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Environmental and tectonic significance of Late Permian reefs in the Linxi and adjacent areas in Inner Mongolia of China

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Abstract Many plateau-edge reefs and reef mounds of the Late Permian have been discovered in Linxi County and adjacent areas of Inner Mongolia, China. These reefs verify that the Hinggan-Inner Mongolia Area was an open and unobstructed sea-trough in Late Permian. Facies and sequences of reef strata in Member 4 and Member 5 of the Linxi Formation were studied for information to reconstruct the closing process of the Linxi-Jiutai chasm in the sea-trough, i.e., to constrain subsidence, uplift, and final closing. Ages of the reef-bearing strata have been determined to be late and end of Late Permian, based on ranges or abundances of diverse fossils. Six reef-building organic assemblages were distinguished, representing different ecologic conditions, according to morphological functions and paleoecological adaptations of organisms including primarily sponges, bryozoans, and calcareous algae. Two types of shelf slopes, the gentle slope and the steep slope, have been interpreted for Member 4 and Member 5 of the Linxi Formation, based on the assemblages. The locations of outcrops, and types of these reefs delineate the north margin of Sino-Korea Platform, and define uplift and final closing of the Linxi-Jiutai chasm at the end of Late Permian.

Keywords Reefs, Facies sequence, Paleoecology, Late Permian, Inner Mongolia

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1. Introduction

There is controversy concerning Late Permian environments in the Hinggan-Inner Mongolia Area. According to plant and bivalve fossils previously cataloged, researchers (Inner Mongolia Autonomous Region Bureau of Geology and Mineral Resources, 1991; Jin et al., 2000) concluded that in Late Permian, the Hinggan-Inner Mongolia Area was a continental basin, which had become isolated from the open ocean at the end of Middle Permian. Some others (Yang et al., 1991; He et al., 1997) proposed that the area was a remnant sea trough or an inland sea in early to middle Late Permian, and only became a continental basin in late Late Permian, based on saltwater bivalve fossils and C and O isotope data. Most recently, Tian et al. (2012) and Zhang et al. (2013) concluded that the Hinggan-Inner Mongolia Sea-trough was reopened to the ocean in early Late Permian, and kept open-sea environments till the end of Late Permian, as evidenced by marine fossils including bryozoans, sponge needles, crinoids, and related fauna collected from the middle and upper Late Permian.

Numerous plateau-edge reefs and reef-mounds of Late Permian have been discovered at many places of the Linxi

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and adjacent areas by the present authors. Those places of reef-sections are Guandi in Linxi County, Beidashan in Keshiketeng Banner, Xingfuzhilu in Bairin Right Banner, and Taohaiyingzi in Alukerqin Banner. The abundance and diversity of these reefs provide further proof that the Hinggan-Inner Mongolia Sea-trough was open and unobstructed throughout Late Permian. Detailed study of the Zhaijiagou section near Guandi (Figure 1), presented here, indicates these reefs were built in the later of the Late Permian, by a very diverse fauna.

Reefs of Linxi County and adjacent areas prove that the Hinggan-Inner Mongolia Sea-trough was open and unobstructed. They also indicate that the area served as the northern margin of the Sino-Korea Platform in the late Late Permian. Confirmation of reef-building environments in this area during Late Permian has major significance for palinspastic restorations and shale-gas exploration.

2. Descriptions and classification of Guandi reef strata

Reef strata of the Linxi and adjacent areas include Member 4 and Member 5 of the Linxi Formation, which were also called C and D members by previous researchers. We measured stratigraphic section through both members where they outcrop near the Zhaijiagou Village of Guandi Town, and systematically collected fossils throughout (Figure 2). Member 4 is characterized by reef mounds built on muddy to sandy grounds. Member 5 includes carbonate plateau deposits with many plateau-edge reefs that accumulated during the rapid closure of the Linxi-Jiutai chasm.

2.1 Member 4 of the Linxi formation

Member 4 of the Linxi Formation in the Guandi can be divided into three sedimentary facies, the basin (offshore), the front-shore (shoreface) and the near-shore (foreshore). The lower part (beds 1–3) consists of deep-water rocks (the basin facies), mainly grey-black shale, dark-grey planar-bedded mudstone and silty mudstone, inter-bedding grey-green lenticular medium- to fine-grained sandstone, and grey-black lenticular syndepositional mud-matrix breccia. Bouma sequences are developed in shale and mudstone bedsets. Trace-fossils and small ripples appear on bedding surfaces of shale and siltstone. Sandstone lenses consist mainly of feldspar grains and syndepositional mud-matrix rubbles, with low-angle oblique–bedding orientation that suggest gravitational flows. A few conchostracan bivalve fossils have been collected from shale surfaces, including *Palaeolimnadia* sp., *Huanghestheria* sp. and *Pemphicyclus* cf. *trochoides*.

The middle part of Member 4 (beds 4–6) can be referred to the front-shore facies, or the transitional zone between the near-shore and the basin. These beds are characterized by a significant increase in siltstone and sandstone compared with the underlying beds. Beds 4–6 mainly consist of grey and grey-green, thin- to medium-bedded, tuffaceous, medium- to fine-grained poorly sorted sandstone, siltstone and silty mudstone, with inter-bedding shale and lenticular

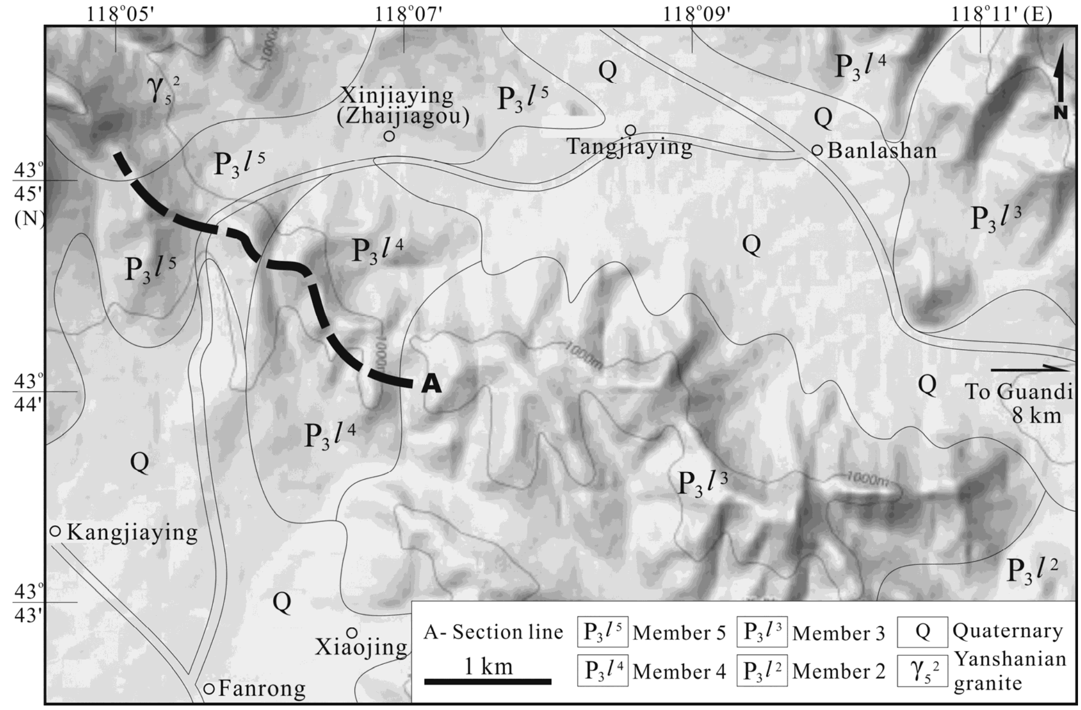

Figure 1 Geological sketch showing the section-line of reef-strata, Guandi in Linxi County.

