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Cambrian stratigraphy of the North China Platform: revisiting principal sections in Shandong Province, China

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ABSTRACT: The Cambrian succession in the North China Platform comprises a mixed carbonate-siliciclastic sequence, superbly exposed in the southern part of Shandong Province, China. In order to refine the lithostratigraphy of the Cambrian succession, this paper presents detailed sedimentary logs of outcrop sections in the Jinan, Laiwu, Jining, and Linyi areas. The entire succession consists of six lithologic units: Liguan, Zhushadong, Mantou, Zhangxia, Gushan, and Chaomidian formations in ascending order. The upper boundary of the Zhushadong Formation is refined as the base of the first purple mudstone bed of the Mantou Formation. The Mantou Formation is, in turn, bounded at the top by a thick oolitic grainstone bed of the Zhangxia Formation. The upper boundary of the Gushan Formation is placed at the base of a distinct bioclastic grainstone bed of the Chaomidian Formation. The constituent members of the Zhushadong, Mantou, and Chaomidian formations are also refined. Seventeen trilobite biozones are recognized, representing the Cambrian Series 2 to the Furongian.

Key words: lithostratigraphy, biostratigraphy, Cambrian, Shandong Province, North China Platform

1. INTRODUCTION

The Cambrian succession in the North China Platform comprises a thick mixed carbonate-siliciclastic sequence (ca. 700 m) formed in an extensive epeiric sea (Meyerhoff et al., 1991; Meng et al., 1997). The succession is superbly exposed in the southern part of Shandong Province, China (Fig. 1), including a number of type sections of the Cambrian stratigraphy (Blackwelder and Willis, 1907; Lu and Dong, 1953). It consists of six lithostratigraphic units: Liguan, Zhushadong, Mantou, Zhangxia, Gushan, and Chaomidian formations in ascending order (Fig. 2) (Bureau of Geology and Mineral Resources of Shandong Province, hereafter BGMRSP, 1996). The succession unconformably overlies the Precambrian basement of granitic gneiss and the Sinian metasedimentary rocks and is, in turn, conformably overlain by the Ordovician carbonate succession (Sanshanzi and Majiagou formations) (Lu and Dong, 1953; China Editorial Committee of Geology and Geological Institute of China Academy of Science, hereafter CECG & GICAS, 1956). The lack of detailed lithologic descriptions and mixed usage of litho- and biostratigraphic nomenclature have, however, caused a number of problems with regard to the lithologic characteristics and lithostratigraphic boundaries. The primary purpose of this study is to provide detailed lithologic and paleontologic descriptions of the principal type sections in the southern part of Shandong Province in order to establish the litho- and biostratigraphy.

2. GEOLOGIC SETTING

The North China Platform was an extensive epeiric platform (1,500 km east-west and 1,000 km north-south), formed on the Sino-Korean Block during the Early Paleozoic (Meng et al., 1997). The platform was tectonically stable during the Cambrian. It is bounded to the north by a major suture zone, the Hinggan Fold Belt (Fig. 1a). The Dabieshan Belt demarcates the southern margin of the block against the South China Block (Fig. 1a). The Tan-Lu Fault, a major sinistral strike-slip fault, offsets the eastern part of the Sino-Korean Block (Chough et al., 2000) (Fig. 1a). Deposition in the platform was initiated in the Cambrian Series 2 with ensued rise in sea level (Meng et al., 1997). The entire plat-

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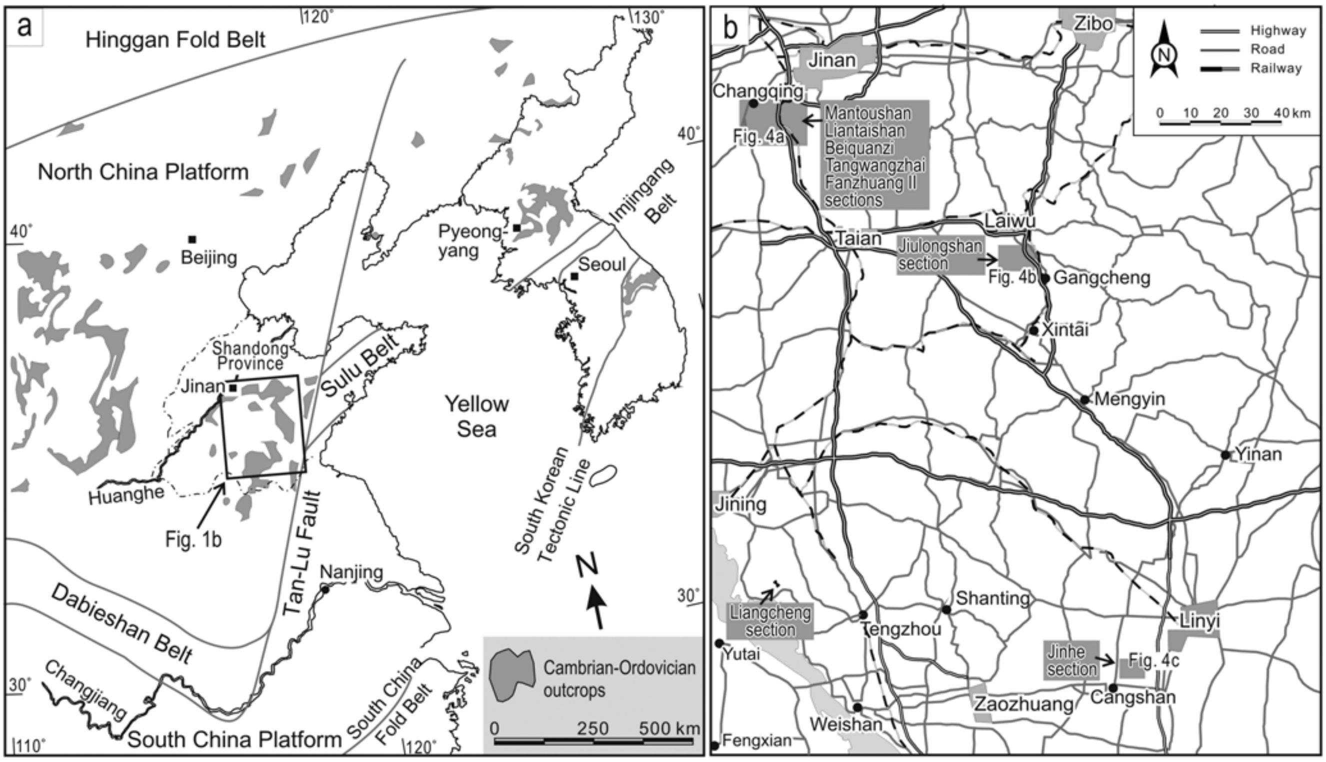

Fig. 1. (a) Major tectonic boundaries of the Sino-Korean Block and distribution of the Cambrian-Ordovician outcrops of the North China Platform. (b) Location map of the study area in Shandong Province, China.

form was submerged in the Cambrian Series 3 except for several highlands in the northwestern part, the Ordos area (Meng et al., 1997).

The lithostratigraphic units of the Cambrian succession in Shandong Province were originally designated by Blackwelder and Willis (1907) as the Manto (Mantou) Shale, Changhia (Zhangxia) Limestone, Kushan (Gushan) Shale, and Chaumitien (Chaomidian) Limestone in ascending order in the Jinan and Laiwu areas (Fig. 3). The stratigraphic scheme had been applied to the entire Cambrian succession of the North China Platform, until revised later into seven formations (Mantou, Maozhuang, Xuzhuang, Zhangxia, Gushan, Changshan, and Fengshan formations in ascending order) (Lu and Dong, 1953; CECG & GICAS, 1956; Zhang and Jell, 1987). This stratigraphic framework of the lithologic subdivision was, however, dependant on the biostratigraphic subdivision (Fig. 3). On the other hand, the Zhushadong Formation was defined at the base of the Cambrian succession in Henan Province (Feng and Zhang, 1951), and the Liguan Formation was identified in the southeastern Shandong Province (Liang, 1980). The Cambrian succession in Shandong Province was finally re-grouped into six formations: Liguan, Zhushadong, Mantou, Zhangxia, Gushan, and Chaomidian formations in ascending order (BGMRSP, 1996) (Fig. 3).

3. SECTION DESCRIPTION

Eight outcrop sections were measured in detail in the southeastern Jinan area (Mantoushan, Liantaishan, Beiquanzi, Tangwangzhai, and Fanzhuang II sections), southern Laiwu area (Jiulongshan section), southeastern Jining area (Liangcheng section), and southwestern Linyi area (Jinhe section) (Figs. 1b and 4). In the Jinan area, five closely spaced outcrop sections including type sections near Zhangxia and Gushan towns have been examined for a composite sedimentary log. The Jiulongshan section in the Laiwu area was investigated for the lithological and biostratigraphic correlation. The Jinhe section in the Linyi area was measured for the Liguan Formation. The Liangcheng section in the Jining area was measured to record lateral variations of the Zhushadong Formation.

3.1. Mantoushan Section

The Mantoushan section, located in the south of Zhangxia town in the Jinan area (Fig. 4a), is the type section for the Mantou Formation. It comprises the north and south subsections (Figs. 5a and b). The north subsection occurs along the small trail in a northward stretching ridge of the Mantou Mountain (Mantoushan). The south subsection occurs in a southern slope of the mountain. The north

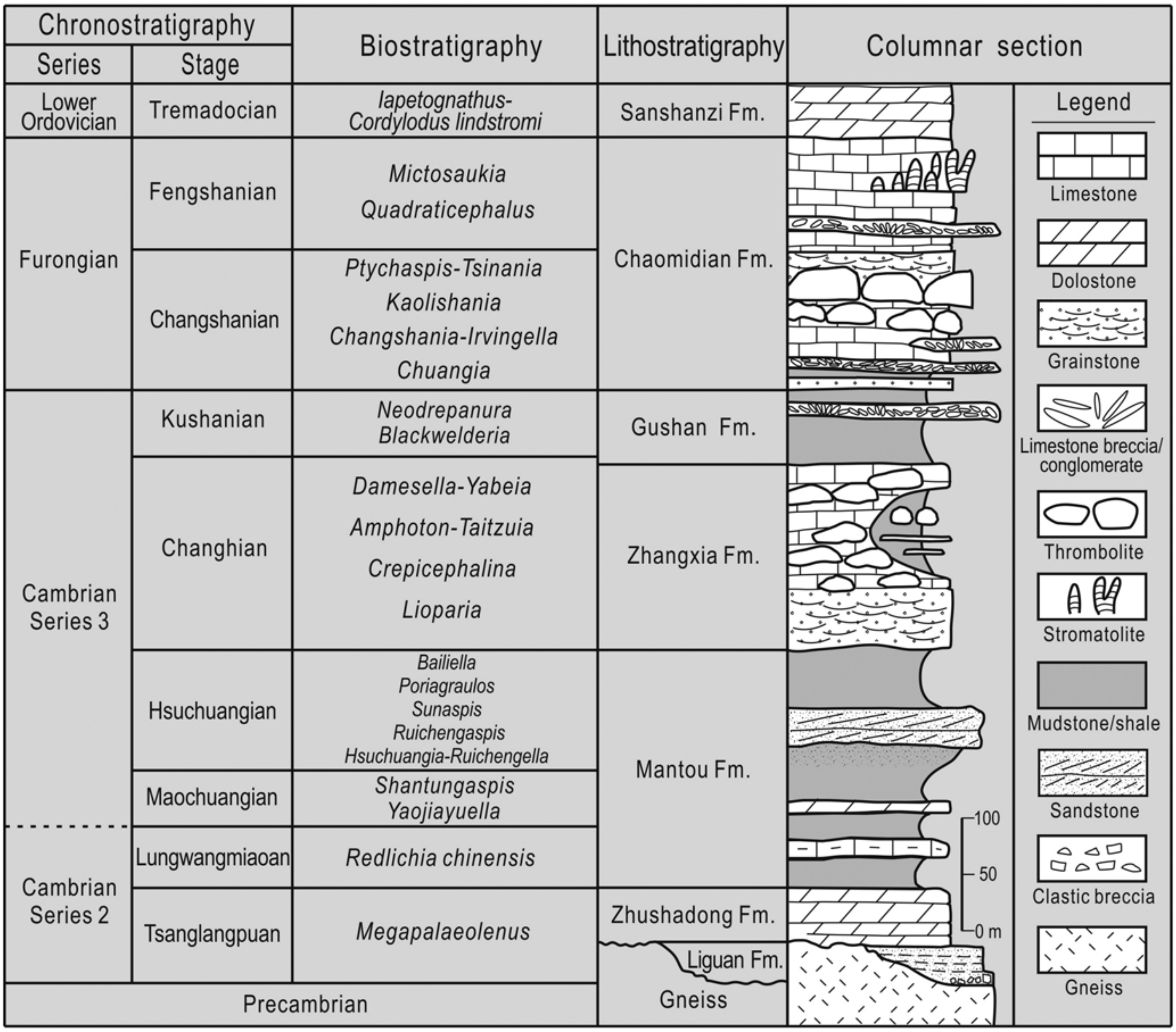

Fig. 2. Litho- and biostratigraphic summary of the Cambrian succession in Shandong Province, China (BGMRSP, 1996).

subsection consists of the Precambrian granitic gneiss, the Zhushadong Formation, and the lower part of the Mantou Formation (Fig. 5a). The Zhushadong Formation is 13 m in thickness, whereas the lower part of the Mantou Formation is 100 m in thickness. A thick purple mudstone bed at the top of the north subsection is correlated to that at the base of the south subsection where the upper part of the Mantou Formation is poorly exposed and partly covered by weathered shale (Fig. 5b).

3.2. Liantaishan Section

The upper part of the Mantou Formation is well exposed in the Liantaishan section (ca. 90 m in thickness), 5 km east of the Mantoushan section (Figs. 4a and 5c). A composite sedimentary log of the upper Mantou Formation is made in the east and west subsections. The lower part of the upper Mantou Formation is correlated to the Mantoushan section by a thick bed of purple mudstone in the middle part. The strata across the lithologic boundary between the Mantou and Zhangxia formations are well exposed in this section (Fig. 5c).

3.3. Beiquanzi Section

The Beiquanzi section, located 8 km northeast of the Mantoushan section, exposes an interval from the uppermost part of the Mantou Formation to the middle part of the Chaomidian Formation (Fig. 5d). The Zhangxia Formation in the Beiquanzi section is well exposed on the southward

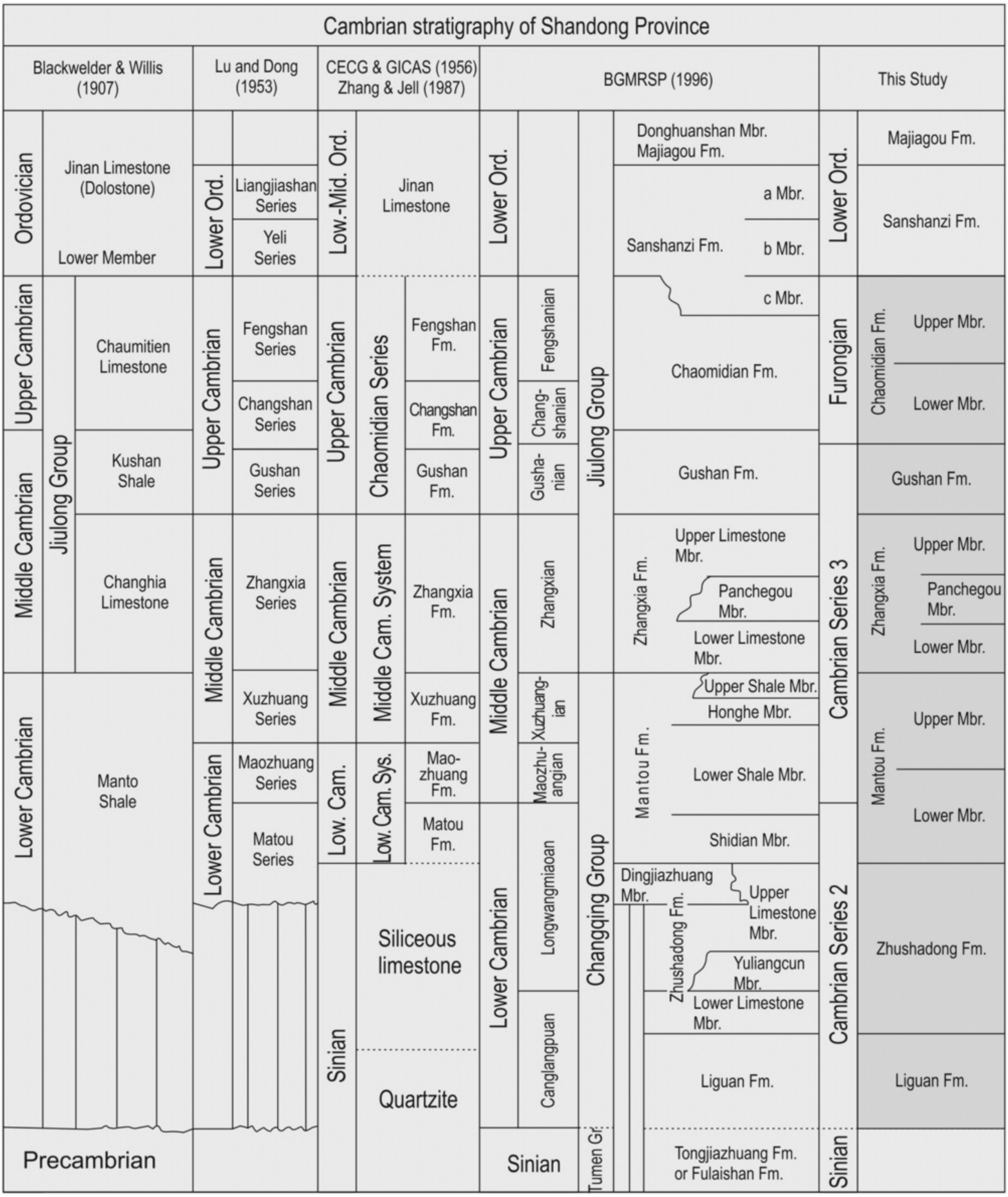

Fig. 3. Stratigraphy of the Cambrian succession in Shandong Province. Ord. = Ordovician, Low. = Lower, Mid. = Middle, Cam. = Cambrian, Sys. = System, Fm. = Formation, Gr. = Group, Mbr. = Member.

stretching ridges and valleys located in the north of the Beiquanzi village, Zhangxia town. The thick and extensive limestone of the Zhangxia Formation was measured in several subsections located on both sides of a valley running north–south. The Zhangxia Formation in the Beiquanzi section is about 180 m in thickness.

