Lower Silurian stromatolites in shallow-marine environments of the South China Block (Guizhou Province, China) and their palaeoenvironmental significance

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Abstract

In northern Guizhou Province (Upper Yangtze Platform, South China Block) two types of reef communities developed in the Lower Silurian (upper Aeronian, Llandovery) Shihniulan Formation; they are calcimicrobial- and metazoan-dominated structures, and existed because of northward deepening of the shallow-marine ramp setting in which they grew. Stromatolitic communities are the focus of the present study and dominated the shallowest reef structures, while metazoan-dominated reefs, previously described in other papers, grew in the outer shelf portion of the ramp.

Stromatolitic reefs occur in several sections (Daijiagou, Baishanxi, Jianba and Lianghekou), palaeogeographically close to Qianzhong Land. Within the stromatolite units, laminar sheets of microbial mats and columns are pronounced, with individual stromatolite thicknesses generally less than one meter. Some very small stromatolites are only centimeters in diameter and thickness. Stromatolitic units are cyanobacterial bindstones mostly associated with shales, siltstones and thin-bedded bioclastic limestones. Their growth was frequently punctuated by siliciclastic sediments, and their shallow-water nature is demonstrated by association with birds-eye structures, cross-stratified sediments, and *Lingulella*-bearing silts in intertidal or/and lagoonal environments. The stromatolites formed during a regression and erosion surfaces are common at the top of the Shihniulan Formation. The Tongzi Uplift, a short-duration expansion of Qianzhong Land, ended the deposition of the late Aeronian limestones.

Keywords: stromatolite, shallow marine, Shihniulan Formation, Lower Silurian, north Guizhou, South China Block

1. Introduction

Following the Hirnantian Stage (latest Ordovician) icehouse climate and global eustatic sea level fall events (Brenchley, 1984), gradual recovery and reorganization of epibenthic shelly communities led to the first appearance of coral-stromatoporoid patch reefs in the Rhuddanian Hilliste Formation of the Baltic Basin (Nestor, 1997). The Aeronian Epoch (Middle Llandovery, Silurian) was a time of global recovery of reef-building communities (e.g. Li and Kershaw, 2003; Copper and Jin, 2012), most likely due to the warmth of marine waters at that time (Li et al., 2008). An 80 million-year period of greenhouse conditions began in the Llandovery Epoch (Early Silurian) and lasted until the latest Devonian, thus was optimum for stable development of reefs (Copper, 1988, 2002). The principal Silurian hermatypic fauna includes tabulate and rugose corals, stromatoporoids and bryozoans with microbial structures acting as binders in most cases (e.g. Scrutton, 1988; Copper and Brunton, 1991; Brunton and Copper, 1994; Brunton et al., 1998; Copper, 2002; Nose, 2006). Nevertheless, typical Silurian stromatolites formed of purely cyanobacterial bindstones are not common; they are quite limited in time and space and less documented (Brett, 1991; Cao, 1996; Soja and Antoshkina, 1997).

Silurian limestones and reefs in the South China Block occur in only the Llandovery sequences temporally and geographically in what is termed the Upper Yangtze Platform (western part of the South China Block; e.g. Zhang et al., 1994; Wan et al., 1997). Late Aeronian reef types in north Guizhou are mainly metazoan framework-dominated structures in an outer-shelf setting (Wang et al., 2014). Coeval stromatolitic units at the Daijiagou section, Tongzi County, were first recognized by the senior author of this paper in the winter of 2005, and also previously recorded in lithological logging by Zhan and Jin (2007). That unit and three more stromatolite-bearing sections are investigated here and altogether the stromatolites occupy a narrow belt spatially. Accordingly, this paper aims to place these unusual stromatolitic units in perspective of Silurian reef studies. We describe the morphological and lithological features of the stromatolites and discuss their depositional setting during a regressional process. This study therefore provides better understanding of the palaeogeographical implications of these Silurian stromatolites following the end-Ordovician biotic crisis.

Facies described in this paper were studied by field observations and logging, followed by hand specimen and thin section study to characterize the material. Comparisons with literature facilitated the discussion.

2. Geological setting

Coeval to the reef-bearing units in Anticosti, Laurentia and Baltica, those in the South China Block were also situated within the low latitudes of the southern hemisphere in Early Silurian time (Scotese et al., 1985; McKerrow and Scotese, 1990; Golonka, 2002). Northern Guizhou lay in the southwestern part of the Yangtze Platform in an epicontinental sea during Silurian time. Qianzhong Land, in the southern part of the study area, played a primary role in configuration of biofacies and lithofacies differentiations of the area (e.g. Rong et al., 2003), leading to interpretations of water depth. The near-shoal belt close to Qianzhong Land in northeastern Guizhou was a shallow, well-oxygenated environment in Rhuddanian time (earliest Silurian). Carbonate facies with shelly benthic communities were gradually reconstructed after the reef-building gap of the Hirnantian Stage cold interval (Ni et al., 2015). The first reefs to appear after the extinction are small-scale coral-stromatoporoid patch reefs in the middle Aeronian upper Xiangshuyuan

Formation in Shiqian area, northeastern Guizhou Province (Li and Kershaw, 2003). Coeval graptolitic black shales of anoxic marine-floor had a much wider distribution regionally including north Guizhou, so reefs were able to form in only limited areas. Updated litho- and biostratigraphic correlation schemes suggest that Llandovery sequences in north Guizhou are comprised of shales and siltstones of the Lungmachi Formation (mainly of Rhuddanian-Middle Aeronian), limestone-dominated Shihniulan Formation (late Aeronian) and siltstones-sandstones of the Hanchiatien Formation (lower Telychian) in ascending order. They were all deposited in a ramp setting deepening seaward to the north (e.g. Chen et al., 2001; Zhan and Jin, 2007). Terrigenous-dominated depositional units of the Lungmachi Formation ended in late Aeronian time. Sequences from Lungmachi to Shihniulan Formations are essentially regressive. Shallow-marine carbonate facies of the late Aeronian expanded on the upper Yangtze Platform. The upper Aeronian Shihniulan Formation is ~100 m thick and is subdivided in ascending order into nodular limestone intercalated with shales and siltstones of the Songkan Member, and bioclastic and intraclastic bank- and reef-dominated facies of the Shihniulan Member (Rong et al., 2003).

