Characteristics of the Middle-Late Triassic sedimentary facies assemblages in the Songpan-Ruoergai area*

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Abstract The Middle-Late Triassic sedimentary rocks in the Songpan-Ruoergai area mainly consist of calcareous siltstone, muddy limestone, lithic arkose, feldspathic litharenite, mudstone, wormkalk, oolithic limestone, and conglomerate. Except for limestone bed increasing eastward longitudinally and vertically, the calcareous component of the sandstones increases obviously. Abundant benthic and plant fossils and their clasts occur within these rocks. The sedimentary structures predominately contain flaser, parallel, tabular, wavy, and herringbone cross beddings. These data coevally imply that the Middle-Late Triassic sediments deposited in the fluvial, lake and tide environments. Additionally, the rocks display graded, parallel, hummocky beddings, and sandy lamination, a feature characteristic of storm deposits.

Keywords: Middle-Upper Triassic; fluvial-lake environments; tide environment; tempestite; Songpan-Ruoergai

The Songpan-Ganze fold belt in eastern Tibet plateau, connecting with the West Qinling orogenic belt to northeast, is mainly composed of a thick (>10 km) sequence of Triassic clastic rocks, with WE length of 2500 km and SN width of about 150—500 km[1]. This belt is a transitional area for different types of orogenic belts and formed in the convergent area between the Tethys and Circum-Pacific orogenic belts, which is separated from the Laurasia land by Animaqing suture zone northward, connecting with the Longmenshan fold belt and Yangzi craton southeastward and with the Qiangtang-Changdu block of the outbroad of the Gangwana land through the Jinshajiang zuture zone to the southwest. It is called "Chinese Nodein" and "Geological Beimuda of China" and thought to be a natural laboratory for studying the key area of the continental geology and dynamics in China[3]. The Triassic in the Songpan-Ganze fold belt, which has a special geometry, orogenic vergence and tectonic framework, was formed and modified by two continuous orogenic events of Paleo-Tethys and Neo-Tethys[2]. Therefore, the evolution of Triassic sedimentary environments in the Songpan-Ganze fold belt is critical to understanding of these tectonic events.

The Triassic sediments of the Songpan-Rouergai area in the Songpan-Ganze fold belt were commonly interpreted as submarine flysch[1,2,4—15]. Recently, we studied the detailed sedimentary structures and rock assemblages of the Middle-Upper Triassic in the Songpan-Ruoergai area. The results imply that the Middle-Upper Triassic sediments mainly deposited in the tidal and fluvial-lake environments.

This study mainly focuses on the characterization of the Middle-Upper Triassic sedimentary environments based on the middle-late Triassic outcrops[16] and sedimentary structures in the Songpan-Ganze area (Fig. 1), and provides some geological evidence for the study of tectonic evolution of the Songpan-Ganze fold belt.

1 Rock associations and petrographical characteristics

The Triassic System in the Songpan-Ruoergai area consists predominantly of the Middle-Upper Triassic, which can be subdivided into three lithologic units.

