmoporella*, *Catenipora*, *Agetolites*, *Fletcheriella*), rugose corals, other bioclasts and micrite. Thirty-four samples were collected and prepared for thin sections in order to further identify uncertain macrofossils and carry out microfacies analysis. We calculated the average proportion of each component in the whole rock and among macrofossils, respectively. We used the Berger–Parker index d (the proportion of the most abundant taxon), as a simple dominance measure for macrofossil assemblages. The reciprocal form of the Berger–Parker index is usually adopted so that an increase in the value of the index accompanies an increase in evenness (Magurran 1988). The low sensitivity to sample size renders the Berger–Parker index a robust and straightforward dominance measure.

RESULTS

Although the content of micrite is high, ranging from 44% to 51% (Fig. 3), calcimicrobes are rare compared to offshore microbial reefs at the north margin of the Zhe-Gan platform (Bian et al. 1996; Li et al. 2004). Calcareous algae (including *Dasyporella* and *Vermiporella*) are the most important in situ microfossils in thin sections (up to 15%), but their overall contribution is low relative to metazoans. Therefore these reefs are metazoan-dominated (Chen et al. 1987; Bian et al. 1996). Both stromatoporoids and tabulate corals are the major reef-builders in the first unit (Fig. 3), and there is an increase in stromatoporoids towards the top. The second unit records a strong dominance of tabulate corals, whereas stromatoporoids account for only 2% of the whole rock. As shown in Fig. 4, dominance is similar in the middle part of both units ($d = 0.35$ and 0.32). There is a slight rise in dominance from the middle part ($d = 0.35$) to the top ($d = 0.47$) within the first unit. Specifically, the first unit is dominated by *Plasmoporella* and *Clathrodictyon*, which together constitute up to 60% of the macrofossils in the framework. In the second reef unit *Catenipora* and *Agetolites* are the two dominant genera comprising about 58% of the skeletal metazoans. Other tabulate corals such as *Plasmoporella* and *Fletcheriella* are also common, while stromatoporoids are very rare.

DISCUSSION

Fossil reefs have demonstrated potential to record changes in community-structure reliably (Edinger et al. 2001). While dominance in fossil reef assemblages may differ from that of living reefs, this shift is mainly attributed to the fast growth and intense rubble pro-