Non-reef lithofacies as well as Llandovery reefs on the Yangtze Platform are evidence that tectonic uplift and clarity of marine water (low turbidity) were key factors controlling reef distribution. Ideal conditions in the late Aeronian Epoch promoted thriving benthic biotas and the formation of diverse bank and reefal units (Li and Kershaw, 2003; Li and Rong, 2007). The short-duration Tongzi Uplift caused northward (regressive) migration of the coastline for tens kilometers and terminated carbonate deposition in latest Aeronian time. Sedimentary features such as palaeokarst surfaces, desiccation mudcracks and birds-eye structures at the top of the Shihniulan Formation indicate subaerial exposure especially in those near-shoal belt sections of the Qianzhong Land (Rong et al., 2012; Deng et al., 2012). A transgressional tract of the early Telychian Hanchiatien Formation in northern Guizhou is mainly composed of terrigenous debris. Silurian marine facies above the Llandovery are quite rare in the South China Block due to large-scale tectonic uplift in the Yangtze region (Chen et al., 1996; Rong et al., 2003).

Typical metazoan patch reefs in the Shihniulan Member in the Shuibatang section of Tongzi County, north Guizhou, which was situated in an outer-shelf belt of the Yangtze epicontinental sea, were described in preliminary work by Wang et al. (2014). Equivalent stromatolitic units have limited spatial distributions in north Guizhou and are confined to the Lianghekou area of Xishui County, the Daijiagou and Baishanxi areas of Tongzi County, and the Jianba area of Suiyang County. Palaeogeographically these sections lay along the near-shoal belt near Qianzhong Land (Fig. 1).

3. Nature of stromatolites

Stromatolites within the Shihniulan Member occur in four sections where the stromatolite-bearing units terminated at erosion surfaces in all sites due to subaerial exposure during the Tongzi Uplift (Fig. 2). The overlying strata belong to the Hanchiatien Formation. Biotic and sedimentary features of the stromatolites, from west to east, are described next.

3.1. Lianghekou section

The stromatolite-bearing unit in the upper Shihniulan Member crops out in a vertical cliff section at Lianghekou section (GPS 28°7'52.56"N, 106°12'24.60"E). Here, the Shihniulan Formation sequences below the stromatolites are covered by a road (Fig. 3A). Column- and mat-shaped stromatolitic units herein are rather thin, only several centimeters thick individually (Fig. 3B). Below and above the stromatolites are dark grey calcareous siltstones and shales. Microfacies of the stromatolites show that dark laminations dominated their structure (Fig. 3C). Some very small stromatolites are only centimeters in width (Fig. 3D). Light-grey micritic limestones capping the stromatolites contain birds-eye structures and in some cases also show stromatolitic texture. Macrofossils are also very rare in these micritic limestone layers (Fig. 3E). A palaeokarst surface of the Tongzi Uplift occurs at the top of the Shihniulan Formation (Fig. 3F).

3.2. Daijiagou section

Daijiagou section (GPS 28°4'57.04"N, 106°47'0.80"E) is one of the best-known sites that record complete successions through the Upper Ordovician to Llandovery sequences in the northern Guizhou areas. Stromatolitic units preliminary reported by Zhan and Jin (2007) are mainly preserved in Beds 25-26 of the logged section as described below:

Bed 26 (5.7 m thick) comprises dark grey, medium- to thick-bedded argillaceous and bioclastic limestones with some stromatolites occurring in the middle part. Associated bioclastic material is composed of mainly brachiopod fragments, in samples AFN113-115, but no complete fossils have been found.

Bed 25, 13.8 m thick, is dominated by dark grey, thin-bedded argillaceous limestone with a few intercalations of calcareous mudstone, siltstone, and coral shell layers. Of 157 AFN106-112 sampled here, Sample AFN107 is a coral shell bed, and AFN109 stromatolite unit.

Of the two major stromatolitic horizons in Beds 25 and 26, the stromatolitic unit of Bed 25 is about 2 m thick, and formed as an accumulation of low-relief mats (Fig. 4A) with horizontal to curving stromatolitic laminae (Fig. 5A). The stromatolite morphology, overall, is similar to that in the Late Archean Campbellrand-Malmani platform of South Africa (Riding, 2011). Bed 26 stromatolites vary from maximum of 1.5 m to about 0.5 m in thickness. They typically formed column-shapes and cabbage-like morphologies (Fig. 4B-C). Microfacies of laminations show great similarity to that of algal-mats from Bed 25 except obvious dome-like structures (Fig. 5B).

Some small stromatolitic units with thicknesses about 10 cm are uncommonly found in greyish black shales and siltstones between these two major stromatolitic units in Bed 25-26. Macrofossils are rare, and represented by few *Eospirifer* and *Linguella* (Fig. 4D).