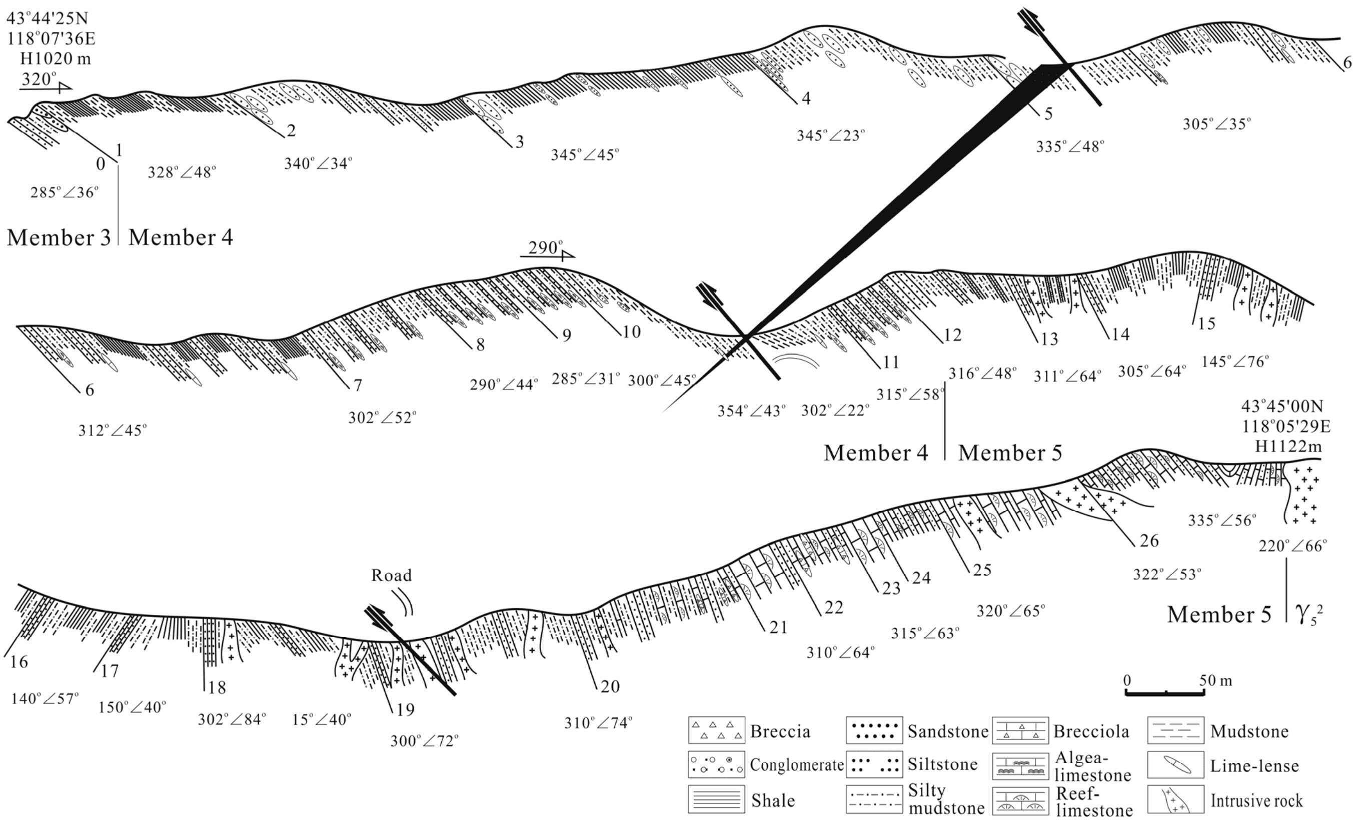

Figure 2 A stratigraphic section of Member 4 and Member 5 of the Linxi Formation, Guandi Town of Linxi County.

sandstone and limestone. Sandstone layers possess oblique low-angle cross-bedding and graded grain sequences, indicating they were formed by gravitational flows. Some fine-branched bryozoan fossils can be found on sandstone surfaces and in lenticular limestone, e.g., *Thamniscus* sp., *Polypora* sp., *Fistulipora* sp. The mudstones commonly bear abundant palynomorphs, e.g., *Vitreisporites signatus*, *Sulcatisporites ovatus*, and *Rhizomaspora radiate*.

The upper part of Member 4 (beds 7–11) belongs to the near-shore facies, which can be divided into two subfacies, sand-ground and mud-ground. Strata of the sand-ground subfacies yield abundant reef mounds, developed on gentle-oblique beddings in sandy lenses. Beds 7–11 are mainly composed of grey, pale gray, and gray-green laminated silty mudstone and muddy siltstone, inter-layered medium- to thick-bedded pebbly sandstone, mud-matrix breccia, and limestone lenses or reef mounds. Abundant reef-building fossils in these strata primarily include sponges *Amblysophonella specialis*, *Peronidella beipeiensis*; bryozoans *Fenestella* sp., *Rhombocladia* sp., *Thamniscus* sp., *Fistulipora* sp., *Stenodiscus* sp., *Fistulimamus* sp.; calcareous algae *Monostysisyrinx circularis*, *Sphaeroporella minima*, *Archaeolithoporella hidensis*; and stromatolite *Baicalia* sp. Associated fossils include bivalves *Palaeanodonta* sp., *Palaeomutela soronensis*, *P.* cf. *trigonalis*, and palynomorph varieties *Vitreisporites signatus*, *Sulcatisporites ovatus* and *Rhizomaspora radiate*.

Strata of the mud-ground subfacies consist of dark grey, thin-bedded mudstone and shale, inter-bedded small mud-rubble lenses and limestone lenses. No fossils have yet been found in this subfacies.

2.2 Member 5 of the Linxi Formation

Member 5 differs from Member 4 in possessing coarser-grained rocks and major plateau-edge reefs, reflecting shallower water. Member 5 can be divided into six facies, shore-face, near-shore, off-shore, basin, front-plateau slope, and carbonate plateau (Figure 3). The lower part (beds 12–13) of Member 5 comprises strata of the shore-face and the near-shore facies, composed mainly of purplish-red, grey-brown, grey-green, thick-bedded muddy sandstone, siltstone and silty mudstone. Sandstones possess wedge-shape cross-beds and organism boreholes. Siltstone and silty mudstone layers yield a few bivalve fossils of *Palaeanodonta* sp.

The middle part of Member 5 (beds 14–19) comprises two inter-bedded facies, the off-shore and the basin, mainly consisting of grey and grey-green, medium to thick-bedded, mud-cemented fine-grained sandstone, muddy siltstone and silty shale. Most of the sandstones have lower-angle inclined beddings. Silty shale layers are rich in palynomorphs and acritarch fossils, *Vitreisporites signatus*, *Sulcatisporites ovatus*, *Rhizomaspora radiata*, *Cordiatina* sp., *Micrhystri-*

