A Middle Ordovician (Darriwilian) *Calathium* reef complex on the carbonate ramp of the northwestern Tarim Block, northwest China: a sedimentological approach

Jianpo Wang[a], Yue Li[b, *], Yuanyuan Zhang[b], Stephen Kershaw[c]

[a] Wuhan Centre of Geological Survey, Wuhan 430205, China

[b] Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China

[c] Department of Life Sciences, Brunel University, Uxbridge, Middlesex, UB8 3PH, UK

* Corresponding author. E-mail address: yueli@nigpas.ac.cn

Abstract

Middle Ordovician carbonates are exposed for 25 km along the Lianglitag Mountains in the Tarim Basin, northwest China. They reflect platform carbonate and reef deposition along the ancient Central Tarim Uplift. The Darriwilian Yijianfang Formation, ~70 m thick, was deposited in a shallow carbonate ramp setting, deepening seaward to the north in current geography. Reefal and biostromal units are constructed primarily by sessile *Calathium* of possible sponge affinity in the Middle Member of the formation. Patch reefs, ~10 m in thickness and tens of meters in diameter, are common in the northern region. Associated shelly faunas, including trilobites, bivalves, and brachiopods, are diverse and preserved as coarse bioclastic materials together with intraclasts. Towards the south, patch reefs are smaller, <1 m in thickness and with low relief. A biostrome formed by *in situ Calathium* framework is interpreted to act as a baffle for fine sediments, with smaller amounts of bioclasts and intraclasts. The biostrome is only ~3 m thick in the southernmost section suggesting a calmer leeward setting initially. Tempestite beds composed of *Calathium* and nautiloid floatstones are abundant through the section, with monospecific brachiopod layers in the tempestite beds. This work demonstrates previously unrecognized paleogeographic variations of the Darriwilian *Calathium* reef complexes, which have larger patch reefs generally developing in the north area, smaller patch reefs dominating southward, and biostromes occurring in the southernmost locations. The reef complex was drowned due to sea-level rise, which is recorded in the upper Yijianfang Formation.

Keywords: morphological variation; reef complex; Yijianfang Formation; Ordovician; Bachu; Northwest China

1. Introduction

Calathium is a cylindrical calcified fossil, one end of which is open, leading to a central cavity, while the other end is closed, with holdfasts (Rowland, 2001). *Calathium* has a porous double-wall, with both walls showing a similar thickness; it seems to have reproduced by budding suggesting that *Calathium* is an aspiculate sponge closely related to archaeocyathans (Li et al., 2015). *Calathium* played a key role in Early-Middle Ordovician reefs (Webby, 2002), but unlike other metazoan taxa of that age, *Calathium* occurred in large accumulations in reef and reef-associated communities. A significant proportion has been found in non-reef units. *Calathium*, found in assemblages in association with lithistid sponges and microbes, spread widely on carbonate platforms prior to development of coral-stromatoporoid-algal-dominated reef systems in the latest Middle Ordovician (Cañas and Carrera, 1993, 2003; Wood, 1999; Webby, 2002; Wang et al., 2011). The oldest *Calathium*-bearing reef occurred in the lower Tremadocian Nantsinkuan Formation on the Yangtze Platform margin, South China Block (Wang et al., 2012). Similar reef complexes have also been widely reported from upper Tremadocian to Darriwillian successions in the Laurentia, Siberia, North China, and Tarim regions (Alberstadt and Repetski, 1989; Cañas and Carrera, 1993, 2003; Church, 1974; Hintze, 1973; Miagkova et al., 1977; Ross, 1996; Toomey, 1970; Toomey and Nitecki, 1979; Pratt and James, 1982; Webby, 1984, 2002; Liu et al., 2003; Kwon et al., 2003; Li et al., 2004; Adachi et al., 2009; Wang et al., 2012; Choh et al., 2013).

Dozens of *Calathium*-bearing reef units of varying geometries in the Darriwilian (late Middle Ordovician) Yijianfang Formation crop out along the Lianglitag Mountains of the Bachu area, Tarim Basin, northwest China (Li et al., 2007; Wang et al., 2012). These reefs were constructed by mainly *Calathium* with a few lithistid sponges and bryozoans (Zhu et al., 2006). Gu et al. (2005) inferred that these Tarim reefs grew in platform margin settings. Jiao et al. (2012) documented lithological and biotic contents of a reef-shoal system and discussed their sequence stratigraphic implications. In the present paper, we document, for the first time, the morphological and lithological variation trends throughout the *Calathium* reef complex that occurs along the Lianglitag Mountains, where a carbonate ramp developed during the reef-building episode of the Yijianfang Formation. Firstly, four time-equivalent *Calathium*-bearing sections from north to south at four sites, namely Yijianfang, P22, Nanyigou, and Yangmaile (Fig. 1C, white dots give GPS-determined locations) in the study area, are described in detail. Six other sections (Fig, 1C, black dots for GPS-determined locations) are also employed for reconstructing morphological variation trends. Morphologic and lithologic variations of the *Calathium* reef complex on a carbonate ramp are thus well illustrated.

2. Geological and stratigraphic setting

The Ordovician shallow and offshore deeper marine carbonates are preserved along a 25 km N-S cross-section through the Lianglitag Mountains surrounded by deserts northeast of the Bachu area (Fig. 1), which, tectonically, are part of the northwestern portion of the Central Tarim Uplift (Zhou et al., 1990; Jia et al., 1995; Ni et al., 2001; Chen and Shi, 2003). The Ordovician strata ranging from dolostone to limestone are assigned to the Yingshan Formation (Dapingian), Yijianfang Formation (Darriwilian), Tumuxiuke Formation (Sandbian), and Lianglitag Formation (lower Katian) in ascending order (Ni et al., 2001; Li et al., 2009).

Of these, the Yijianfang Formation is 69 m thick and comprised of three lithological members. The lower member, 14 m thick, consists of thin-medium bedded intraclastic packstones and a calcimicrobial bindstone unit with fenestral fabrics. The middle member, 30 m thick, is dominated by massive to medium-bedded litho/bioclastic pack- to grainstone and contains the *Calathium* reef complex. The upper member, 25 m thick, is composed of thin-bedded nodular bioclastic wackestone and mudstone intercalated with thin-bedded cherty layers or lenses (Li et al., 2009). This formation is marked by a palaeokarst surface at its base (Li et al., 2007) and is conformably overlain by the Tumuxiuke Formation. The latter comprises thin-bedded nodular micritic limestone and yields abundant nautiloids and conodonts assignable to the *Yangtzeplacognathus jianyeensis*, *Baltoniodus variabili*, and *B. alobatus* Zones in ascending order, characteristic of the Sandbian faunas (lower Upper Ordovician) (Li et al., 2009).

A Middle Ordovician age for the Yijianfang Formation was suggested on the basis of the presence of nautiloid *Protocycloceras wangi* by Zhou et al. (1990) and Ni et al. (2001). Xiong et al. (2006) obtained abundant conodonts *Microzarkodina parva*, *Lenodus variabilis* and *Eoplacognathus crassus* of Darriwilian age from the same formation. Li et al. (2007) further confirmed that the middle Yijianfang Formation, and therefore its enclosed *Calathiu*m reefs, are Darriwilian in age (Fig. 2).

The Yijianfang *Calathium* reefs from the northern Lianglitag Mountains were inferred as having grown on the platform margin by Gu et al. (2005) and Jiao et al. (2012). However, due to lithological features of rich packstones indicating a very shallow and turbulent marine belt and lack of deeper water facies of typical slope conditions, Li et al. (2009) deduced the palaeoenvironmental setting as a ramp, deepening to the present geographical north as graptolitic black shale of the Darriwilian Sargan Formation northward of Bachu formed in typical stagnated basin of the Kalpin region (Zhou et al., 1990; Ni et al., 2001). Ma et al. (2013) further defined the Yangjikan section as the slope-break location (Fig. 1B). Well logs from the Mazatag area, southward of the Lianglitag Mountains (location shown in Fig. 1B) show complete absence of the Darriwillian strata indicating that region was exposed above sea level.