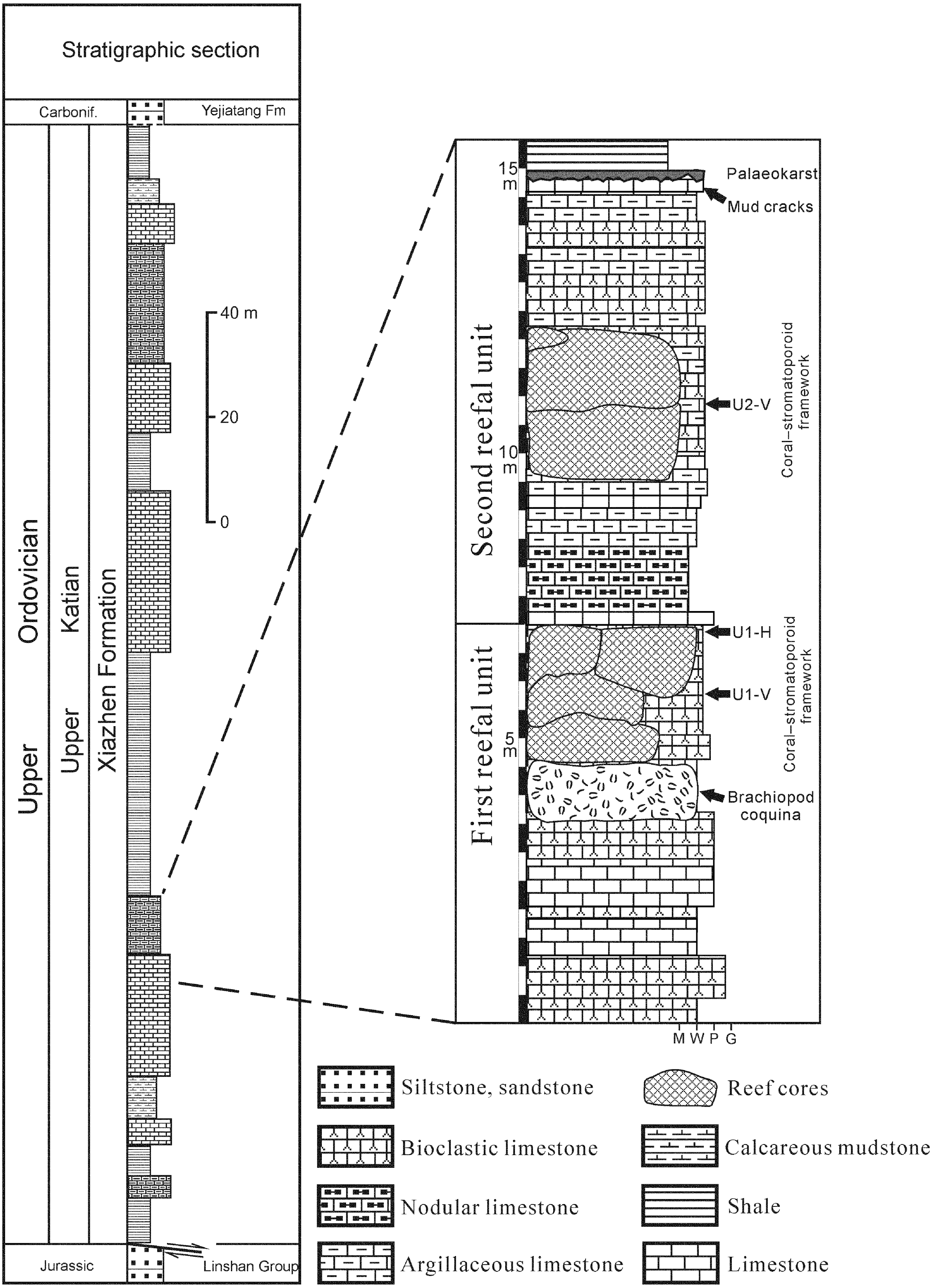

Fig. 1. Lithologic column of the Xiazhen Formation at Zhuzhai (modified from Zhan et al. 2002) and the two reefal units in its lower part. M, mudstone; W, wackestone; P, packstone; G, grainstone.

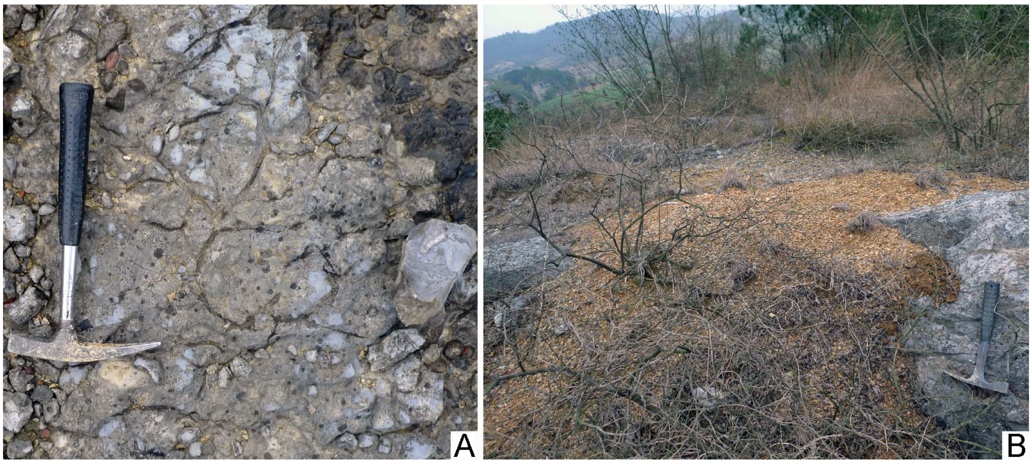

Fig. 2. Outcrop photographs of the top of the second unit in the Xiazhen Formation at Zhuzhai. **A**, mud cracks implying regression and exposure, hammer length is 28 cm; **B**, field exposure of the contact between limestones of the second unit and overlying shale beds, hammer length is 28 cm.