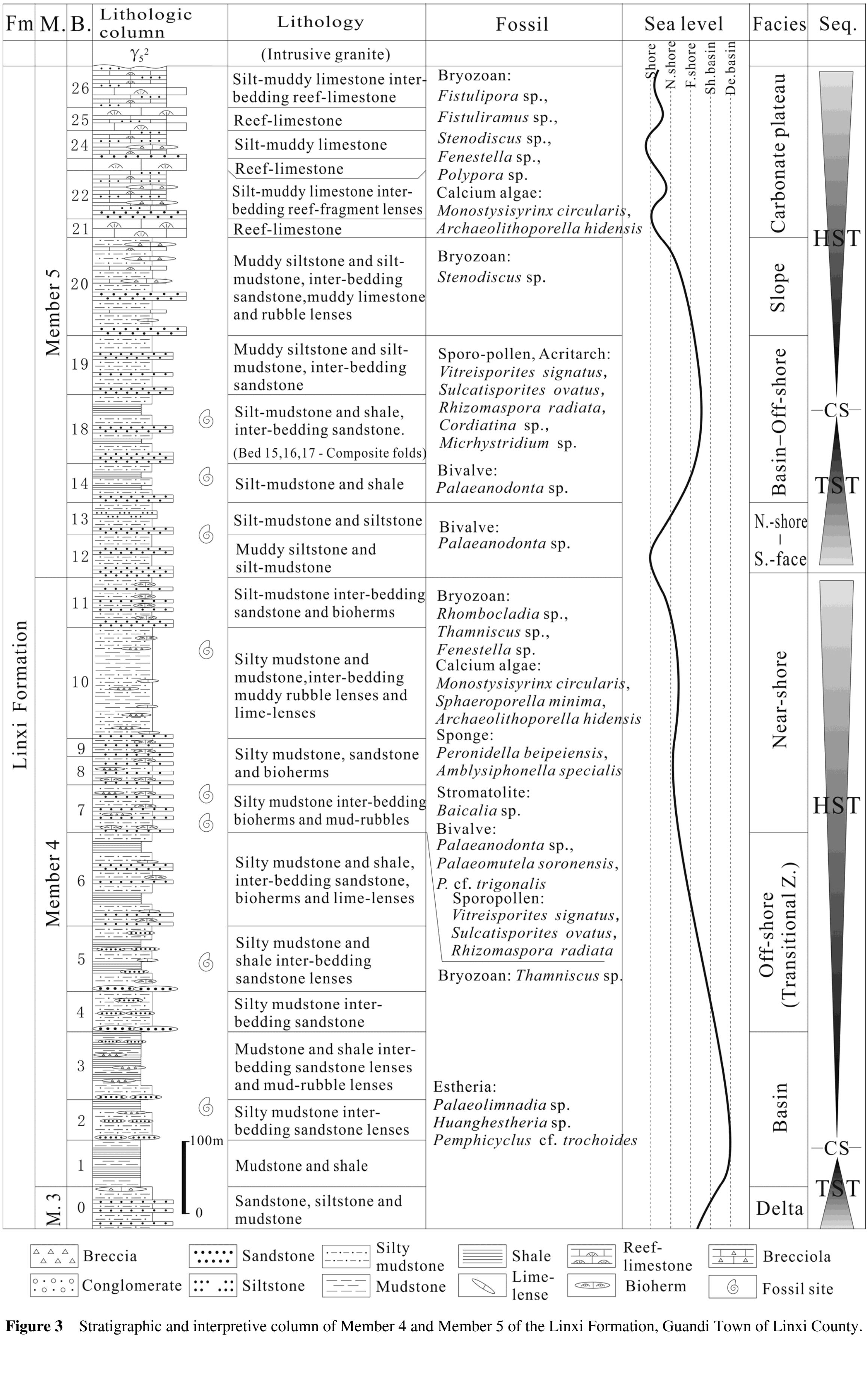

Figure 3 Stratigraphic and interpretive column of Member 4 and Member 5 of the Linxi Formation, Guandi Town of Linxi County.

dium sp. and a few bivalve fossils, *Palaeanodonta* sp.

The upper part of Member 5 (beds 20–26) also consists of two facies, the front-plateau and the carbonate plateau, both of which contain abundant reefs. Strata of the front-plateau mainly consist of grey and dark-grey, medium- to thick-bedded and fine-grained sandstone, siltstone, muddy siltstone and silty mudstone, with inter-bedded thin- to medium-bedded silty limestone and mud-rubble lenses.

The carbonate plateau facies can be divided into three subfacies, front-reef, reef-core and back-reef. Strata of the front-reef mainly consist of dark-grey, thin- to medium-bedded, muddy fine-grained sandstone and silty limestone, with inter-bedding reef-rubble lenses. The front-reef includes many branched bryozoan fossils, particularly *Stenodiscus* sp.

Strata of the reef-core consist of grey, grey-brown and grey-black, thick- to blocky-bedded, reef framework silty limestone; inter-bedding grey, thick-bedded, medium- to fine-grained sandstone and syndepositional rubble lenses. Reef-building organic fossils include chiefly bryozoans (*Fistulipora* sp., *Fistuliramus* sp.) and calcareous algae (*Archaeolithoporella hidensis*). Reef frameworks were built by bryozoans and bound by encrusting *A. hidensis*. Sandstone layers have cross-bedding indicating conditions of high-energy banks. Clasts in the co-occurred rubbles are mostly 1–6 cm long, and variously composed of sandy, limy and muddy fragments.

Strata of the back-reef mainly consist of grey-black and black, thin- to medium-bedded, muddy limestone and silty limestone, with inter-bedding thick-bedded framework limestone, syndepositional breccia and bamboo conglomerate. Reef-building organism fossils include chiefly bryozoans *(Stenodiscus* sp., *Fenestella* sp., *Polypora* sp.) and calcareous algae (*Monostysisyrinx circularis*, *Archaeolithoporella hidensis*).

3. Ages of reef-bearing strata

The age of these reef-bearing strata has been in contention. Gu et al. (1982) named these strata Members C and D of the Linxi Formation, and attributed them to the upper part of the Upper Permian, and correlated them with the Taohaiyingzi Formation. He et al. (1997, 1998) pointed out that Member D includes continental deposits that might be Lower Triassic. We hereby name these reef-bearing strata of Member 4 and Member 5 of the Linxi Formation, and assign them to the upper part of the Upper Permian, based on the ranges and thriving peaks of many fossils—sponges, bryozoans, calcareous algae, palynomorphs, cephalopods.

3.1 Reef-building organic fossils

Sponge fossils primarily include two species, *Amblysophonella specialis* and *Peronidella beipeiensis* in these reef-bearing strata. Both species have also been reported from the Changching Formation of the Upper Permian in South China, such as the Beibei reef of Chongqing, the Lichuan reef of Hubei and the Cili reef of Hunan (Fan et al., 1996; Rigby et al. 1994; Tian et al., 2002). These sponges were the major reef-building organisms on the carbonate plateaus of the Changxing Formation, and they became extinct at the end of Permian. The earliest occurrences of these sponges need to be studied further, but the peak distribution and extinction timing could prove that the reef-bearing strata of Member 4 and Member 5 belong to the upper part of Upper Permian.

Bryozoan fossils of this area need to be studied more deeply, as there are few classifications so far (Yang et al., 1962, 1965). Bryozoan genera and higher classifications are based on interior textures and microstructures, and can be easily confirmed. But species are distinguished mainly on exterior shapes of their hard bodies, which more directly reflect their living conditions. Therefore, each bryozoan genus contains many ecologic forms difficult to classify. We have classified these bryozoan fossils only to genera, both for convenient discussion and because the external features of reef-building bryozoan fossils cannot be easily discerned. The common preservation of these bryozoans in massive reef carbonates means the external surfaces are nearly always encased in carbonate and cannot be seen on polished surfaces.

Bryozoan fossils of the Linxi Formation are also preserved in muddy limestone. Differential weathering of the reef rocks made both internal features and microstructures clearly visible, so these fossils are easy to appraise into the genus. Bryozoan genera in the Linxi and adjacent areas (*Fenestella*, *Rhombocladia*, *Thamniscus*, *Fistulipora*, *Stenodiscus*, *Fistulimamus,* and *Polypora*) all ranged from the Silurian to the Permian and thrived in the Carboniferous through the Permian, but they never occurred in the Triassic.

Calcareous algae in the Linxi Formation include primarily four genera and species: *Monostysisyrinx circularis*, *Sphaeroporella minima*, *Archaeolithoporella hidensis,* and *Anthracoporella spectabilis*. These algae crowded together to build up reef frameworks in Linxi and adjacent areas. These calcareous algae were also superior reef-builders in the Permian, in South China (Mu, 1981; Wu, 1991).