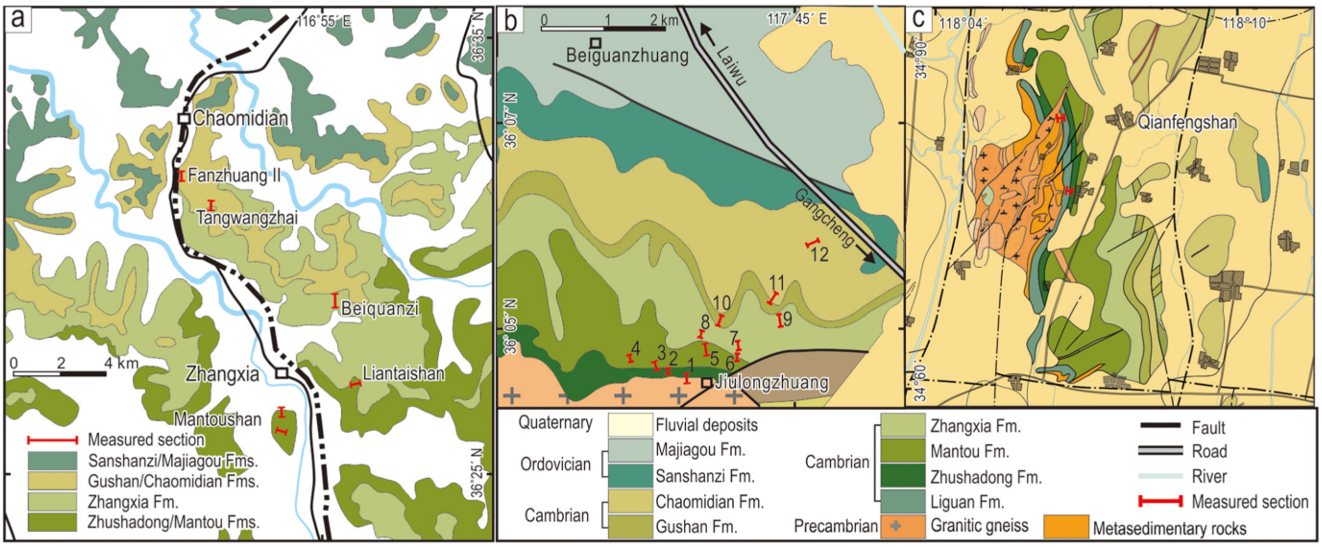

Fig. 4. (a) Geologic map of the south Jinan area (modified from Zhang and Jell, 1987). (b) Geologic map of the south Laiwu area. (c) Geologic map of the southwest Linyi area.

Fig. 5. Photographs of measured sections in the Jinan area. (a) North subsection of the Mantoushan section. (b) South subsection of the Mantoushan section.

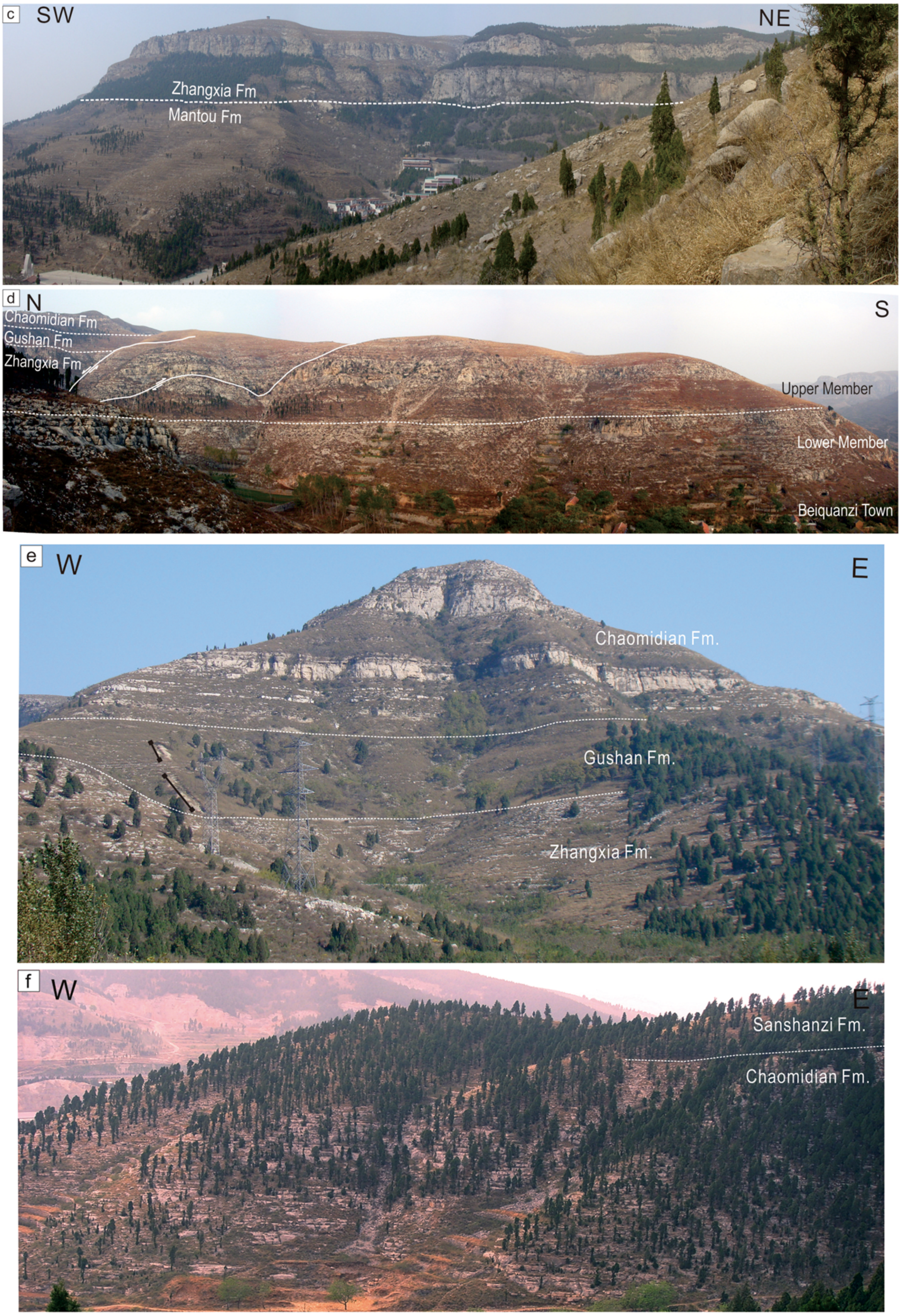

Fig. 5. (continued). (c) Liantaishan section. (d) Beiquanzi section. (e) Tangwangzhai section. Black bars indicate trenches. (f) Fanzhuang II section.

3.4. Tangwangzhai Section

The Tangwangzhai section, located 10 km northwest of the Beiquanzi section, is the type section for the Gushan and Chaomidian formations. The section comprises the upper part of the Zhangxia Formation (ca. 100 m), the Gushan Formation (ca. 52 m), and the lower two-thirds of the Chaomidian Formation (128 m) (Fig. 5e). The shale-dominated Gushan Formation was poorly exposed due to weathering and vegetation, and hence two trenches were made for detailed observation of the Gushan Formation (Fig. 5e). The Chaomidian Formation was measured continuously upward along the ridge to the top, which can be divided into microbialite-dominant lower part and wackestone-dominant upper part.

3.5. Fanzhuang II Section

The Fanzhuang II section is located in the eastern part of the Fanzhuang village, Gushan town, about 1.5 km northwest of the Tangwangzhai section (Fig. 4a). This section is about 500 m northwest of the original Fanzhuang section which was examined by Blackwelder and Willis (1907) and considered as a type section for the Chaomidian Formation along with the Tangwangzhai section. The measured section on the southeastern face of a short ridge covers the interval from the upper part of the Chaomidian Formation to the lower part (ca. 90 m) of the overlying Sanshanzi Formation (Fig. 5f). Although several vertical faults with small displacement are recognized, the sedimentary strata and the boundary between the Chaomidian and Sanshanzi formations are readily traceable across the faulted blocks.

3.6. Jiulongshan Section

The Jiulongshan section (in the southern part of the Laiwu area) is located 84 km southeast of the Mantoushan section (Fig. 1b). This section was initially investigated by Blackwelder and Willis (1907) (Fig. 6a). It consists of twelve subsections (Fig. 4b). The Zhushadong Formation in subsections 1 and 2 (Fig. 4a) unconformably overlies the Precambrian basement with paleosol at the base (Fig. 6b). This formation is about 40 m in thickness. The Mantou Formation is exposed in subsections 3 through 6 (Figs. 6c and d), represented by an alternation of carbonate- and siliciclastic-dominant lithofacies. The lower part of the Mantou Formation was measured in subsections 3 and 4, whereas the upper part in subsections 5 and 6. The Mantou Formation in the Jiulongshan section is about 220 m in thickness. The lower and upper parts of the Zhangxia Formation consist mainly of limestone beds (Figs. 6e and f), which were measured in subsections 7 and 9, respectively. The middle part of the Zhangxia Formation is, in contrast, predominantly composed of shale which is mostly weathered. The middle part is measured in subsection 8 (Fig. 6g). The Zhangxia Formation in the Jiulongshan section is about 170 m in thickness. The Gushan Formation is well exposed in subsection 10 (Fig. 6g). The Gushan Formation, about 105 m in thickness, is characterized by shale-dominant facies. The lower part of the Chaomidian Formation is exposed in subsection 11, whereas the upper part is in subsection 12 (Fig. 6h). These two subsections, about 1.5 km apart, are correlated by a biohermal microbialite bed. The Chaomidian Formation in the Jiulongshan section is about 240 m in thickness.

3.7. Jinhe Section

The Jinhe section (in the southwestern part of the Linyi area) is located 140 km southeast of the Jiulongshan section (Laiwu area), and comprises the north and south subsections (Fig. 4c). The north subsection occurs along the roadcuts and represents the lowermost Liguan Formation which overlies the Sinian metasedimentary rocks (Fig. 7a). The south subsection, 2 km south of the north subsection, occurs in local quarries and exposes the upper part of the Liguan Formation and the lower part of the Zhushadong Formation (Fig. 4b). The Liguan Formation consists of amalgamated medium sandstone beds in the lower part (about 25 m thick) and dark gray mudstone beds with fossil fragments and bioturbation in the upper part (about 15 m thick).

3.8. Liangcheng Section

The Liangcheng section (in the southwestern part of the Jining area) is located 130 km southwest of the Mantoushan section (Jinan area) (Fig. 1b). This section comprises several quarries and small forest road to the hill (Fig. 7b). The Zhushadong Formation, overlying the Precambrian granitic gneiss with paleosol at the boundary, is well exposed in this section. The Zhushadong Formation consists mainly of stromatolite and bioturbated limestone, whereas the Mantou Formation comprises weathered shale (Fig. 7b). The Zhushadong Formation in the Liangcheng section is about 40 m in thickness.

4. STRATIGRAPHY

Thirty-two lithofacies are identified in the Cambrian succession, based on lithology, sedimentary structures, and fossil contents: 12 siliciclastic facies (Fig. 8) and 20 carbonate facies (Fig. 9) (Tables 1 and 2). Siliciclastic facies are dominant in the lower part of the succession, the Liguan and Mantou formations, whereas carbonate facies occur throughout the entire succession (Tables 2 and 3). Carbonate facies are basically classified according to the Dunham's (1962) scheme, although common facies names such as limestone conglomerate and various microbialites (stromatolite, throm-

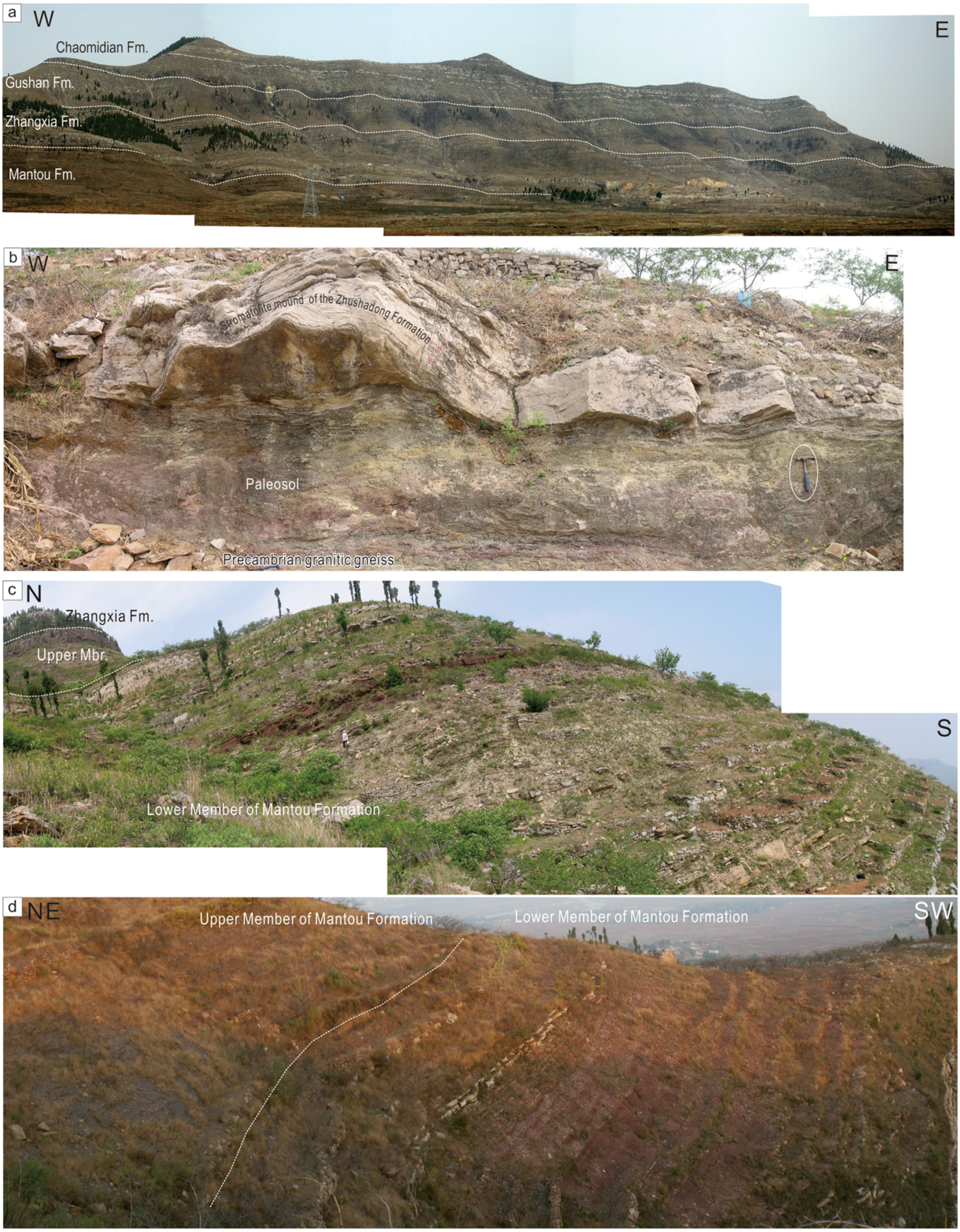

Fig. 6. Photographs of measured subsections in the Jiulongshan section. (a) Overview of the Jiulongshan section from the south of the mountain. (b) Paleosol and the overlying stromatolite bed in the lowermost part of the Zhushadong Formation in the Jiulongshan subsection 1. Hammer for scale is about 30 cm long. (c) The lower part of the Mantou Formation in subsection 3. (d) The middle part of the Mantou Formation in subsection 4.

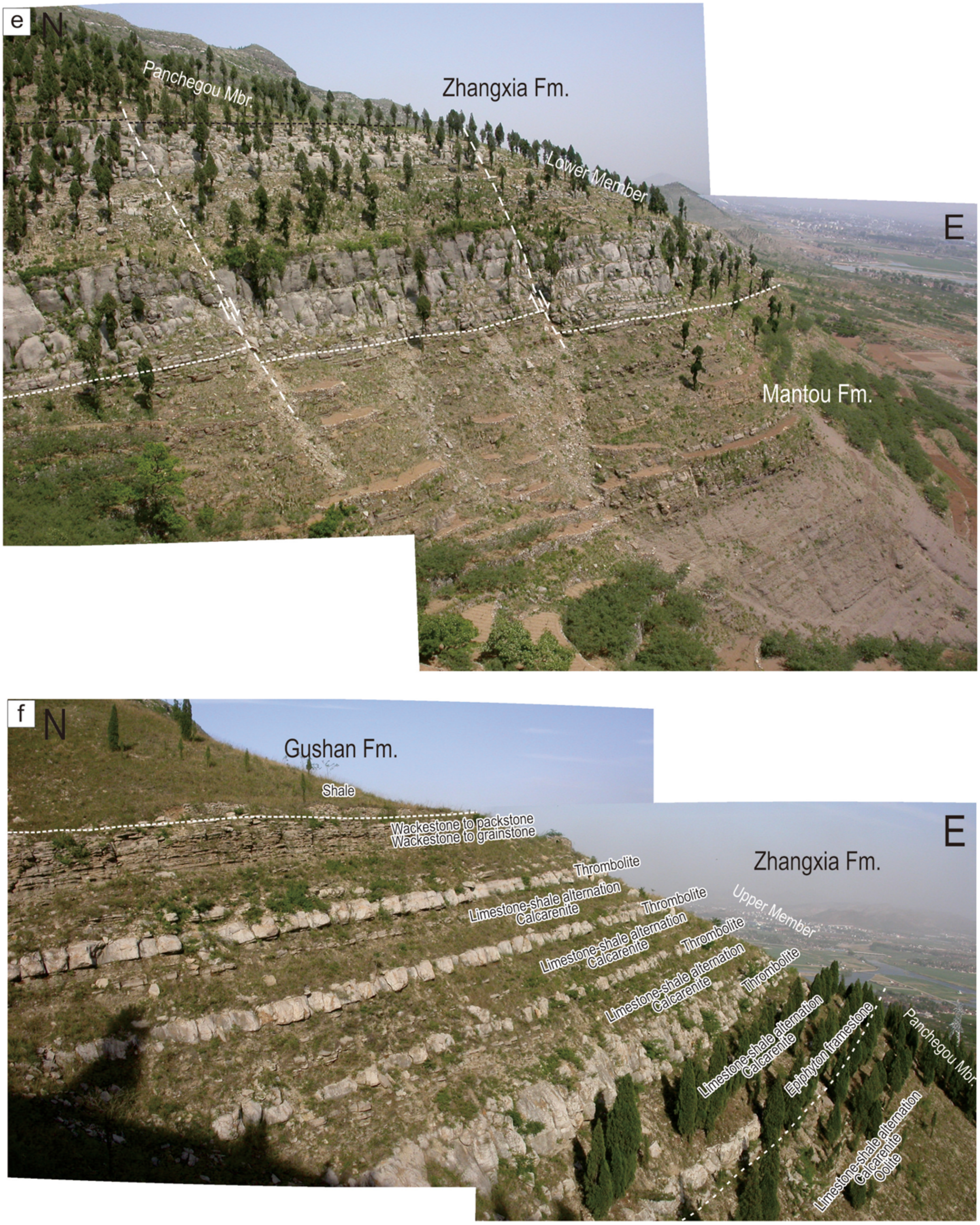

Fig. 6. (continued). (e) Subsections 6 and 7 showing the uppermost part of the Mantou Formation and the lowermost part of the Zhangxia Formation. (f) The uppermost part of the Zhangxia Formation and the overlying Gushan Formation in subsection 9.

bolite, and dendrolite) are used instead of rudstone, floatstone, and boundstone.

Since Lu and Dong (1953) suggested 17 biozones for the Cambrian succession in central Shandong Province, the scheme has served as a template for the Cambrian biostratigraphy of the North China Platform. The subsequent studies have modified several biozones (Xiang et al., 1981; Zhang and Jell, 1987; BGMRSP, 1996; Zhang, 2003). This

Fig. 6. (continued). (g) Subsections 8 and 10 in the northern part of Jiulongshan Mountain. (h) Subsection 12 showing the upper part of the Chaomidian Formation (ca. 170 m thick).