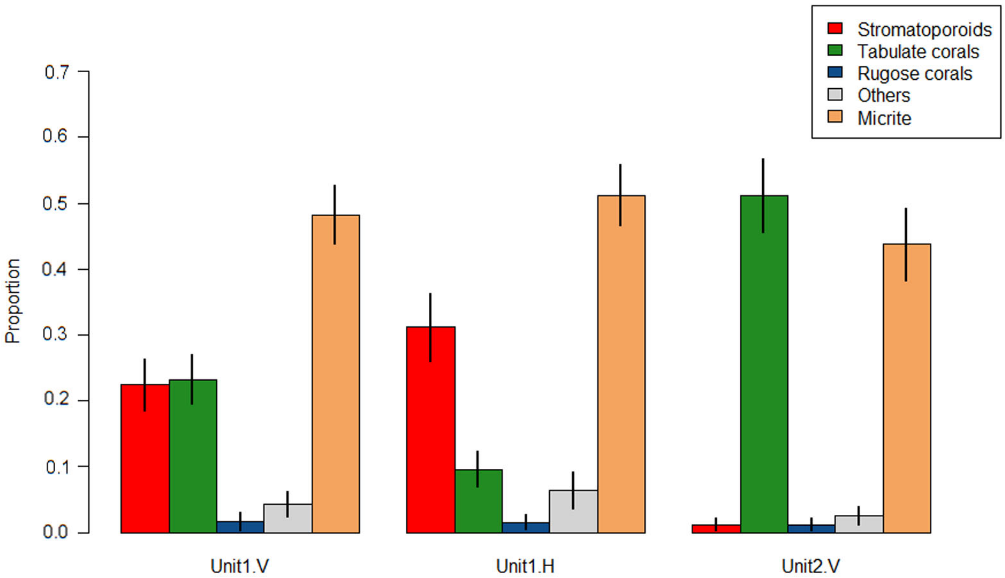

Fig. 3. Relative abundance of each component in the measured framework. Unit1.H, horizontal data from the first unit (120 points); Unit1.V, vertical data from the first unit (120 points); Unit2.V, vertical data from the second unit (80 points).

duction of branching corals (Edinger et al. 2001), which are absent in our case. Therefore we propose that our dominance metric should reflect a biological signal. Although the *Plasmoporella–Clathrodictyon* community dominates the framework of the first reef unit, the quantitative examination implies a subtle ecological succession, similar to successions described in other Ordovician and Silurian reefs (Walker & Alberstadt 1975). In our case, the succession is manifested in a proportional increase in stromatoporoids and an increase in dominance. Sampling bias between vertical and horizontal surfaces cannot explain this shift in community composition (Webb 1999). This subtle succession could be driven by the interactions among organisms (autogenic succession) or by physically induced changes in the environment (allogenic succession) (Tansley 1935; Mewis & Kiessling 2013). Although it is difficult to distinguish between the two types of succession in fossil reefs, we suggest that the absence of a distinct facies change within the first unit may indicate an autogenic succession.

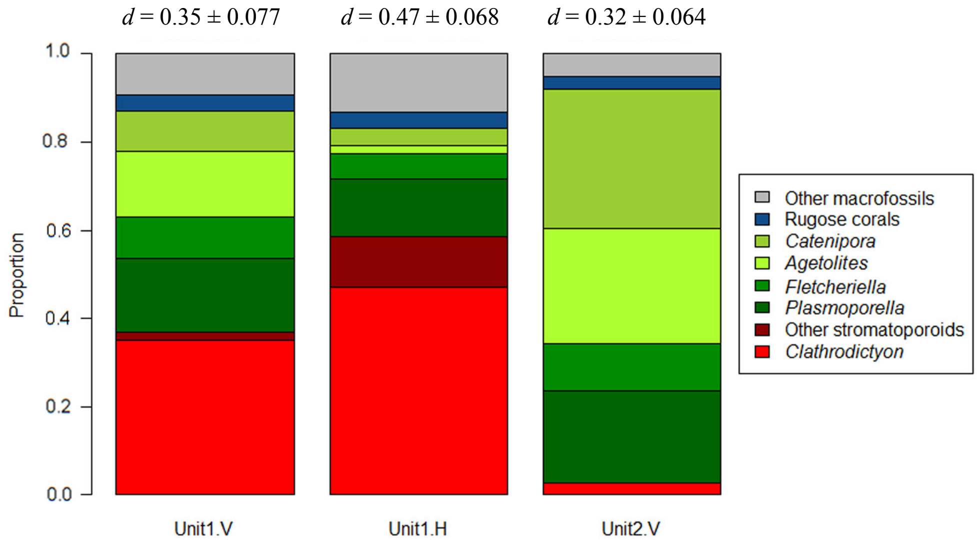

Fig. 4. Relative abundance of the macrofossils in the measured framework and the Berger–Parker index for each community. Unit1.H, horizontal data from the first unit; Unit1.V, vertical data from the first unit; Unit2.V, vertical data from the second unit.