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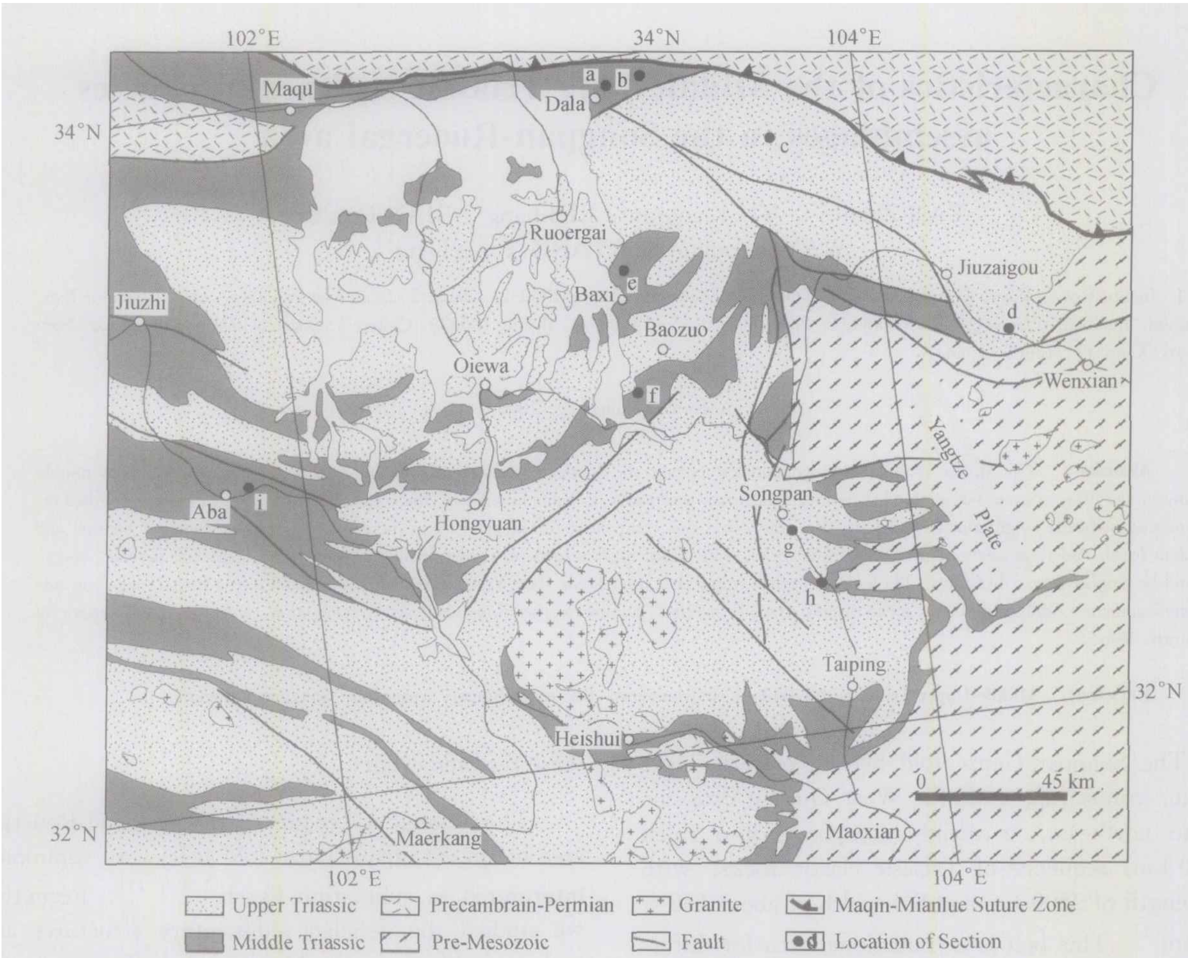

Fig. 1. Simplified geological map of the Songpan-Ruoergai area[16].

(1) The alternating beds of grey, dark-grey thinner mudstone and siltstone occur in the lower part of the lower lithological unit (T_2^a; Fig. 2(a)), and thinly interlayered limestone also exists at the bottom of this unit; dark-grey medium-thick fine-grained sandstone, lithic arkose, feldspathic litharenite, mudstone and muddy siltstone are major lithofacies of the upper part of the unit. Ripple, flaser, and lenticular beddings are abundant in the mudstones, and large-scale tabular cross-bedding is relatively rare, only occurring in the sandstones. The rock associations of this unit are relatively stable in the regional distribution, mainly occurring in the Qiewa, Baozuo, and Baxi areas of the southern and eastern of the Ruoergai County. The limestone interlayers increase in the outcrops of the Baxi and western Baozuo. The *Pecopteris* (?) sp. and abundant Brachiopoda fossils occur in the mudstone, siltstone and limestone[17]. Lenticular limestone increases evidently in the Jiuzaigou area, and Calamites sp. occurs in the sandstone and silty mudstone[18].

(2) The middle lithological unit (T_2^b) predominately crops out in the Qiuji and Mazanggou areas in the eastern Ruoergai and Aba counties. Medium-thick yellow-grey lithic arkose, feldspathic litharenite, conglomerate with grey-green mudstone are dominant in the lower part of this unit. The upper part of this unit consists of grey, thinly micrite layers with calcarenite and grey-green mudstone interlayers, containing abundant angular plant clasts (Fig. 2(f), (h), (i)). The conglomerate mainly consists of quartz and muddy siltstone clasts with black, thinner (~2 mm) mudstone interlayers. Dark-grey muddy nodules and muddy breccias are common in the siltstone and greywacke; clear horizontal laminations exist in the muddy nodules. Syngenetic breccias are developed within the grey calcareous sandstone near the Aba County. In the Dala Forestry, this unit is dominated by conglomerate, mudstone, calcareous siltstone, micrite, and calcarenite. The conglomerate beds with calcareous silty matrix occur at the bottom of this unit, which mainly consist of subrounded,

grey mudstone, siltstone, and yellow-grey greywacke clasts. Imbricative structures are a characteristic of these clasts.