3. *Calathium* reefs and biostrome

Calathium fossils are easily recognized in outcrops, displayed as double-walled conical forms in longitudinal section and circular forms in transverse section. On the exposure *Calathium* individuals are preserved as boundstone, which consists of sessile *Calathium* and lesser calcimicrobes (i.e., *Girvanella* and *Nuia*, Jiao et al., 2012; Rong et al., 2014), lithistid sponges, and bryozoans. The associated fossil fragments include nautiloids, gastropods, trilobites, bivalves, and brachiopods (see Section Yijianfang). The overall morphologies and compositions of the *Calathium* reef complex vary at various observation sites in the study area.

3.1. Yijianfang section

The paleogeographic configuration of the Bachu area shows that the Yijianfang section (GPS: 40°08'37"N, 78°49'31"E) was situated on the windward slope of the ramp setting along the Lianglitag Mountains. Several reef-cores and their surrounding bioclastic shoals are present on the south-side outcrop of the mountains (Jiao et al., 2012). Individual reef-cores vary from 1 to 4 meters in thickness and 2 to 18 m in diameter (Fig. 3A). Most of the *Calathium* fossils are toppled (Fig. 3B), but some are densely packed together *in situ* (Fig. 3C). Bioclastic components, microbialite and micrite in the spaces of the *Calathium* frameworks occupy 40-60 % in volume. Surrounding bioclastic limestones, especially pelmatozoan, particles are poorly sorted (Fig. 3D). Zhou et al. (1990) documented extremely abundant shelly faunas from the reef core of the *Calathium* reef complex in the Yijianfang locality. They include nautiloids (*Tarphiceras*, *Dideroceras*, *Protocycloceras*, *Clytoceras*, *Aphetoceras*, *Shumadoceras*, *Chisiloceras*, *Sinocochlioceras*, *Eostromatoceras*, and *Tragoceras*), gastropods (*Lesueurilla*, *Maclurites*), aphid trilobites (*Illaenus*, *Scotoharpes*, *Lyralichas*, *Cydonocephalus*, *Nileus*, *Kawina*, and *Remopleurides*), parallelodontid bivalve (*Cleinychia*), and brachiopods (*Liricamera* and *Triplesia*) (Zhou et al., 1990).

3.2. P22 section

The *Calathium* reef complex is well exposed at P22 section (GPS: 40°07'57"N, 78°50'41"E) where the reef core is 2-10 m thick and preserved as a lenticular form. The reef core is composed of mostly *in situ* preserved *Calathium* framework that makes up to 60-80 % of the volume of the core (Fig. 4A). Sizes of *Calathium* skeletons vary from centimeters to decimeters. Two lithofacies of the reef core are recognized as 1) very abundant bafflestones mainly formed by large *Calathium* skeletons (Fig. 4B) and 2) common occurrence of *Calathium*-calcimicrobial bindstones rich in micritic laminated crusts (Fig. 4C). *Calathium* fragments are also occasionally present in nearby shoals. The reef bases, flanks, and tops share similar lithofacies types of bioclastic grain-packstones, in which coarse pelmatozoan particles account for 50-70 % of the components (Fig. 4D).

3.3. Nanyigou section

The Nanyigou section (GPS: 40°05’20”N, 78°50’42”E) records the most complete succession throughout the upper Yingshan Formation (upper Upper Qiulitag Subgroup) to the lower Lianglitag Formation with total thicknesses of 300 m in the basin (Zhang et al., 2015). Many *Calathium* reef cores are also preserved in the middle Yijianfang Formation. They are, however, usually 0.5-2.0 m thick, and thus much thinner than the same unit exposed at other localities. Of these, one patch of irregular lenticular reef core (Fig. 5A) is 1 m thick and 6 m in diameter, and surrounded by bioclastic packstone. *Calathium* skeletons make up about 20-40 % of the reef core (Fig. 5B). Individuals are mostly erect and preserved *in situ*, and they encrust each other to form a framework (Fig. 5C), in which rare fragments of lithistid sponges and bryozoans occur. Thin-bedded packstones of the reef-flanks are rich in pelmatozoan debris (40-60 % in volume) (Fig. 5D) and small amounts of trilobite, brachiopod, ostracod, gastropod, and microbial (*Girvanella*, *Nuia* and *Vermiporella*) debris.

3.4. Yangmaile section

The *Calathium* reef-bearing strata at Yangmaile section (GPS: 39°57’6”N, 79°03’10”E) are subdivided into four successive beds (Beds 1-4; Fig. 6). Bed 1 contains abundant *in situ* and uniformly small-sized *Calathium* skeletons that form bafflestone and are 3-5 cm in diameters (Fig. 6a-d). Of these, *Calathium* skeletons are extreme abundant and occupy 30-50% of bafflestone. Although these *Calathium* bafflestones are collectively assigned to the reef core, they are usually 3 m thick and form a single bed, thus are more appropriately described as a biostrome due to its lower relief (Fig. 6A). Bed 2 comprises tempestite layers (up to 4.5 m thick) and is composed of *Calathium*-nautiloid floatstones of unsorted and broken *Calathium* skeletons and nautiloid fragments. These floatstones are here interpreted to have been derived from northern patch reef units by storms (Fig. 6B). Bed 3, 10-20 cm thick, is a shelly layer composed of monospecific unbroken brachiopod shells, possibly indicating a restricted and calm environment (Fig. 6C). Bed 4, 1.5 m thick, shares similar lithology with Bed 2 that is interpreted as tempesite layers (Fig. 6D).

4. Discussion

4.1 Formation of the Calathium reef complex

In the study area there is no recognizable shoreline, oolitic or clastic facies, visualized by James (1983) and Fagerstrom (1987). The Bachu *Calathium* reef complex was deduced to have developed in a mid-ramp location by Li et al. (2009). Gradual northward deepening over a distance of a few tens of kilometers influenced variation of the *Calathium*-bearing units in aspects of thicknesses, relief and taphonomic features. Thickness and extent of the *Calathium*-bearing units varying laterally on the ramp is reconstructed in Figure 7.

We interpret the *Calathium*-bearing reefs, biostrome and bioclastic units as benefiting from *Calathium* cluster growth and having formed above wave base. Larger *Calathium* patch reefs with thicknesses >5 m are concentrated in the northern region, which may well have been the windward part. Reef cores were dominated by *Calathium* with few bryozoans, lithistid sponges and calcified microbes, whereas abundant pelmatozoans are interpreted to form a fringing setting for construction of *Calathium* framework indicated by poorly sorted debris of surrounding bioclastic limestones at Yijianfang section and common micritic infillings of the framework at the P22 section. Storms interrupted reef expansion sporadically and bioclastic shoals covered the reefs, followed by re-establishments of reef facies.

Patch reefs in southern localities share the same factors in that they are small, 0.5-2 m, showing lower reef-growth potential. The southernmost Yangmaile strata represent low energy back reef deposits favouring *in situ Calathium* biostromes that initiated reef construction. Coarse-grained tempestite beds were derived by storm currents from the open sea to the north geographically, thus broken *Calathium* and nautiloids were presumably rapidly deposited once the environmental turbulence weakened. Tempestite beds punctuated development of the *in situ* biostrome. Short-term calm and restricted environments were ideal for development of the monospecific brachiopod community, but overlain by the tempestite bed, indicating resurgence of storms. Disappearance of the reef complex of the Middle Member is interpreted to have been caused by transgression, indicated by finer grained sediments in the Upper Member of the Yijianfang Formation (Li et al., 2009).