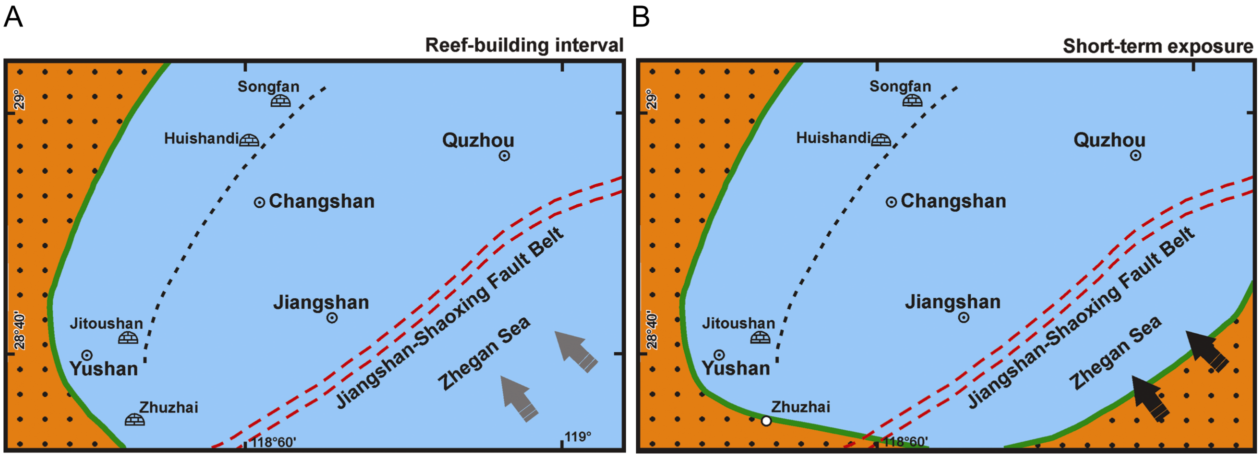

Fig. 5. Palaeogeographic changes during the Late Katian (modified from Rong et al. 2010). **A**, reef-building interval (the two reefal units); **B**, short-term exposure. Double red dashed lines indicate the Jiangshan–Shaoxing Fault Zone; the yellow-brown area with black dots indicates oldland; green lines show the proposed palaeo-shoreline; semicircular limestone mark shows carbonate mud mounds and reefs; black dashed lines indicate the platform margin; grey arrows show the Cathaysian Block approaching the Yangtze Block; black arrows denote the uplifting and expanding of the Cathaysian Oldland.

The substantial difference between the two reef units, however, can be attributed to a facies change. Argillaceous limestone in the upper reef unit suggests a muddier environment than in the lower reef unit. Tabulate corals dominate here presumably because they show a higher tolerance to turbidity. Palaeozoic corals in general tend to have a greater preference for muddy environments than modern scleractinians (Scrutton 1999). Dominance in the second reef unit is lower than in any portion of the first unit, which is surprising given the visually striking abundance of *Catenipora*. These findings suggest that there is probably an allogenic succession between the two reef units. We propose that this change in community composition was driven by the increasing terrestrial input as a result of the Cathaysian orogeny. The Yangtze and Cathaysian blocks may have amalgamated within the South China plate during this interval, leading to uplift of the Jiangshan–Changshan–Yushan area and northwestward expansion of the Cathaysian Oldland (Rong et al. 2010). This regional orogeny not only led to turbid shallow marine environments but also to a shallowing sea level. The orogeny also had substantial influence on the bio- and lithofacies in general (Rong et al. 2010). Reefs of the Lower Xiazhen Formation were ultimately terminated by a short-term exposure of the sea floor (Fig. 5), as demonstrated by mud cracks and palaeokarst surface above the second unit.

CONCLUSIONS

1. We demonstrated a late Katian palaeokarst surface on top of the coral–stromatoporoid reefs of the Lower Xiazhen Formation at Zhuzhai.
2. Two reef units were recognized in the Lower Xiazhen Formation. Both are metazoan-dominated as shown by quantitative line-transects. Stromatoporoids and tabulate corals are the major reef-builders in the first unit, while the second unit is strongly dominated by tabulate corals, which may represent an allogenic succession.
3. The main driver of this allogenic succession and the end of the coral-stromatoporoid reefs is attributed to the Cathaysian orogeny in the latest Ordovician.

Acknowledgements. This research was supported by the National Natural Science Foundation of China (projects 41072002, 412210012011, ZX05008-001-B0 and 41290260) and China Scholarship Council (File No. 201204910171). This paper is a contribution to project IGCP 591 'The Early to Middle Palaeozoic Revolution'. We thank Birgit Leipner-Mata (University of Erlangen-Nürnberg) for assistance with making the thin sections. We are grateful to Kathleen Histon (Varese, Italy) and the anonymous reviewer for many helpful comments.