(3) The upper lithological unit (T_2^c) consists predominately of dark-grey, thinner mudstone, muddy limestone with fine-grained feldspathic litharenite interlayers. Lenticular and ripple beddings are common in the mudstone, and tabular cross-beddings develop in the sandstone. In the Jiuzhaigou area, this unit is composed of mudstone, muddy limestone, and calcarenite. The sandstone and mudstone contain abundant plant fossils, such as *Necalamites* sp. and *Calamites* sp.[18].

The petrographical facies of the Upper Triassic in the studied areas vary considerably, which consists of dark-grey, medium-thick, fine-grained sandstone, feldspathic litharenite, calcareous siltstone and black mudstone in the Dala Forestry, and dark-grey, black, medium-thick calcareous fine-grained sandstone, siltstone, mudstone, limestone, silty mudstone and feldspathic litharenite in the eastern Qiuji. Current ripple mark and tabular cross-beddings are developed in the sandstone, lenticular and ripple beddings are common in the mudstone. In the Baigusi and Luocha areas of the eastern and western Dala, calcareous siltstones are dominant with grey-black, massive and medium-thin calcarenite, oolithic limestone interlayers. Chert interlayers occur in the calcarenite locally. The fossils of *Lamellbranchiata* and *Ammonites* exist in the limestone[17]. The upper Triassic in the southern Songpan County consists predominately of black mudstone with intercalated layers of calcarenite. The calcarenite beds with tabular cross-beddings are lenticular and interclated within the mudstones in some areas. The thickness of the limestone is commonly about 8 cm, and the mudstones are thick-bedded (1—2 m). Abundant striped calcarenite occurs as interlayers, and lenticular and herringbone cross-beddings are common characteristics of the mudstones. To the south, the Upper Triassic consists of alternating beds of calcareous siltstone and mudstone. There are abundant large-scale tabular cross-beddings and ripple beddings in the calcareous siltstone and mudstones, respectively. In the Taiping area, alternating beds of black calcareous mudstone and siltstone are dominant with thin-bedded marl locally. Horizontal, herringbone and ripple beddings and abundant fine-grained pyrite are distinctive characteristics of them. However, the Upper Triassic in the Jiuzai area consists of grey-green, thick-bedded sandstone with silty mudstone linterlayers in the lower section, grey-green calcareous siltstone, thin-bedded sandstone with grey, medium-thin bedded calcarenite, micrite interlayers and some lenticular limestone in the middle section, and grey, thick-bedded oolitic micrite, wormkalk, breccia limestone with a 10 m-thick, black shale interlayers in the upper section. Banded chert and angular siliceous limestone pebbles occur in some areas.

Regionally, limestone and plant fossil clasts within the Middle Triassic increases longitudinally, and limestone also increases laterally to the east. Abundant plant clasts and large-scale tabular cross-beddings are developed in the sandstone, and siltstone and calcarenite have abundant ripple laminations. The mudstones have abundant lenticular, herringbone, and ripple beddings. Sandstone interbeds decrease and calcareous components increase longitudinally in the Upper Triassic, but limestone increases, and sandstone and mudstone decrease laterally. Thick-bedded wormkalk exists near the margin of the Yangtze plate. The Middle-Upper Triassic is dominated by fine-grained sandstone with stable limestone laterally. Except for *Lamellbranchiata* and *Ammonites*, there are abundant oolite and plant clasts in the Middle-Upper Triassic.

2 Sedimentary facies analysis

Our studies demonstrate that the Middle-Upper Triassic in the Songpan-Ganzi area consists of six sedimentary facies.

2.1 Sublacustrine and deep-lake sediments

Sublacustrine and deep-lake are the dominant sedimentary environments of the Upper Triassic along Anhong-Taiping in the southern Songpan County adjacent to the Yangzi plate, which consist predominately of altering layers of thin-bedded, dark-grey calcareous siltstone and dark calcareous mudstone (Fig. 3(a)) with thin-bedded marl locally. The thickness of each cyclothem is 1—2 cm, commonly about 1 cm. Authigenic minerals of pyrite and siderite are abundant in these rocks. Parallel and herringbone beds mainly occur in the calcareous siltstone, and mudstone has abundant ripple laminations (Fig. 3(b)). These rock assemblages do not vary seriously in the lateral, with integrated sequence vertically (Fig. 2(h)).

