Earthquake sedimentary event record in Early Triassic in southeastern Sichuan Basin, SW China

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Abstract

There are some macroscopic and microscopic sedimentary structures of seismic events in the outcrops in Lower Triassic Feixianguan Fm (T_1f). and Jialingjiang Fm (T_1j). in southeastern parts of Sichuan Basin. The following basic types of sedimentary structures could be observed: Soft-sediment liquefied deformation structures include curled deformation (sliding deformation structure," sausage structure") and microscopic folds (laminated plastic deformation). Seismites emerge in T_1f^1 and T_1f^2 in Baimiaozi section, Beibei, Chongqing, while in T_1j^2 at Longdongwan, Xuyong, Sichuan, as well as the same strata at Xingwen, Sichuan and Xishui, Guizhou. The sedimentary sequences of seismites in outcrops are clear, presenting the whole process of paleoearthquake from strong to weak. The author argues that the Sanjiang tectonic belt represented by the evolution of Yidun arc in the western Sichuan had strong activities at the west margin of the upper Yangtze plate, which may be related to the formation of seismites in the early Triassic. Earthquake activities and volcanic eruption can be triggered in large areas by the plate collision and the subduction of oceanic crust in the Sanjiang tectonic belt.

1. Introduction

Earthquake is reckoned as instantaneous catastrophic event, mostly caused by the tectonic movement. Since Seilacher defined seismites in 1984, many scholars have had some systematical discussions and summaries about seismites and tsunamites triggered by earthquake and tsunamites (Nikolaeva, 2009; Patil and Kale, 2011; Wallace and Eyles, 2015; Feng et al., 2016; Brogi et al., 2018; Morsilli et al., 2020), which promoted the development of sedimentology about earthquake events. China has the vast amplitude where geological structures are diversiform. From geological history until today, earthquake events occur occasionally. Since the late 1980s, many geologists initiated a lot of research programs about the seismites and sequences of seismites conserved in strata from Precambrian to Cenozoic, and attained a series of plentiful achievements that kept abreast with international standard (Nan et al., 1996; Zhou et al., 1998; Qiao et al., 1999; Du et al., 1996, 2001; Guo et al., 1999; Shanmugam, 2016; Serkan et al., 2019). However, previous studies involving Upper Yangtze plate were very few, especially in Sichuan basin, only Liang et al (1991;1994) reported the unconformity and seismites triggered by earthquake at the continental margin of the western Sichuan basin and the western Yunnan province in Permian, and Wu and Yin (1992) studied the seismites sequences in lacustrine clastic rocks in the late Jurassic at Emei, Sichuan Basin. During the process of the field geological investigation in Lower Triassic of T_1f. and T_1j in the southern and southeastern Sichuan basin, the author discovers a series of macroscopic and microscopic special sedimentary structures triggered by earthquake, like soft-sediment deformation, breccia of seismites, tabular-pebbles, intraformational microscopic faults and so on. With the analysis of sedimentary structures in field outcrop (macroscopic and microscopic features), it is speculated that these special sedimentary structures should have close relationship with tectonic evolution at the west margin of Upper Yangtze plate. In early Triassic, the Sanjiang tectonic belt represented by the evolution of Yidun arc in western Sichuan has strong activities at the west margin of the Upper Yangtze plate, which may be related to seismites growing.

2. Geological Setting

The Sichuan Basin, located in southwestern China (Fig. 1a), was formed above the pre-Sinian basement (before 800 Ma). The basin covers an area of about 180,000 km^2, with a total thickness of about 12,000 m from the Sinian to Quaternary, and it experienced six main tectonic orogenies or movements: the Yangtze (before 630 Ma), Caledonian (630–320 Ma), Hercynian (320–252 Ma), Indosinian (252–195 Ma), Yanshanian (195–65 Ma), and Himalayan (65–0 Ma) (Zhai, 1989; Ma et al., 2007). Before the Early Indosinian movement, the basin was dominated by subsidence and uplift developed in an extensional setting with mainly marine carbonate and shale deposits. From the Late Indosinian movement to the Yanshanian movement, the basin was dominated by folding and uplift developed in a lateral compression environment, resulting in terrigenous clastic deposits. Finally, it was shaped into folds and uplifts during the Yanshanian and Himalayan movements (Zhai, 1989).

At the end of the Early Permian, the tectonic extension in the NE Sichuan Basin occurred contemporaneously with the large scale basalt eruptions in the southwestern Sichuan Basin (He et al., 2003; Shellnutt, 2014). Consequently, the northwest-southeast-striking K-L trough was developed in the NE Sichuan Basin (Fig. 1a). An isolated platform was formed to the northeast of the K-L trough, while a large platform with a secondary depression was developed to the southwest (Fig. 1a). The sedimentary framework during the early T_1f (deposition of the first and second members of T_1f) was inherited from the sedimentary framework of P_2c. Beibei-Xiushan area in the east of the study area is carbonate platform deposition, and the southwest of the study area is sea to land transitional facies deposition (Fig. 1a).