3.2 Palynomorph and Cephalopod Fossils

Palynomorph fossils are very abundant in Member 4 and Member 5 of the Linxi Formation (Figure 4). They primarily include *Vitreisporites signatus*, *Sulcatisporites ovatus*, *Rhizomaspora radiata*, *Cordiatina* sp., and *Micrhystridium* sp. Among them, *Vitreisporites signatus* is a standard species of the Late Permian worldwide. Genus *Cordiatina* defined in the Permian of the Ural, Russia, area and flourishes in the Middle Permian, from the Artinskian to the Kungurian

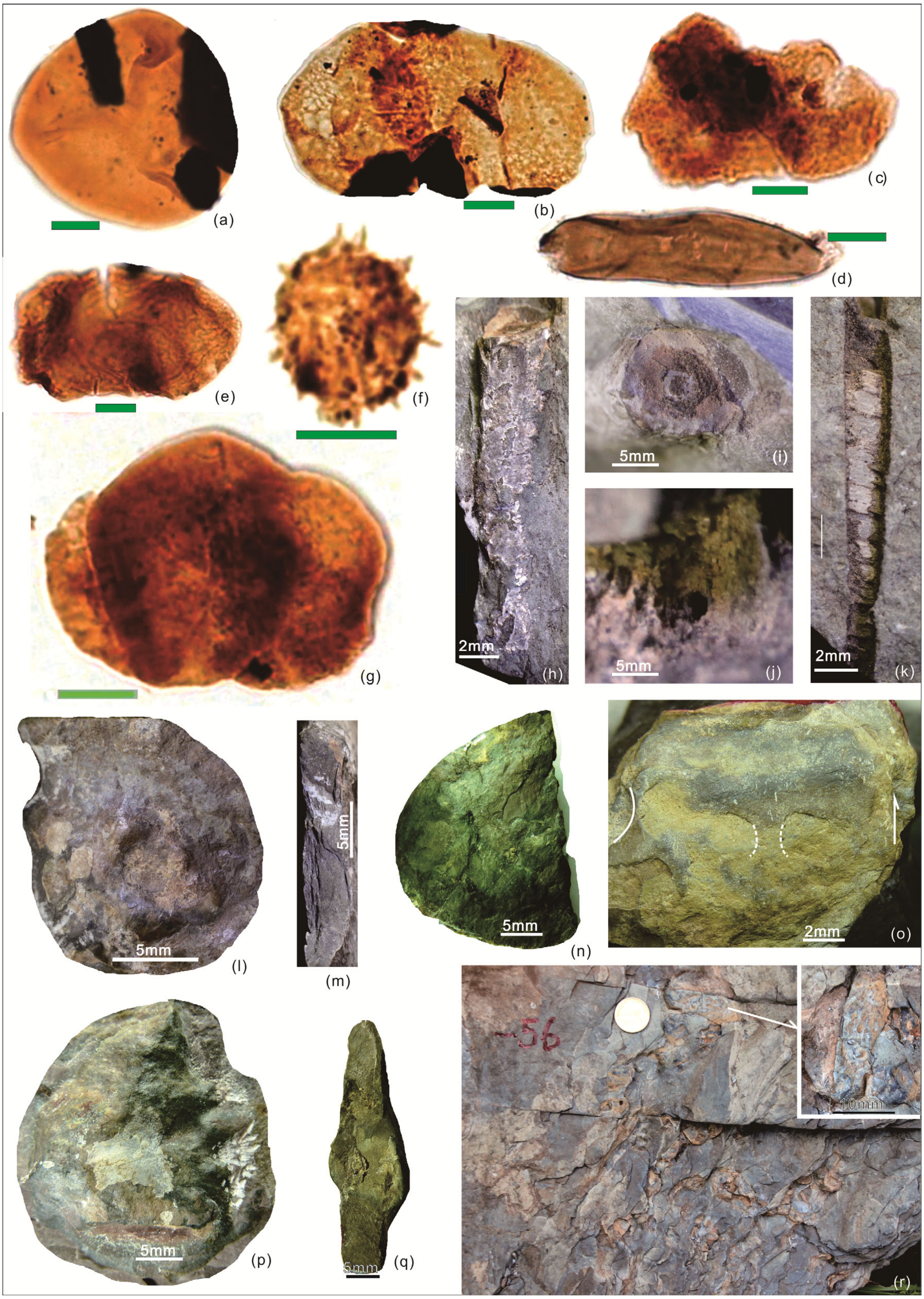

Figure 4 Late Permian fossils of the Linxi Fm, Guandi of Linxi County. (a)–(g) Palynomorph fossils in Member 4 and Member 5 of Linxi Fm. (scales: 5μm). (a) *Gulisporites cochlearis* Imgrund 1960, sample number: 2013LG-74-2-1; (b) *Sulcatisporites ovatus* (Balme and Hennelly) Balme 1970, sample number: 2013LG-74-3-1; (c) *Vitreisporites signatus* Leschik 1957, sample number: 2013LG-74-2-1; (d) *Leiofusa* sp., sample number: 2013BACH-5-2-1; (e) *Rhizonaspora radiata* Wilson 1962, sample number: 2013LG-74-4-1; (f) *Micrhystridium* sp., sample number: 2013LG-74-4-1; and (g) *Alisporites shanx-iensis* Gao 1984, sample number: 2013LG-74-3-4. (h)–(r) Cephalopod fossils in Member 3 of Linxi Fm. (h)–(k) *Lopingoceras of guangdeense* Zhao, Liang et Zheng 1978, sample number: 2014-LGD-6; (l)–(r) Ammonoidea gen. et sp. indet., sample number: 2014-LGD-6.

stages. But in North China, a large number of specimens are found in the Shangshihezi Formation of the Upper Permian, and can be divided into some thriving biostratigraphic zones. Other genera and species commonly occur in the Permian (Gao, 2008).

Cephalopod fossils, ammonites and nautiluses, have been discovered recently in Member 3 of Linxi Formation in Guandi. Ammonite fossils are abundant, but poorly preserved in silty mudstone, and can only be identified as *Ammonoidea* indeterminate. Many ammonite fossils verify that the upper part of the Linxi Formation consists of normal marine deposits. Nautilus specimens are better preserved and defined as *Lopingoceras guangdeense* Zhao, Liang et Zheng. This species was defined in the Dushan area of Anhui Province, in the Changxing Formation of the Upper Permian (Zhao et al., 1978). Nautilus *Lopingoceras guangdeense* and *L. lopingense* (Stoyanov), both are important members of a cephalopod group in the Changxingian Stage. Specimens of *L. guangdeense* prove that the reef-bearing strata of the Linxi Formation belong to the later part of the Late Permian.

4. Morphological functions of reef-building organisms

4.1 Sponge

A sponge is a multicellular animal with a basal holdfast, and a central cavity surrounded by multiple layers of bubble-cells. Each bubble-cell has an enter-hole and an exit-hole with some collar-cilia. Bubble-cell holes, collar-cilia and the central cavity make up the water-flow system of the sponge. Sponges filter foods and drain off wastes using the water-flow systems, with collar-cilia swaying continuously. Filter feeders like sponges commonly live in clear seawater with relatively dynamic wave and current energies. Calcareous sponges are major reef-builders, generally crowding together on hard substrates in shallow marine water.

Sponge fossils, primarily *Amblysophonella specialis* and *Peronidella beipeiensi* (Figure 5a–d), are found in Member 4 of the Linxi Formation. Specimens of both species present inverted horn-tapers, and were fixed on medium- to fine-grained sandy substrates with their smallest end, crowded together to group reef mound frameworks. Sponge reef mounds reflect conditions of muddy to sandy grounds with relatively strong water-flows.

4.2 Bryozoan

A bryozoan is a kind of group-living animal that affixes to hard bases or float. Most bryozoan animals can secrete hard bodies, which may be preserved as fossils. Bryozoans catch foods in flowing waters by swinging tentacles around their mouths. Modern bryozoans can adapt to many adverse conditions, e.g., a water-depth of 5500 m and cool waters in polar areas. However, most bryozoans are thriving in shallow seas, from the wave-base to the euphotic zone, where waters are clear, warm and neither hypo- nor hyper-saline.

Many bryozoan-built reefs have been reported in cold-water areas of the Carboniferous-Permian of North America, Germany, Siberia, and Inner Mongolia of China (Heckel, 1989; Tian et al., 2011). Bryozoan fossils are good markers for indicating facies, owing to their sensitivity to conditional factors. Reef-building bryozoans can be divided into four morpho-types reflecting paleo-ecological conditions in the Linxi and adjacent areas.

(1) The fine-branch type (Figure 5i). Bryozoan fossils with slender branch-shapes include primarily *Fistulipora* sp., *Thamniscus* sp., and *Polypora* sp. Frameworks built by this type have been collected from the Linxi Formation and the Taohaiyingzi Formation. These bryozoans were scattered on surfaces of silty mudstone or siltstone, and constituted small reef mound frames. These bryozoans might be living in low-energy environments, and could indicate conditions of the front-shore, the side-reef or the back-reef.