Siltstones and shales intercalated with some limestone with little macrofossil content occur above the stromatolite of Bed 26, in which thin-bedded limestone contains cross bedding (Fig. 4, E). A palaeokarst surface is pronounced at the top of the thin-bedded limestone, indicating an unconformable boundary between the Shihniulan Formation and the overlying lower Telychian Hanchiatien Formation (Fig. 4F).

3.3. Baishanxi section

Two stromatolitic units intercalated with thin-bedded bioclastic limestone occur in the Baishanxi section (GPS: 28°8'4.97"N, 106°56'2.11"E) (Fig. 6A). Therein columnar stromatolites are pronounced, and they are 0.5 m and 0.7 m thick in the lower and upper units, respectively (Fig. 6B-C). Most columns are 5-8 cm in diameter. Individual thicknesses of the laminae are somewhat variable in both lower (Fig. 6D) and upper (Fig. 6E) stromatolitic units, in which they are largely light-coloured horizontal laminae.

3.4. Jianba section

The stromatolitic unit about 1-1.5 m below the top of the Shihniulan Member is about 0.7 m in thickness at this section (GPS 28°4'20.90"N, 106°2'42.64"E). The base and top layers of the stromatolitic unit are thin-bedded yellow calcareous siltstones containing uncommon fine-grained bioclastic components (Fig. 7A). Stromatolites are column-shaped with individual columns being 3-10 cm in diameter and with the widest column being 25 cm in diameter (Fig. 7B). Dark laminae are most common and regularly intercalated with bright laminae. Some horizontal laminae are not very clear due to dolomitization. Fine-grained dolomite is commonly present.

4. Discussion

4.1. General setting

Most stromatolites described in this paper are underlain or overlain by dark siltstones and/or shales. Thus sporadic turbidity and possible anoxic lagoonal conditions are interpreted to have punctuated growth of the microbial communities and constrained development of the stromatolites. The low diversity and abundance of brachiopod fauna of *Lingulella* and *Eospirifer* at the Daijiagou section are possibly indicators of BA1, a benthic association in the very shallow belt close to the land (based on the well-known benthic assemblage depth scheme described by Ziegler, 1965; Boucot and Johnson, 1973; and Johnson et al., 1985). Cross-stratification in the Daijiagou sequence also suggests an intertidal to shallow subtidal setting. Micritic limestones with birds-eye structures above the stromatolites in the Lianghekou section are similar to the descriptions and environmental interpretations by Ham (1952) and Flügel (2004); they are indicators of very shallow lime-mud flats occasionally exposed above sea level. Therefore, the palaeonvironment is interpreted as lagoonal to intertidal close to the coastline of the Qianzhong Land and was unfavorable for diverse metazoan fauna but advantageous for opportunistic taxa of cyanobacteria.

4.2. Controls on formation of stromatolites

Coral-stromatoporoid reef communities of the Yangtze Platform, South China

Block, originated in the Late Ordovician Period; they were strongly affected by the cooling Hirnantian Stage regression (e.g. Li et al., 2004). Metazoan reef recovery started in the near-shoal belt of Qianzhong Land in the middle Aeronian Xiangshuyuan Formation, and can be recognized in the Xiangshuyuan and Baisha sections, Shiqian, northeastern Guizhou. Carbonate platforms and the metazoan-dominated biota expanded stepwise towards outer-shelf positions in the late Aeronian Epoch (Li and Kershaw, 2003); the Shihniulan Formation succession indicates a full recovery of colonial rugose and tabulate corals, stromatoporoids and high diversity reef-attached biota. Wang et al. (2014) suggested that these changes represent a global evolutionary step in the aftermath of the latest Ordovician mass extinction event, further indicated by coeval global analogues comprising similar biotic structures in Anticosti (Copper and Jin, 2012) and in Kazakhstan (Berg et al., 1980; Zadoroshnaya and Nikitin, 1990). About eight major units of carbonate platforms with a total of 30 patch reefs of the late Telychian Ningqiang Formation demonstrate the peak stage of Silurian reefs in the northwest margin of the Yangtze Platform (Li et al., 2002). Therefore, the late Aeronian Epoch is a time of evolutionary significance for full recovery of reefs. Wide resurgence of post-extinction microbial buildups of the earliest Silurian in Nevada and Utah (Sheehan and Harris, 2000, 2004) and the Early Triassic (Schubert and Bottjer, 1992; Yang et al., 2011; Kershaw et al., 2007, 2012; Chen et al., 2014; Luo et al., 2016) have been interpreted as anachronistic facies, indicating the harsh environments following major biotic crises (Sepkoski et al., 1991; Schubert and Bottjer, 1992; Chen and Benton, 2012). However, late Aeronian stromatolitic units documented here were not evolutionary analogues of a disaster episode. Instead, they are clearly placed as communities in near-shoal positions co-existing with thriving reefal metazoans that were present in the outer shelf.

Biotic structure and size of reefs are governed by multiple oceanographic parameters (Copper, 1994a, b) resulting in low biodiversities and simple fabrics in some Silurian reefs (Watkins, 1979). Silurian stromatolites occurred more frequently in restricted environments, especially in deep water habitats or hypersaline zones in which the predating pressure was not as high as that in a typical open reef-setting (Brett, 1991; Copper and Brunton, 1991). Although the Shihniulan stromatolites grew in shallow niches, they inhabited similar environmental settings to Silurian stromatolites of other areas mentioned above. When compared with the worldwide spread of metazoan-dominated reefs during the Silurian, cyanobacterial buildups including stromatolites are limited and occurred locally during that time (Textoris and Carozzi, 1966; Cherns, 1982; Soja and Riding, 1993; Soja, 1994; Soja et al., 2000). Soja and Antoshkina (1997) inferred ecological similarity and palaeogeographical significance of Upper Silurian subtidal stromatolites in Alaska and the Ural Mountains, built by an unusual consortium of microbial taxa in association with distinctive sphinctozoan sponges. Microbialites and algal framework fabrics are also present in the Middle-Late Silurian stromatoporoid-tabulate coral reefs in Baltic Gotland (Nose et al., 2006). In addition to the aspects of biotic evolution, reefs are also constrained by water depth and turbidity (Li and Kershaw, 2003). The