3. Materials And Methods

Field investigations were conducted in Southeast of Sichuan Basin, China, including Beibei, Xingwen, Xishui and Xuyong. The first time of the field investigations was on 2–24 January 2020 and the second time was from April 2, 2021. to May 28, 2021. We measured each of the outcrops and collected rock samples in each outcrop for rock slice analysis. We observed the sedimentary structures carefully and noted down them by camera for further analyzing.

4. Results

4.1. Stratigraphic distribution of seismites

Seismites is discovered in T_1f^1 and T_1f^2 in Beibei, Chongqing, and Xingwen, Sichuan and Xishui, Guizhou, while in T_1j^2 in Xuyong, Sichuan (Fig. 1a).

4.1.1. Baimiaozi section

The outcrop of T_1j in Baimiaozi section is located in south bank of Guanyin Gorges (Jiangling River), Beibei, Chongqing. The lithology of T_1f^1 is mainly purple-brown calcareous shale and marl, with a thickness of 72.72m. The lower part of T_1f^1 contains many pyroclastics (tuffaceous siltstones) (Yan, 1987), with abundant of horizontal beddings and ripple beddings. The middle part contains interlayers with gravel argillaceous limestone (seismites) and micritic limestone, with abundant of horizontal beddings and unidirectional flow ripple beddings, small-scale contemporaneous faults, liquefied deformation structures, interformational microscopic erosion, mini water escape structures, trace fossils and so on. The fossils, such as *Claraia sp.*, *Lingula sp.*, and *Hollinella tingi.*, are only appeared in layers of shale on the bottom of T_1f^1. The lithology of T_1f^2, with a thickness of 29.35m, are mainly gray laminated limestones interbedded with laminated algae stromatolite limestones, seismites and oolitic limestones, with abundant of herringbone cross beddings, flaser bedding, crinkling lamina, cracks, and so on. The lithology of T_1f^3 are thin-and-thick purple-brown marl with bioclastic limestones (Fig. 1a-b). Few fossils are found in T_1f^1 to T_1f^1. Conodont fossils are only obtained in T_1f^4, and *Neogondolella carinata* assemblage extends from the bottom to the middle of T_1f^4, which represents middle Induan in the early Triassic (Jiang, 1982). Therefore, the first to the second members belong to the lower Induan.

4.1.2. Longdongwan section

Bulleted lists look The outcrop of T_1j in Longdongwan section is located in Xuyong County, in the south of Sichuan basin. T_1j can be divided into five members of T_1j^1, T_1j^1, T_1j^1 and T_1j^1. T_1j^1 (Tongjiezi member), with a thicknes of 99 m, is composed of grey and green grey, variegated medium-thick and thin layered argillaceous limestones containing tabular calciferous silty mudstone, and grayish-green silty shale at the bottom, obtaining *Entolium disoites*, *Eumorphotis inaequicostata*, *Gervillia sp.*, *Lingula sp.* and so on. T_1j^2, with a thicknes of 186 m, is composed of deep grey and black, thin and medium-thick layered limestone with biological clastic limestone lens, with abundant of horizontal beddings, unidirectional flow ripple beddings, liquefied deformation structures, interformational microscopic erosion, wave ripples, trace fossils, etc in the lower and middle parts, obtaining *Eumorphotis inaequicostata*, *Unionites fassaensis*, *Gervillia sp*. These fossil assemblages are important symbol of Lower Triassic in Yangtze plate.

4.2. Main types of seismites

Seismites is discovered in T_1f^1 and T_1f^2 in Beibei, Chongqing, and Xingwen, Sichuan and Xishui, Guizhou, while in T_1j^2 in Xuyong, Sichuan (Fig. 1a). The seismites with special sedimentary structures is produced by a redeposition process triggering by earthquakes. Earthquake deposition can be triggered not only on land, including surface and subsurface, but gravity flows rebuild deposition caused by earthquake and tsunamis on seabed as well. The diagnostic criteria of seismites are in dispute till now, though there are several kinds of diagnostic criteria proposed by different scholars. Besides, there is no technical term describing deformation structures of seismites. According to previous researches (Seilacher, 1984; Lowes, 1976; Rodriguez et al., 2000; Song, 1988; Qiao et al., 1994; Qiao, 1996; Feng, 2017; Brogi et al., 2018), there are main diagnostic criteria to identify earthquake records in geological period, including ground fissures, intraformational slippages, intraformational step faults, intraformational folds, pseudonodule, liquefied sandstone veins, flame structures and vibrational liquefied curled deformation structures, etc. In general, sedimentary rocks formed by earthquake deposition include seismites (unit A, in-situ system), tsunamites (unit B, quasi-in-situ system), and earthquake turbidites (unit C, allogene system), plus background deposition (unit D), which form basic sedimentary units of sedimentary sequences of seismites, and they are different in internal components of each sedimentary unit (Du and Han, 2000a, b). We can observe not only macroscopic sedimentary structures about earthquake events in outcrop sections and drilling cores, but also microscopic sedimentary structures about earthquake events in those slices (Song and Liu, 2009). Macroscopic and microscopic sedimentary structures about earthquake events are the following basic types in T_1j and T_1j.