(2) The layer-frame type (Figure 5e–g). Bryozoan fossils with layer-frames mostly spread on surfaces of siltstones and fine sandstones in Member 4 of the Linxi Formation These layer-frames include three layers, proximal membranes, net-bodies and over-superstructures. Net-bodies are inclined to proximal membranes in *Rhombocladia* sp., and could be built up by irregular branch-bodies that piled upon proximal membranes as in *Thamniscus* sp. This bryozoan morph-type reflects that the animals were adapted to relatively shallower and stronger waters. Bryozoan fossils of this type generally indicate muddy to sandy substrates on upper shelf-slopes.

(3) The node-root type (Figures 5j; Figure 6f, g). Bryozoan fossils with node-roots are mostly found in upper layers of Member 4 and Member 5 of the Linxi Formation Fossils of this type mostly include *Fenestella* sp. and *Polypora* sp. These fossils also appear to have larger fan-bodies or branch-bodies excepting those with large node-roots, but they are not covered by alga *Archaeolithoporella* sp. The node-root type bryozoans generally co-occur with conglomerate lenses or sandy breccia. These bryozoans attached to the substrate with nodular pseudo-roots, for resisting against high-energy water in the front-reef or the side-reef.

(4) The thick-pipe type (Figure 6 a–e; Figure 7 a–d, f, h). Bryozoan fossils of the thick-pipe type are very abundant in the thick- to blocky-bedded silty limestone of Member 5 of the Linxi Formation, and primarily include *Fistulipora* sp., *Stenodiscus* sp., and *Fistulimamus* sp. These fossils commonly possess large, strong, hard bodies in various straight pipe-forms or branch-shapes. The outer walls of these bodies are thicker than other types of bryozoans and have some inner partitions or foam tissues. Most of the thick-pipe type bryozoan hard bodies are covered and connected to each other by the alga *Archaeolithoporella* sp. Bryozoans of this

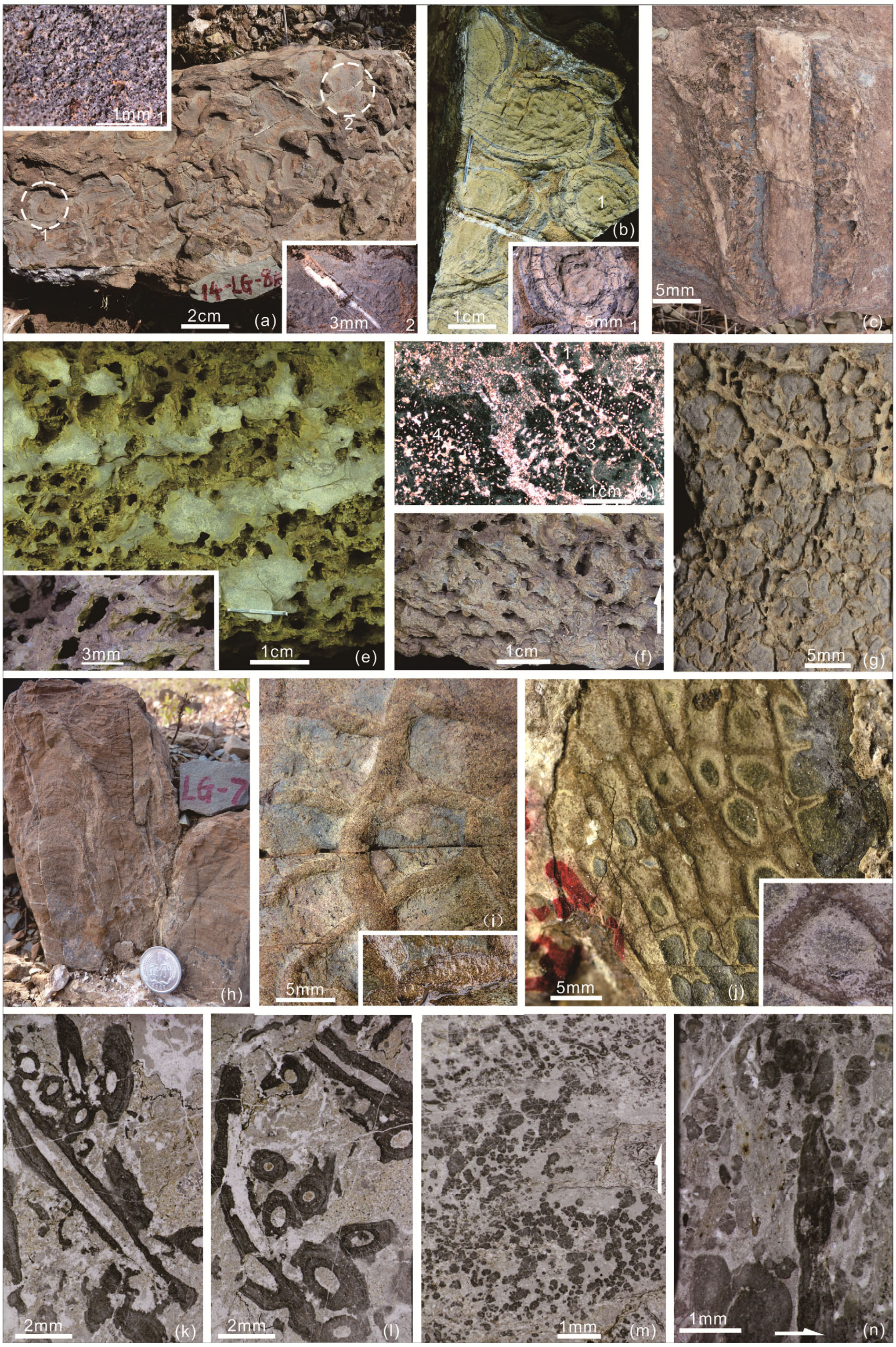

Figure 5 Organic reefs of Member 4 of the Linxi Formation, Guandi of Linxi County. (a), (b) Social reef-frames built by sponge *Peronidella* and *Amblysiphonella*, sample number: 14-LG-8; (c) an eroded fossil-section of sponge *Amblysiphonella specialis* Rigby, Fan and Zhang 1989, sample number: 14-LG-9; (d-1), (d-2) fossil-section of sponge *Peronidella beipeiensis* Rigby, Fan and Zhang 1989, sample number: 14-LG-9; (d-3), (d-4) fossil-section of sponge *Peronidella regulara* Rigby, Fan and Zhang 1989, sample number: 14-LG-9; (e), (f) layer-form reef-frames built by bryozoan *Rhombocladia* sp., sample number: 14-LG-8; (g) clump-hinder reef-frame built by bryozoan *Thamniscus* sp., sample number: 14-LG-9; (h) clump-hinder reef-frame of stromatolite *Baicalia*, sample number: 14-LG-7; (i) Bryozoan *Fistulipora* sp., sample number: 14-LG-5; (j) clump-hinder reef-frame built by bryozoan *Fenestella* sp., sample number: 14-LG-11; (k), (l) clump-hinder reef-frames built by alga *Monostysisyrina circularis* Wu, 1991 and *Archaeolithoporella hidensis* Endo, 1959, sample number: 14-LG-11; (m) clump-hinder reef-frame built by alga *Sphaeroporella minima* Wu, 1991， sample number: 14-LG-11; (n) organic bank piled up by alga *Sphaeroporella minima* Wu, 1991 and co-occurred gravels, sample number: 14-LG-11.