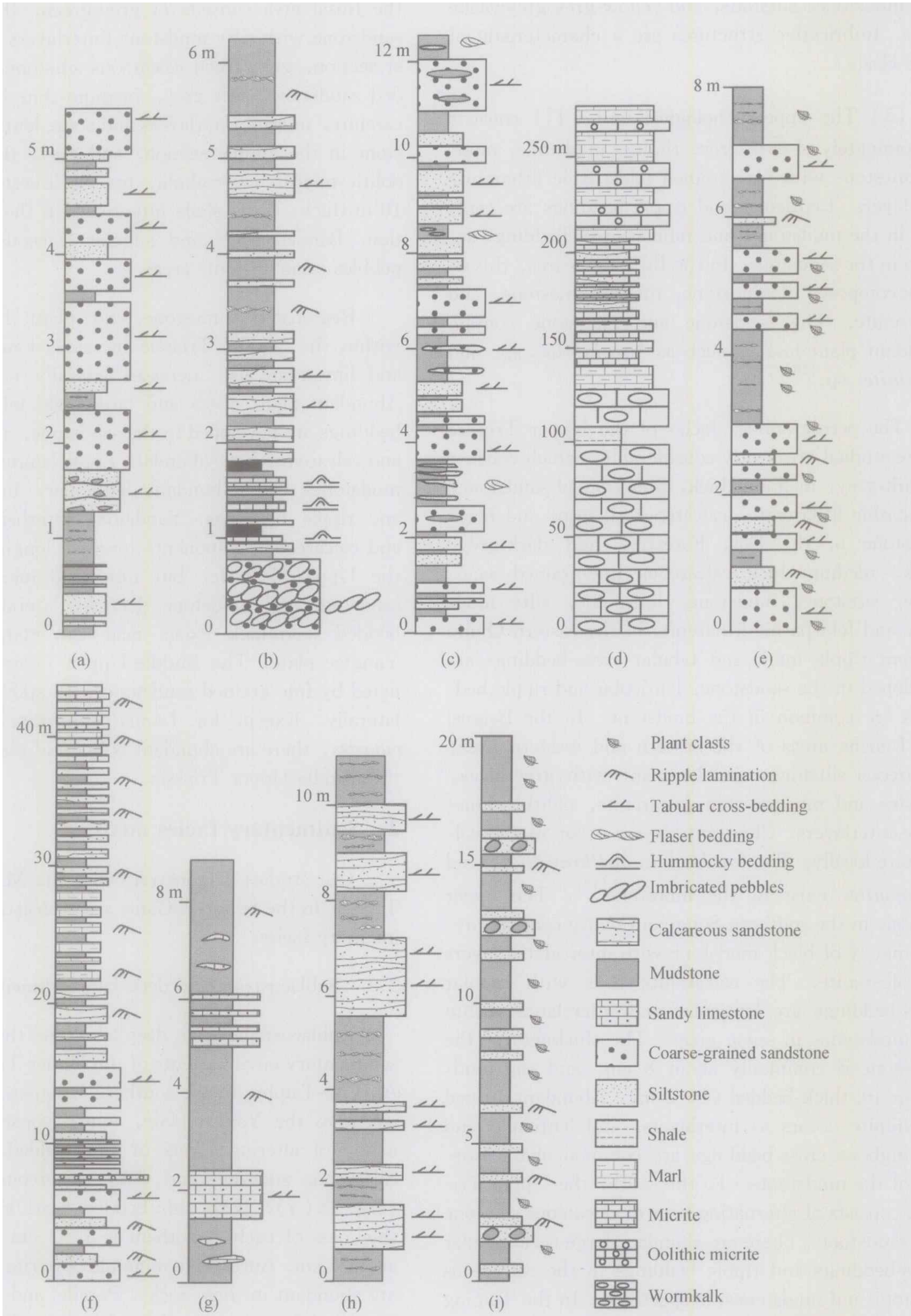

Fig. 2. Representative Middle-Upper Triassic sedimentary log from the Songpan-Ganzi area. (a) Dala (T_2^a); (b) Dala (T_2^a); (c) Dala (T_3); (d) Jiuzaigou (T_3); (e) Baxi (T_2^b); (f) Baxi (T_2^b); (g) Songpan (T_3); (h) Anhong (T_2^b); (i) Aba(T_2^b).