Llandovery sea-level change curves reconstructed worldwide indicate a highstand level (or transgressional interval) during the late Aeronian (Leggett et al., 1981; Johnson et al., 1991; Ross and Ross, 1996; Jeppsson et al., 1997; Loydell, 1998; Haq and Schutter, 2008; Johnson, 2010). Surprisingly, the Shihniulan stromatolites described in this paper are confined to the intertidal or lagoonal belt close to Qianzhong Land during the late Aeronian Epoch. The record of the high-frequency sea-level changes in the near-shoal belt might reflect small-scale sea-level drops in morphological differentiations of algal-mats and column-shape stromatolites. The sedimentary features, especially in subaerially exposed surfaces at the top of the Shihniulan Formation from the near-shoal facies sections mentioned above, reinforce our view that the Tongzi Uplift played a key role in configuration of the distribution of land and sea regionally. Sporadic inputs of muddy and silty debris in near-shoal belts also affected the growth of the stromatolites in the northern Guizhou areas. Such a turbid environmental setting is attributed to gradual expansion of land during the Tongzi Uplift (Rong et al., 2012).

5. Conclusions

A wide carbonate ramp with northward-deepening sea was favorable for differentiation of reef communities in the upper Aeronian (Llandovery, Silurian) Shihniulan Formation in northern Guizhou. Distinctive stromatolites formed solely by cyanobacterial communities are restricted to the near-shoal belt close to Qianzhong Land; coeval metazoan reefs occupied the outer shelf. Deposition of siliciclastic sediment in this marginal marine environment constrained the size of the stromatolites. Termination of the Shihniulan Formation as well as calcimicrobial inhabitation was mainly caused by shallowing up, including subaerial exposure, due to the northern seaward migration of the coastline during the Tongzi Uplift episode. Overall, the Shihniulan stromatolites are interpreted as one of a subfacies of a reef complex together with metazoan reefs from the outer shelf.

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Figure captions

Fig. 1 Localities of four stromatolite deposits in the southern region and one metazoanal reef in the northern region sections in the Shihniulan Formation in north Guizhou. The southern region of these localities was Qianzhong Land closer to the location of stromatolite formation than the metazoan reefs. The greyish lines in the south and greyish dot line in the north are the coastlines of the beginning and end, respectively, of the Shihniulan Formation deposition (base palaeogeographic reconstruction map after Rong et al., 2012).

Fig. 2. Lithological logs of the four stromatolite-bearing sections in north Guizhou.

Fig. 3. Sedimentary features of the upper Shihniulan Member at Lianghekou section, Xijiu, Xishui. (A) a cliff showing the horizons of stromatolite of (B) and (D) and associated micritic limestone with birds-eye structures of (E). (B) stromatolitic unit in dark grey silts and shales (lens cap = 8 cm for scale). (C) microfacies of the stromatolite of B. (D) centimeter-scale stromatolite. E, micritic limestone with birds-eye structures above the stromatolitic unit. (F) erosion surface as the unconformable boundary between Shihniulan and overlying Hanchiatien formations.

Fig. 4. Successions of the Shihniulan Member, Shihniulan Formation at the Daijiagou section, Tongzi. (A) mat-like stromatolites. (B) plan-view of columnar stromatolites; the hammer is 28 cm long. (C) profile view of stromatolite columns. (D) small loaf-shape stromatolite surrounded by greyish black siltstones and shales yielding brachiopods *Lingulella* (a) and *Eospirifer* (b). (E) thin-bedded limestones with cross-bedding above the stromatolitic units. (D) palaeokarst surface at the top of the boundary between the Shihniulan and Hanchiatien formations.

Fig. 5. Microfacies of the stromatolites at the Daijiagou section. (A) calcimicrobial mat-like stromatolite from the Bed 25. (B) columnar stromatolite from Bed 26.

Fig. 6. Lithological features of the stromatolites in the Shihniulan Member at the Baishanxi section, Tongzi. (A) thin-bedded nodular bioclastic limestone between the lower and upper stromatolitic units. (B–C) both upper (B) and lower (C) stromatolitic units are columnar. (D–E) pale laminations are common in both lower (D) and upper (E) stromatolitic units.

Fig.7. Lithological features of the stromatolites of the Shihniulan Member at Jianba section, Suiyang. (A) upper part of the Shihniulan Member showing the horizon of stromatolite-bearing unit; (B) columnar and dome-shaped stromatolites, white scale=8 cm; (C–D) microfacies showing open spaces between stromatolitic laminae (C) and dolomitization of stromatolites locally (D).

Highlights:

1) Early Silurian biofacies differentiation on a carbonate ramp in the Upper Yangtze Platform were essentially controlled by depth of the sea.

2) Small-sized stromatolites formed in a regressional setting close to Qianzhong Land showing algal mat and column-shape.

3) Associated facies were typically formed in intertidal or/and lagoonal environments.

4) Tectonic uplif ended the deposition of limestones.