4.2 Geological implications of the Calathium reef complex

The principal constructors of the Bachu *Calathium* reef complex are two *Calathium* species that were named by Liu et al. (2005) as *C. elongates* and *C. bachuensis*. The type specimens of these two species were collected from the Yijianfang reef. *C. elongates* has a curved elongate steep conical shape similar to *Soanites bimralis* but is >30 cm high and 35-40 mm diameter at the open end, whereas *C. bachuensis* has a curved, horn-cylindrically obconical shape and more like *S. delicates* and *Calathium frechi* but is >30 cm high and >10 cm in diameter at the upper side (Liu et al., 2005). These large *Calathium* fossils were interpreted by Li et al. (2015) for supporting the cooling hypothesis during the Ordovician based on "temperature-size rule" (Atkinson, 1994; Atkinson and Sibly, 1997), which relates increased body size to cooling. However, *in situ* preserved *Calathium* from the biostrome in Bed 1 of the Yangmaile section are small in size and quite different from those in Yijianfang and P22 patch reefs in the northern region. Therefore, size variations of the *Calathium* may instead be related to environmental parameters. Larger-sized *Calathium* that have potential for wave-resistance are more abundant in the windward belt.

Comparing with the lithistid sponge-*Calathium* reefs of the Lower Ordovician Hunghuayuan Formation (Floian) on the Yangtze Platform, South China Block described by Li et al. (2015), the Bachu *Calathium* would be expected to be more easily toppled because they mostly lack conspicuous outgrowths and were likely less stable (Liu et al., 2005). Microbial encrustation and early cement may have provided reef rigidity. Different reef sizes of the reef complex (cases of the P22 and Nanyigou) are interpreted here to correlate with development of microbial binding because no evidence of early cementation was observed. Thus *Calathium* reef-building potential may have been supported by growth of microbial encrustation in the windward area. Collapse of *Calathium* reef construction during the Middle Ordovician may have been due to decline of microbial carbonates with increasing metazoan competition following the Ordovician radiation (Riding, 2006). This interpretation is consistent with the hypothesis of Webb (1996) that Phanerozoic reef history was controlled by the distribution of microbial carbonates and biologically induced cements.

The Yijianfang and P22 reefs also seem to have benefited from the protecting presence of pelmatozoan fringes, where easily-toppled *Calathium* could be preserved *in situ* in a high-energy setting; it may be deduced that continual larval settlement (Jackson, 1977) persisted to develop a dense assemblage (Wood, 1999) of *Calathium* to develop a reef. On the contrary, a low-energy back reef setting at the Yangmaile site may have favoured *Calathium* developments until storms destroyed them. Wood (1999) interpreted relatively small and short-lived solitary organisms to have not projected substantially above a substrate, therefore producing little topographic relief. The small-size reefs at the Nanyigou site and nearby sites may thus have been sensitive to deposition of surrounding sediments and were easily terminated by sediment accumulation.

The Middle Ordovician Bachu *Calathium* reefs were described as the latest *Calathium*-constructed reefs by Wang et al. (2011). However, it is questionable why *Calathium* could not construct reefs from later Ordovician time onward as these organisms survived until the Silurian Period (Nitecki et. al., 2004). The Bachu cases show that *Calathium* was easily able to develop reefs by cluster growth. Alberstadt and Walker (1976) also indicated a *Calathium*-dominated pioneer community in the Later Ordovician Elk River reef (Carters Limestone) although they referred to *Calathium* as calathid. Wang et al. (2011) affirmed competition from corals and stromatoporoids resulted in disappearance of *Calathium* reefs because colonial corals and stromatoporoids have competitive superiority for space on hard-substrates (Jackson, 1985; Wood et al., 1992). The Elk River reef also provides evidence for this interpretation that the *Calathium* pioneer community provided hard-substrate for the coral-stromatoporoid reef community and then was replaced by it eventually (Alberstadt and Walker, 1976).

5. Conclusions

The middle Ordovician (Darriwilian) *Calathium* reef complex in the Lianglitag Mountains in the Tarim Basin of northwest China shows morphological and lithological variation trends over a distance of 25 km along an environmental gradient from deeper to shallower water in a geographically southward direction on a carbonate ramp. From north to south, large patch reefs, ~10 m thick and tens of metres in diameter, in the north and smaller patch reefs, ~1 m thick and several metres in diameter, in the south are composed of *Calathium* constructions and associated with shoals of marine bioclasts. Shallower positions in the most southerly part of the ramp contain thin biostromal deposits were constructed by *Calathium* and micritic sediments. Windward settings favoured *Calathium* patch reef development, microbial encrustation and the surrounding depositional rate controlled reef sizes.

Acknowledgments

We appreciate referees of Professor Paul Copper, Zhong-Qiang Chen, Thomas Algeo and George Stanley for their benefit advises on revision of the manuscript. This study was supported by National Natural Science Foundation of China (41072002, XDB10010503 and 41521061).

References

Adachi, N., Ezaki, Y., Liu, J.B., Cao, J., 2009. Early Ordovician reef construction in Anhui Province, South China: a geobiological transition from microbial- to metazoan-dominant reefs. Sediment. Geol. 220, 1-11.

Alberstadt, L.P., Repetski, J.E., 1989. A Lower Ordovician sponge/algal facies in the southern United States and its counterparts elsewhere in North America. PALAIOS 4, 225-242.

Alberstadt, L.P., Walker, K.R., 1976. A receptaculitid-echinoderm pioneer community in a Middle Ordovician reef. Lethaia 9, 261-272.

Atkinson, D., 1994. Temperature and organism size: a biological law for ectotherms. Adv. Ecol. Res. 25, 1-58.

Atkinson, D., Sibly, R.M., 1997. Why are organisms usually bigger in colder environments? Making sense of a life history puzzle. Trends Ecol. Evol. 12, 235-239.

Cañas, F.L., Carrera, C., 1993. Early Ordovician microbial-sponge-receptaculitid bioherms of the Precordillera, western Argentina. Facies 29, 169-178.

Cañas, F.L., Carrera, C., 2003. Precordilleran reefs. In: Benedetto, J.L. (Ed.), Ordovician Fossils of Argentina. Secretaría de Cienciay Técnica, Universidad Nacional de Córdoba, pp.131-153.

Chen, Z.Q., Shi, G.R., 2003. Late Paleozoic depositional history of the Tarim basin, northwest China: An integration of biostratigraphic and lithostratigraphic constraints. AAPG Bull. 87, 1323-1354.

Choh, S.J., Hong, J., Sun, N., Kwon, S.W., Park, T.Y., Woo, J., Kwon, Y.K., Lee, D.C., Lee, D.J., 2013. Early Ordovician reefs from the Taebaek Group, Korea: constituents, types, and geological implications. Geosci. J. 17, 139-149.

Church, S.B., 1974. Lower Ordovician patch reefs in western Utah. 21. Brigham Young University Geology Studies, pp. 41-62.

Fagerstrom, J.A., 1987. The Evolution of Reef Communities. John Wiley & Sons, New York.

Gu, J.Y., Zhang, X.Y., Luo, P., Luo, Z., Fang, H., 2005. Development characteristics of organic reef-bank complex on Ordovician carbonate platform margin in Tarim Basin. Oil & Gas Geol. 26, 277-282 (in Chinese with English abstract).

Hintze, L.F., 1973. Lower and Middle Ordovician stratigraphic sections in the Ibex area, Millard County, Utah. Brigham Young Univ. Geol. Stud. 20, 3-36.

Jackson, J.B.C., 1977. Competition on marine hard substrata: the adaptive significance of solitary and colonial strategies. Am. Natur. 111, 743-767.