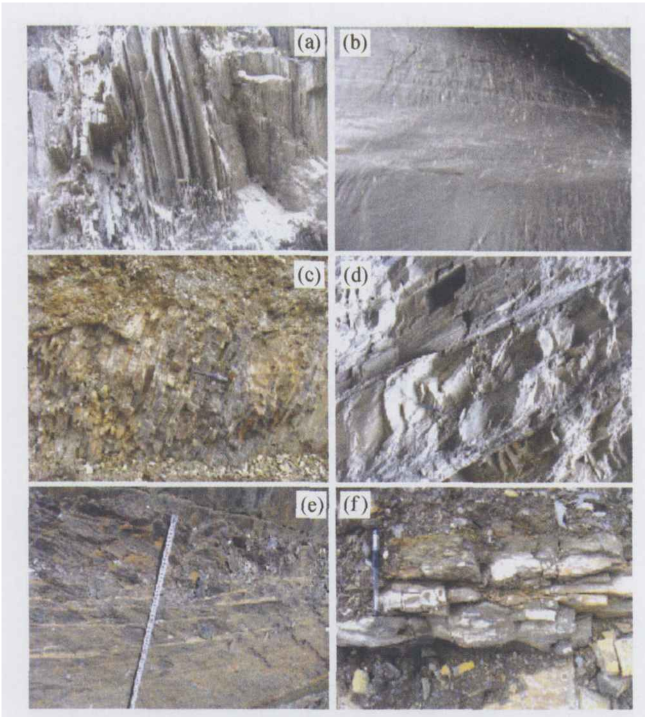

Fig. 3. Photographs of the Middle-Upper Triassic deep-shallow lake sedimentary rocks from the Songpan-Ruoergai area. (a) Alternating beds of the calcareous mudstone with muddy siltstone of the deep-lake environment; (b) ripple lamination (upper), pinnate (middle) and horizontal (lower) laminations; (c) alternating beds of the marl, micrite and muddy siltstone; (d) tabular, pinnate and horizontal beddings of the calcareous mudstone and muddy siltstone; (e) flaser beddings; (f) ripple lamination of the marl.

Abundant horizontal beddings in the siltstone imply that the water is relatively deep and stable compared with turbulent. Ripple laminations of the mudstone may reflect that the water body was interfered by wind and tidal currents during sedimentation. Abundant finely authigenic pyrite and siderite in the siltstone and mudstone demonstrate that they should deposit in an anaerobic environment in the Upper Triassic.

2.2 Shallow lake sediments

Shallow lake is one of the dominated environments for the Middle Triassic in the Songpan-Ruoergai area, mainly located in the Baxi, Songpan, and Dala areas. The deposits consist of calcareous siltstone, mudstone, muddy limestone, calcarenite and micrite (Fig. 3(c), (d)). The thickness of each cyclical sequence is 2—3 cm. These characteristics are different evidently from that of the deep-lake deposits. Horizontally, herringbone and tabular (Fig. 3(d)), lenticular (Fig. 3(e)) and ripple (Fig. 3(f)) beddings are major sedimentary structures of these rocks with some small scale cross-beddings and symmetrical wave ripples. Abundant fossils are kept with good shapes, mainly consisting of benthic community such as *Gasteropod* and *Lamellibranchiata*[17]. Authogenic siderite formed in the anaerobic environments is relatively rare.

2.3 Littoral lake sediments

The littoral lake deposits mainly occur in the Rouergai area, consisting predominately of the Middle Triassic coarse-grained sandstone, siltstone with muddy clasts, and mudstone (Fig. 4(a), (b)) with a coarsing-upward sequence. Tabular, ripple and lenticular beddings are abundant. Black, yellow-grey mudstone and siltstone assemblage with some pebbly coarse-grained sandstone (Fig. 4(a)) are distributed in the Aba and Baxi areas. Herringbone (Fig. 4(b), (c)), and horizontal, ripple and tabular (Fig. 4(d)) beddings are their major characteristics; slump structures (Fig. 4(b)) also exist within them. There are abundant plant clasts. These characteristics imply that these rocks should be the deposits of the mud bank and mud flat environments, differing from the