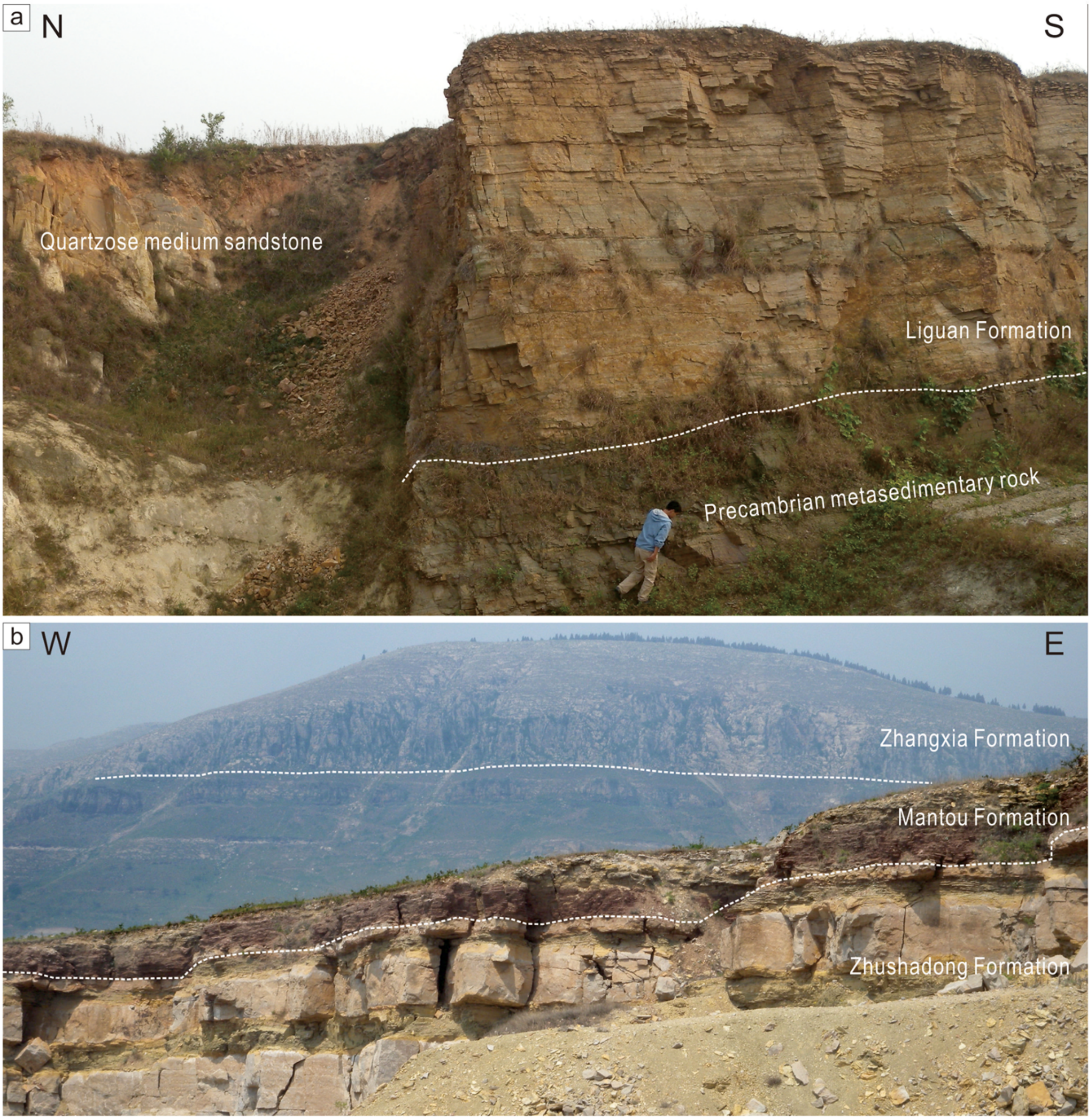

Fig. 7. Photographs of (a) the Jinhe section in the Linyi area and (b) the Liangcheng section in the Jining area. Note that the Precambrian metasedimentary rock is overlain by the Liguan Formation.

study mainly follows the biozonal scheme of BGMRSP (1996) (Table 3).

4.1. Liguan Formation

The Liguan Formation occurs in a limited area of southeastern Shandong Province (Fig. 4c). This formation was initially defined by Liang (1980) as a unit of breccia, sandstone, mudstone, and limestone in the town of Liguan of the Linyi area. The Liguan Formation was later refined as a sandstone- and mudstone-dominated unit by BGMRSP (1996).

The Liguan Formation in the Jinhe section can be divided into the lower and upper parts (Fig. 10). The lower part overlies the Sinian metasedimentary rocks and comprises massive and cross-stratified sandstone intercalated with gray mudstone (Table 3, Fig. 7a). Amalgamated sandstone beds (1 to 12 m in thickness, facies Sc) consist predominantly of quartz grains and a few mudstone chips. These

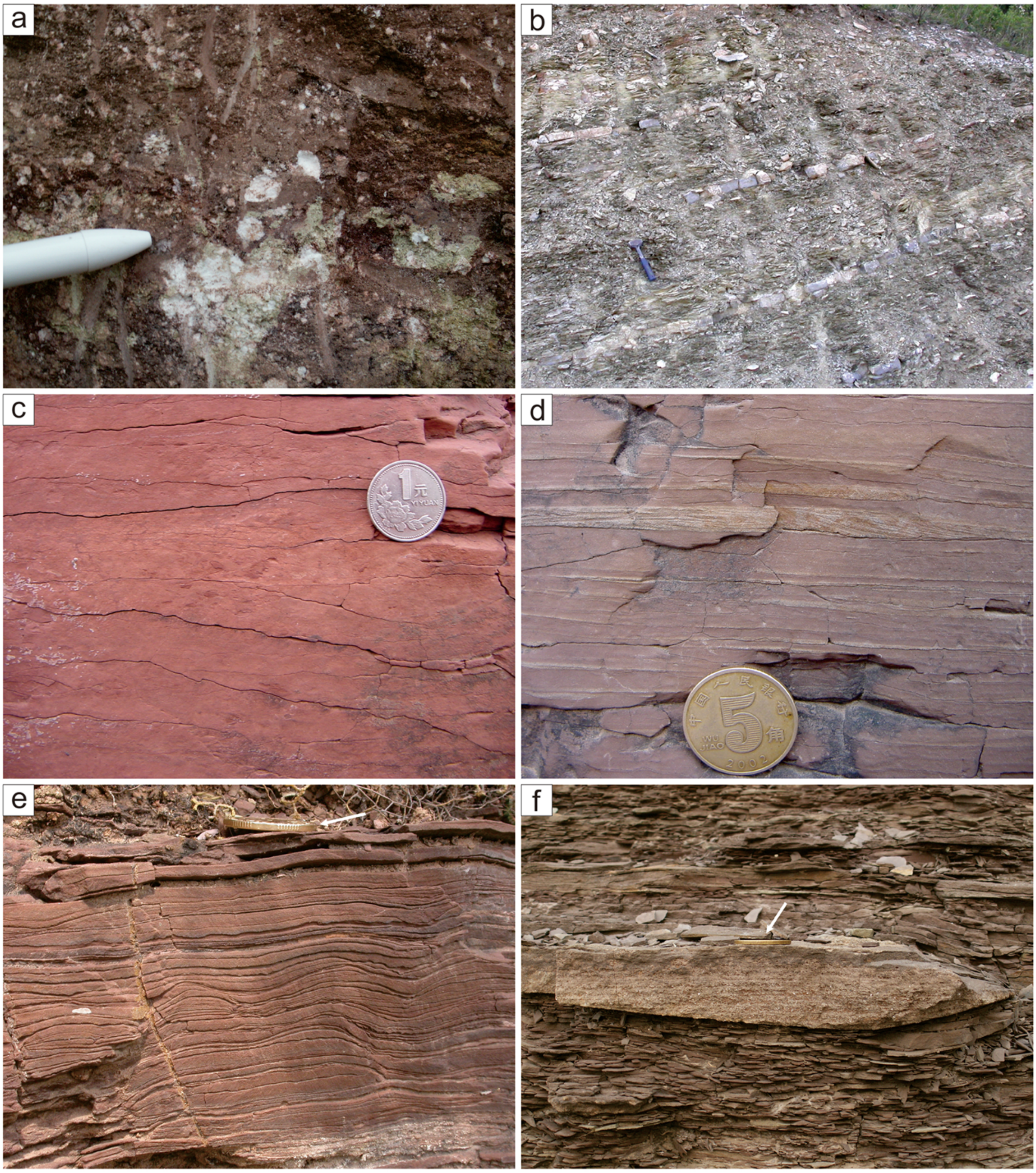

Fig. 8. Photographs of representative siliciclastic lithofacies. (a) Paleosol. Pen for scale is about 5 cm long. (b) Shale intercalated with thin calcarenite beds. Hammer for scale is about 30 cm long. (c) Homogeneous purple mudstone. Coin for scale is 19 mm in diameter. (d) Laminated purple mudstone. Coin for scale in figures (d)–(f) is 20.5 mm in diameter. (e) Irregular-laminated mudstone to fine sandstone. (f) Dark purple mudstone and sandstone alternation.

sandstone beds show sheet- and wedge-shaped geometry (Fig. 7a). Interlayered gray mudstone beds (facies Fg) are a few meters thick, showing sharp lower and upper boundaries (Fig. 10). The upper part of the formation is characterized by thick dark gray laminated fine sandstone and mudstone (Fig. 10b). Laminated fine sandstone includes

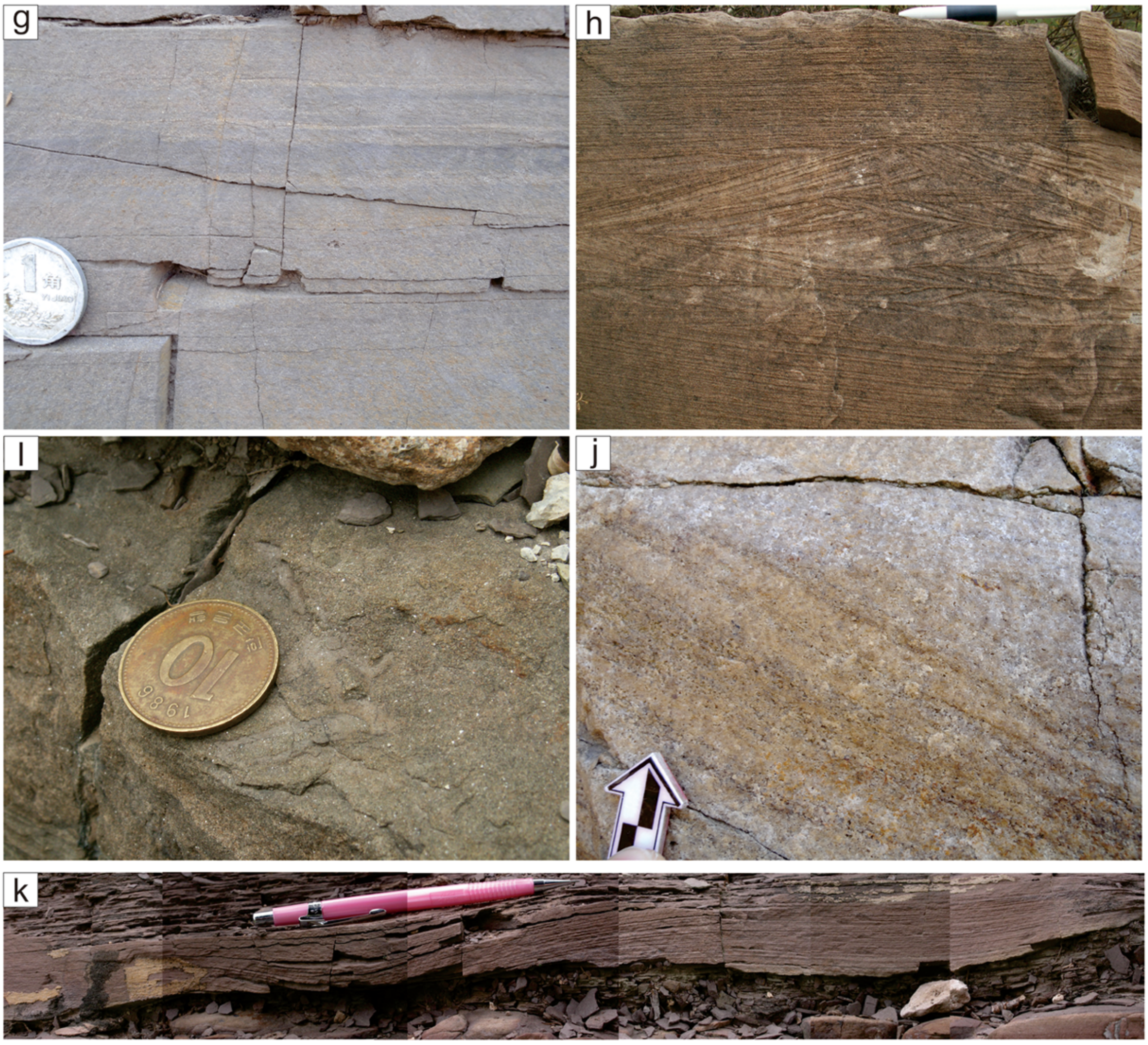

Fig. 8. (continued). (g) Horizontally laminated fine sandstone. Coin for scale is 22.5 mm in diameter. (h) Planar and trough cross-stratified sandstone. (i) Bioturbated sandstone. Coin for scale is 23 mm in diameter. (j) Crudely stratified sandstone. Scale is 2 cm in length. (k) Hummocky and swaley cross-stratified sandstone. Pencil for scale is 14 cm long.

large amounts of muscovites and shows horizontal and cross-lamination (Figs. 10a and b). The amounts of calcareous nodules with fossil fragments increase upward. The fine sandstone in the upper part of the Liguan Formation changes upward into bioturbated limestone-shale alternation (facies LS) of the Zhushadong Formation. The Liguan Formation is about 45 m in thickness (Fig. 10).

4.2. Zhushadong Formation

The Zhushadong Formation was initially defined in Henan Province as "multi-colored limestone intercalated by thin shale beds" (Feng and Zhang, 1951). It was correlated to the limestone and dolostone beds in the basal part of the Cambrian succession in Shandong Province, which had been regarded as the lower part of the Mantou Formation (Blackwelder and Willis, 1907). The formation was further divided into three members based on occurrence of shale beds in the middle part: the Lower Limestone Member, the Yuliangcun Shale Member, and Upper Limestone Member in ascending order (BGMRSP, 1996). These members were, however, ill-defined due to the diverse constituent lithofacies and the thickness variations (10 to 40 m in thickness). The *Megapalaeolenus* Zone was established in the lower part of the Zhushadong Formation in Henan Province.

The Zhushadong Formation in Shandong Province is refined as the basal carbonate unit of the Cambrian succession, consisting of laminated dolomudstone, stromatolite, bioturbated wackestone, and oolitic packstone to grainstone (Table 3). The formation rests conformably on the Liguan Formation in the Jinhe section and unconformably on the Precambrian basement with thick (30 cm to 1 m) paleosol in the Mantoushan, Jiulongshan, and Liangcheng sections (Figs. 5a, 6b, and 11e). The locally distributed paleosol

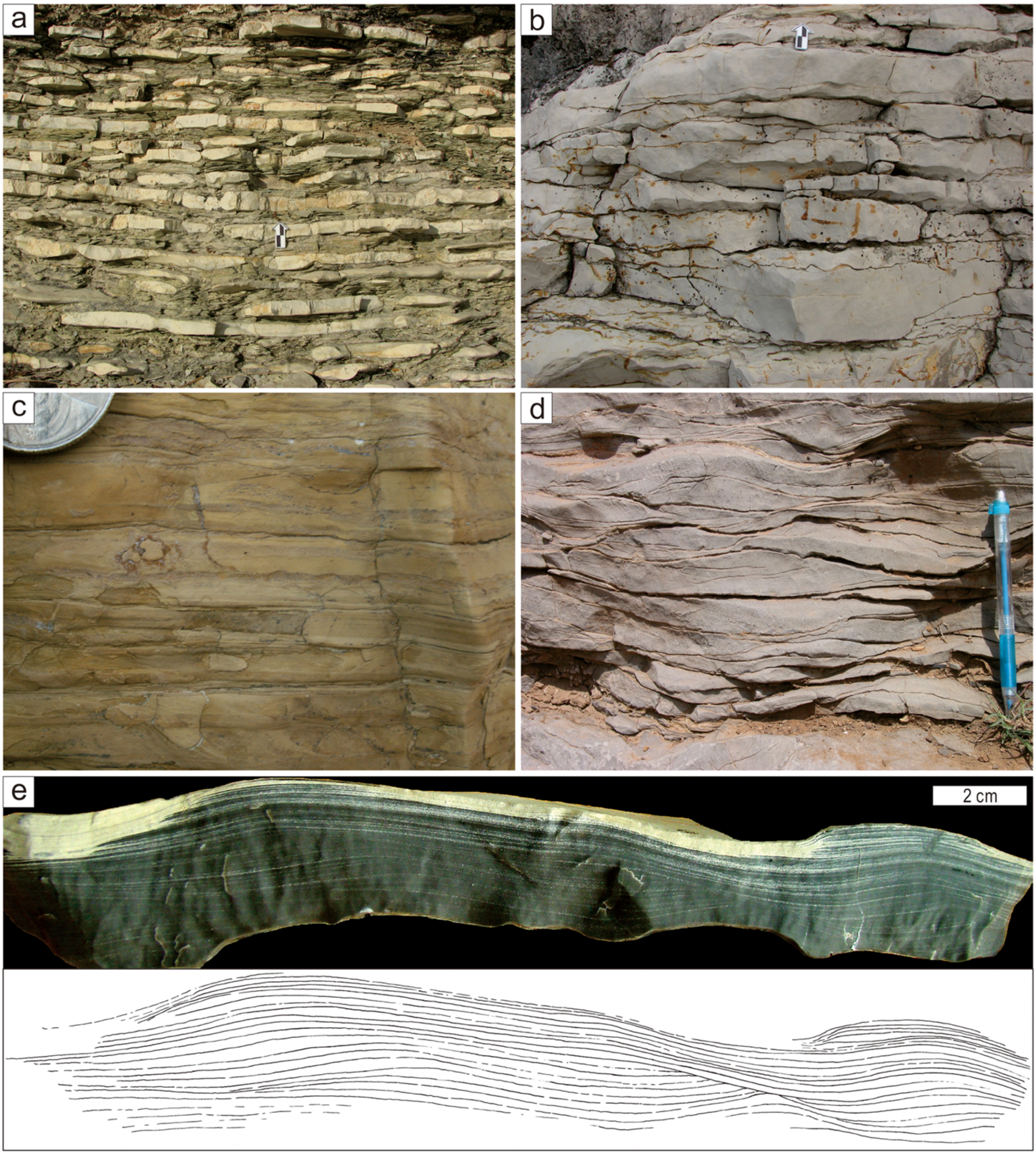

Fig. 9. Photographs of representative carbonate lithofacies. (a) Limestone and shale alternation. Scale in figures (a), (b), (f), (g), (n), and (p) is 2 cm long. (b) Thin-bedded lime mudstone. (c) Laminated dolomudstone. Coin for scale is 24 mm in diameter. (d) Wavy-laminated wackestone. Pencil for scale is 14 cm long. (e) Low-angle cross-laminated calcisiltite.