Figure1
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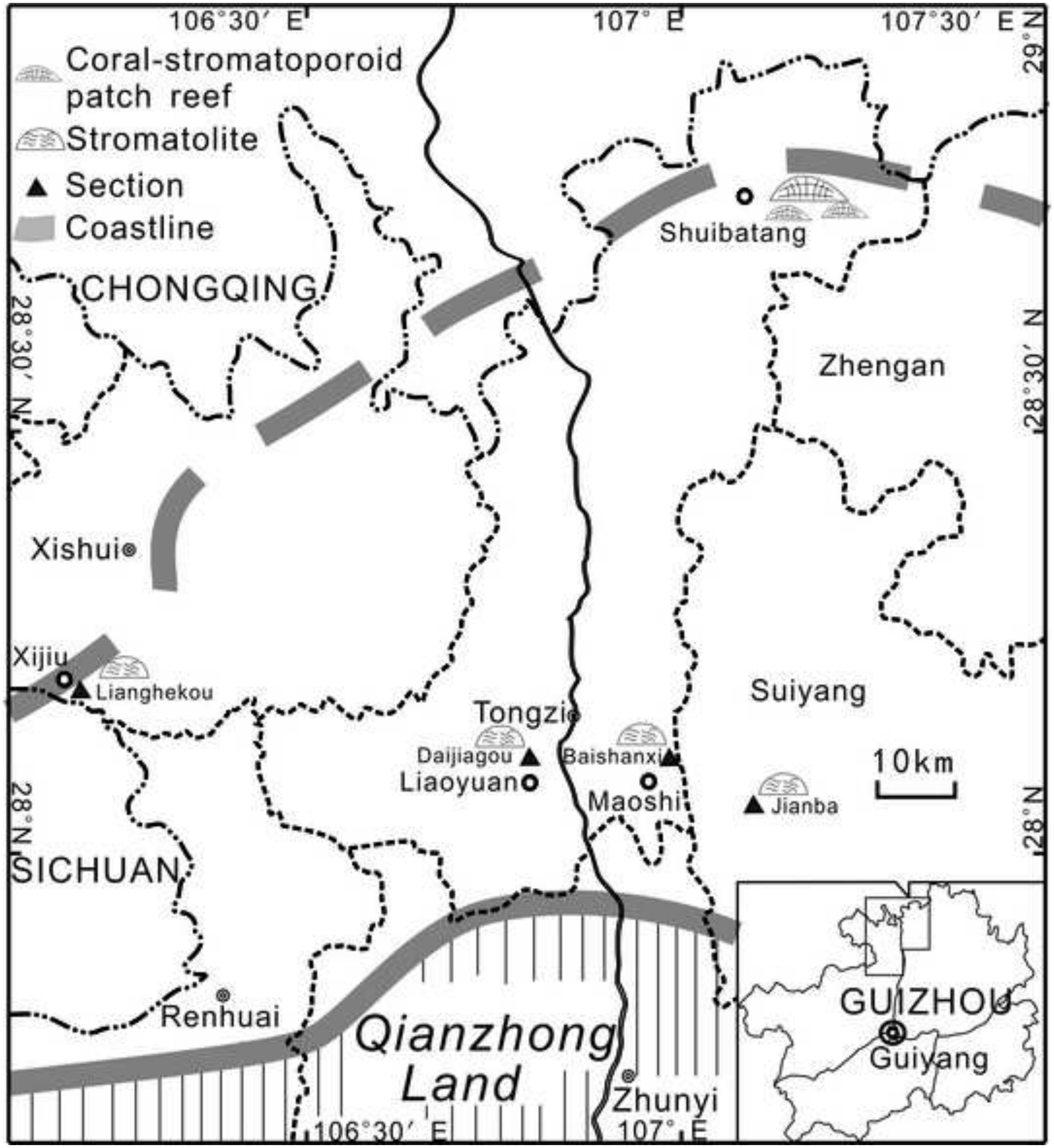

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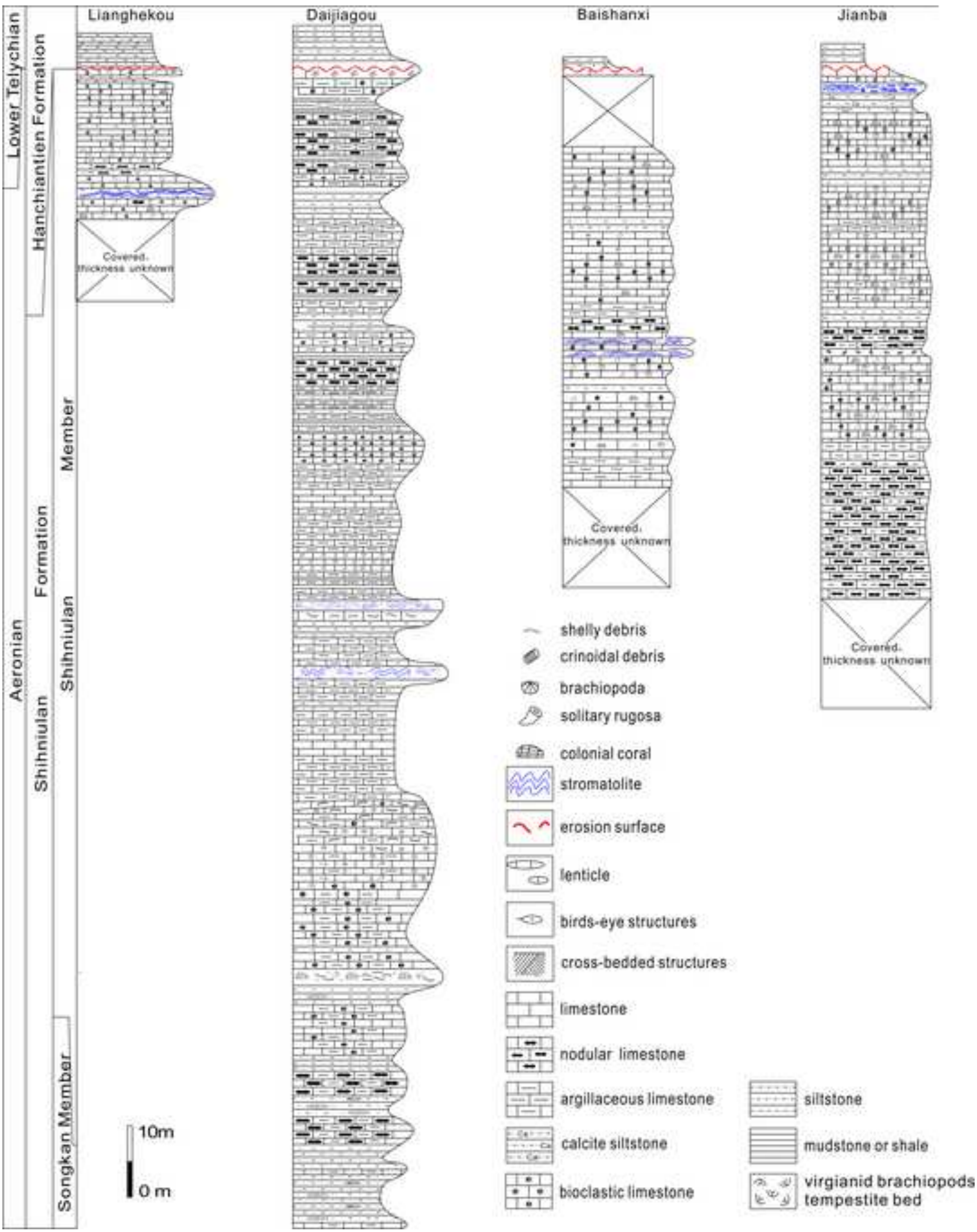