Jackson, J.B.C., 1985. Distribution and ecology of clonal and aclonal benthic invertebrates. In: Jackson, J.B.C., Buss, L.W., Cook, R.E. (Eds), Population Biology and Evolution of Clonal Organisms. Yale University Press, New Haven, pp. 297-355.

James, N.P., 1983. Reefs. In: Scholle, P.A., Bebout, D.G., Moore, C.H. (Eds.), Carbonate Depositional Environments. American Association of Petroleum Geologists, Tulsa, pp. 345-462.

Jia, C.Z., Wei, G.Q., Yao, H.J., Li, L.C., 1995. Tectonic Evolution and Regional Structure Geology of the Tarim Basin. Petroleum Industry Press, Beijing (in Chinese).

Jiao, Y.Q., Wu, L.Q., Rong, H., Wang, Y.B., Wang, R., 2012. Paleoecology of the Ordovician reef-shoal depositional system in the Yijianfang Outcrop of the Bachu Area, West Tarim Basin. J. Earth Sci. 23, 408-420.

Kwon. Y.K., Lee, D.J., Choi, D.K., Chough, S.W., 2003. Lower Ordovician sponge bioherms in the Makkol Formation, Taebaeksan Basin, Mideast Korea. Facies 48, 79-90.

Li, Q.J., Li, Y., Wang, J.P., Kiessling, W., 2015. Early Ordovician lithistid sponge-*Calathium* reefs on the Yangtze Platform and their paleoceanographic implications. Palaeogeogr. Palaeoclimatol. Palaeoecol. 425, 84-96.

Li, Y., Kershaw, S., Mu, X.N., 2004. Ordovician reef systems and settings in South China before the Late Ordovician Mass extinction. Palaeogeogr. Palaeoclimatol. Palaeoecol. 205, 235-254.

Li, Y., Huang, Z.B., Wang, J.P., Wang, Z.H., Xue, Y.S., Zhang, J.M., Zhang, Y.D., Fan, J.X., Zhang, Y.Y., 2009. Conodont biostratigraphy and sedimentology of the Mid-Upper Ordovician, Buchu, Xinjiang, NW China. J. Strat. 33, 113-122 (in Chinese with English abstract).

Li, Y., Wang, J.P., Shen, A.J., Huang, Z.B., 2007. Evolutionary significance of the *Calathium* reef mound from the Yijianfang Formation, Bachu, Xinjiang. Acta Palaeontol. Sin. 46, 347-354 (in Chinese with English abstract).

Liu, B.L., Rigby, J.K., Zhu, Z.D., 2003. Middle Ordovician lithistid sponges from the Bachu-Kalpin area, Xinjiang, northwestern China. J. Paleontol. 77, 430-441.

Liu, B.L., Zhu, Z.D., Li, X.M., A discussion on several problems of calathid fossils. Acta Palaeontol. Sin. 44, 267-282 (in Chinese with English summary).

Ma, L., Zhang, Z.L., Wang, G., Li, Y., 2013. Microfacies of the carbonates and palaeogeography of the Saergan Formation (Middle-Upper Ordovician), Kalpin stratigraphic region, Tarim, NW China. Acta Micropalaeontol. Sin. 30, 344-352 (in Chinese with English abstract).

Miagkova, E.I., Nestor, H.E., Einasto, R.E., 1977. Razrez ordovika i silura reki Moiero, Sibirskaya platform (Ordovician and Silurian sequence of the Moiero River, Siberian platform). Akademiya Nauk SSSR, Sibirskoe Otdelenie, Institut Geologii i Geofizikii, Trudy 303, 176.

Ni, Y.N., Geng, L.Y., Wang, Z.H., Zhao, Z.X., Chen, T.E., Zhang, Y.B., Wang, H.F., Zhang, S.G., Yuan, W.W., Zhang, S.B., Gao, Q.Q., Li, J., 2001 Ordovician. In: Zhou, Z.Y. (Ed.), Stratigraphy of the Tarim Basin. Science Press, Beijing, pp. 39-80 (in Chinese with English summary).

Nitecki, M.H., Webby, B.D., Spjeldnaes, N., Zhen, Y., 2004. Receptaculitids and algae. In: Webby, B.D., Paris, F., Droser, M.L., Percival, I.G. (Eds.), The Great Ordovician Biodiversification Event. Columbia University Press, New York, pp. 336-347.

Pratt, B.R., James, N.P., 1982. Cryptalgal-metazoan bioherms of Early Ordovician age in the St. George Group, western Nerfoundland. Sedimentology 29, 543-569.

Riding, R., 2006. Microbial carbonate abundance compared with fluctuations in metazoan diversity over geological time. Sediment. Geol. 185, 229-238.

Rong, H., Jiao, Y.Q., Wang, Y.B., Wu, L.Q., Wang, R., 2014. Distribution and geologic significance of *Girvanella* within the Yijianfang Ordovician reef complexes in the Bachu area, West Tarim Basin, China. Facies 60, 685-702.

Ross, R.J.Jr., 1996. Quintessence of the Ordovician: from Rocky Mountain beaches to the depths of Nevada. In: Longman, M.W., Sonnenfeld, M.D. (Eds), Paleozoic Systems of the Rocky Mountains Regions. SEPM, Rocky Mountain Section, pp. 47-62.

Rowland, S.M., 2001. Archaeocyaths: a history of phylogenetic interpretation. J. Paleontol. 75, 1065-1078.

Toomey, D.F., 1970. An unhurried look at a Lower Ordovician mound horizon, southern Franklin Mountains, west Texas. J. Sediment. Petrol. 40, 1318-1334.

Toomey, D.F., Nittecki, M.H., 1979. Organic buildups in the Lower Ordovician (Canadian) of Texas and Oklahoma. Field. Geol. 2, 181.

Wang J.P，Li Y.，Zhang Y.Y, Li Q.J, Deng X.J, 2011. Early-Middle Ordovician *Calathium* reef mounds: history and palaeoecology. Acta Palaeontol. Sin. 50, 132-140 (in Chinese with English abstract).

Wang, J.P., Deng, X.J., Wang, G., Li, Y., 2012. Types and biotic successions of Ordovician reefs in China. Chin. Sci. Bull. 57, 1160-1168.

Webb, G.E., 1996 Was Phanerozoic reef history controlled by the distribution of nonenzymatically secreted reef carbonates (microbial carbonate and biologically induced cement)? Sedementology 43, 947-971.

Webby, B.D., 1984. Ordovician reefs and climate: a review. In: Bruton, D.L. (Ed.), Aspects of the Ordovician System. University of Oslo, Palaeontological Contributions 295, pp. 89-100.

Webby, B.D., 2002. Patterns of Ordovician reef development. In: Kiessling, W., Flügel, E., Golonka, J. (Eds.), Phanerozoi Reef Patterns. SEPM Special Publication 72, SEPM, Tulsa, Oklahoma, pp. 129-179.

Wood, R., 1999. Reef Evolution. Oxford University Press, Oxford.

Wood, R., Zhuravlev, A.Y., Debrenne, F., 1992. Functional biology and ecology of Archaeocyatha. Palaios 7, 131-156.

Xiong, J.F., Wu, T., Ye, D.S., 2006. New advances on the study of Middle-Late Ordovician conodonts in Bachu, Xinjiang. Acta Palaeontol. Sin. 45, 359-373 (in Chinese with English abstract).

Zhang, Y.Y., Wang, J.P., Munnecke, A., Li, Y., 2015. Ramp morphology controlling the facies differentiation of a Late Ordovician reef complex at Bachu, Tarim Block, NW China. Lethaia, 48, 509-521.