(facies P) is crudely stratified and poorly sorted with abundant calcite glaebules (Fig. 8a). It is overlain by laminated and homogeneous dolomudstone (facies Dl) (Figs. 6b and 11e). The Zhushadong Formation generally comprises laminated dolomudstone and stromatolite (facies Dl and ST) (Figs. 12 and 13). It is subordinately interlayered with wavy bedded packstone and oolitic grainstone (facies Pw and O) (Fig. 13). The dolomudstone beds are thinly to thickly bed-

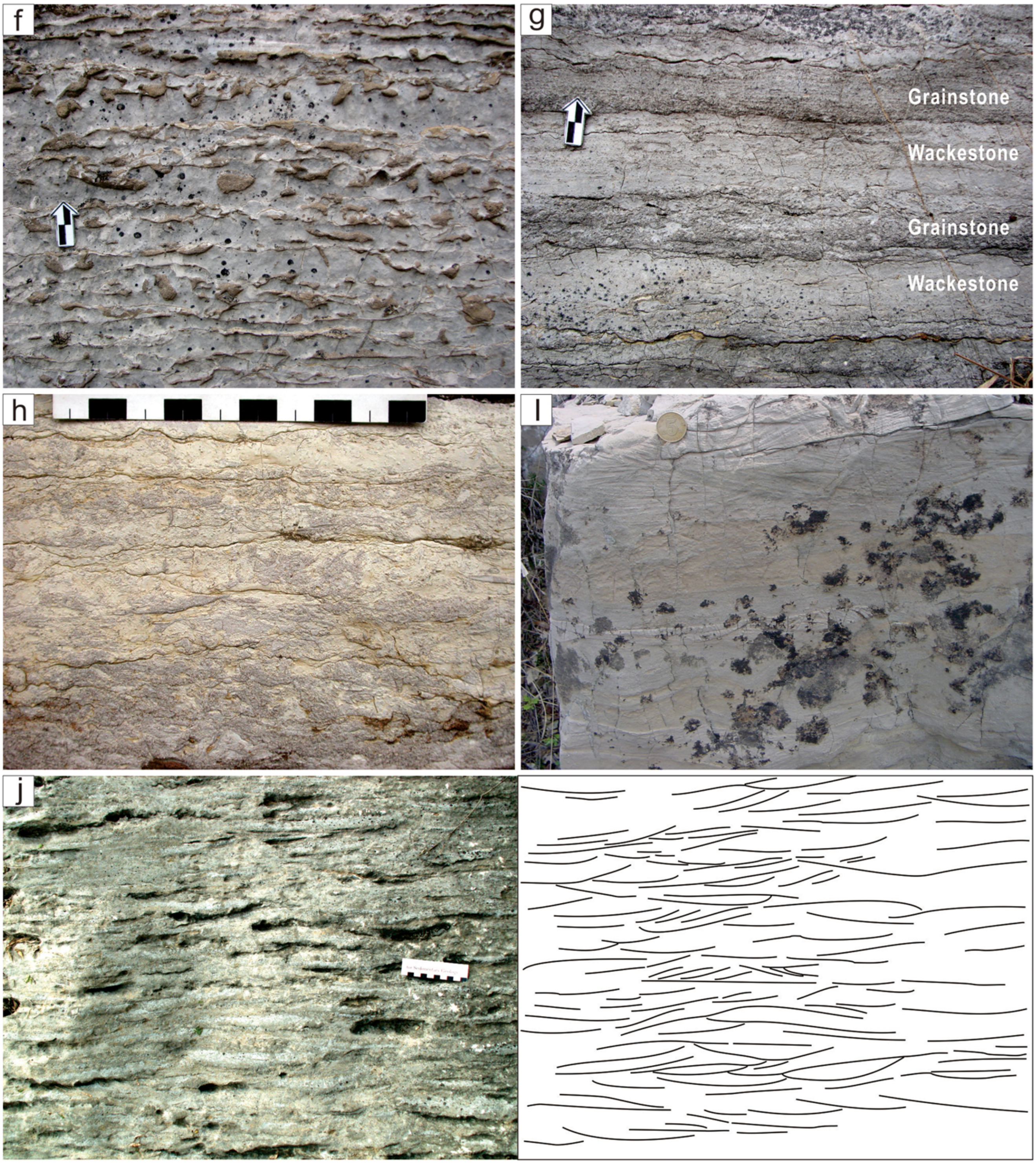

Fig. 9. (continued). (f) Bioturbated wackestone. (g) Wackestone to grainstone. (h) Thin-bedded wackestone to packstone. Scale in figures (h) and (j) is 10 cm long. (i) Wavy bedded packstone. Coin for scale is 20.5 mm in diameter. (j) Oolitic packstone to grainstone.

ded and include chert concretions and several brecciated layers. The stromatolite is usually characterized by domal and irregular geometry and is overlain by massive oolitic grainstone. The Zhushadong Formation is about 15 m thick in the Mantoushan section, 35 m in the Jiulongshan section, and 40 m in the Liangcheng section, showing a southeastward thickening trend (Figs. 11c, 12, and 13). Thrombolite, grainstone, and bioturbated wackestone (facies TH, WG,

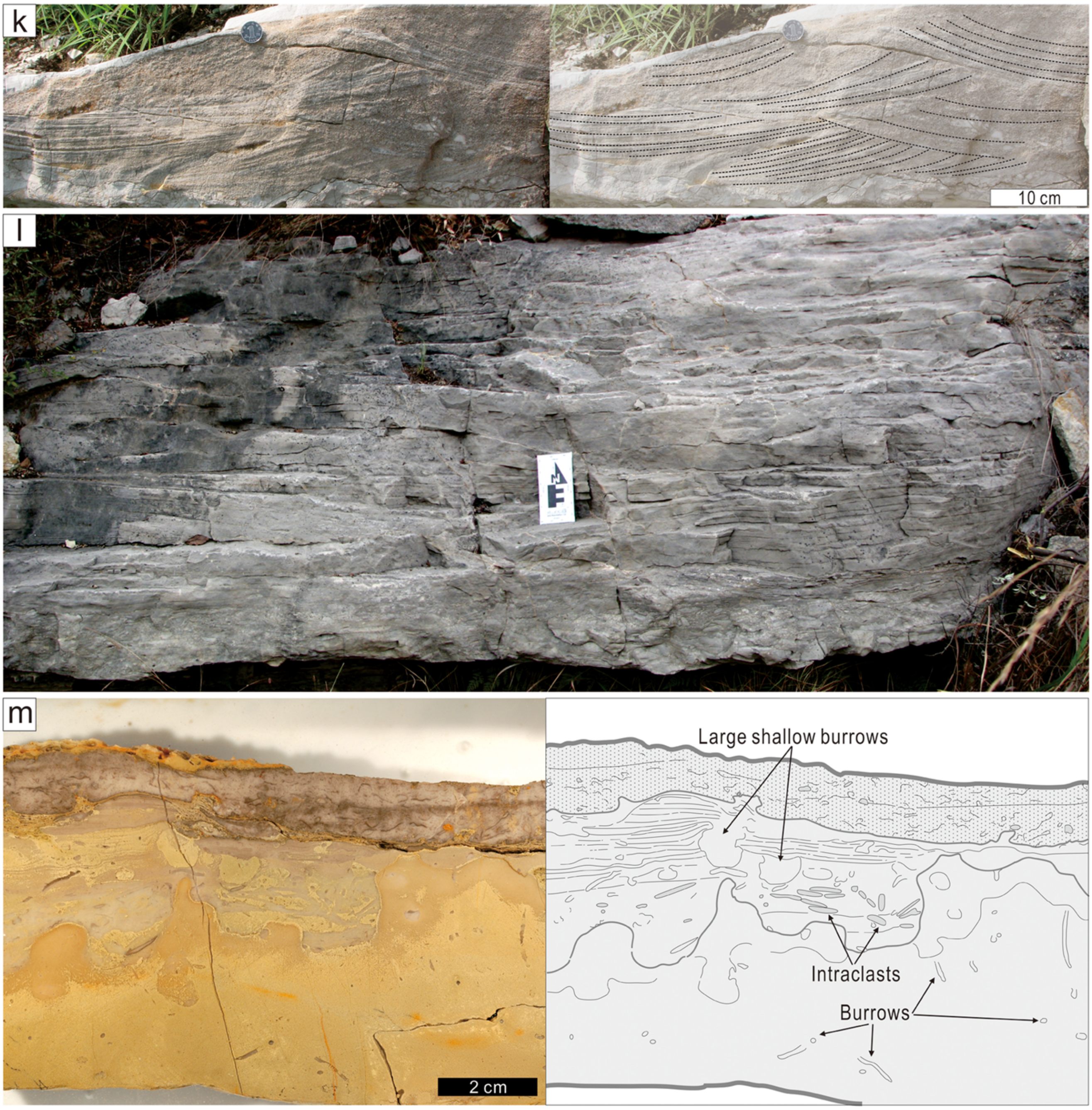

Fig. 9. (continued). (k) Trough cross-stratified grainstone. Coin for scale is 19 mm in diameter. (l) Hummocky cross-stratified grainstone. Scale is 15 cm long. (m) A slab of calcarenite with small intraclasts and loading structures.

and Wb) are restricted to the Liangcheng section (Fig. 11). Wavy laminated wackestone, limestone-shale alternation, and greenish gray mudstone (facies Wl, LS, and Fg) exclusively occur in the Jiulongshan section (Fig. 13). The upper boundary of the Zhushadong Formation is placed at the base of the first purple mudstone bed of the Mantou Formation, which can be well correlated among the sections (Figs. 12 and 13).

4.3. Mantou Formation

The Mantou Formation was defined by Blackwelder and Willis (1907) in the Mantoushan section. Three chronostratigraphic units were defined by Lu and Dong (1953); Mantou, Maozhuang, and Xuzhuang series, which were subsequently adapted to the formations (CECG & GICAS, 1956; Zhang and Jell, 1987). BGMRSP (1996) pointed out

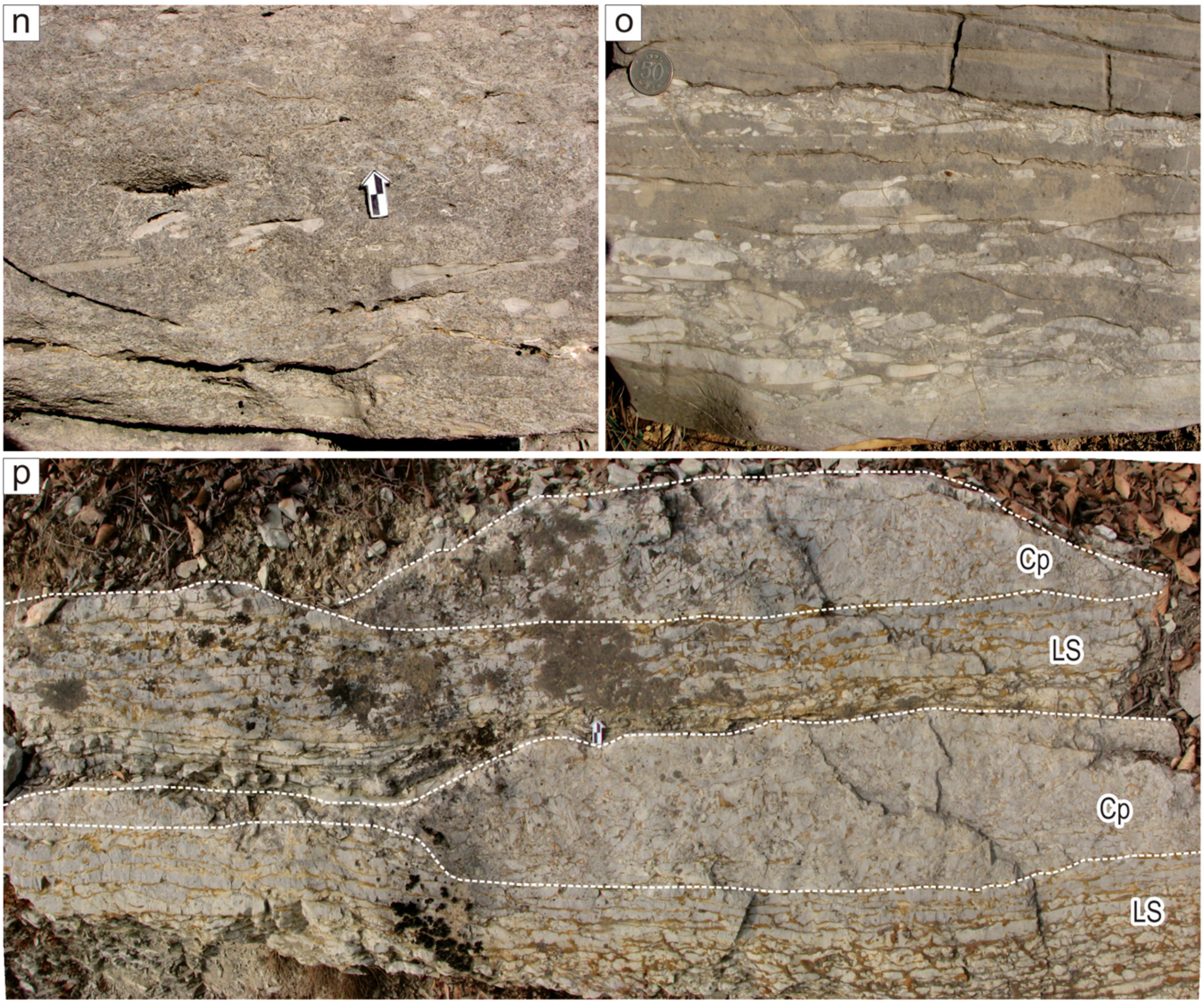

Fig. 9. (continued). (n) Gravelly grainstone. (o) Cross-stratified limestone conglomerate. Coin for scale is 22 mm in diameter. (p) Limestone pseudoconglomerate.

that the chronostratigraphic nomenclature should not be applied to the lithologic units and refined the Mantou Formation as a succession of reddish shale, limestone, and sandstone, discrediting the usage of Maozhuang and Xuzhuang formations. The eight biozones were noted by BGMRSP (1996): the *Redlichia chinensis*, *Yaojiayuella*, *Shantungaspis*, *Hsuchuangia-Ruichengella*, *Ruichengaspis*, *Sunaspis*, *Poriagraulos*, and *Bailiella* zones in ascending order (Fig. 14). The *Redlichia chinensis* Zone is recognized exclusively in the lower part of the Mantou Formation, whereas the other seven biozones occur in the upper part. The *Redlichia chinensis* Zone can be recognized by the occurrence of the eponymous trilobite (Fig. 14b) in the lower part of the Mantou Formation, representing the middle Lungwangmiaoan Stage. The *Yaojiayuella* and *Shantungaspis* zones form the Maochuangian Stage. The base of the Maochuangian Stage may be regarded as the base of the Cambrian Series 3 (BGMRSP, 1996; Zhang, 2003). The overlying Hsuchuangian Stage comprises the remaining five biozones.

The Mantou Formation in Shandong Province has been divided into four members: the Shidian, Lower-Shale, Honghe, and Upper-Shale members in ascending order (BGMRSP, 1996). The Shidian Member (ca. 77 m thick) is characterized by the alternation of brick-red, yellow-gray dolomudstone, shale, dolomitic mudstone, and limestone. The Lower-Shale Member (ca. 83 m thick) is dominated by thick red shale intercalated with oolite, muscovite-rich siltstone, and bioclastic grainstone, occupying the middle part of the Mantou Formation. The Honghe Member (ca. 24 m thick) is characterized by thick cross-stratified calcareous sandstone. The Upper-Shale Member (ca. 31 m thick) mainly consists of ferrous and micaceous shale intercalated with

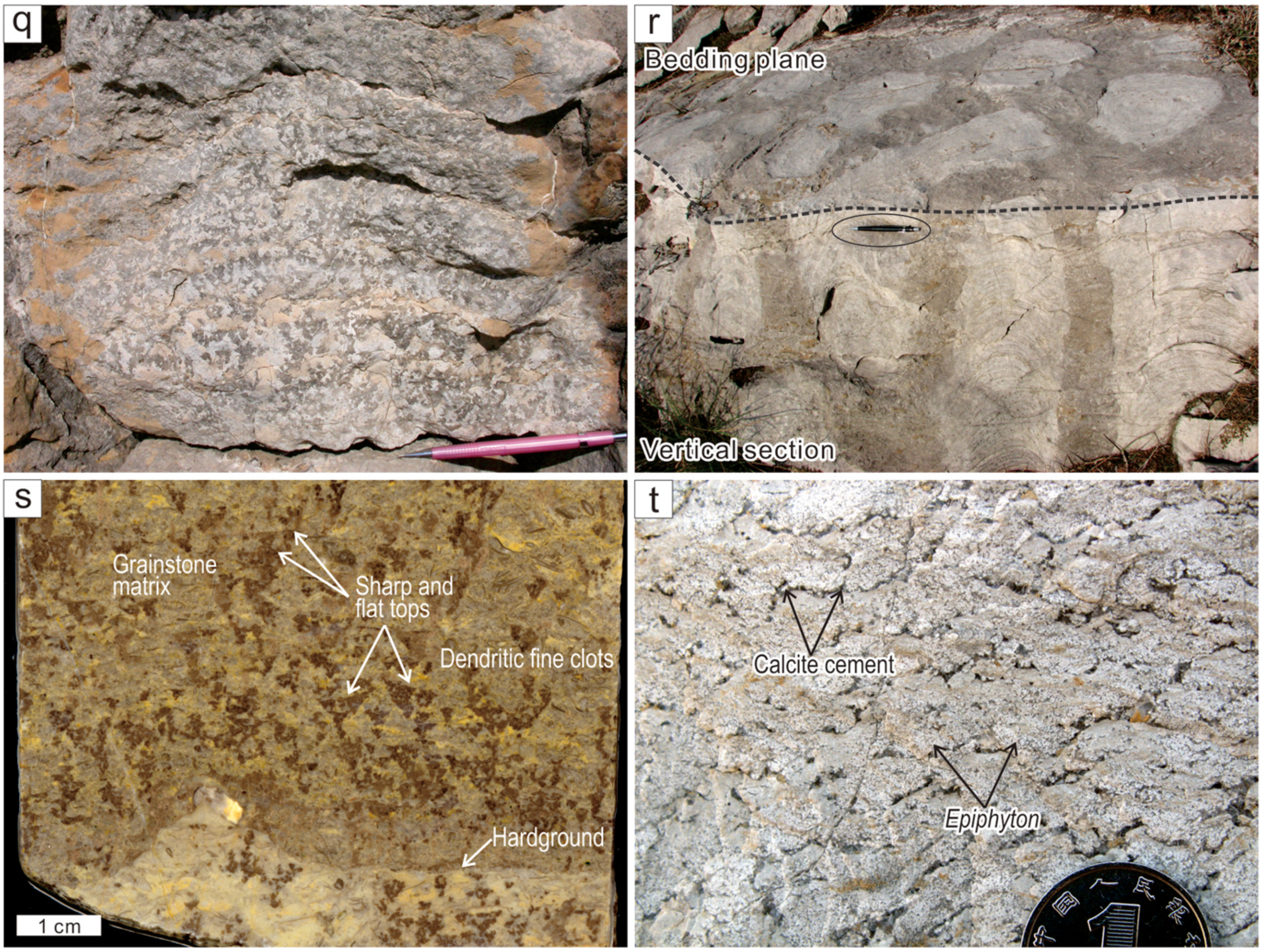

Fig. 9. (continued). (q) and (r) is 14 cm long. (r) Stromatolite. (s) Dendrolite. (t) *Epiphyton* framestone. Coin for scale is 19 mm in diameter.

oolite. However, the Honghe and Upper-Shale members are difficult to identify in the Liantaishan and Jiulongshan sections due to the lateral variations in lithofacies and thickness; bioturbated and cross-stratified sandstone beds are not exclusive to the Honghe Member but also occur in other stratigraphic horizons (Figs. 12 and 13). These sandstone beds are variable in thickness, 8 m in the Liantaishan section and 15 m in the Jiulongshan section. The Upper-Shale Member is composed of shale and oolite, and also shows a considerable lateral variation in thickness from the Liantaishan to Jiulongshan sections. These shale beds wedge out to the southeast.

The Mantou Formation in Shandong Province is now divided into the Lower and Upper members (Table 3). The Lower Member includes the previous Shidian Member and the lower part of the Lower-Shale Member, whereas the Upper Member incorporates the Lower-Shale, Honghe, and Upper-Shale members. The Lower Member mainly consists of wavy and lenticular laminated mudstone, homogeneous purple mudstone, limestone-shale alternation, and microbialite (facies Fl, Fh, LS, and ST) (Table 3). The Upper Member is mainly represented by dark purple mudstone and sandstone, cross-stratified sandstone, bioturbated sandstone, hummocky cross-stratified sandstone, cross-stratified oolite, and massive oolitic grainstone (facies Fp, Sx, Sb, Shs, Gptc, and O) (Table 3). The base of the Upper Member is defined by the first appearance of massive oolite and hummocky cross-stratified sandstone (Figs. 12 and 13). The upper boundary of the Upper Member is marked by an occurrence of thick oolitic grainstone beds (more than 10 m in thickness) of the Zhangxia Formation (Figs. 12 and 13). A thick oolite bed (ca. 10 m thick) occurs in the Lower Member in the Jiulongshan section, whereas a thick homogeneous purple mudstone bed (ca. 10 m thick) occurs in the Upper Member in the Liantaishan section (Figs. 12 and 13). The Lower Member is about 100 m thick in the Mantoushan section and 125 m thick in the Jiulongshan section, whereas the Upper Member is about 105 m thick in the Liantaishan section and 100 m thick in the Jiulongshan section.