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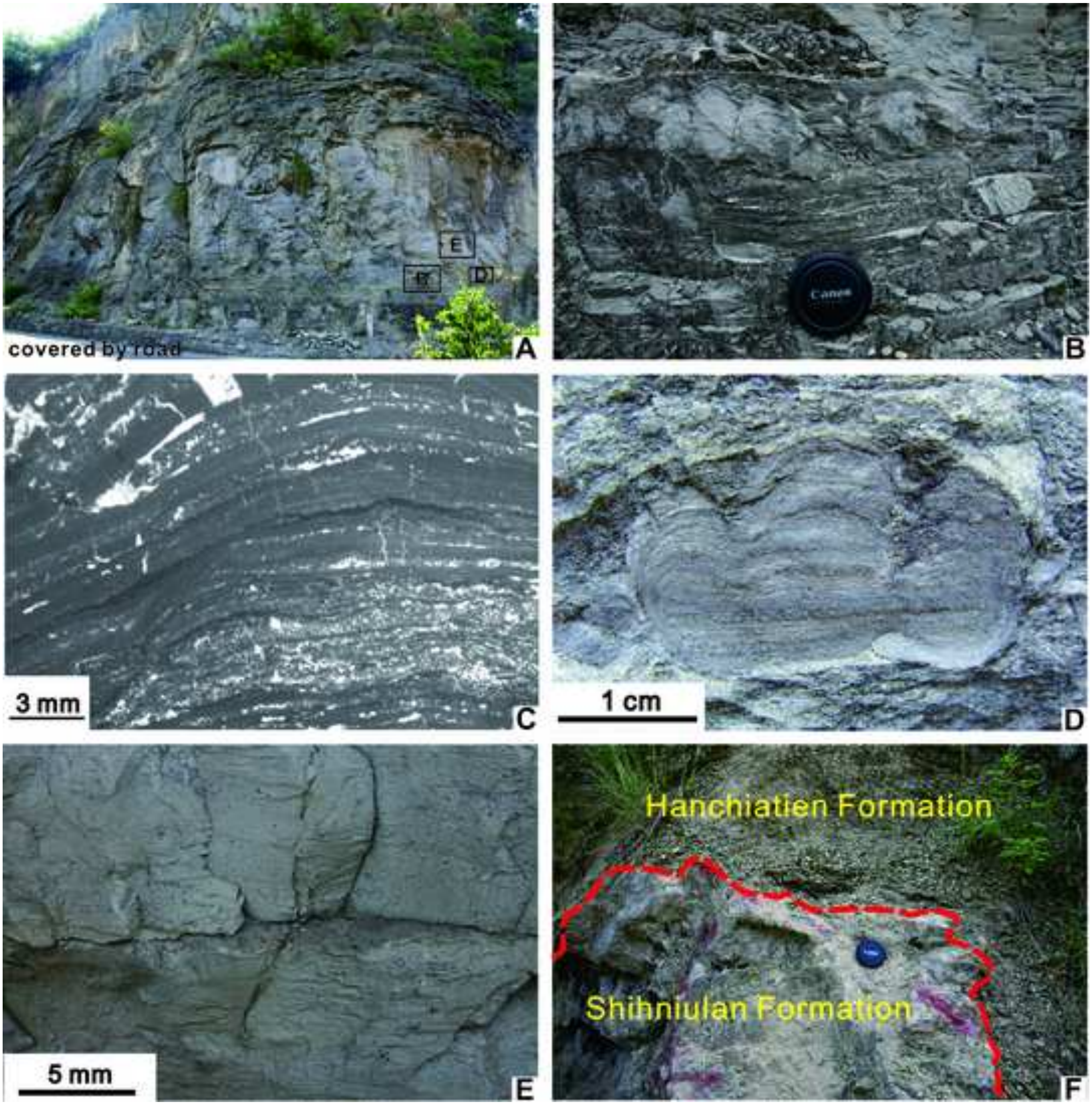