Zhou, Z.Y., Chen, X., Wang, Z.H., Wang, Z.Z., Li, J., Geng, L.Y., Fang, Z.J., Qiao, X.D., Zhang, T.R., 1990. Ordovician of Tarim. In: Zhou, Z.Y., Chen, P.J. (Eds), Biostratigraphy and Geological Evolution of Tarim. Science Press, Beijing, pp. 56-130.

Zhu, Z.D., Hu, M.Y., Liu, B.L., Xiao, C.T., Yang, W., Li, X.M., 2006. Early-Middle Ordovician Reefs in China. Geology Publication, Beijing, 178 pp (in Chinese).

Figure captions

Fig. 1. Locations of the sections containing *Calathium* reefs along the Lianglitag Mountains, Tarim Block, NW China. A) Tarim Block in Xinjiang, Northwest China. B) Tectonic division of the Tarim Block (simplified after Jia et al., 1995) and the position of the Lianglitag Mountains. Locations of the Mazatag Well Block and Yangjikan section in Kalpin region are also marked. C) Aerial image showing the available sections along the Lianglitag Mountains.

Fig. 2. Biostratigraphic scheme of the Middle-Upper Ordovician Period (after Li et al., 2009) and lithologic column of the Yijianfang Formation.

Fig. 3. Photographs of *Calathium* patch reefs at Yijianfang section. A) *Calathium* patch reef core and surrounding shoal facies. B) Bafflestone formed by dense *Calathium* frameworks. C) Closely clustered *Calathium* fossils (right) are surrounded by micrite (left). D) Bioclastic packstones rich in pelmatozoan debris from shoal facies.

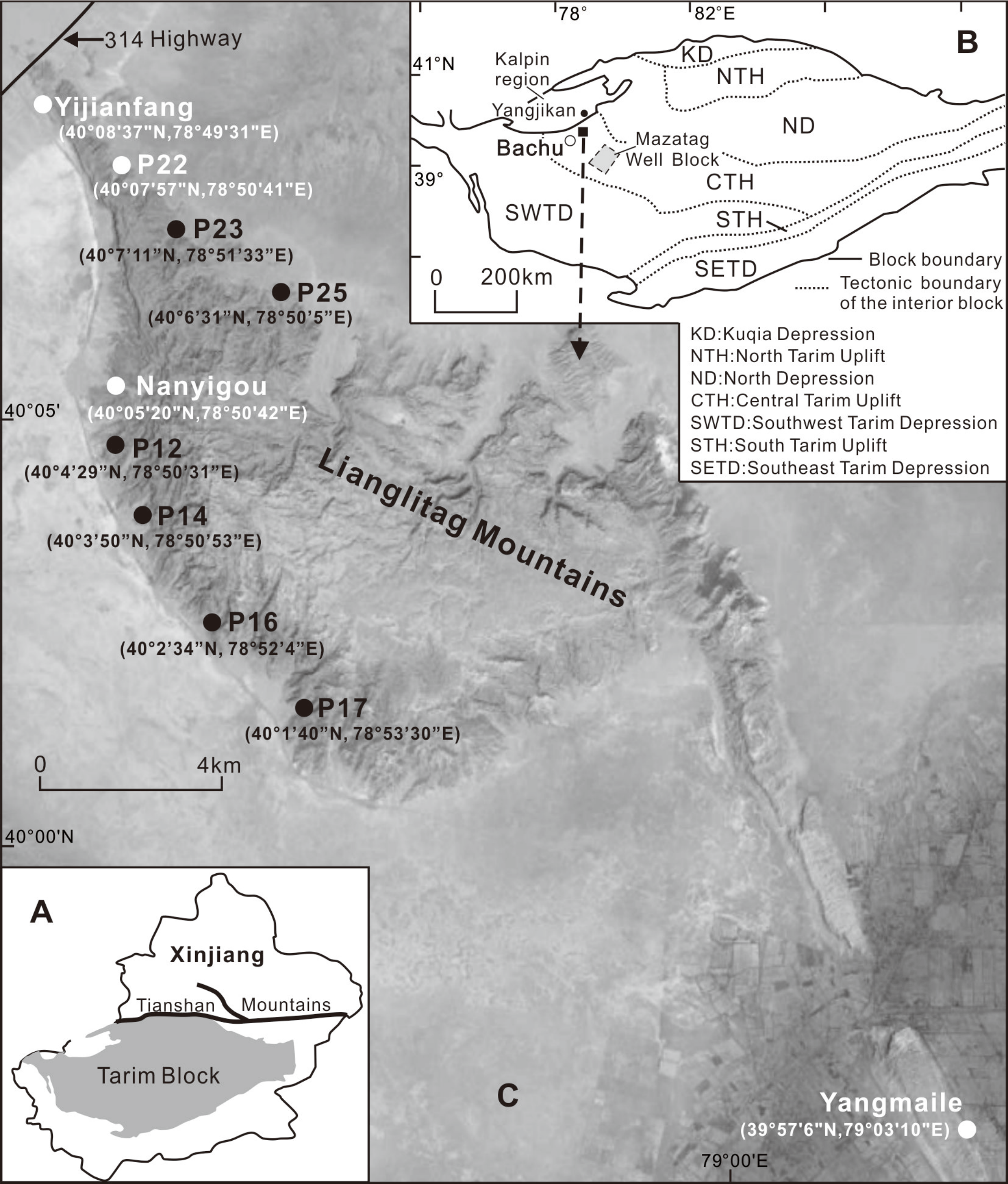
Fig. 4. *Calathium* patch reefs in the P22 site. A) Diverse-sized *Calathium* patch reef units and their associated shoal facies. B) Bafflestones formed by huge *Calathium* fossil in the reef-core. The pen scale bar is 1 cm long. C) Framework constructed by *Calathium* (Cal) and encrust microbes (Em). Note coeloms filled by sparry calcite. D)

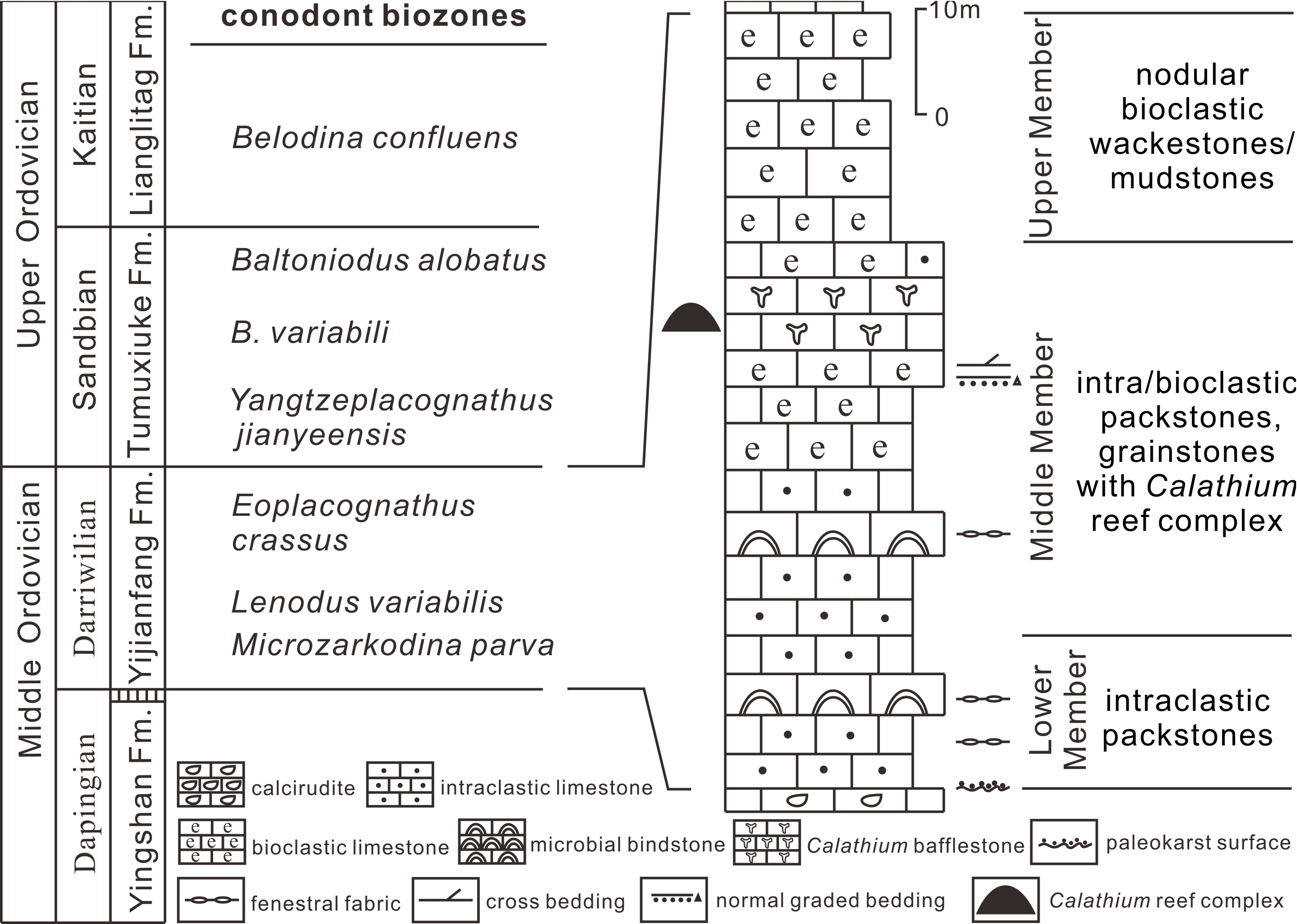
Bioclastic packstone of the shoal facies rich in pelmatozoan debris.