Table 1. Siliciclastic lithofacies of the Cambrian succession in Shandong Province

Siliciclastics	Description	Interpretation
Paleosol (P)	Granule-bearing mudstone (Fig. 8a); overlying the Precambrian granitic gneiss; quartz (45%), calcite and dolomite (20%) as well as organic carbon (0.05%), clay minerals (20%), and hematite (<6%); amounts of calcite and dolomite increasing-upward up to 45%; quartz decreasing to 13%; purple and greenish gray to yellowish gray in color, showing crude stratification; abundant altered feldspar and quartz near the lower boundary, rapidly decreasing upward; calcite graebules dispersed horizontally	Paleosol above the Precambrian basement
Shale (Sh)	Shale dominant (Fig. 8b), partly intercalated with fine sandstone, calcareous nodules, or irregular concretions, color variation from gray to purple, partly well-preserved bedding-parallel mold and body of trilobites, brachiopods, etc. (e.g., hyolith, *Chancelloria*, *Blackwelderia*, and *Neodrepanura*)	Settling of suspended materials under low-energy and either oxidizing or reducing conditions; deep subtidal platform to basin sedimentation
Homogeneous gray mudstone (Fg)	Gray, yellowish gray mudstone; faintly laminated; sharp upper and lower boundaries with cross-stratified medium sandstone; mottled partly; severely weathered	Suspension settling of fine-grained material; reducing condition
Homogeneous purple mudstone (Fh)	Homogeneous purple mudstone (10 cm to a few meter thick) (Fig. 8c); quartz (40%), calcite and dolomite (25%) as well as organic carbon (0.05–0.1%), clay minerals (20%), and hematite (6%); mottled and bioturbated structures made of hematitic and clay rich part; gradational lower boundary and sharp upper boundary	Deposition of suspended mud most likely on uppermost intertidal flat under oxidizing conditions
Laminated purple mudstone (Fl)	Wavy and lenticular laminated purple mudstone and dolomite as well as fine sandstone and siltstone (Fig. 8d); normally graded and bidirectional ripple cross-laminated dolomite and calcareous fine sandstone; desiccation cracks and burrows commonly present; upward-thinning or thickening laminae	Tidal deposits in shallow subtidal and intertidal environments
Irregular laminated mudstone to fine sandstone (Fi)	Irregular-laminated dark purple siltstone to fine sandstone (a few dm to a meter thick) (Fig. 8e); compose of quartz (60%), hematite (8%), and carbonate minerals (7%); less than 3 mm thick lamina dominant; wrinkled and irregular cross- or horizontal-stratified; dark purple, dusky red, alternating dusky red and yellow in color	Intertidal to lowermost shoreface sediments stabilized and modified by microbial mats
Dark purple mudstone and sandstone alternation (Fp)	Alternation of dark purple mudstone and fine calcareous sandstone (Fig. 8f); discontinuous and wavy sandstone beds (a few mm to 10 cm thick); normally graded or low-angle cross-laminated; abundant fragments of trilobite, echinoderm, and brachiopod; dispersed glauconite grains; mudstone composed of quartz (60%), hematite (8%), carbonate minerals (6%), and clay minerals (18%); sandstone sheet, pot, and gutter cast present; thickening- or thinning-upward trend of sandstone layers	Lower shoreface to offshore environments; lagoonal or subtidal environment with frequently introduced sandy sediments
Horizontally laminated fine sandstone (Shl)	Finely laminated fine sandstone (Fig. 8g); horizontally laminated with a-few-mm thickness; partly cross-laminated; muscovite-rich; discontinuous fossil-rich layers occurred with bioturbation; calcareous nodules; gray, dark gray, and dark purple in color; mudstone chips and layers frequently recognized	Suspension settling of fine-grained material with frequent input of sandy grains and fossil fragments; alternation of background settling deposits and distal siltstone by storm or currents
Planar and trough cross-stratified sandstone (Sx)	Planar and trough cross-stratified calcareous medium sandstone (Fig. 8h); sandstone composed of well-sorted quartz grains and small amounts of ooids and fragments (trilobite and brachiopod); cross-stratification represented by alternation of medium and fine sandstones; 5–25 cm thick cross-set; yellowish gray and gray in color	2D and 3D dune migration on calcareous sand shoal in upper shoreface
Bioturbated sandstone (Sb)	Yellow bioturbated calcareous medium sandstone (ichnofacies index –3 and –4) (Fig. 8i); yellowish gray and gray in color; crude stratification, represented by alternation of medium and fine sandstones	Shoreface or intershoal deposit with abundant biogenic activities of benthic organisms
Crudely cross-stratified sandstone (Sc)	Crudely cross-stratified and massive medium sandstone (Fig. 8j); planar cross-stratified partly; partly ripples on the top of surface; mudstone pebble clasts aligned; wedge- and sheet-shaped geometry; a few cm to dm thick beds amalgamated; partly parted by thin fine-grained layers; thickening- or thinning-upward trends; abundant quartz	Deposition by 2D and 3D dune migration; rapid sedimentation from heavy sediment-laden flow
Hummocky and swaley cross-stratified sandstone (Shs)	Hummocky and swaley cross-stratified purple medium to fine sandstone (Fig. 8k); changing upward from swaley cross bedding to hummocky, trough, and ripple cross-lamination; sand volcanoes (a few dm in thickness and 3–5 cm in diameter) in swaley cross-bedded part; ripples on the top of swaley cross bed; lateral variation from amalgamated to thin-mudstone-parting swaley cross beds	Deposition of sand by storm-induced currents and waves in lower shoreface

Table 2. Carbonate lithofacies of the Cambrian succession in Shandong Province

Carbonates	Description	Interpretation
Limestone-shale alternation (LS)	Alternation of homogeneous or laminated limestone and dolomitic shale or marlstone (Fig. 9a); microstylolites commonly present in dolomitic shale layers; intraclasts and desiccation cracks partly present; wedge-shaped grainstone with erosional boundary partly occur; *Planolites, Paleophycus,* and *Skolithos*; containing fossiliferous horizons	Cyclic input of carbonates and background sedimentation of argillaceous materials; intertidal to shallow subtidal, or deep subtidal environments
Thin-bedded lime mudstone (Ltb)	Thin-bedded lime mudstone (Fig. 9b); thin shale parting either flaser or flat lime mudstone to wackestone beds; sporadic horizontal to inclined burrows; partly irregular-lamination, normal-grading, and erosional features	Deposits of relatively low-energy conditions; subtidal to intertidal environments, partly modified by burrows
Laminated dolomudstone (Dl)	Irregularly and discontinuously laminated dolo-mudstone interlayered with wackestone to peloidal grainstone (Fig. 9c); dispersed quartz grains, halite pseudomorph and desiccation cracks in certain laminae; alternation of thick (about 500 μm) and coarse (about 30–50 μm) crystalline lamina and thin (about 70 μm) and fine (<10 μm) lamina	Deposition in shallow intertidal environments with frequent subaerial exposure
Wavy laminated limestone (Wl)	Wavy laminated wackestone (Fig. 9d); planar and ripple cross-laminated; interlayered shale from 1 to a few mm in thickness; cross-laminated packstone and grainstone, showing discontinuous wavy bedding; well sorted peloidal grainstone interlayered; small stromatolite mound and channelized conglomerate with erosional lower boundary	Deposition above normal wave base under relatively high-energy conditions such as sandy tidal flat based on intercalated conglomerate and small stromatolite mounds
Laminated calcisiltite (Cl)	Parallel, ripple, and low-angle cross-laminated calcisiltite intercalated with dolomitic marlstone or shale (Fig. 9e); composed of silt-sized calcite particles; wavy-bedded, unidirectional and low-angle cross-lamination with truncational boundary; climbing ripples; partly bioturbated with burrows cutting laminae	Subtidal deposits by unidirectional currents (partly combined with oscillatory movement of water) induced by storms, marlstone deposited during fair weather
Bioturbated wackestone facies (Wb)	Moderately to severely bioturbated (Fig. 9f); gray lime mudstone to wackestone; horizontal to inclined burrows; mottled texture; composed mainly of micrite and fossil fragments and peloids; partly intercalated with thin bioclastic grainstone with sharp lower boundary; oncoids with distinct laminae and irregular diffuse laminae; brachiopods, spicule of *Chancelloria*, and filaments of *Girvanella* partly present	Low-energy subtidal deposits modified by bioturbation
Wackestone to grainstone facies (WG)	Thin-bedded or flaser-bedded wackestone separated by shale partings (Fig. 9g); slightly bioturbated; often intercalated with lenses or thin layers of grainstone with sharp lower boundary, partly normally graded and stratified; partial concentration of fossil fragments; lime mudstone clasts derived from the base; partly loading structures	Relatively low-energy subtidal conditions with intermittent higher energy episodes
Thin-bedded wackestone to packstone (WP)	Thin-bedded alternation of irregularly bounded pack-grainstone and bioturbated finer sediments (Fig. 9h); lime mudstone clasts derived from the base; lenses of grainstone; loading structures	Deposition near the fair-weather wave base in moderately agitating, shallow subtidal environments
Wavy bedded packstone (Pw)	Wavy laminated or bedded calcareous dolopackstone to peloidal grainstone (Fig. 9i); discontinuous and wavy stratification represented by an alternation of yellow dolomudstone and dolopackstone with sharp or erosional boundary; crude stratification and bidirectional ripple cross-lamination commonly present; sharp lower and upper boundaries	Intertidal deposits modified by tidal currents
Oolitic packstone to grainstone (O)	Massive and crudely stratified oolitic and oncolitic packstone to grainstone (Fig. 9j); common occurrence of hardground; glauconitic grains and round intraclasts of oolite commonly present	Shallow subtidal shoal with intensive reworking of waves and reduced sedimentation rate
Planar and trough cross-stratified grainstone (Gptc)	Planar or trough cross-stratified oolitic or bioclastic grainstone (Fig. 9k); glauconite grains present; cross-sets a few to 10 cm in thickness; dolomudstone clasts present, thrombolite and dendrolite beds, and wedge-shaped conglomerate partly intercalated, partly undulatory bedforms	Migration of 2D and 3D dunes on shoal or foreshore environments
Hummocky and swaley cross-stratified grainstone (Ghsc)	Peloidal grainstone (Fig. 9l), composed of coarse silt- to very fine sand-grade peloids and small fraction of fossil fragments; laterally discontinuous and undulatory stratum, varying in thickness from a few dm to 2 m; thick beds amalgamated with internal sharp boundaries; *Skolithos*, 1–5 cm in depth	Deposits modified by storm-induced combined flows

Table 2. (continued)

Carbonates	Description	Interpretation
Calcarenite (CA)	About 5–20 cm in thickness; sharp internal bounding surfaces (Fig. 9m); partly erosional base; containing small lime mudstone clasts and bioclastic grains; faintly laminated or homogeneous; horizontal burrows; loading and flame structures; amalgamated thicker beds	Fast deposition from dilute turbidity currents, modified by sediment loading
Gravelly grainstone (Gg)	Massive or normally graded gravelly packstone to grainstone (Fig. 9n); composed of bioclasts (trilobite, brachiopod, algae, echinoderm, and cephalopod) and peloids; subangular granules and pebbles of lime mudstone to grainstone commonly at base	Deposition from storm-induced currents
Cross-stratified limestone conglomerate (Cs)	Granule- to pebble-grade polymictic clasts with subangular to rounded corners (Fig. 9o); clasts of lime mudstone, dolomudstone, grainstone, purple mudstone, and limestone conglomerate; coarse-grained matrix composed of bioclast, peloid, and ooid; mostly flat-lying and imbricated clasts; normally graded or cross-stratified	Deposition by bedload transportation; generation of clasts by reworking of previous deposit by strong currents or waves
Limestone pseudoconglomerate (Cp)	Oligomictic to polymictic clasts in a matrix of marlstone and/or grainstone (Fig. 9p); flat to irregular sheet-, disc-, or blade-shaped clasts; random internal fabrics (intact, thrusted, mosaic, and disorganized); transitional boundaries from underlying bed	Diagenetic conglomerate due to differential early cementation and deformation
Thrombolite (TH)	Clots of dark-colored micritic carbonate in light-colored lime mudstone and dolomitic matrix (Fig. 9q); very faint internal structures in some cases; scarce fossil fragments; biostromal and biohermal; calcimicrobes such as *Epiphyton* and *Girvanella*; sessile metazoans like sponges	Formed by blotchy microbial masses; trapping and baffling of carbonate grains; low- to intermediate- energy subtidal environment
Stromatolite (ST)	Finely to thickly laminated convex-up mat encrusting various sediments (Fig. 9r); finely laminated by alternation of different-colored micrite; occasional presence of filamentous calcimicrobe, *Girvanella* in laminae; thick laminae with various sand-sized skeletal and glauconitic grains trapped between laminae; either flat, domal, LLH, or columnar in shape	Encrustation of microbial film or mat over substrates; trapping and binding sediments with contribution of microbially induced calcite cementation; intertidal to subtidal
Dendrolite (DN)	Columnar and digitate dense dark micritic masses (Fig. 9s); mixture of shaly material and coarse skeletal peloidal grains among the columns; concave-up stratification in pack-grainstone among the columns	Rapid growth of microbial colony with branching morphology which baffles coarse-grained sediments; higher-energy shallow subtidal conditions
Epiphyton framestone (EP)	Forming meter scale buildups (Fig. 9t); stacked or coalescent thick buildup and isolated in muddy sediment; association with coarse debris from the buildup	Shallow marine platform margin setting

4.4. Zhangxia Formation

A thick limestone succession overlying the shale-dominated unit of the Mantou Formation was referred to the Zhangxia Formation by Blackwelder and Willis (1907) in the Jinan area. BGMRSP (1996) proposed the subdivision of the Zhangxia Formation into the Lower-Limestone, Panchegou (shale-dominated), and Upper-Limestone members (Fig. 3). BGMRSP (1996) recognized four biozones: *Lioparia*, *Crepicephalina*, *Amphoton-Taitzuia*, and *Yabeia* zones in ascending order. For the uppermost part of the formation, however, the traditional *Damesella-Yabeia* Zone (Zhang and Jell, 1987) is preferable, since *Damesella* commonly occurs from the upper part of the Zhangxia Formation (Fig. 2).

This study basically follows the BGMRSP's (1996) tripartite lithostratigraphic scheme, with refinement of the lithologic characteristics and modification in member names deleting the lithologic modifiers. The Lower Member is dominated by oolite (facies O) and lesser amounts of microbial carbonates (facies TH, DN, EP, and ST). In the Beiquanzi section, it is about 65 m thick and characterized by a thick oolite bed (facies O) in which microbe-metazoan bioherms (facies TH and EP) were locally developed (Figs. 5b and 12). A finer-grained interval of bioturbated wackestone (facies Wb) occurs in the lower part of the member. This member thins eastward to about 40 m in the Jiulongshan section. It consists of a thick oolite bed (facies O) at the base and biohermal thrombolite and oolite (facies TH and O) in the upper part. A thin and continuous shale layer (facies Sh) occurs in the Jiulongshan section between the lowermost oolite (facies O) and the overlying thrombolite beds (facies TH) (Figs. 6 and 13). This member is overlain directly by microbialite-dominated carbonate succession of the Upper Member in the western part (Beiquanzi section), whereas it is abruptly overlain by the shale-dominated Panchegou Member in the eastern part (Jiulongshan section). The Lower Member involves *Lioparia* Zone in Beiquanzi section, whereas it includes *Lioparia* and *Crepicephalina* zones in Jiulongshan section.

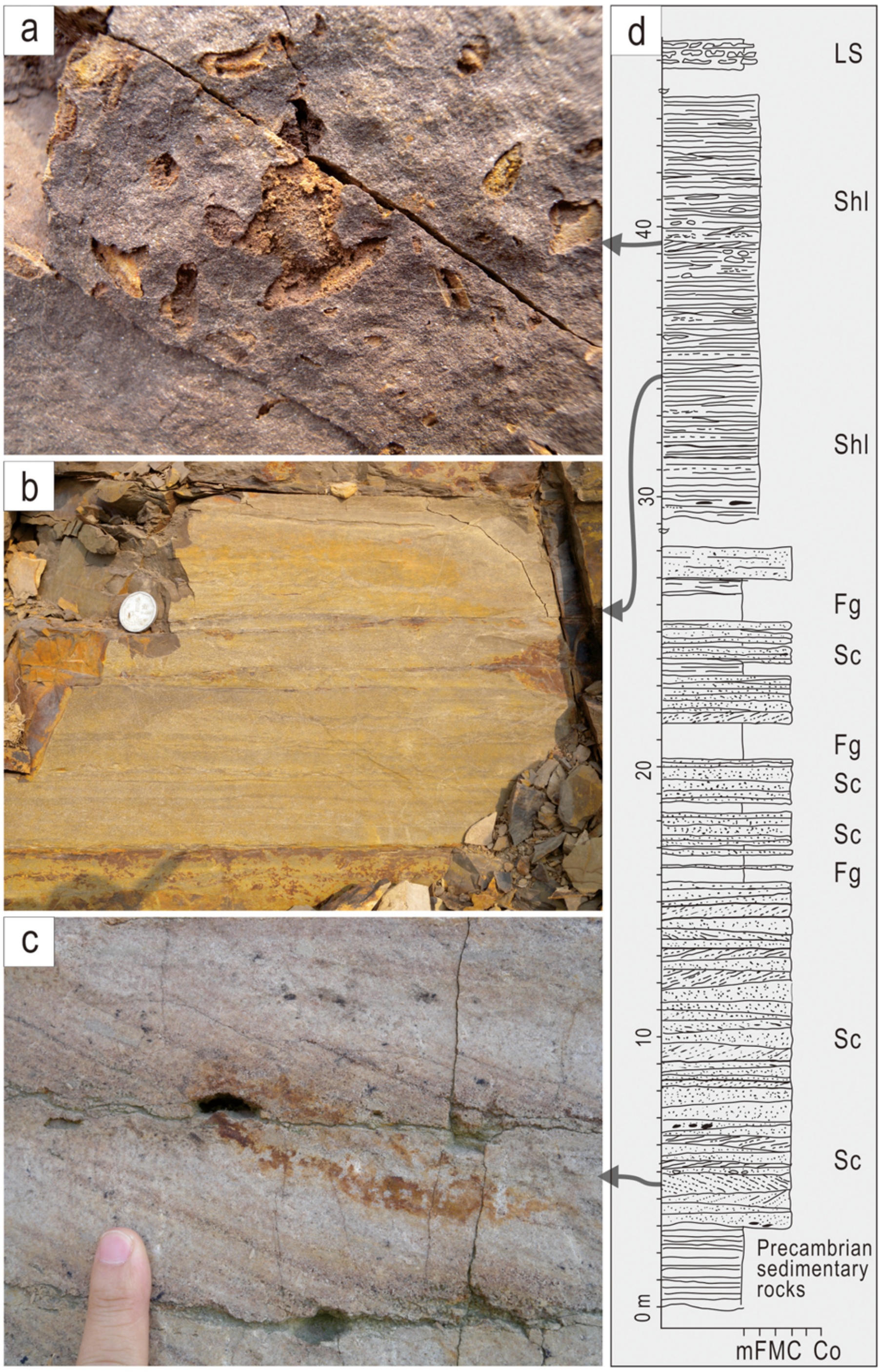

Fig. 10. Photograph and sedimentary log of the Jinhe section in the southwest Linyi area. (a) Laminated gray fine sandstone with trilobite fragments. (b) Discontinuous lamination in fine sandstone. (c) Crudely cross-stratified medium sandstone with abundant quartz. (d) Composite sedimentary log of the Liguan Formation in the Jinhe section. m = mudstone, F = fine sandstone, M = medium sandstone, C = coarse sandstone, Co = conglomerate. For facies code, see Tables 1 and 2.