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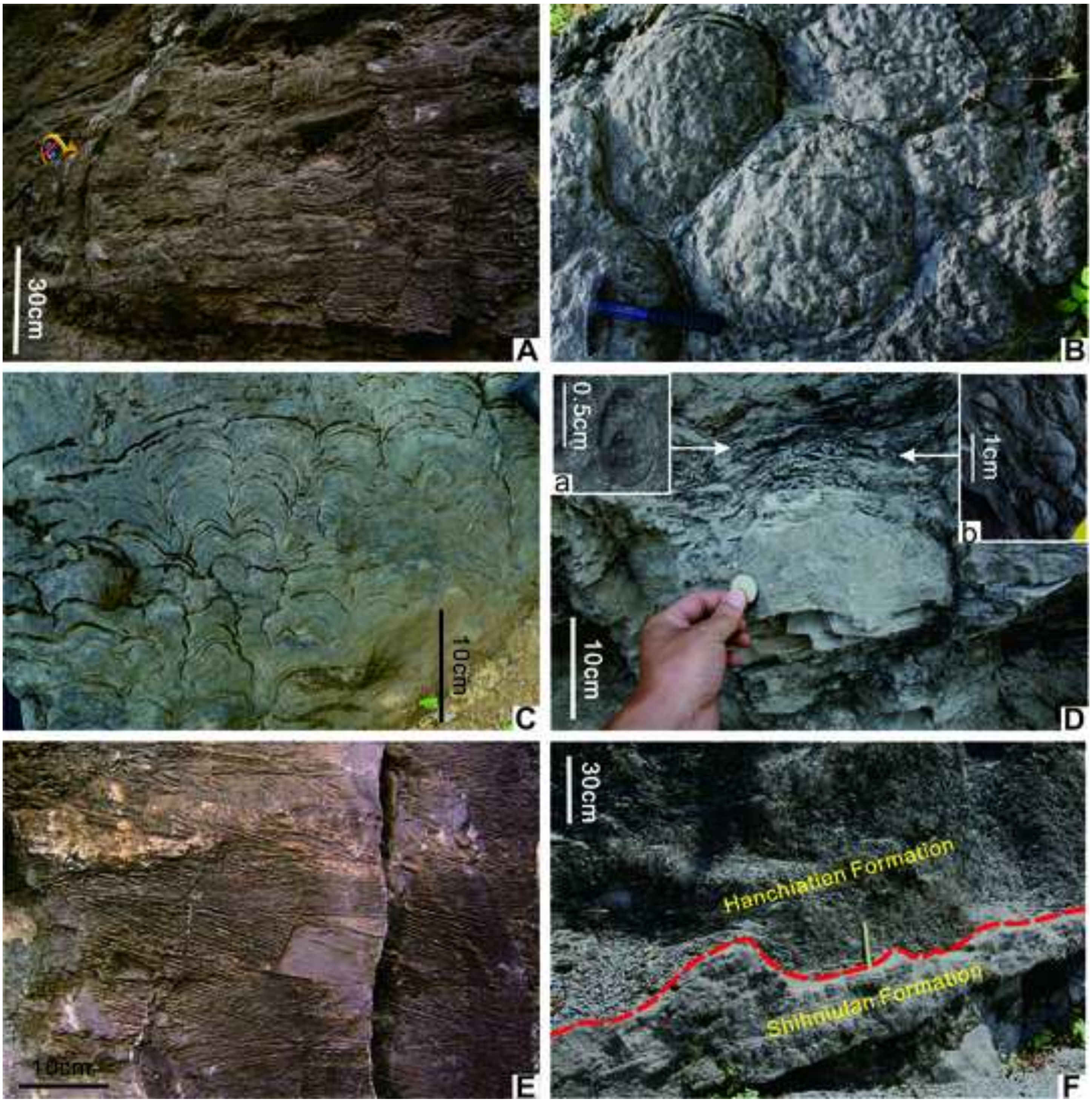