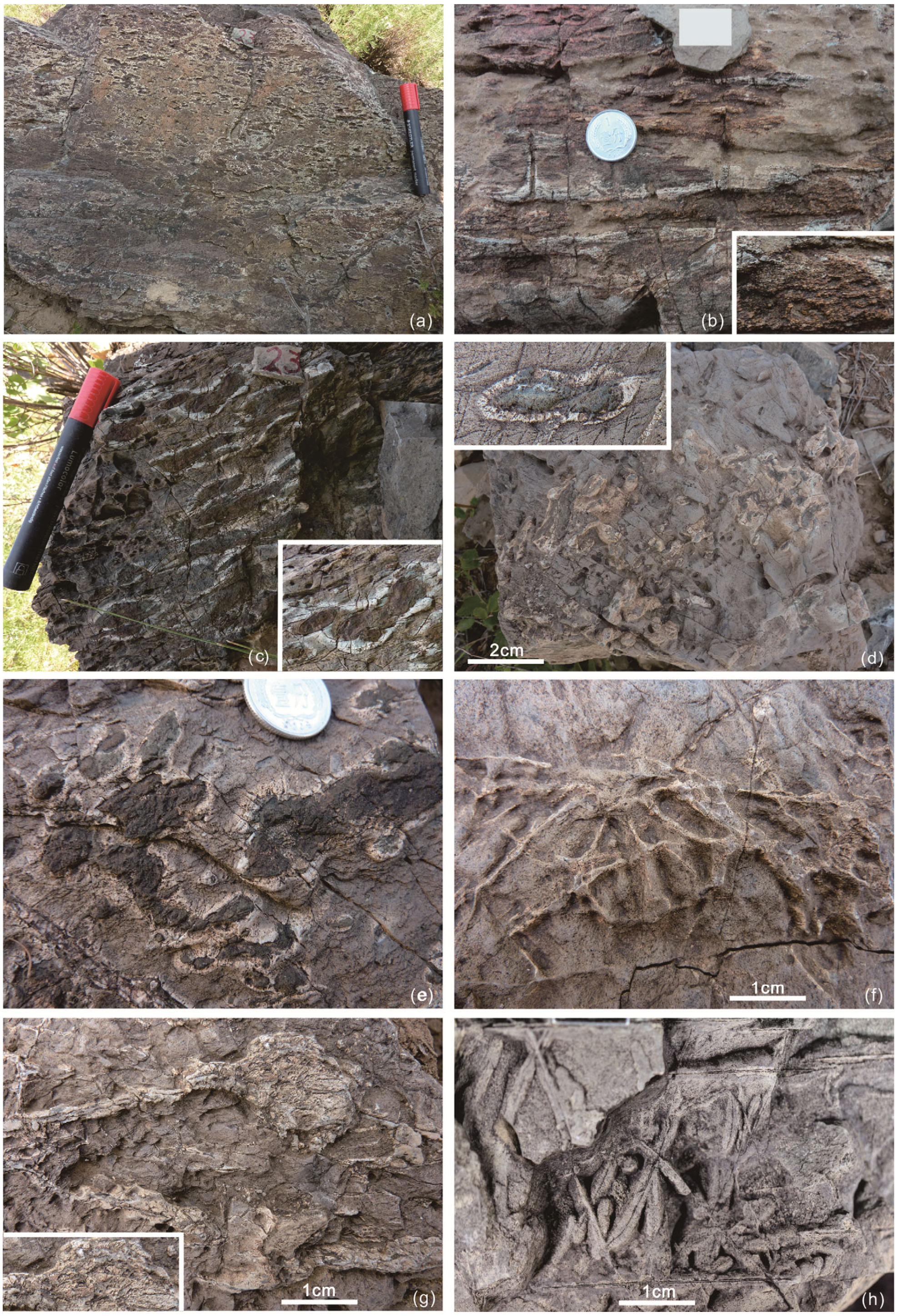

Figure 6 Organic reefs of Member 5 of the Linxi Formation, Guandi of Linxi County. (a)–(c) Clump-hinder reef-frames built by bryozoan *Fistulipora* sp. covered by alga *Archaeolithoporella hidensis* Endo, 1959, sample number: 14-LG-23; (d) clump-hinder reef-frame built by bryozoan *Stenodiscus* sp. covered by alga *Archaeolithoporella hidensis*, sample number: 14-LG-21; (e) clump-hinder reef-frames built by bryozoan *Fistuliramus* sp. covered by alga *Archaeolithoporella hidensis*, sample number: 14-LG-21; (f) clump-hinder reef-frame built by bryozoan *Fenestella* sp., sample number: 14-LG-21; (g) clump-hinder reef-frame built by bryozoan *Polypora* sp., sample number: 14-LG-24; (h) clump-hinder reef-frame built by alga *Monostysisyrina circularis* covered by alga *Archaeolithoporella hidensis*, sample number: 14-LG-24.

type crowded together to make up high, large frameworks of the plateau-edge reefs and block reefs. The morphology of the thick-pipe type hard bodies resists turbulent and high-energy waters.

Many straight pipe-form fossils, *Fistulipora* sp., have been also found in the Taohaiyingzi Formation, in the Taohaiyingzi area of Alukerqin Banner. These fossils are well-preserved in laminated tuffaceous rocks, piled together

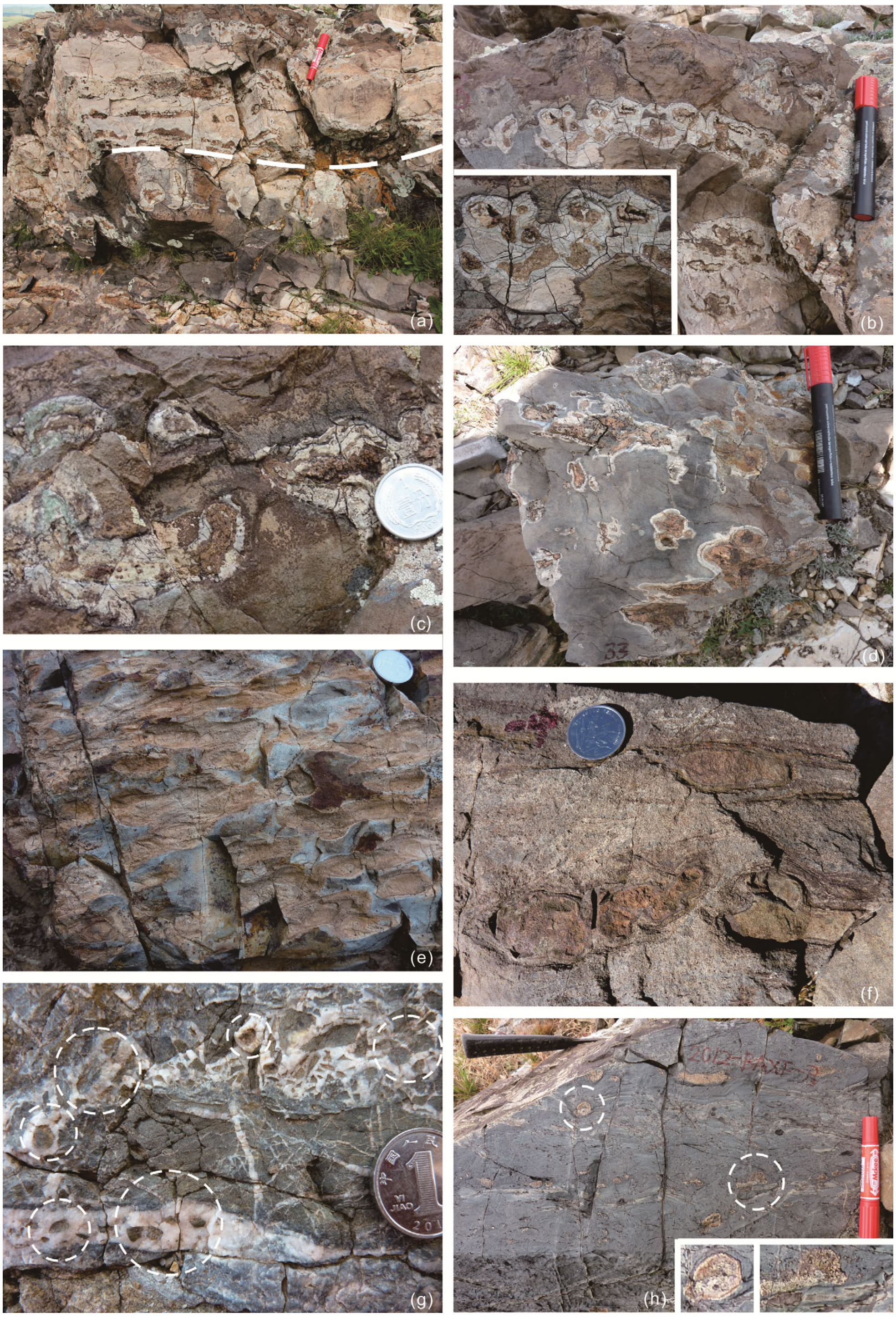

Figure 7 Late Permian organic reefs in adjacent areas of Linxi. (a)–(d) Late Permian reefs of the Beidashan Fm, the Beidashan of Keshiketeng Banner. (a) Reef-frames built by bryozoan *Fistuliramus* sp. and *Fistulipora* sp., covered by alga *Archaeolithoporella hidensis* Endo, 1959; (b) enlarged patterns of *Fistulipora* sp.; (c), (d) enlarged patterns of *Fistuliramus* sp., sample number: 14-KBB-33. (e)–(g) Late Permian reefs of the Taohaiyingzi Fm, the Taohaiyingzi of Alukerqin Banner. (e) Accumulations removed of bryozoan *Fistulipora* sp., sample number: 09-ALT-52; (f) reef-frames built by bryozoan *Fistulipora* sp. covered by alga *Archaeolithoporella hidensis*, sample number: 09-ALT-36; (g) clump-hinder reef-frames built by alga *Anthracoporella spectabilis* Pia, 1920, sample number: 09-ALT-5. (h) Clump-hinder reef-frames built by bryozoan *Fistulipora* sp. of the Linxi Fm, the Xingfuzhilu of Balin Right-banner, sample number: 14-XFZL-10.

in a death assemblage but having moved only a short way. Appearances of these fossils represent that they flourished near shallow-water areas.