The Panchegou Member, about 100 m thick in the Jiulongshan section, consists predominantly of shale (facies Sh and LS) and thin limestone of calcarenite/calcirudite (facies CA). It pinches out in the western part of Shandong Province. The member contains relatively thick limestone beds of skeletal grainstone (facies Gptc) and small-scale microbial bioherms (about 50 cm in height) in the lower part. The thickness and grain size of the intercalated limestone beds increase upward (Figs. 6e and 13). The base of the first continuous thrombolite bed marks the upper boundary of the member. Panchegou Member yields trilobite fauna of *Amphoton-Taitzuia* Zone.

The Upper Member in the Beiquanzi section (about 120 m thick) is composed mostly of microbial carbonates (facies TH, EP, DN, and ST) and lesser amounts of oolite (facies O), whereas that in the Jiulongshan section, about 50–60 m thick, is characterized by limestone-shale alternation, microbial carbonates, and oolite (facies LS, TH, EP, and O).

Table 3. Constituent facies of lithostratigraphic units and trilobite biozones

Fm.[a]	Mbr.[b]	Constituent lithofacies: Jinan area[e]	Constituent lithofacies: Jiulongshan section	Trilobite biozones	GA[c]
Chaomidian	Upper	Bioturbated wackestone (Wb) Wackestone to grainstone (WG) Gravelly grainstone (Gg) Limestone and shale alternation (LS)	Bioturbated wackestone (Wb) Wackestone to grainstone (WG) Gravelly grainstone (Gg) Columnar stromatolite (ST) Limestone and shale alternation (LS)	*Mictosaukia* *Quadraticephalus*	Furongian
	Lower	Planar and trough cross-stratified grainstone (Gptc) Hummocky and swaley cross-stratified grainstone (Ghsc) Thrombolite (TH) Thin-bedded lime mudstone (Ltb) Limestone and shale alternation (LS) Shale (Sh)	Planar and trough cross-stratified grainstone (Gptc) Hummocky and swaley cross-stratified grainstone (Ghsc) Thrombolite (TH) Thin-bedded lime mudstone (Ltb) Limestone and shale alternation (LS) Shale (Sh)	*Ptychaspis-Tsinania* *Kaolishania* *Changshania-Irvingella* *Chuangia*	
Gushan		Planar and trough cross-stratified grainstone (Gptc) Cross-stratified limestone conglomerate (Cs) Laminated calcisiltite (Cl) Limestone pseudoconglomerates (Cp) Limestone and shale alternation (LS) Shale (Sh)	Cross-stratified limestone conglomerate (Cs) Laminated calcisiltite (Cl) Limestone and shale alternation (LS) Calcarenite (CA) Limestone and shale alternation (LS) Shale (Sh)	*Neodrepanura* *Blackwelderia*	Cambrian Series 3
Zhangxia[d]	Upper	Thrombolite (TH) Dendrolite (DN) Planar and trough cross-stratified grainstone (Gptc) *Epiphyton* framestone (EP) Oolitic packstone to grainstone (O) Stromatolite (ST)	Thrombolite (TH) *Epiphyton* framestone (EP) Limestone and shale alternation (LS) Planar and trough cross-stratified grainstone (Gptc)	*Damesella-Yabeia* *Amphotom-Taitzuia* *Crepicephalina* *(Damesella-Yabeia)*	
	Panchegou	–	Shale (Sh) Calcarenite (CA) Limestone and shale alternation (LS)	*(Amphotom-Taitzuia)*	
	Lower	Thrombolite (TH) Oolitic packstone to grainstone (O) Bioturbated wackestone facies (Wb)	Thrombolite (TH) Planar and trough cross-stratified grainstone (Gptc) Dendrolite (DN) Oolitic packstone to grainstone (O)	*Lioparia* *(Crepicephalina* *Lioparia)*	
Mantou	Upper	Homogeneous purple mudstone (Fh) Dark purple mudstone and sandstone alternation (Fp) Planar and trough cross-stratified sandstone (Sx) Limestone pseudoconglomerates (Cp)	Oolitic packstone to grainstone (O) Dark purple mudstone and sandstone alternation (Fp) Hummocky and swaley cross-stratified sandstone (Shs) Planar and trough cross-stratified sandstone (Sx) Shale (Sh) Planar and trough cross-stratified grainstone (Gptc) Thrombolite (TH) Oolitic packstone to grainstone (O)	*Bailiella* *Poriagraulos* *Sunaspis* *Ruichengaspis* *Hsuchuangia-Ruichengella* *Shantungaspis* *Yaojiayuella*	
	Lower	Laminated purple mudstone (Fl) Laminated dolomudstone (Dl) Stromatolite (ST) Homogeneous purple mudstone (Fh) Irregular laminated mudstone to fine sandstone (Fi)	Homogeneous purple mudstone (Fh) Laminated purple mudstone (Fl) Oolitic packstone to grainstone (O) Limestone and shale alternation (LS) Hummocky and swaley cross-stratified sandstone (Shs) Irregular laminated mudstone to fine sandstone (Fi)	*Redlichia chinensis*	Cambrian Series 2
Zhushadong		Laminated dolomudstone (Dl) Stromatolite (ST) Paleosol (P) Liangcheng section Bioturbated wackestone (Wb) Laminated dolomudstone (Dl) Stromatolite (ST) Paleosol (P)	Oolitic packstone to grainstone (O) Laminated dolomudstone (Dl) Stromatolite (St) Paleosol (P)		
Liguan		Jinhe section Homogeneous gray mudstone (Fg) Horizontally laminated fine sandstone (Sh) Crudely cross-stratified sandstone (Sc)			

[a]Fm. = Formation, [b]Mbr. = Member, [c]GA = Geologic Age.
[d]Biozones of the Zhangxia Formation in parenthesis are for the Jiulongshan section.
[e]Jinan area includes Mantoushan, Liantaishan, Beiquanzi, Tangwangzhai, and Fanzhuang II sections.

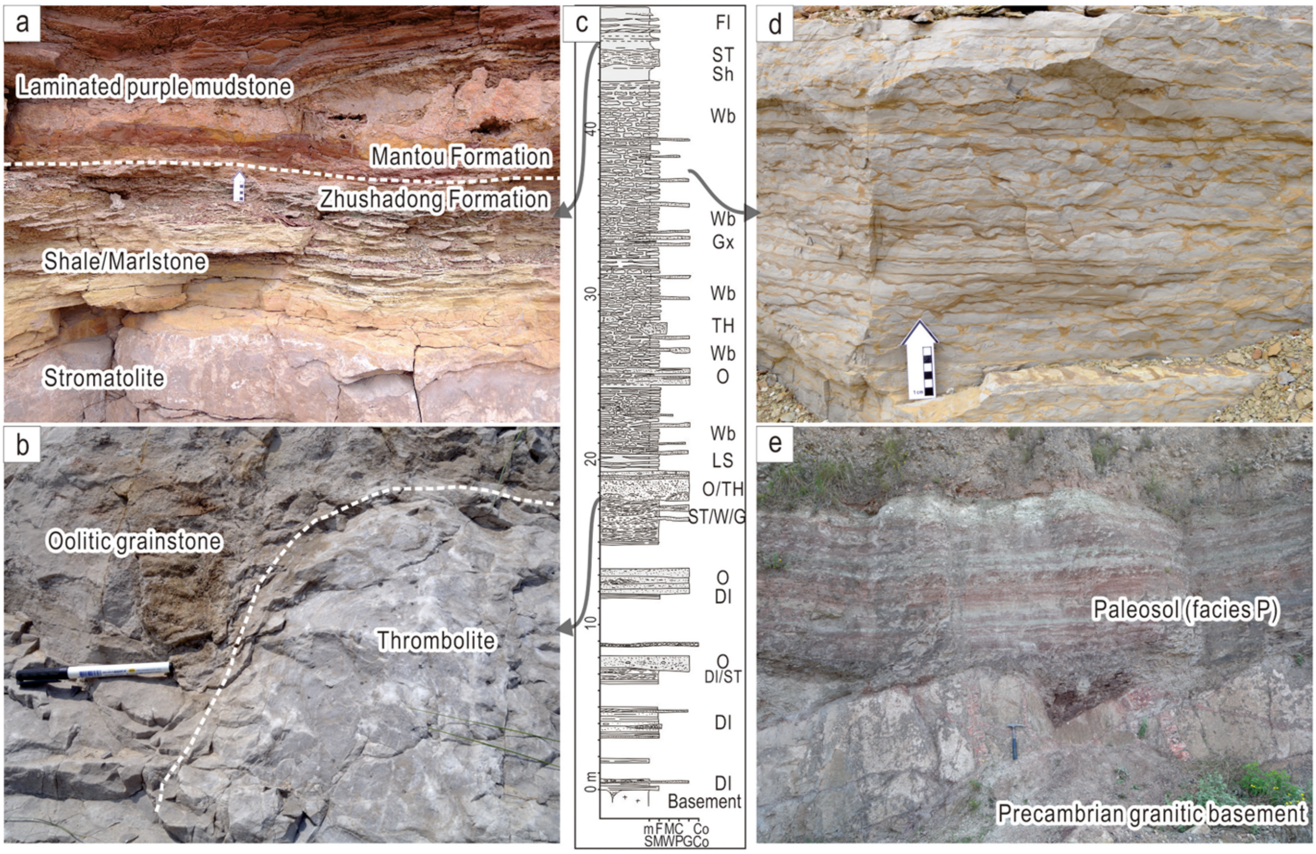

Fig. 11. Photograph and sedimentary log of the Liangcheng section in the southeast Jining area. (a) The boundary between the Zhushadong and Mantou formations. (b) Thrombolite mound intercalated with oolitic grainstone. (c) Sedimentary log of the Zhushadong Formation in the Liangcheng section. m = mudstone, F = fine sandstone, M = medium sandstone, C = coarse sandstone, Co = conglomerate; S = shale, M = lime mudstone, W = wackestone, P = packstone, G = grainstone, Co = conglomerate. (d) Bioturbated wackestone interlayered with yellowish shale. (e) A thick paleosol that covers the Precambrian basement. This bed pinches out in short distances (ca. 500 m). For facies code, see Tables 1 and 2.

Microbial carbonates in the Beiquanzi section include more facies (facies TH, DN, EP, and ST) and tend to be biostromal (Fig. 12). The uppermost part of the Zhangxia Formation in this section is characterized by oolitic and skeletal packstone to grainstone (facies O and Gptc) which is partly rich in glauconite. The Upper Member in the Jiulongshan section is characterized by distinct layers of ovoid or domal microbial bioherm (facies TH and EP) embraced by shaly sediments (Fig. 13). The uppermost unit of the Zhangxia Formation in the Jiulongshan section is characterized by light-colored thin-bedded skeletal lime mudstone and wackestone intercalated with thin lenses of packstone to grainstone (facies WP). The Upper Member in Beiquanzi section includes *Crepicephalina*, *Amphoton-Taitzuia*, and *Damesella-Yabeia* zones, whereas it contains only *Damesella-Yabeia* Zone in Jiulongshan section. A sharp boundary between the Zhangxia and Gushan formations is marked by an abrupt lithologic change from the limestone (facies Gptc, O, WG, and WP) of the uppermost Zhangxia Formation to shale (facies Sh) of the Gushan Formation.

4.5. Gushan Formation

The Gushan Formation was originally designated as a thick shale unit overlying the Zhangxia Formation in the Tangwangzhai section (Blackwelder and Willis, 1907). The upper boundary of the Gushan Formation was placed at disappearance of shale. This boundary was not easily recognizable because of the gradual change from shale to limestone and the severe weathering of the shale. The formation is redefined herein as the shale-dominant unit sharply underlain by the Zhangxia Formation and overlain by a distinct bioclastic grainstone bed of the Chaomidian Formation.

The lower part of the Gushan Formation consists mainly of the alternation of purple shale and greenish-grey to yellowish shale (facies Sh) with calcareous nodules. Several beds of limestone pseudoconglomerate and calcarenite (facies Cp and CA) are intercalated in the limestone-shale/marlstone alternations (facies LS) in the middle part. Limestone pseudoconglomerate beds are discontinuous and often pinch out in short distances. Some calcarenite beds show flame and

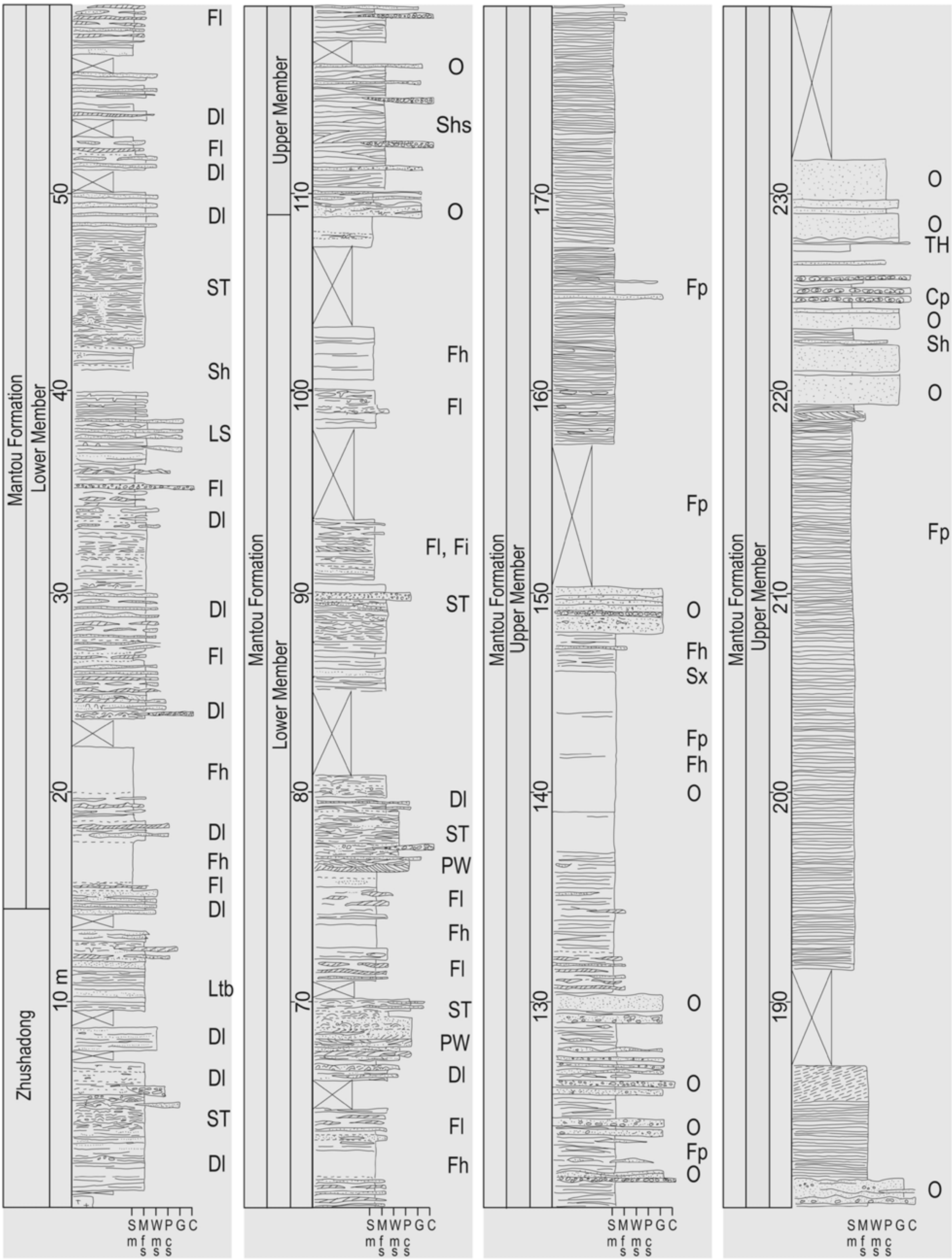

Fig. 12. Sedimentary log of the Cambrian succession in the Jinan area. S = shale, M = lime mudstone, W = wackestone, P = packstone, G = grainstone, C = conglomerate; m = mudstone, fs = fine sandstone, ms = medium sandstone, cs = coarse sandstone. For facies code, see Tables 1 and 2.

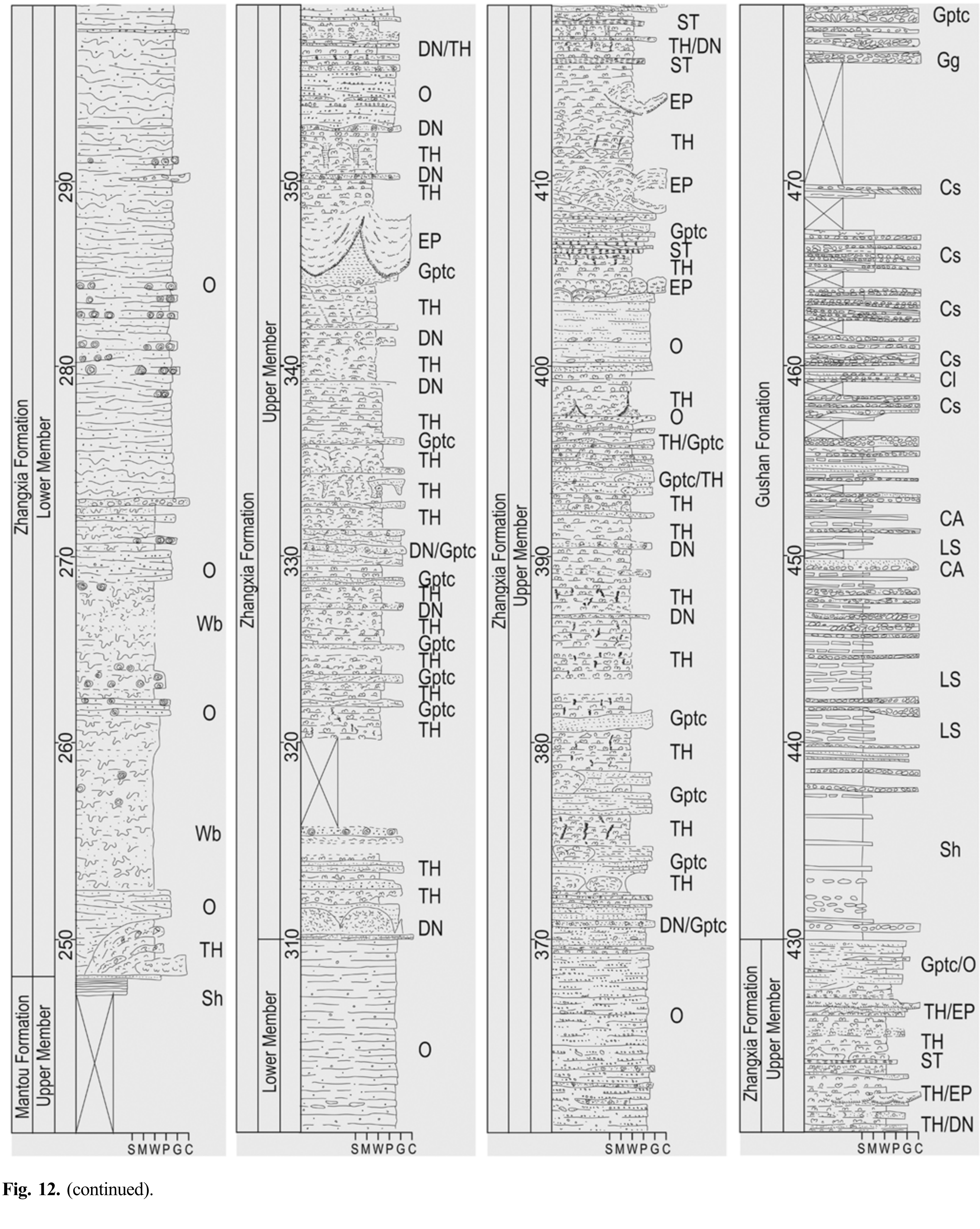

Fig. 12. (continued).