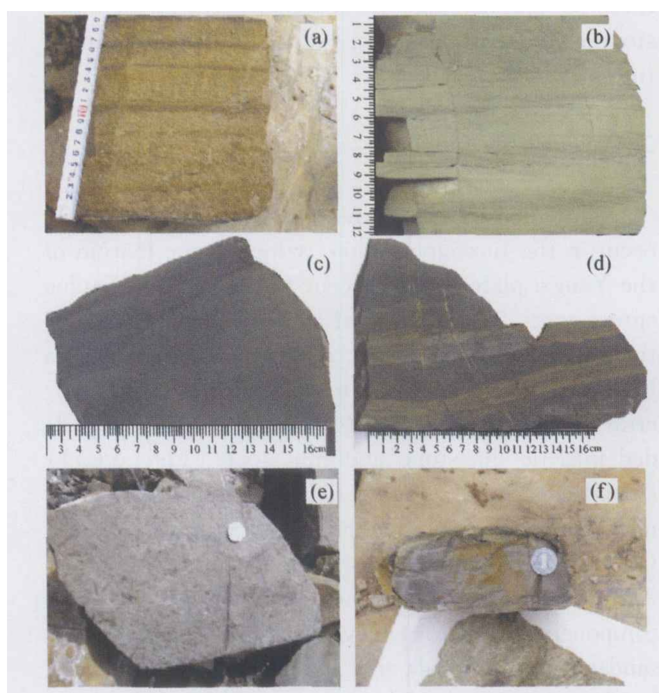

Fig. 4. Photography of the Middle Triassic littoral-lake sedimentary rocks from the Songpan-Ruoergai area. (a) Alternating beds of the coarse-grained sandstone, siltstone and mudstone. Quartz pebbles and abundant mica clastics are in the coarse-grained sandstone and mudstone respectively, and pinnate laminations are abundant in the siltstone; (b) pinnate (lower), horizontal (middle) beddings and slump structures (upper) in the green-gray mudstone; (c) pinnate beddings in the mudstone; (d) horizontal, ripple and pinnate beddings in the mudstone; (e) angular plant clasts in the muddy siltstone; (f) mudy nodule with horizontal beddings.

deposits of the deep- and shallow-lake environments. The plant clasts are angular and have a clear texture (Fig. 4(e)), implying *in situ* deposits without being transported for a long-distance. Muddy nodules (Fig. 4(f)) and muddy pebbles can be observed in the siltstone and coarse-grained sandstone; the coarse-grained sandstone is massive and muddy cemented. Except for rounded quartz grains, abundant angular mica clasts in the contact plane between sandstone and mudstone indicate that they should be scoured, sorted and elutriated by surf. Quartz grains are milky white, 2—4 mm in diameter, and cemented by yellow-grey muddy silt. Mica clasts in 0.5 cm-thick layer of black-grey, yellow-grey mudstone and muddy siltstone between the pebbly sandstone layers are concentrative, but oriented mica clasts do not exist. Additionally, mica clasts are subangular-subrounded, indicating they are not the products of post-tectonism (Fig. 4(a)). In the Songpan County area, calcarenite and mudstone of the Upper Triassic are deposits of littoral lake environment. Horizontal lamination and small tabular cross-beddings are common in the calcarenite, and herringbone beddings occur in the mudstone. Mudstone and thin-bedded calcarenite constitute of alternating beds.

2.4 Tidal flat sediments

The tidal flat sediments are limited, and mainly occur in the Jiuzaigou region, which is the margin of the Yangzi plate, and adjacent to the Maqin-Mianlue suture zone. They consist of alternating beds of grey, thick-bedded oolithic micrite, wormkalk, breccia limestone and medium-thin-bedded calcarenite, micrite and siltstone. The alternating beds of thin-bedded micritic limestone and mudstone (Fig. 5(a)) should deposit in a mixed flat environment; oolithic micrite, wormkalk, and breccia limestone (Fig. 5(b)) should be the deposits of the intertidal zone. Additionally, synsedimentary breccias with the same components of the cements within calcareous/silty sandstones in the Dala area should be formed by wave break.

In the Dala area adjacent to the Maqin-Mianlue suture zone, alternating beds of thinner calcareous siltstone, mudstone and marl with horizontal and ripple laminations show the characteristics of muddy flat deposits (Fig. 5(d)). Moreover, ripple and lenticular beddings in the sandstone, siltstone and mudstone interlayers, together with sandstone lenses with basal-scouring and large-current ripple cross-beddings within them, demonstrate these sandstone lenses should deposit in the tidal channels[19].