4.3 Calcareous algae

Calcareous algae are also important reef-builders, both in geologic history and in the present. Algal frameworks may be built up by growing separate algal bodies or by several twining together. Calcareous algae contain both green algae and red algae; most thrive in water depths of 20–30 m (the strong-light zone), and affix themselves to non-muddy substrates. A few calcareous algae can survive to about 60 m deep (the euphotic zone). Fossil calcareous algae are very abundant in the Linxi and adjacent areas, and include primarily *Monostysisyrinx circularis*, *Sphaeroporella minima*, *Archaeolithoporella hidensis*, *Anthracoporella spectabilis* and *Baicalia* sp. These algae reflect shallow seas with various moderate- to low-energy waters.

(1) Genus *Monostysisyrinx* (Figure 5k, l; Figure 6h). Genus *Monostysisyrinx* belongs to the Phylum Chlorophyta. Algal bodies of this genus present straight-circular tubes un-diverged, and were usually covered and connected together by *Anthracoporella*, which facilitated resistance to waves and strong currents. Fossils of *Monostysisyrinx* include primarily two sorts, slender ones and sturdy ones, in the Linxi and adjacent areas. Slender ones possess short, small bodies about 5–10 cm high and 0.5 cm thick, and they are collected from Member 4 of the Linxi Formation. Occurrences of these fossils reflect sand-grounds in shallow waters with moderate to low energies. These slender algae crowded together to construct reef mound frames.

Sturdy fossils of genus *Monostysisyrinx* are found in Member 5 of the Linxi Formation. Their forms are taller and thicker than the slender algal bodies of this genus; some can be meters high and 1.5–3 cm thick. These sturdy algal bodies are preserved in the thick- to blocky-bedded reef limestone, and clearly indicate environments of the front-reef and the side-reef with relatively high-energies.

(2) Genus *Sphaeroporella* (Figure 5m). Genus *Sphaeroporella* also belongs to the Phylum Chlorophyta. These algae commonly crowd together to constitute reef-mound frames. Each algal body is made up of branches on which many alga-spheroids are strung together. Alga-spheroids get larger as the branch grows. Diameters of alga-spheroids vary from 0.1 cm to 0.8 cm, and their midsections consist of radiate pipes. *Sphaeroporella* fossils are collected from Bed 10 of Member 4, where they grew on mud-grounds in relatively quiet waters. However, in Bed 11, these algae are scattered randomly in grainstones, and were clearly transported to sandy grounds with turbulent waters, where they were preserved by burial.

(3) Genus *Baicalia* (Figure 5h). Genus *Baicalia* comprises stromatolites, which are structures of blue-green algae. Silk-shape or leaf-shape algal bodies cohere with fine-grained deposits, and alternately pile up to frameworks. Features of these fossils include dark-light veins, which together with structural stromatolite patterns indicate dynamic strengths and water depths (Hoffman, 1976). Stromatolites of *Baicalia* sp. are found at top of Member 4 in Linxi and adjacent areas, consisting of column-like branches of diameters about 1.2–2 cm. Dark-light veins on stromatolite specimens bend like arches and vein-fibers are indistinct, and spaces between branches are filled by silty and calcareous materials. Branches of *Baicalia* sp. crowd and construct reef frameworks of reef mounds. These reef mounds commonly average 32 cm high and 1.6 m long. Occurrences of these fossils reflect conditions of muddy to sandy substrates with a moderately dynamic energy system.

(4) Genus *Anthracoporella* (Figure 7g). Genus *Anthracoporella* are classified as green algae. Fossils of this genus have been found in the lower part of the Taohaiyingzi Formation in Taohaiyingzi area of Alukerqin Banner. Algal bodies of these fossils present circular tube forms, and their tube diameters are mostly 3.5–5.1 mm. Most of the fossils are bifurcated with a side branch generally smaller than the main branch. Calcareous tube walls are about 0.7–1.5 mm thick and comprised of micro-pipes. These algal fossils appear to have lived on silty limestone lenses, and to have crowded together to make reef frameworks. These fossils indicate muddy to sandy grounds in shallower seas.

5. Reef-building assemblages and shelf-slopes

According to topographical gradients, water dynamics and building-reef patterns (He et al., 1987; Chen et al., 2004), marine shelf-slopes are commonly divided into three basic types. Three slope-types and their features include: the mud mound slope with quiet waters, the reef mound gentle slope with weakly to moderately dynamic waters, and the framework reef steep slope with highly dynamic waters. Based on the sedimentary facies, organic paleo-ecologies and reef patterns, two shelf slopes have been interpreted for Member 4 and Member 5 of the Linxi Formation (Figure 8). Their features conform to the reef mound gentle slope and the framework reef steep slope.

5.1 Gentle shelf slope of Member 4

This shelf slope of Member 4 was even and gently inclined to the basin (the sea-trough), probably by less than 15°. Water-flows on the shelf slope might have been lower to moderate energies, including primarily coastal flows and currents. This gentle shelf slope developed many muddy to sandy substrates especially suitable for growing various reef mounds. The algal fossil abundances suggest the water depth was not more than a few tens of meters (the strong-light zone).

Three fossil assemblages have been distinguished on the gentle shelf slope. They reflect variations of reef building factors, i.e. adaptation to increasing dynamic energies associated with increasingly shallower waters. The *Thamniscus-Polypora* assemblage primarily contained fine-branched bryozoan fossils *Thamniscus*, *Polypora* and *Fistulipora*. These slender bryozoans scattered in lower parts of the gentle shelf slope. The *Rhombocladia-Amblysiphonella* assem-

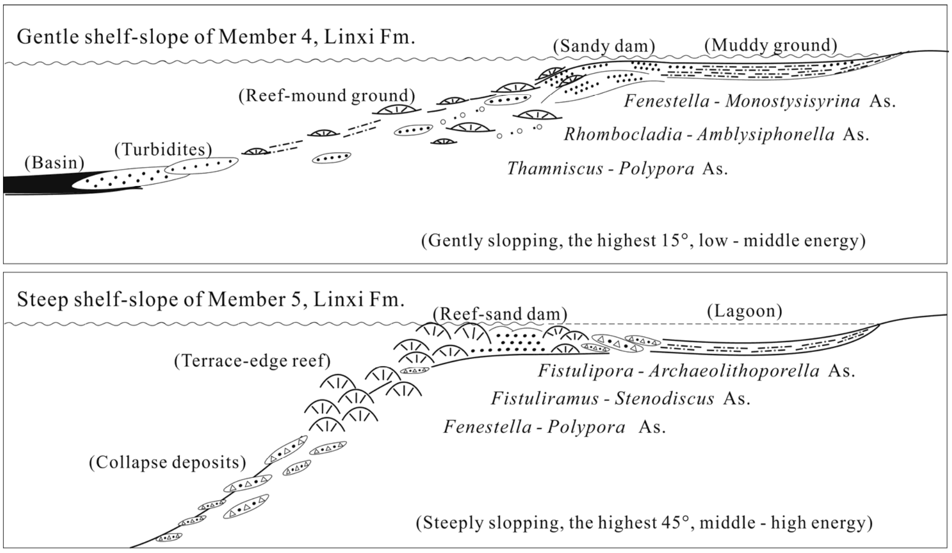

Figure 8 Shelf-slope features of Member 4 and Member 5 of the Linxi Formation in Guandi of Linxi County.

blage consisted of various fossils, including the sponge *Peronidella*, bryozoan *Thamniscus,* and stromatolite *Baicalia*; this assemblage occupied most of the gentle shelf slope. Finally, the *Fenestella-Monostysisyrina* assemblage included diverse fossils, mainly the bryozoan *Fenestella*, and algae *Monostysisyrina,* and *Anthracoporella*, and thrived in the shallows of gentle shelf slope, where the water was commonly agitated by wind and waves.