Fig. 5. *Calathium* reef unit at the Nanyigou section. A) Gentle relief patch reef with thickness about 1 m surrounded by bioclastic packstones. B) *In situ* erect *Calathium* in the reef core. C) *Calathium* cluster from reef-core. D) Bioclastic packstone rich in pelmatozoan debris from the reef-flank.

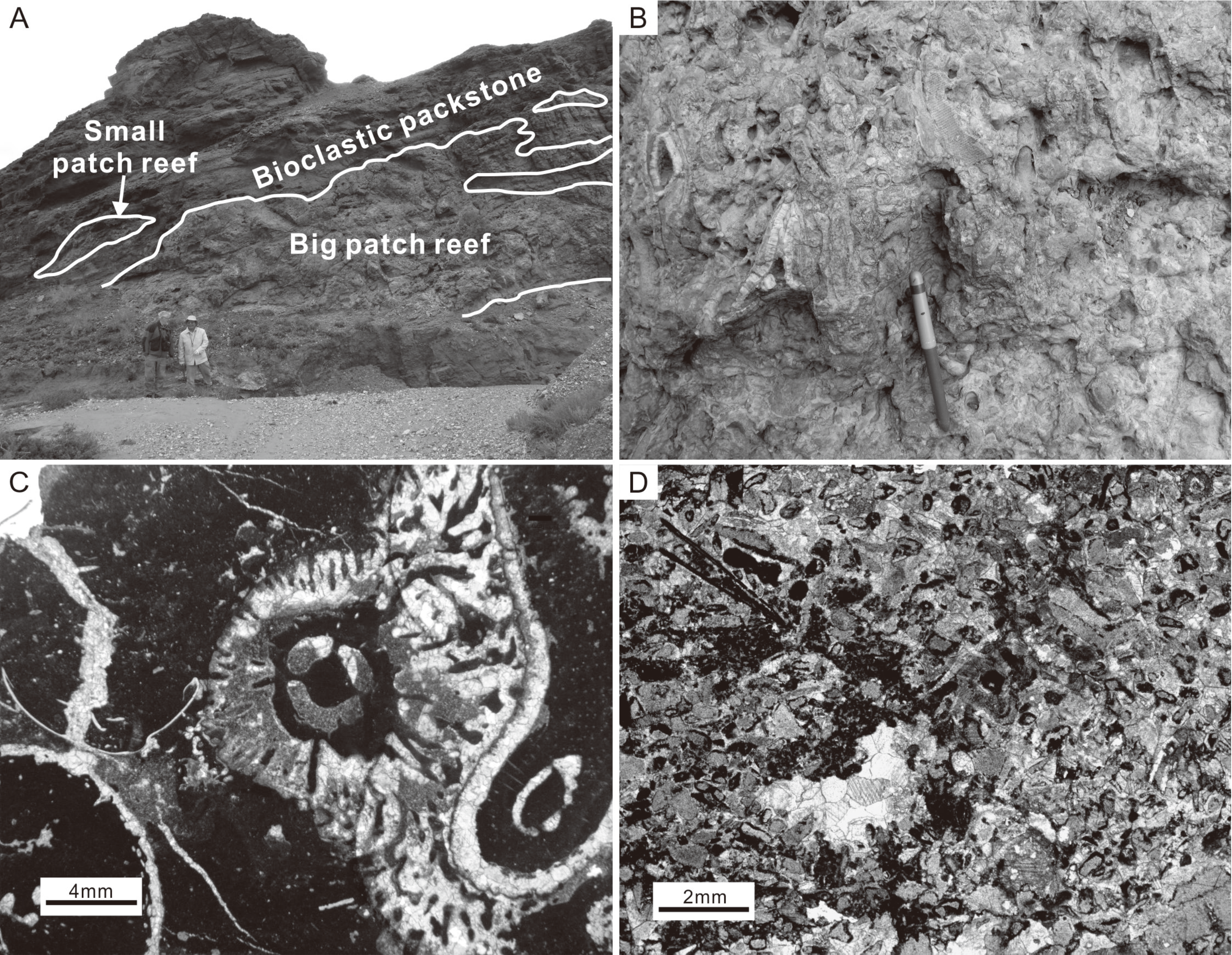
Fig. 6. Depositional sequences at the Yangmaile section. A) *In situ* preserved *Calathium* bafflestone of the biostrome. B, D) Tempestite beds composed of coarse nautiloids and *Calathium* fragments. C) *In situ* preserved shelly bed composed of a single species of brachiopods.