loading structures as well as normal grading. The upper part of the Gushan Formation consists of more carbonate deposits and lesser shale than the lower part (Figs. 12 and 13). Faintly laminated calcisiltite (facies Cl) is dominated and is commonly bioturbated with mottled texture. Cross-stratified fine-pebble conglomerate beds (facies Cs) with undu-

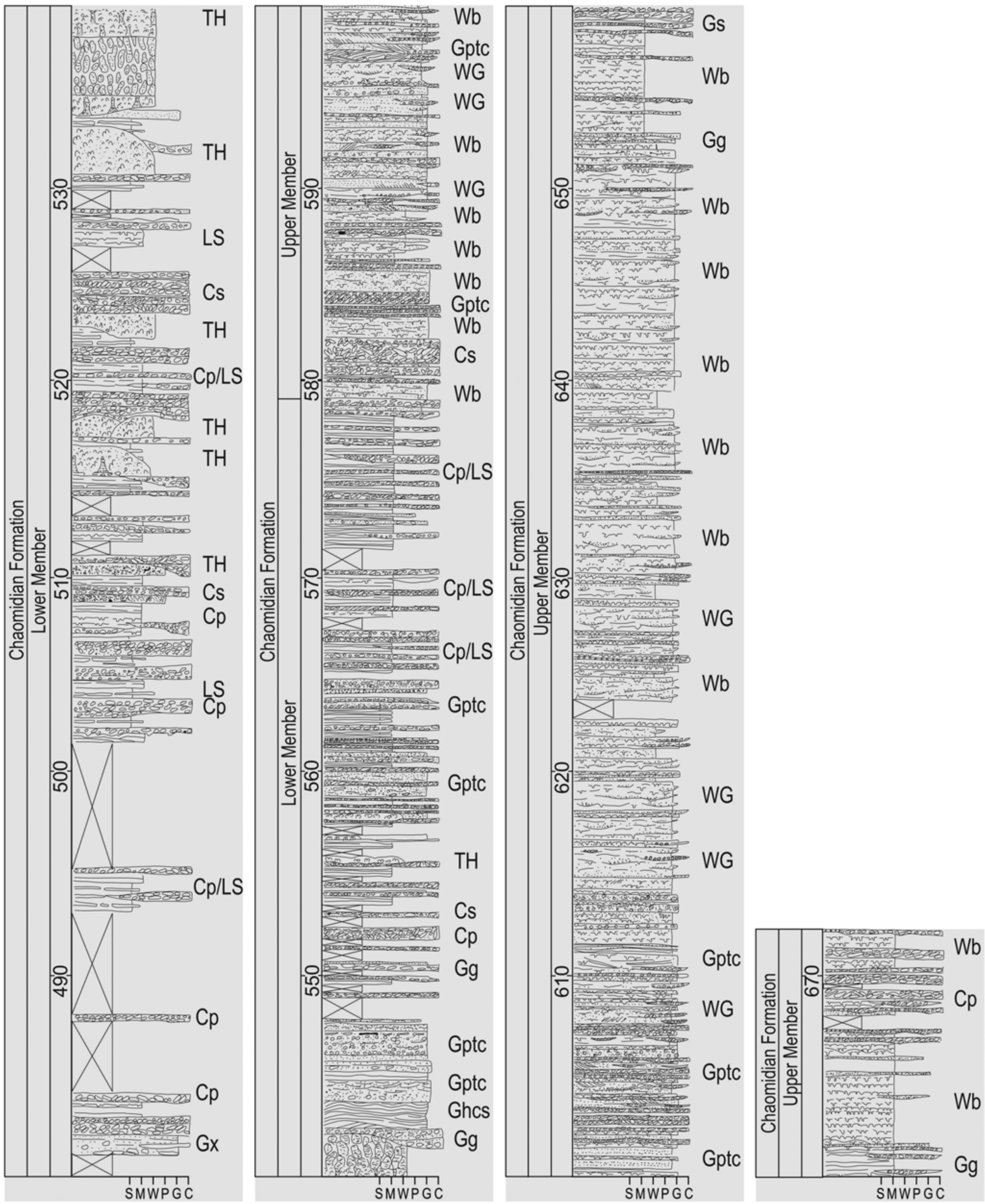

Fig. 12. (continued).

latory bedforms (mega-ripple or dune) are intercalated within calcisiltite facies. A few oolitic grainstone beds (facies Gptc) occur in the uppermost part. The upper boundary of the Gushan Formation is placed at the base of an extensive,

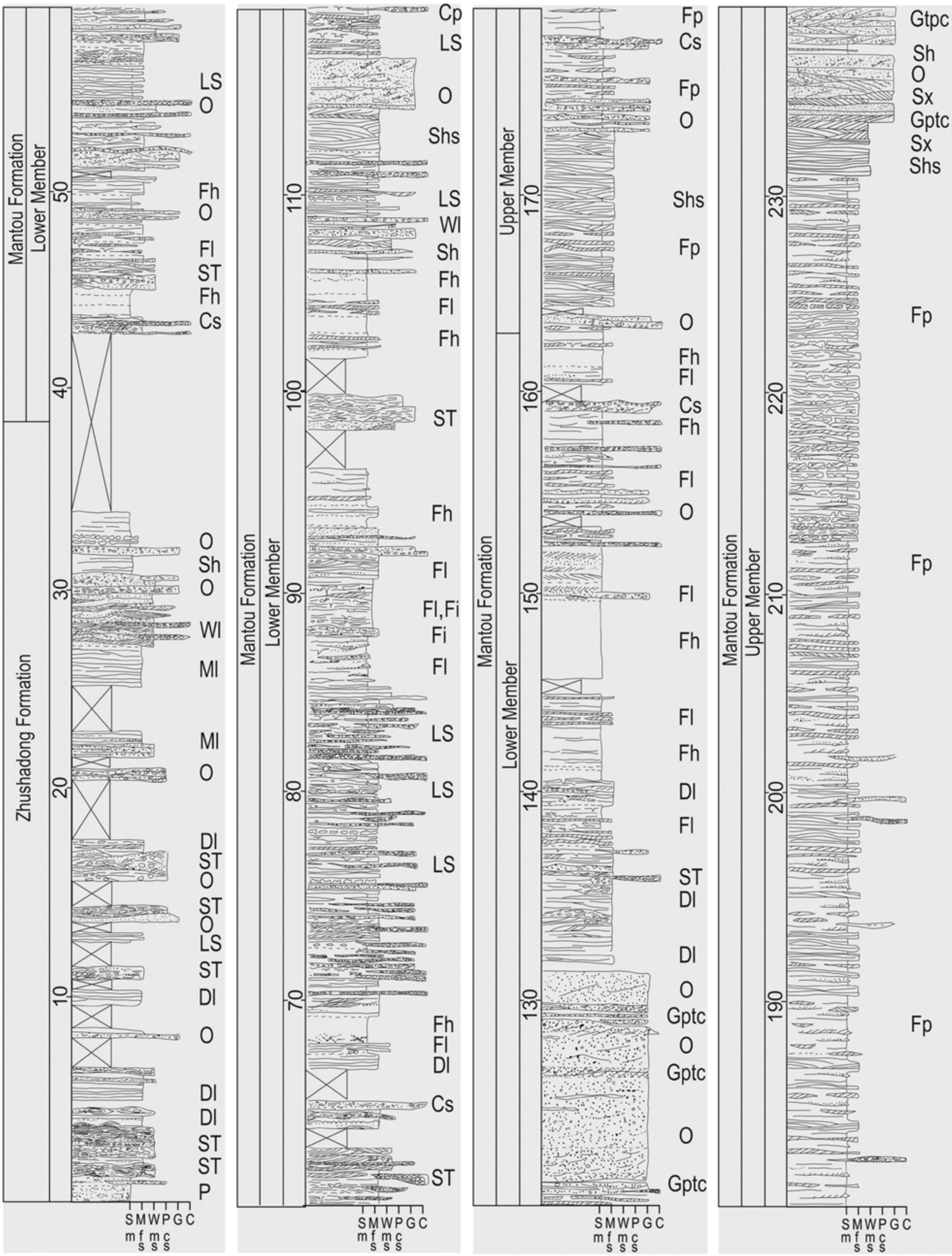

Fig. 13. Sedimentary log of the Cambrian succession in the Jiulongshan section, Laiwu area. S = shale, M = lime mudstone, W = wackestone, P = packstone, G = grainstone, C = conglomerate; m = mudstone, fs = fine sandstone, ms = medium sandstone, cs = coarse sandstone. For facies code, see Tables 1 and 2.

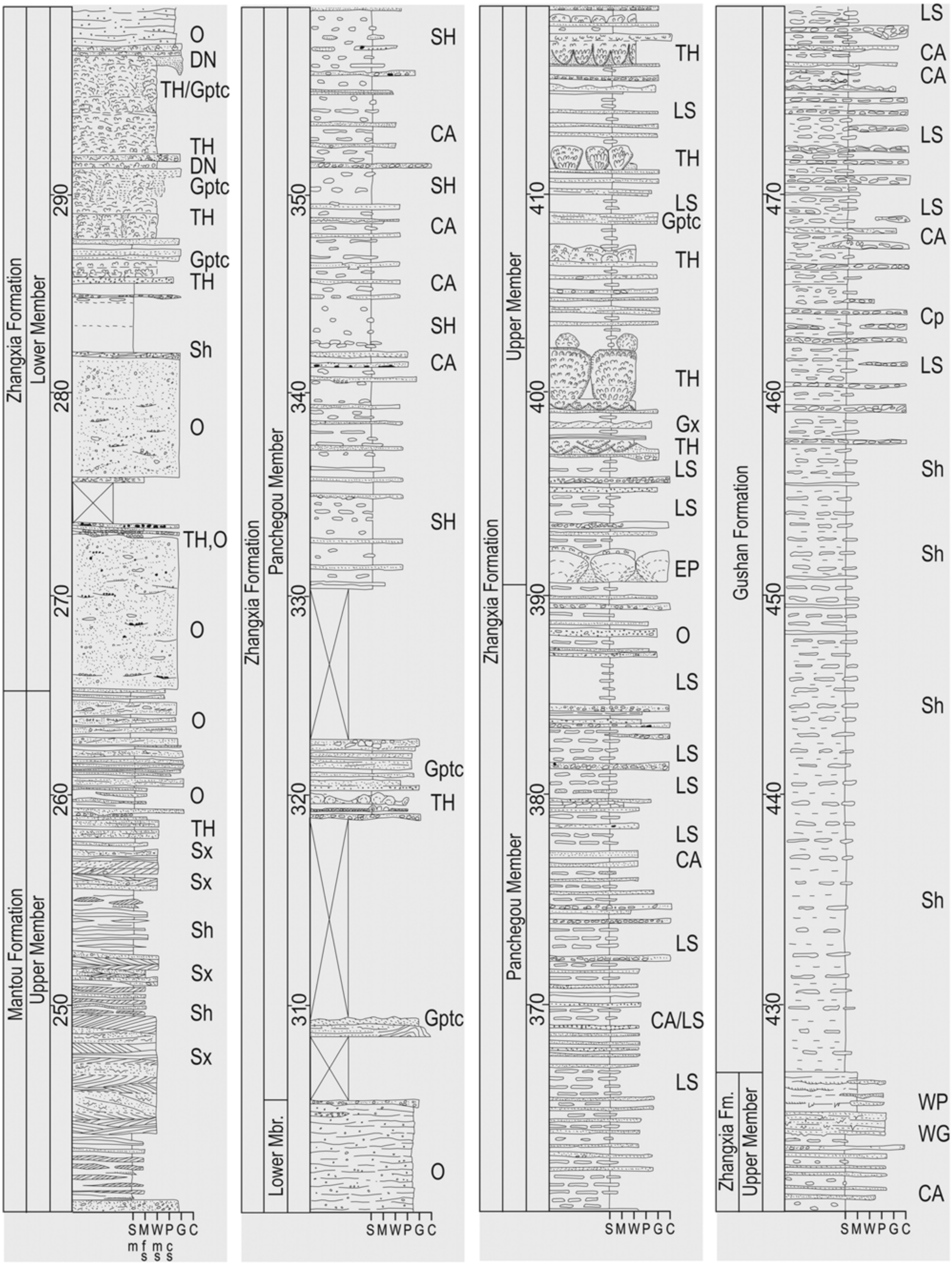

Fig. 13. (continued).

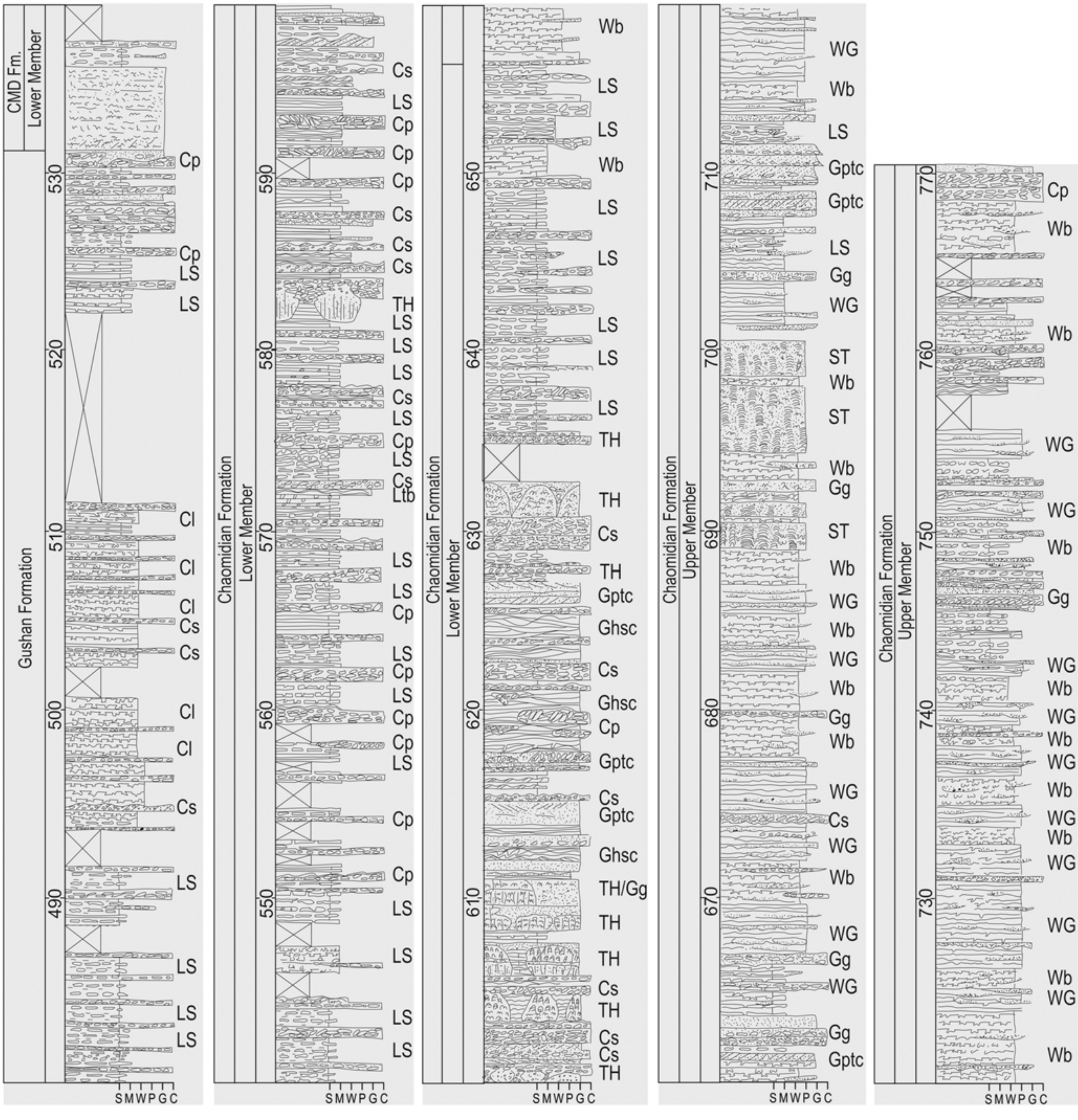

Fig. 13. (continued).

relatively thick (0.6–4.5 m) bioclastic grainstone bed (Figs. 12 and 13). The thickness of the Gushan Formation is highly variable, 105 m in the Jiulongshan section and 52 m in the Tangwangzhai section (Figs. 12 and 13).

The Gushan Formation contains the *Blackwelderia* and *Neodrepanura* zones of the Kushanian stage (Zhang and Jell, 1987). The overlying *Chuangia* and *Changshania-Irvingella* zones were included in the upper part of the formation (BGMRSP, 1996). In this study, however, the base of the overlying Chaomidian Formation is redefined at the first occurrence of a thick bioclastic grainstone bed which yields *Chuangia*. Hence, the *Chuangia* and *Changshania-Irvingella* zones are included in the overlying Chaomidian Formation. The base of the *Blackwelderia* Zone was considered equivalent to the base of the Gushan Formatoin (Zhang and Jell, 1987). According to the recent study by Park et al. (2008), however, the lower 40 m interval of the Gushan Formation at the Jiulongshan section yields *Dame-*