5.2 Steep shelf-slope of Member 5

The steep shelf slope of Member 5 was characterized by growth of large plateau-edge reefs and block reefs. The steepest part of the shelf slope was probably about 45°. Stronger currents, wind, and waves regularly disturbed the water there. Specially owning to the base rising, more terrigenous materials were input here from adjacent areas. The very large framework reefs divided the shelf slope into microenvironments including the reef-core, the front-reef, the side-reef, and the back-reef.

Three fossil assemblages have been distinguished on the steep shelf slope of Member 5. The *Fenestella-Polypora* assemblage contained many slender fossils, and spread in some conditions with weakly to moderately dynamic waters, i.e., the front-reef and the back-reef. The *Fistuliramus-Stenodiscus* assemblage included thicker-walled fossils that thrived in the side-reef and the reef-core, where waters might be stirred commonly by high-energy flows. The *Fistulipora-Archaeolithoporella* assemblage was composed of the tube-form bryozoan *Fistulipora*, overgrown and connected by the alga *Archaeolithoporella*, which together occupied areas near the top of the reef-core, where they were exposed and eroded by high-energy water-flows and waves; reef rocks with this assemblage appear red-brown in outcrop.

6. Tectonic significance of these organic reefs

Organic reefs in different patterns can indicate environments (Gong et al., 2013), and can also be used to study tectonic evolution of various geographies (Fan, 1996). Plateau-edge reefs and block reefs can signal steep shelf slopes, higher fault ledges and extensive or high-offset faults. Reef mounds and isolated reefs mark gentle shelf slopes and epeiric sea-basins. Ring reefs and pinnacle reefs outline the edges of islands and sea-terrains. The many plateau-edge reefs and reef mounds that developed in the Linxi and adjacent areas demarcated marginal shelf slopes of the Sino-Korea Platform at the end of Late Permian (Figure 9).

Plateau-edge reefs of the Linxi Formation are exposed at many places, including the Beidashan, Guandi, Xingfuzhilu, and Taohaiyingzi reefs. Reef-building organisms primarily included bryozoans, sponges and calcareous algae, which crowded together to construct reef frameworks. Sometimes, the bryozoans, in particular, might be overgrown and consolidated by the algae *Archaeolithoporella*, which allowed for greater resistance to stronger water flows, wind, and waves. Plateau-edge reefs are distinctly large, e.g., 148 m thick at the Beidashan outcrop and 275 m thick at the Guandi location detailed here, with these thicknesses extending horizontally over some kilometers.

Reef mounds of the Linxi Formation are small and circular, with typical diameters of 20–60 cm, though some are meters large. Framework-building organisms of the reef mounds primarily include bryozoans, sponges, and calculate algae, which crowded together to build relatively flat or clump-shaped reef frames.

Late Permian reefs of Linxi and adjacent areas have two differences, compared with those reefs of South China. First, reef frames of the Linxi Formation are preserved in

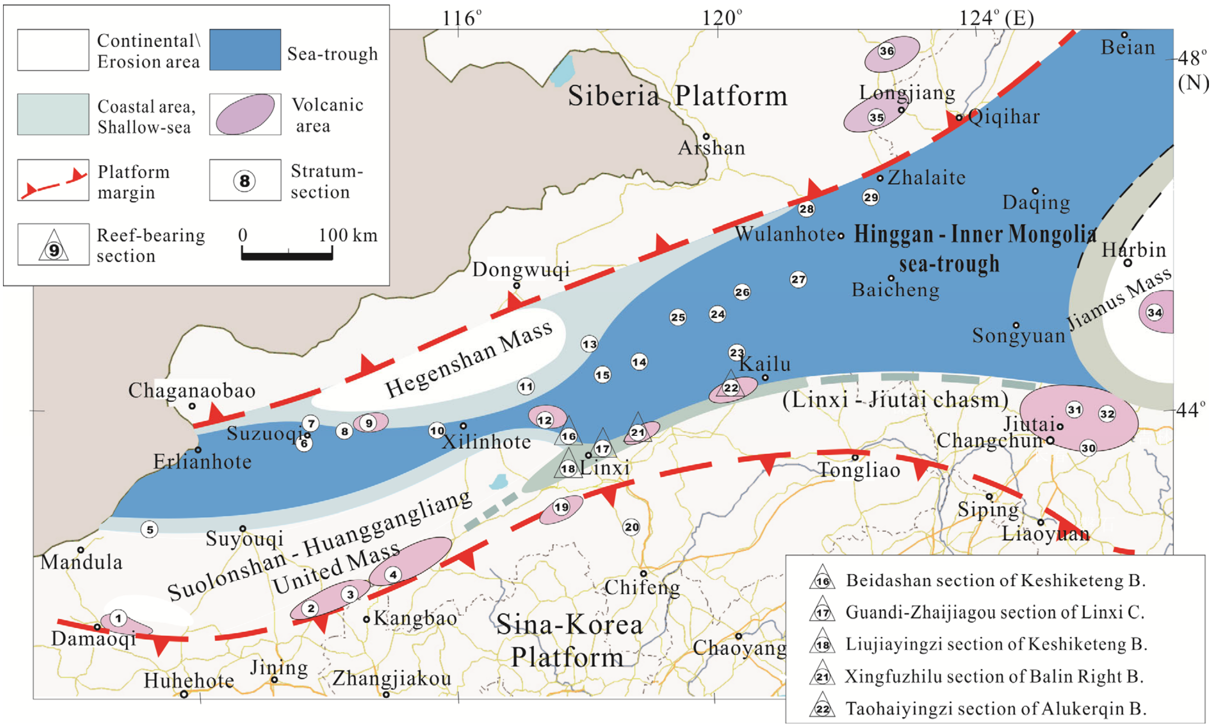

Figure 9 A sketch showing tecto-geographic patterns and strato-sectional seats at the end of Late Permian, eastern Inner Mongolia.

calcareous siltstone or silty limestone, because of greater availability of terrigenous materials at the north margin of the Sino-Korea Platform. But Late Permian reefs of South China are hosted generally in pure limestone, because of the paleo-geographic location in an epeiric sea.

Second, reef-building organisms of the Linxi Formation were comprised mainly bryozoans, and only some reef mounds were built by sponges. Bryozoan reefs represent cold waters and climates. The South China Permian reefs were mainly constructed by sponges, with a few reefs constructed by corals; organisms of South China lived in warm waters and climates.

Bryozoan reefs of the Linxi and adjacent areas verify that these areas had cold water-bodies and belonged to the Angara Region in the Late Permian. Because they contain a few sponge reef mounds, these areas possess some transitional features between two bio-geographical regions (Huang, 1993).

Finally, the linear extensions of the plateau-edge reefs represent the northern margin of the North China Platform and the Linxi-Jiutai chasm in the Late Permian. The chasm initiated in early Late Permian, splitting off between the China-Korea Platform and the Siberia Platform and stretching as a zone along Zhengxiangbai Banner-Linxi County-Alukerqin Banner-Jiutai County. In later Late Permian, the chasm began to slowly close and uplift, forming gentle shelf slopes with abundant reef mounds of Member 4 of the Linxi Formation. After deposition of Member 4, the chasm closed and uplifted quickly till the end of Late Permian, with compression led by the China-Korea Platform, where there appeared steep shelf slopes with large plateau-edge reefs and block reefs, marked by deposition of Member 5 of the Linxi Formation. These reefs mark the final closure of the chasm.

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