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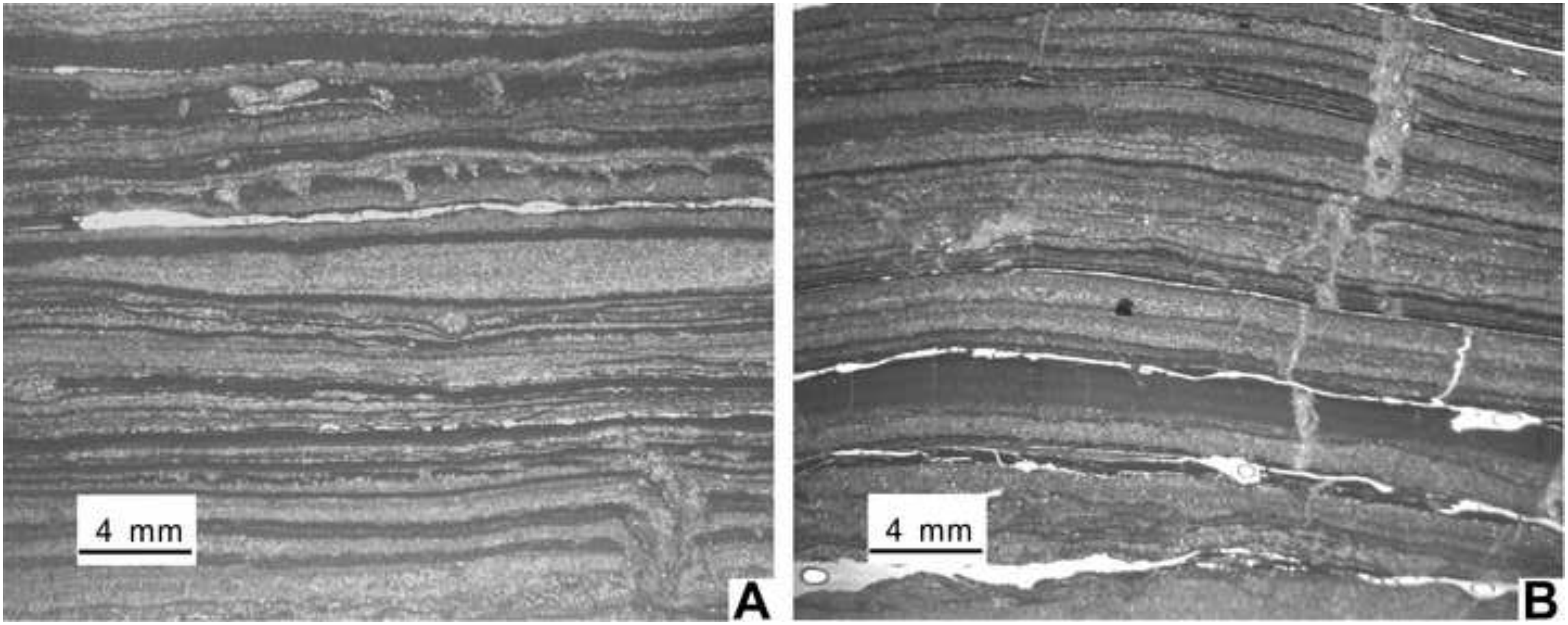

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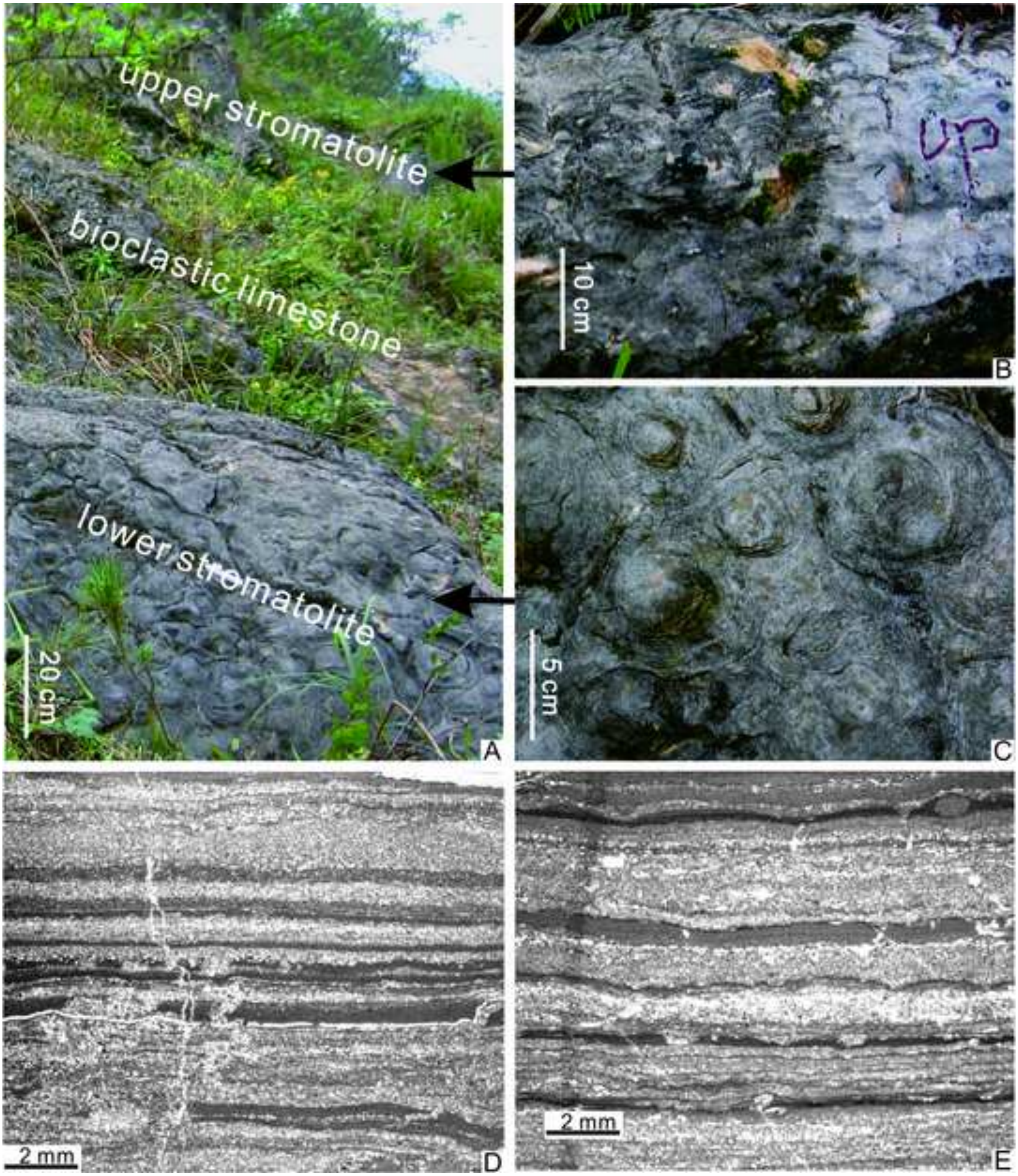

Figure7

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