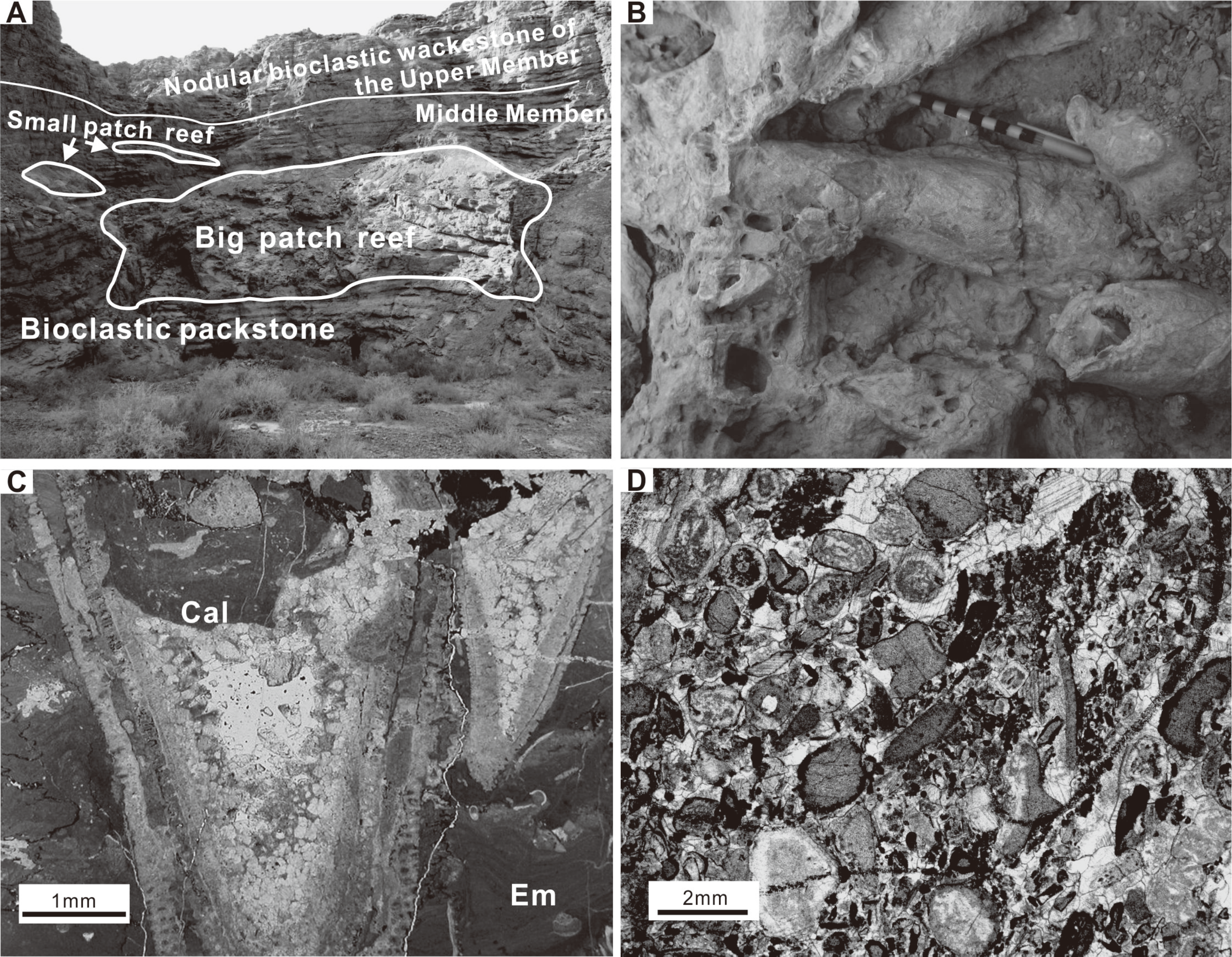
Fig. 7. Paleoecologic and geographic reconstruction of the *Calathium* reef complex transect, from north to south along the Lianglitag Mountains.


314 Highway
Yijianfang
(40°08'37"N,78°49'31"E)
P22
(40°07'57"N,78°50'41"E)
P23
(40°7'11"N, 78°51'33"E)
P25
(40°6'31"N, 78°50'5"E)
Nanyigou
(40°05'20"N,78°50'42"E)
40°05'
P12
(40°4'29"N, 78°50'31"E)
P14
(40°3'50"N, 78°50'53"E)
Lianglitag Mountains
P16
(40°2'34"N, 78°52'4"E)
P17
(40°1'40"N, 78°53'30"E)
0
4km
40°00'N
78°
82°E
B
41°N
Kalpin region
Yangjikan
KD
NTH
ND
Bachu
Mazatag Well Block
39°
CTH
SWTD
STH
SETD
0
200km
Block boundary
Tectonic boundary of the interior block
KD:Kuqia Depression
NTH:North Tarim Uplift
ND:North Depression
CTH:Central Tarim Uplift
SWTD:Southwest Tarim Depression
STH:South Tarim Uplift
SETD:Southeast Tarim Depression
A
Xinjiang
Tianshan
Mountains
Tarim Block
C
Yangmaile
(39°57'6"N,79°03'10"E)
79°00'E