4.3. Macroscopic features

4.3.1. Soft-sediment deformation

Soft-sediment liquefied deformation structures include curled deformation (sliding deformation structure, "boudinage structure") and microscopic folds (laminated plastic deformation). Curled deformation structure is represented by curling layers of mudstone, presenting coil shape and wavy shape, etc in T_1f^1 at Beibei, Chongqing (Fig. 2a), and folds in thin-layer micrites, with compactly closed shape and wavy shape (dimension are about 20cm×10cm), in T_1j^2 at Longdongwan section, Xuyong Sichuan (Fig. 2b). Boudinage structure, with limy ingredients, is emerged in thick-layer silty mudstone in T_1f^1 at Beibei, Chongqing. It is of a thickness vary from several to ten centimeters, with vary axial surfaces and morphology of folds (Fig. 2c). Microscopic folds (lamina plastic deformation) is found in T_1f^2 at Beibei, Chongqing and T_1j^2 at Longdongwan section, Xuyong Sichuan, and microscopic folds is emerged in laminated thin-layer limestones, presenting slight folds of low radian and undulation in laminated thin-layer limestones (Fig. 2d-e). Besides, in Jichang, Xuanhan County and Shuanghui, Wangcang County, Sichuan Province, some soft-sediment deformation structures such as convolute layers, microscopic folds and so on developping in T_1f^1 may be related to paleo-earthquake activities (Wang et al., 2009). Soft-sediment deformation is formed through differential compaction, liquefaction, sliding, slumping after deposition and before consolidation, whose process is always accompanied by some factors triggered by earthquake (Du et al., 2007). Generally, curled deformation structures are formed in sedimentary environments like platform margin, delta front, or continental slope, etc with a certain slope (Elliot and Williams, 1988; Morton, 1988). However, earthquake also can trigger curl deformation of sediments that are in the flat sedimentary landforms. After the detailed research about modern deposition of the Klamath River’s delta in the Gariglia State, Field et al (1982) argued that curl deformation structures triggered by earthquake could be formed in plain marine environment with slope gradient less than 0.25 degree, and the earthquake magnitude that could trigger these deformation structures ought to reach 6 to 7 level. Although great storm waves caused by hurricane could produce strong bottom flow, the former scholars (Vaughan et al., 1987; Morton, 1988; Boss and Neumann, 1993; Shinn et al., 1993) argued that huge storm waves usually do not make soft sediments deformed through researches about the modern shelf carbonate platform depositional environment, lime mud sediments and sedimentary characteristics of continental shelf in Great Bahama Beach. Guiraud et al (1993) discussed the relationship between seismites and magnitude of cretaceous paleoearthquake, at the same time connected forming process of soft sediment liquefied curled deformation with earthquake facies triggered by activities of growth faults, taking the relationship among focal depth, magnitude and sediments liquefaction into consideration, and excluded deformation caused by ancient slope, gravity load and diagenesis. In geological history, soft-sediment curled deformation structures with some small growth faults have a wide distribution, which are associated with the earthquake vibration, and they are considered as a crucial key to determine whether the paleoearthquake exists or not (Obermeier, 1996; Pope et al., 1997; Ettensohn et al., 2000; Moretti, 2000; Zhang et al., 2007; Houston et al., 2008; Khan and Shah, 2016; Ezquerro et al., 2016; Deev et al., 2018, 2019); Qiao et al., (1994) called layers with curled deformation and boudinage structures as earthquake fold rocks, which were formed when these original sediments were transformed in situ.