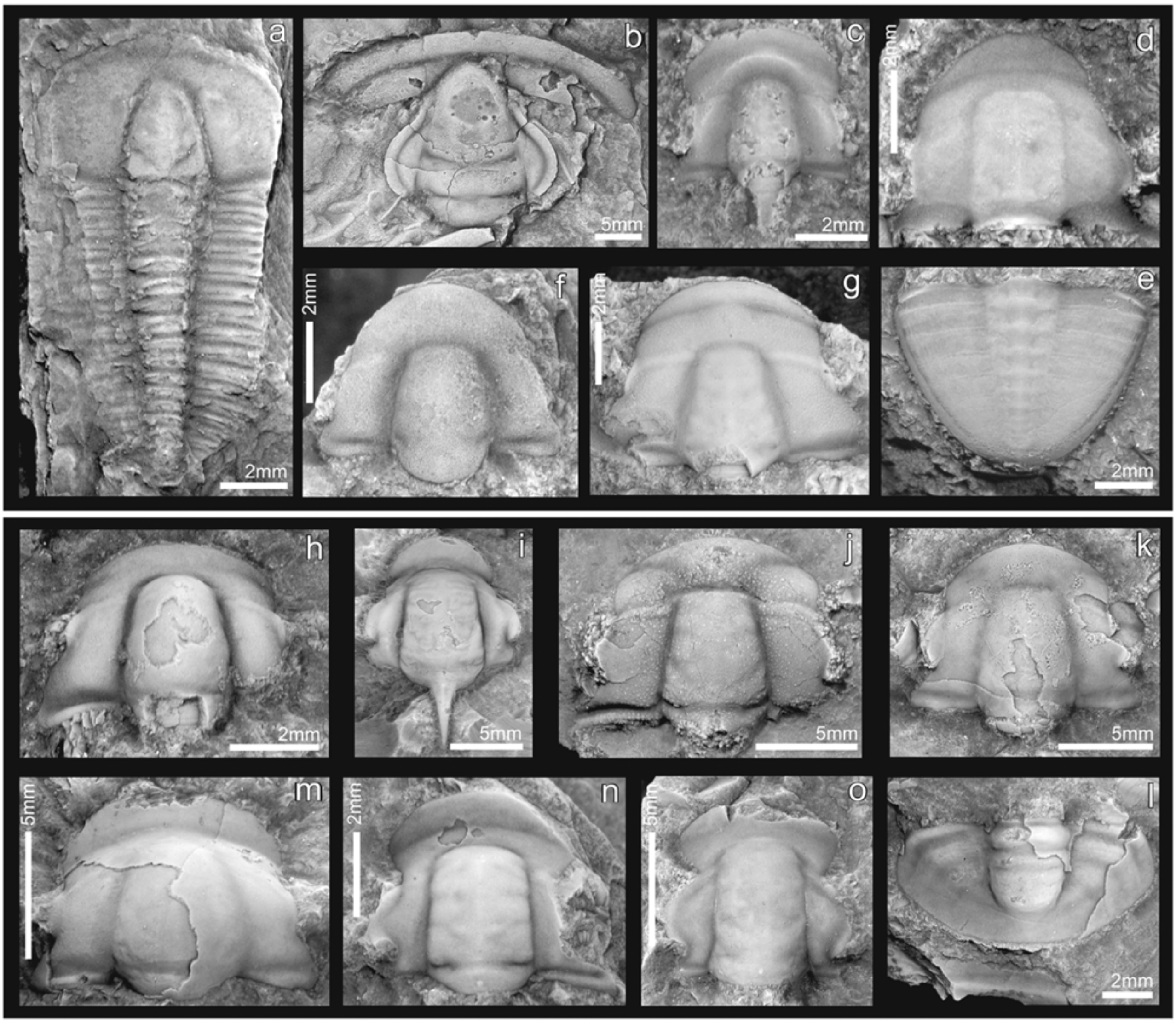

Fig. 14. Representative trilobites from the Mantou and Zhangxia formations. (a–g) trilobites from the Mantou Formation. (a) A complete specimen of *Bailiella* sp., Liantaishan section, SNUP5094. (b) *Redlichia chinensis* Walcott, 1905, cranidium, Jiulongshan section, SNUP5095. (c) *Lorenzella* sp., cranidium, Jiulongshan section, SNUP5096. (d–e) *Sunaspis* sp.; (d) cranidium, Liantaishan section, SNUP5097.; (e) pygidium, Jiulongshan section, SNUP5098. (f) *Ruichengaspis* sp., cranidium, Jiulongshan section, SNUP5099. (g) *Yaojiayuella granosa* (Walcott, 1905), cranidium, Jiulongshan section, SNUP5100. (h–o) trilobites from the Zhangxia Formation. (h) *Yabeia tutia* (Walcott, 1905), cranidium, Jiulongshan section, SNUP5101. (i) *Platylisania* sp., cranidium, Jiulongshan section, SNUP5102. (j) *Poshania* sp., cranidium, Jiulongshan section, SNUP5103. (k–l) *Megagraulos* sp.; (k) cranidium, Jiulongshan section, SNUP5104.; (l) pygidium, Jiulongshan section, SNUP5105. (m) *Liopeishania* sp., cranidium, Jiulongshan section, SNUP5106. (n) *Proasaphiscus* sp., cranidium, Jiulongshan section, SNUP5107. (o) *Anomocarella* sp., cranidium, Jiulongshan section, SNUP5108.

sella (Fig. 15g), whereas *Blackwelderia* was not recognized from the interval. The lower part of the Gushan Formation, therefore, should include the *Damesella-Yabeia* Zone, which extends from the upper part of the Zhangxia Formation (Fig. 2). A detailed biostratigraphic revision from the upper part of the Zhangxia Formation to the Gushan Formation has yet to be made. The overlying *Neodrepanura* Zone was originally known as the *Drepanura* Zone (Lu and Dong, 1953; Zhang and Jell, 1987; BGMRSP, 1996). However, *Drepanura* Bergeron, 1899 was preoccupied by a collembolan insect and *Neodrepanura* Özdikmen, 2006 was proposed as the replacement, hence the new biozone name, *Neodrepanura* Zone, is adopted herein.

4.6. Chaomidian Formation

A thick succession of limestone-dominated interval overlying the Gushan Formation was defined as the Chaomidian Limestone in the Tangwangzhai and Fanzhuang sections by Blackwelder and Willis (1907). Sun (1924, 1935) recog-

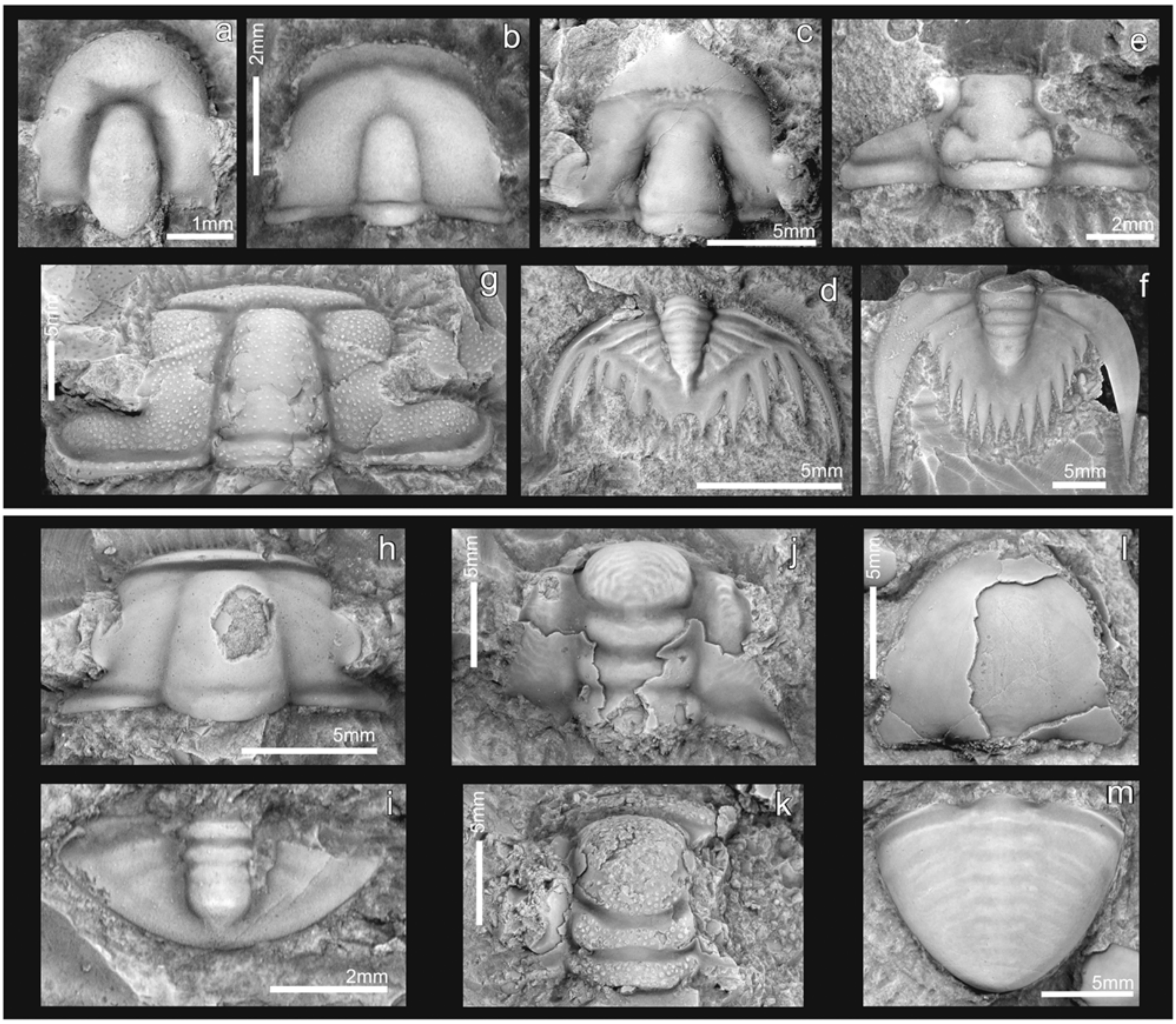

Fig. 15. Representative trilobites from the Gushan and Chaomidian formations. (a–g) trilobites from the Gushan Formation. (a) *Jiulongshania acalle* (Walcott, 1905), cranidium, Tangwangzhai section, SNUP5024. (b) *Liostracina* sp., cranidium, Tangwangzhai section, SNUP5109. (c–d) *Shantungia spinifera* Walcott, 1905; (c) cranidium, Tangwangzhai section, SNUP5093.; (d) pygidium, Tangwangzhai section, SNUP5110. (e–f) *Neodrepanura premesnili* (Bergeron, 1899); (e) cranidium, Tangwangzhai section, SNUP5111.; (f) pygidium, Tangwangzhai section, SNUP5112. (g) *Damesella* sp., cranidium, Jiulongshan section, SNUP5113. (h–m) trilobites from the Chaomidian Formation. (h–i) *Chuangia batia* (Walcott, 1905); (h) cranidium, Jiulongshan section, SNUP5114.; (i) pygidium, Jiulongshan section, SNUP5115. (j) *Asioptychaspis* sp., cranidium, Tangwangzhai section, SNUP5116. (k) *Mictosaukia* sp., cranidium, Fanzhuang section, SNUP5117. (l–m) *Tsinania canens* (Walcott, 1905); (l) cranidium, Tangwangzhai section, SNUP5118.; (m) pygidium, Tangwangzhai section, SNUP5119.

nized lateral variations in lithology of the upper part of the Chaomidian Formation and defined the Orthocerida Layer in the Jinan area and the Kaolishan Layer in the Taian area (see Fig. 1 for regions). Lu and Dong (1953) established the Changshan Series in the lower part of the formation and the Fengshan Series in the upper part. CECG & GICAS (1956) used 'Formation' instead of 'Series' in order to establish lithostratigraphic units. BGMRSP (1996) combined these two formations into the Chaomidian Formation as the uppermost lithostratigraphic unit of the Cambrian succession.

The Chaomidian Formation comprises various carbonate facies such as limestone-shale alternation, microbialite, grainstone, limestone conglomerate, and wackestone to packstone (facies LS, TH, Gptc, Ghsc, Cs, Cp, Wb, and WG). It can be divided into two members (Figs. 12 and 13). The lithofacies in both Jinan and Laiwu areas are similar to each other, although the formation is slightly thicker in the Jiulongshan section. The Lower Member (ca. 104–120 m thick) consists of thin-bedded limestones such as limestone-shale/marlstone alternation, thin-bedded lime mudstone, laminated calcisiltite, and limestone conglomerates (facies LS, Ltb, Cl, Cs, and Cp), and thick beds of microbialites (facies Th; ca. 10 m thick) and grainstones (facies Gg, Gptc, and Ghsc; 10–20 m thick). The Upper Member (ca. 89–120 m thick) is characterized by a thick monotonous succession of bioturbated wackestone and wackestone to grainstone (facies Wb and WG) with lesser amounts of limestone-shale alternation, gravelly grainstone, planar and trough cross-stratified grainstone, and limestone conglomerate (facies LS, Gg, Gptc, and Cs). An 11-m-thick interval of columnar stromatolites (facies ST) occurs in the middle part of the Upper Member in Jiulongshan section (Fig. 13), whereas it is absent in the Jinan area. The Chaomidian Formation changes gradationally into the Ordovician Sanshanzi Formation, which is characterized by dolostone with obliterated primary structures.

The Chaomidian Formation, based on the revised lithostratigraphy, includes six trilobite biozones: the *Chuangia*, *Changshania*-*Irvingella*, *Kaolishania*, *Ptychaspis*-*Tsinania*, *Quadraticephalus*, and *Mictosaukia* zones in ascending order (Fig. 2) (Zhang and Jell, 1987). The *Chuangia*, *Changshania*-*Irvingella*, and *Kaolishania* zones represent the Changshanian Stage. The latter three biozones constitute the Fengshanian Stage. The base of the Changshanian Stage in the North China Platform is correlated with the base of the Furongian Series based on the stable isotope excursion (SPICE) identified at the Tangwangzhai section (Zhu et al., 2004). Recently, Sohn and Choi (2007) noted that all the species from North China and Korea assigned to *Ptychaspis* are morphologically distinct from the species of *Ptychaspis* from Laurentia, and transferred them to *Asioptychaspis* Kobayashi, 1935. They proposed the *Asioptychaspis* Zone in Korea and correlated it with the *Ptychaspis*-*Tsinania* Zone of North China. So far, only *Asioptychaspis*-form (Fig. 15j) has been discovered from Shandong Province. A detail biostratigraphic research on the Chaomidian Formation may result in the change of the biozone name, the *Ptychaspis*-*Tsinania* Zone to the *Asioptychaspis*-*Tsinania* Zone.

5. SUMMARY

The Cambrian succession in Shandong Province can be subdivided into six lithostratigraphic units i.e., Liguan, Zhushadong, Mantou, Zhangxia, Gushan, and Chaomidian formations in ascending order (Table 3). The Liguan Formation, unconformably overlying the Sinian metasedimentary rocks, occurs only in southeastern Shandong Province (e.g., Linyi area) and consists mainly of quartzose sandstone and laminated mudstone. The Zhushadong Formation is characterized by laminated dolomudstone, stromatolite, and bioturbated wackestone. It formed during the late Tsanglangpuan Stage and the early Lungwangmiaoan Stage of the Cambrian Series 2. The first occurrence of purple mudstone bed marks the base of the Mantou Formation which is divided into the Lower and Upper members. The Lower Member is dominated by laminated dolomudstone, microbial laminite, and purple mudstone. It contains the *Redlichia chinensis* Zone of the Cambrian Series 2. The Upper Member comprises cross-stratified grainstone, dark purple mudstone-sandstone alternation, and hummocky cross-stratified sandstone. It contains the *Yaojiayuella, Shantungaspis, Hsuchuangia-Ruichenpella, Ruichengaspis, Sunaspis, Poriagraulos,* and *Bailiella* zones which are indicative of the Cambrian Series 3. The Zhangxia Formation is subdivided into three members. The Lower Member is characterized by the dominance of thick oolitic grainstone beds with trilobite fauna of *Lioparia* Zone in Beiquanzi section and *Lioparia* and *Crepicephalina* zones in Jiulongshan section. The Panchegou Member in the middle part is dominated by shale with alternating thin beds of limestone and occurs only in southeastern Shandong Province (e.g., Laiwu area). The member involves *Amphoton-Taitzuia* Zone. The Upper Member consists mainly of microbial carbonates with regional variations in morphology and yields trilobites of the *Crepicephalina*, *Amphoton-Taitzuia*, and *Damesella-Yabeia* zones in Beiquanzi section and those of the *Damesella-Yabeia* Zone in Jiulongshan section. The *Damesella-Yabeia* Zone straddles the boundary between Zhangxia and Gushan formations. The Gushan Formation comprises mainly shale and thin-bedded limestones, and includes the *Blackwelderia* and *Neodrepanura* zones. The base of the Chaomidian Formation is suggested at the base of an extensive (0.6–4.5 m thick) bioclastic grainstone bed. The boundary also represents the base of the Changshanian Stage, the first stage of the Furongian Series. The Chaomidian Formation is further divided into the Lower and Upper members. The Lower Member is dominated by thin-bedded limestone, limestone conglomerate, microbialite, and grainstone. It contains the *Chuangia, Changshania-Irvingella*, *Kaolishania*, and *Ptychaspis-Tsinania* zones. The Upper Member is represented by a monotonous succession of bioturbated wackestone to grainstone with the *Quadraticephalus* and *Mictosaukia* zones, and is conformably overlain by the Ordovician Sanshanzi Formation.

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REFERENCES

Bergeron, J.N., 1899, Étude geologique du massiv ancien situe au Sud du Plateau Central. Annales Scientifique Geology, 22, 333–337. (in French)

Blackwelder, E. and Willis, B., 1907, Stratigraphy of Shantung. In: Willis, B., Blackwelder, E., and Sargent, R.H. (eds.), Descriptive Topography and Geology. Research in China, Vol. 1. Pt. 1. Carnegie Institution of Washington, Publication, 54. 19–58

Bureau of Geology and Mineral Resources of Shandong Province (BGMRSP), 1996, Stratigraphy (Lithostratigraphic) of Shandong Province. China University of Geoscience Press, Beijing, 328 p. (in Chinese)

China Editorial Committee of Geology and Geological Institute of China Academy of Science (CECG & GICAS), 1956, Table of China Regional Strata (draft). Science Press, Beijing, 693 p. (in Chinese)

Chough, S.K., Kwon, S.-T., Ree, J.-H., and Choi, D.K., 2000, Tectonic and sedimentary evolution of the Korean Peninsula: a review and new view. Earth-Science Reviews, 52, 175–235.

Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture. p. 108–121. In: Ham, W.E. (ed.), Classification of carbonate rocks. AAPG Memoir, No. 1, Tulsa, 108–121.

Feng, J. and Zhang, B., 1951, Report of geological and mineralogical investigation in west Henan Province. Institute of Geological Investigation of Henan Province, Zhengzhou. (in Chinese)

Liang, Z., 1980, On the Lower Cambrian "Wushan Formation" in the central and southern parts of Shandong Province. Journal of Stratigraphy, 4, 282–287. (in Chinese)

Kobayashi, T., 1935, The Cambro-Ordovician formations and faunas of South Chosen. Paleontology, Part III, Cambrian faunas of South Chosen with a special study on the Cambrian trilobite genera and families. Journal of the Faculty of Science, Imperial University of Tokyo, Section II, 4, 49–344.

Lu, Y. and Dong, N., 1953, Revision of the Cambrian type sections of Shantung. Acta Geologica Sinica 32, 1–23.

Ma, L. and Qiao, X., 2002, Geological atlas of China. The Geological Publishing House, Beijing, 222–223. (in Chinese)

Meng, X., Ge, M., and Tucker, M.E., 1997, Sequence stratigraphy, sea-level changes and depositional systems in the Cambro-Ordovician of the North China carbonate platform. Sedimentary Geology, 114, 189–222.

Meyerhoff, A.A., Kaye, M.K., Chen, C., and Taner, I., 1991, China-stratigraphy, paleogeography and tectonics. Kluwer Academic Publishers, Deventer, 188 p.

Özdikmen, H., 2006, Nomenclatural changes for fourteen trilobites genera. Munis Entomology and Zoology, 1, 179–190.

Park, T.-Y., Han, Z.-Z, Bai, Z.-Q., and Choi, D.K., 2008, Two middle Cambrian trilobite genera, *Cyclolorenzella* Kobayashi, 1960 and *Jiulongshania* gen. nov., from Korea and China. Alcheringa, 32, 247–269.

Sohn, J.W. and Choi, D.K., 2007, Furongian trilobites from the *Asioptychaspis* and *Quadraticephalus* zones of the Hwajeol Formation, Taebaeksan Basin, Korea. Geosciences Journal, 11, 297–314.

Sun, Y.Z., 1924, Contributions to the Cambrian faunas of North China. Palaeontologica Sinica, series B, 1, 1–109.

Sun, Y.-C., 1935, The Upper Cambrian trilobite faunas of North China. Palaeontologia Sinica, series B, 7, 1–93.

Walcott, C.D., 1905, Cambrian faunas of China. In: Proceedings of the United States National Museum, 29, 1–106.

Xiang, L., An, T., Guo, Z., Li, S., Nan, R., Qian, Y., Yang, J., Yuan, K., and Zhou, G., 1981, Stratigraphy of China, 4, the Cambrian System of China. Geological Publishing House, Beijing. 198 p. (in Chinese)

Zhang, W.T., 2003, Cambrian biostratigraphy of China. In: Zhang, W., Chen, P., and Palmer, A.R. (eds.), Biostratigraphy of China. Science Press, Beijing, 599 p.

Zhang, W.T. and Jell, P.A., 1987, Cambrian trilobites of North China; Chinese Cambrian trilobites housed in the Smithsonian Institution. Science Press. Beijing, 459 p.

Zhu, M.-Y, Zhang, J.-M., Li, G.-X., and Yang, A.-H., 2004, Evolution of C isotopes in the Cambrian of China: implications for Cambrian subdivision and trilobite mass extinctions. Geobios, 37, 287–301.

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