REFERENCES

Bian, L.-Z. & Zhou, X.-P. 1990. Calcareous algae from the Sanqushan Formation (Upper Ordovician) at the border area between Zhejiang province and Jiangxi province. *Journal of Nanjing University (Earth Sciences)*, **2**, 1–23 [in Chinese, with English abstract].

Bian, L.-Z., Fang, Y.-T. & Huang, Z.-C. 1996. On the types of Late Ordovician reefs and their characteristics in the neighbouring regions of Zhejiang and Jiangxi Provinces, South China. In *The Ancient Organic Reefs of China and their Relations to Oil and Gas* (Fan, J.-S., ed.), pp. 54–75. Marine Press, Beijing [in Chinese].

Chen, X. & Rong, J.-Y. 1992. Ordovician plate tectonics of China and its neighbouring regions. In *Global Perspectives on Ordovician Geology* (Webby, B. D. & Laurie, J. R., eds), pp. 277–291. Balkema, Rotterdam.

Chen, X., Rong, J.-Y., Qiu, J.-Y., Han, N.-R., Li, L.-Z. & Li, S.-J. 1987. Late Ordovician stratigraphy, sedimentology and environment of Zhuzhai of Yushan, Jiangxi. *Journal of Stratigraphy*, **11**, 23–34 [in Chinese, with English abstract].

Chen, X., Rong, J.-Y., Wang, X.-F., Wang, Z.-H., Zhang, Y.-D. & Zhan, R.-B. 1995. *Correlation of the Ordovician Rocks of China: Charts and Explanatory Notes*. International Union of Geological Sciences, Trondheim, 104 pp.

Edinger, E. N., Pandolfi, J. M. & Kelley, R. A. 2001. Community structure of Quaternary coral reefs compared with recent life and death assemblages. *Paleobiology*, **27**, 669–694.

Li, Y., Kershaw, S. & Mu, X.-N. 2004. Ordovician reef systems and settings in South China before the Late Ordovician mass extinction. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **205**, 235–254.

Magurran, A. E. 1988. *Ecological Diversity and Its Measurement*. Croom Helm, London, 179 pp.

Mewis, H. & Kiessling, W. 2013. Environmentally controlled succession in a late Pleistocene coral reef (Sinai, Egypt). *Coral Reefs*, **32**, 49–58.

Rong, J.-Y., Zhan, R.-B., Xu, H.-G., Huang, B. & Yu, G.-H. 2010. Expansion of the Cathaysian Oldland through the Ordovician–Silurian transition: emerging evidence and possible dynamics. *Science in China Series D: Earth Sciences*, **53**, 1–17.

Scrutton, C. 1999. Palaeozoic corals: their evolution and palaeoecology. *Geology Today*, **15**, 184–193.

Tansley, A. G. 1935. The use and abuse of vegetational concepts and terms. *Ecology*, **16**, 284–307.

Walker, K. R. & Alberstadt, L. P. 1975. Ecological succession as an aspect of structure in fossil communities. *Paleobiology*, **1**, 238–257.

Wang, J.-P., Deng, X.-J., Wang, G. & Li, Y. 2012. Types and biotic successions of the Ordovician reefs in China. *Chinese Science Bulletin*, **57**, 1160–1168.

Webb, G. E. 1999. Youngest early Carboniferous (late Visean) shallow-water patch reefs in eastern Australia (Rockhampton Group, Queensland): combining quantitative micro- and macro-scale data. *Facies*, **41**, 111–139.

Webby, B. D. 2002. Patterns of Ordovician reef development. In *Phanerozoic Reef Patterns* (Kiessling, W., Flügel, E. & Golonka, J., eds), *Society for Sedimentary Geology, Tulsa, Special Publication*, **72**, 129–179.

Zhan, R.-B., Rong, J.-Y., Jin, J.-S. & Cocks, L. R. M. 2002. Late Ordovician brachiopod communities of southeast China. *Canadian Journal of Earth Sciences*, **39**, 445–468.

Zhan, R.-B., Jin, J.-S. & Liu, J.-B. 2013. Investigation on the great Ordovician biodiversification event (GOBE): review and prospect. *Chinese Science Bulletin*, **58**, 3357–3371 [in Chinese, with English abstract].

Zhang, Y.-D., Chen, X., Yu, G.-H., Dan, G. & Liu, X. 2007. *Ordovician and Silurian Rocks of Northwest Zhejiang and Northeast Jiangxi Provinces, SE China*. University of Science and Technology of China Press, Hefei, 189 pp.