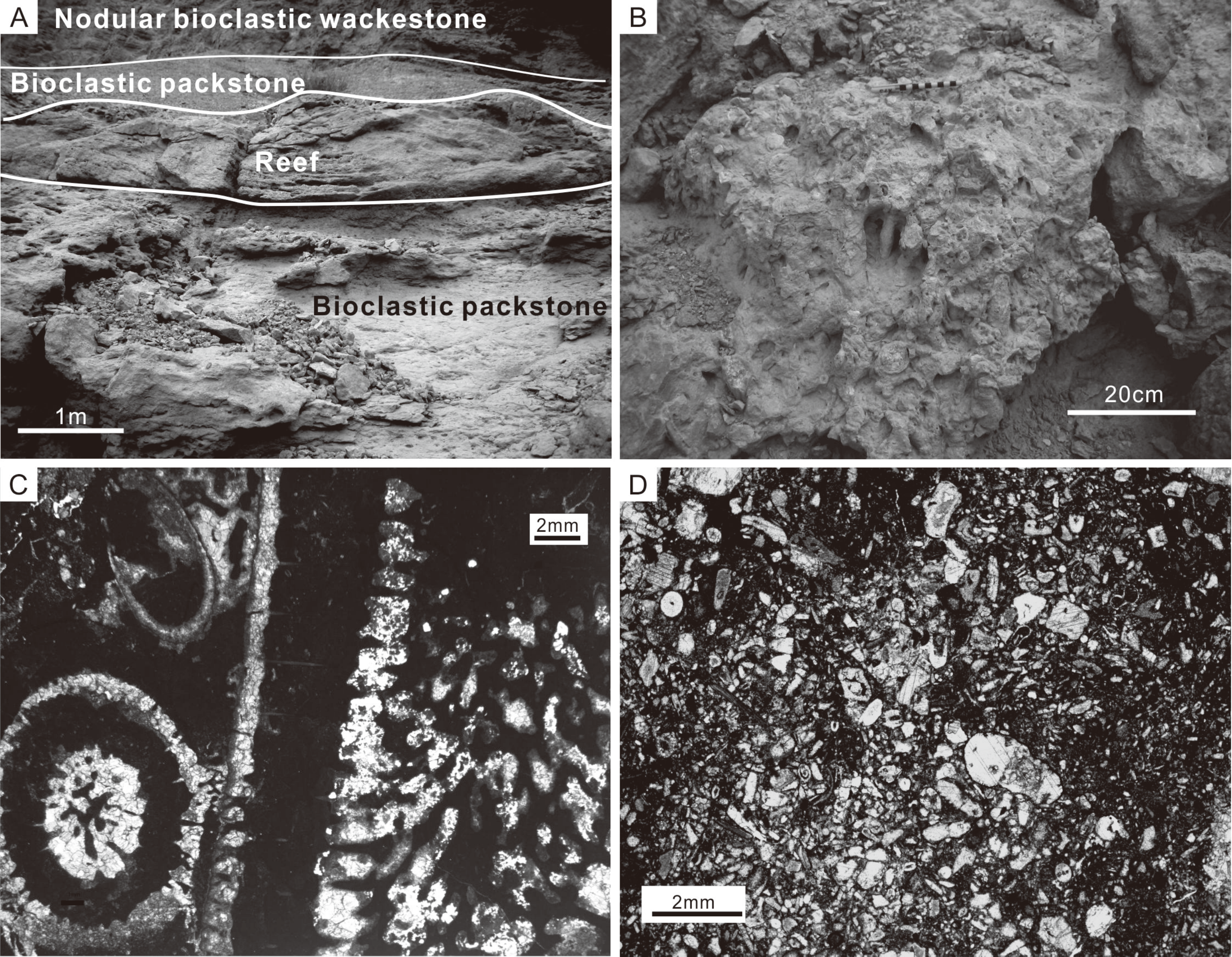


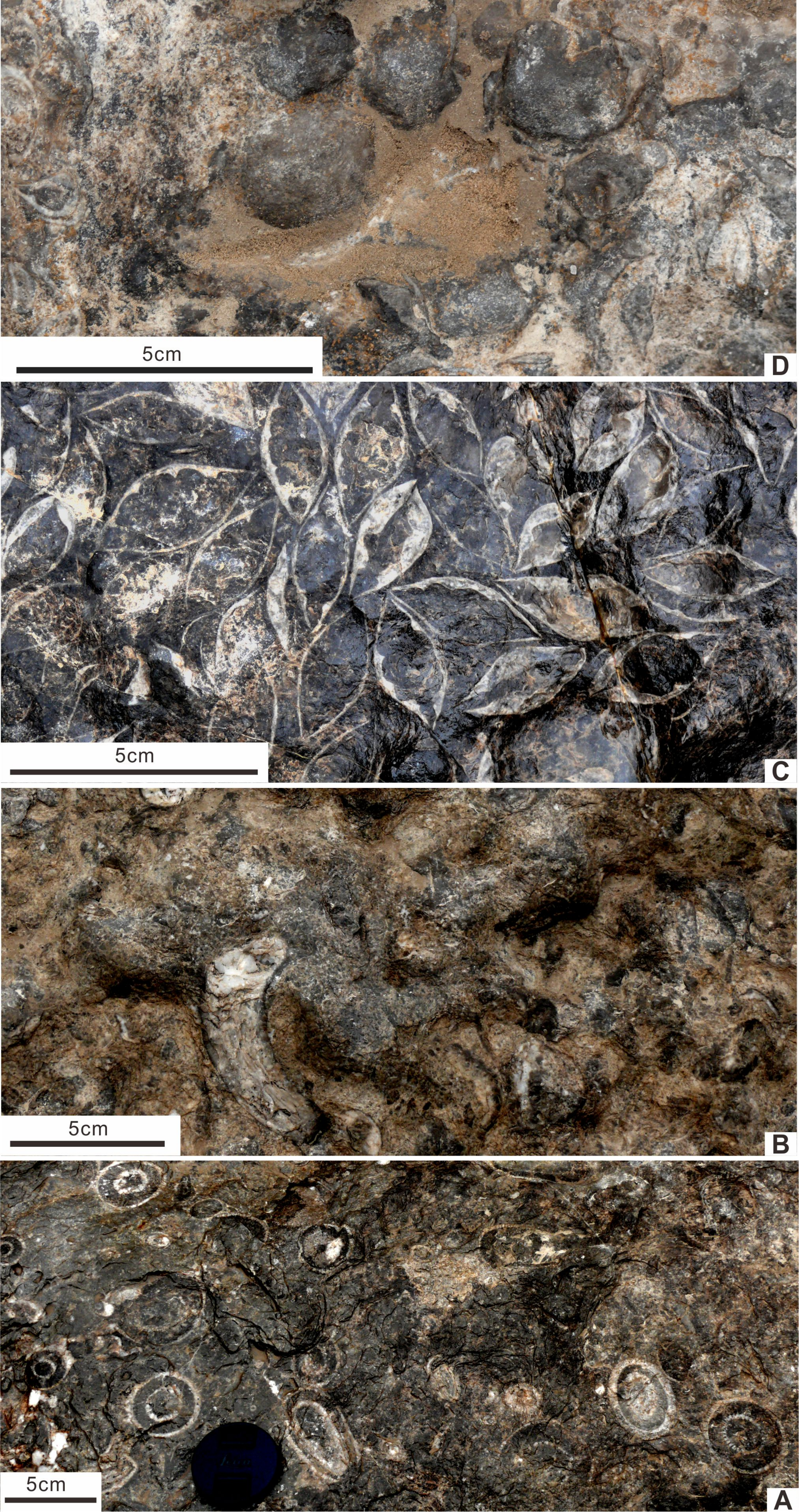
Middle Ordovician
Upper Ordovician
Dapingian
Darriwilian
Sandbian
Kaitian
Yingshan Fm.
Yijianfang Fm.
Tumuxiuke Fm.
Lianglitag Fm.
conodont biozones
Belodina confluens
Baltoniodus alobatus
B. variabili
Yangtzeplacognathus jianyeensis
Eoplacognathus crassus
Lenodus variabilis
Microzarkodina parva
10m
0
Upper Member
nodular bioclastic wackestones/ mudstones
Middle Member
intra/bioclastic packstones, grainstones with Calathium reef complex
Lower Member
intraclastic packstones
calcirudite
intraclastic limestone
bioclastic limestone
microbial bindstone
Calathium bafflestone
paleokarst surface
fenestral fabric
cross bedding
normal graded bedding
Calathium reef complex

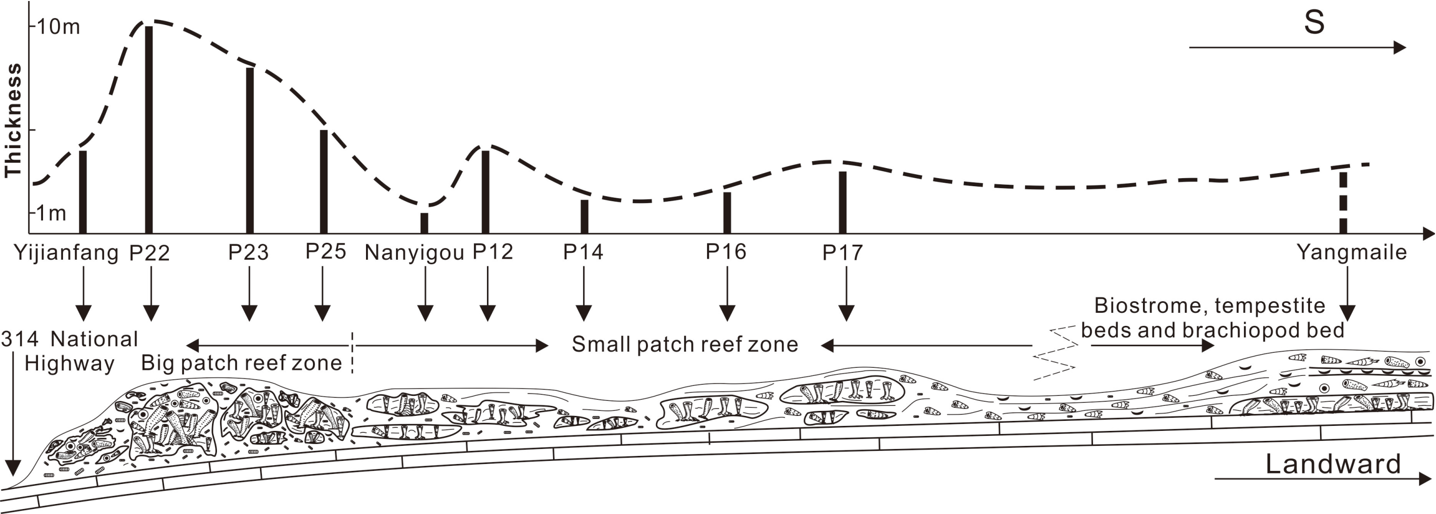

A
Small patch reef
Bioclastic packstone
Big patch reef
B
C
4mm
D
2mm



A
Nodular bioclastic wackestone of the Upper Member
Middle Member
Small patch reef
Big patch reef
Bioclastic packstone
B
C
Cal
Em
1mm
D
2mm


A
Nodular bioclastic wackestone
Bioclastic packstone
Reef
Bioclastic packstone
1m
B
20cm
C
2mm
D
2mm


5cm
D
5cm
C
5cm
B
5cm
A



S
10m
1m
Thickness
Yijianfang
P22
P23
P25
Nanyigou
P12
P14
P16
P17
Yangmaile
314 National Highway
Big patch reef zone
Small patch reef zone
Biostrome, tempestite beds and brachiopod bed
Landward