2.5 Storm deposits

The middle section of the Lower Unit of the Middle Triassic in Dala mainly consists of thinner micrite, calcarenite, calcareous siltstone and mudstone (Fig. 2(b)). Calcarenite shows clear graded-beddings ripple cross-beddings (Fig. 5(e)) and base scouring. Hummocky beddings are common in the micrite (Fig. 5(f)), and horizontal and ripple laminations are abundant in the siltstone and mudstone. Vertically, grading, horizontal, hummocky and ripple beddings form an integrated assemblage of the

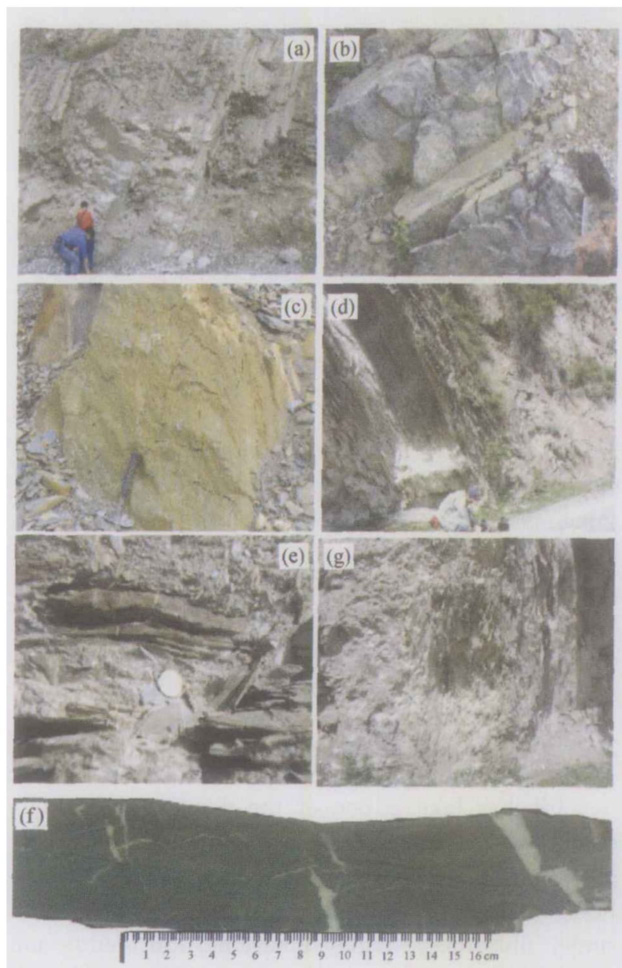

Fig. 5. Photography of the Middle Triassic shallow sea and fluvial sedimentary rocks from the Songpan-Ruoergai area. (a) Alternating beds of the mcrite and mudstone; (b) oolitic limestone with syngenetic breccias; (c) calcareous siltstone with syngenetic breccias; (d) alternating beds of the calcareous siltstone, mudstone and marl; (e) grading bedding and cross-bedding of the sandy limestone; (f) hummocky bedding; (g) cobbles with sandy matrix (near the hammer).

typical storm deposits[19], indicating a shelf environment probably.

2.6 Fluvial deposits

A 50 cm-thick conglomerate underlies the tempestite of the Middle Triassic Lower Unit near the Dala area. The cobbles consist of sandstone and mudstone and are mainly cemented by sand matrix, which were derived from the basement. These conglomerates are clast- and matrix-supported (Fig. 5(g)). Imbricative pebbles and local reverse-normal grading show debris deposits of alluvial fan[20].

Additionally, sandstone lens with abundant tabular cross-beddings interbedded within the siltstone and mudstone in the Aba area. Some sandstone lenses consist of synsedimentary breccias. These lenses have clear base scouring, and siltstone and mud rip-up adjacent to the scouring base of some lenses indicates that the current modifies the previously deposited sediments, displaying the characteristics of the fluvial channel deposits[21].

3 Discussion

Sedimentary structures and abundant fossils coevally demonstrate that Early-Middle Triassic deposits are major sediments of fluvial-lake and shallow-sea in the Songpan-Ganzi area adjacent to the western margin of the Yangtze plate. Indeed, local flysh deposits should not be excluded. Lithological associations and their relative grain variation indicate that fluvial and costal sediments, consisting of fine-grained conglomerate, pebbly mudstone, calcarenite, intraclast limestone, arkose and lithic greywacke with imbricative pebbles and hummocky beddings, mainly occur in the north part of the Songpan-Ganzi area. To the south, there are marl, mudstone, siltstone and micrite with herringbone, ripple beddings and slump structures. These characteristics indicate that the deposits became fining sediments and the depth of the water was deepening southward in the early-middle Triassic. The late-Triassic sediments in the south part of the Songpan-Ruoergai area are dominated by grey, black mudstone and marl with herringbone and large tabular cross-beddings, and abundant pyrite, indicating a deoxidized environment and a deepen depth of the water. These facts are consistent with the results that "sedimentary environment of the Songpan-Ganzi basin are deep-water in the southwest and shallow-water in the northeast, and the shallow-water sediments are proximal, much unmatured deposits", which was inferred from the Nd isotope of the Triassic sandstones[22].

Bian et al.[23] studied the Animaqing ophiolite complex and tectonic evolution and suggested that the Triassic in the Animaqing-Bayankalashan area should be the fills of a continental sea overlying the Permian deposits unconformably. However, Sengor[5,24], Klimetz[4], Nie et al.[8] and Chang[13] interpreted the Triassic System in the Songpan-Ganzi area as a subduction-accretion complex surrounded by Animaqing and Jinshajiang suture zones. Yin et al.[7], Zhou et al.[9] and Ingersoll et al.[14] suggested that the Triassic in the Songpan-Ganzi area was the fills of Tethys remnant oceanic basin. Gu[25], Hsu et al.[26] and Burchfiel et al.[27] suggested that the Triassic in the Songpan-Ganzi area was deep-marine flysch fills of the backarc basin. Yang[28] studied the regional framework and then suggested that the Triassic in the Songpan-Ganzi area was deep-marine flysch fills of the forearc basin. Pan et al.[11,29] and Xu et al.[30] thought that the Triassic in the Songpan-Ganzi area was a foreland basin fills. Although the tectonic setting of the Triassic System in the Songpan-Ganzi is still debated, there is a common sence that the Triassic System is deep-marine flysch.

Zhang[10] systemically studied the Triassic spatial characters of sedimentary environments in the Songpan-Ganzi area and suggested that Triassic sedimentation should asynchronously be different in different regions. Early-middle Triassic deposits in the Animaqing, Yushu and Dege areas were demonstrated to be deep-marine flysch and coastal-shelf sediments, but late-Triassic deposits in these areas were shallow-sea deposits with abundant bivalve fossils and alternated marine-terrestrial sediments. Chang[13] reported that the Triassic System in the Songpan-Ganzi area consisted of shallow-marine, continental shelf, and deep-marine deposits. These results are consistent with our results from the systemically studies of the Triassic lithology, spatial variation of lithological associations, and sedimentary structures in the Songpan-Ganzi area. Lithofacies association and their relatively spatial variation coevally demonstrate that Middle-Late Triassic deposits were formed by lake, fluvial and tidal flat sedimentation, containing abundant terrestrial and shallow-marine fossils and facies marks. This cognition can provide new evidences for the study of tectonic evolution and tectonic setting of the Songpan-Ganzi Basin.

Recently, a systemical analysis of deep seismic reflection section data indicates that the basement of the Songpan-Ganzi fold belt is uplifted evidently adjacent to the eastern boundary of the Longmenshan fault, and velocity vectors of the basement are very different from that of the oceanic crust ($7.0\ km\cdot s^{-1}$). This may be the results from the remnant Yangtze-South China block[31]. Yang et al.[32] suggested that the Songpan-Ganzi fold belt was separated from the northwest part of the Yangtze plate in the process of Caledonian. If these suggestions are right, the Triassic System overlying the continental basement should not be the accretionary complex, forearc or backarc basin fills, it should be the fills of foreland basin in front of the Yangtze plant[11,29,30]. This conclusion is in accord with the results of our sedimentary facies studies. Detrital zircon U-Pb dating from the Triassic sandstones[33—35] indicates that the Triassic provenance is mixed, and derived from North China, Yangtze plant, North Qinling and South Qinling. This fact demonstrates that the Triassic System in the Songpan-Ganzi area was derived from both craton and adjacent orogenic belt, showing provenance characteristics of the foreland basin.

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