4.3.2. Tabular-pebbles

Laminated thin-layer micritic limestone layer is developed in carbonate tidal flat sedimentary environment in T_1f^2 at Beibei, Chongqing (Niao and Hu, 2008), and tabular-pebbles with different-size diameters is developed in the lower part of T_1f^2 wrapping into laminated thin-layer micritic limestone of normal sequences. This tabular-pebbles were defined as the sedimentary products of storm origin in the past (Niao and Hu, 2008). Obviously, storm origin interpretation could not explain why there is no erosion surface and particle sequence in the lower part of tabular-pebbles layer. It is speculated that micritic limestone with algal laminated and horizontally laminated beds is developed in carbonate tidal-flat during weak tectonic activity period, Some semi-consolidated thin-layer plastic sedimentary layers, with fractures in the transverse direction, are cracked by earthquake, forming different size of blocks tabular-pebbles during intense tectonic activity period. Fractured tabular-pebbles are usually lacerated, distributed beddingly, and adjacent rock blocks sometimes can be spliced together (Fig. 2f), they are mostly in primitive sedimentary state without displacement, and are a type of earthquake cracked rocks. Some tabular blocks are disturbed by waves (tsunami) triggered by earthquake, redeposited, and then formed mussily accumulated tabular-pebbles after redeposition (Fig. 2g-h; Fig. 3). Pratt (2017, 2021) studied the mixed and disorderly tabular-pebbles depositing in Deadwood Formation of Upper Cambrian in the middle and northern parts of Montana, the United States. The tabular-pebbles, with lithology of thin-layer calcareous fine sandstone and silty mud shale, are interbedded with horizontal-lamina calcareous fine sandstone and silty mud shale. He argued that the tabular-pebbles is related to storm wave (tsunami) triggered by earthquake. Sedimentary characteristics of tabular gravel layers are comparable with those in T_1f at Beibei, Chongqing, which are also quasi in-situ deposition.

4.3.3. Breccia of seismites

Gravels with different size, shape and psephicity are developed in T_1f^1 at Baimiaozi Section, Beibei Chongqing, and in T_1j^2 at Longdongwan section, Xuyong, Sichuan. The irregular shape of gravels, with a size ranging from 0.5 to 25 cm, is spherical or tabular. The gravels, with a lithology of grey and grey white thick-layer massive micrite with certain psephicities, are different from surrounding rocks, indicating a short distance transport and redeposition. Some larger tabular gravels with 'V' shape and tabular-pebbles in T_1f^1 of Beibei, Chongqing, and tabular-pebbles in T_1j^2 of Xuyong, Sichuan sink in the unconsolidated surrounding rocks, triggering curved lamila (Fig. 4a-d, Fig. 5). This 'V' shape 'penetration bedding' structure of tabular gravels (Luo et al., 2009), is triggered by earthquake, making the unconsolidated rock strata in adjacent points broken, and then depositing in the unconsolidated plastic sediments after a short distance transportation with intense disturbance of tsunami and wave (Shanmugam, 2006). Du et al (2005) describes this sedimentary structure as rockfall subsidence structure, which represents the quasi in-situ deposition. Breccia of seismites is different from earthquake collapse rock that Qiao et al (1994, 1996) defined. The massive earthquake collapse rock is scattered distribution, and its bedding is not consistent with surrounding rock, However, the earthquake collapse rock, with the elements is as same as the surrounding rock, deposit in-situ triggering by earthquake related collapse.

4.3.4. Interformational microscopic faults

Interformational microscopic faults are developed at Baimiaozi section in T_1f at Beibei, Chongqing. Sometimes the faults emerge seperately, and sometimes presents parallelly like stairs. The faults, with a small slip and slow angle of fault plane, develop limitedly without cutting through the upper and lower strata. They are formed in unconsolidated sedimentary layers, causing by vibration when earthquake occurs.

4.4. Microscopic characteristics

Microscopic seismites sedimentary structures are identified in rock slices, including liquefied curled deformation, tabular-pebbles layer, slip, flame structure, and Lumachella.

4.4.1. Microscopic liquefied curled deformation structure

Similar to macroscopic liquefied curled deformation structure, the Microscopic one show a curled deformation and fold characteristics in lamina of micritic limestone. This structure reflects that unconsolidated lime mud lamina are deformed causing by vibration triggered by earthquake, representing earthquake events of in-situ deposition (Fig. 4e-f).

4.4.2. Microscopic tabular-pebbles layer

Microscopic tabular-pebble layers are wrapped in mm-scale of thin laminated micritic limestone. These structures arrange irregularly, such as 'V' shape, chrysanthemum shape and imbricate shape. There is no displacement and original depositional attitude, though the microscopic tabular-pebbles in the lower part are cracked. It is comparable of the shape and origin between microscopic tabular-pebbles layer and macroscopic one (Fig. 4g-h).

4.4.3. Microscopic slip

These mm-scale slices microscopic slips, developing in T_1j at Longdongwan, Xuyong Sichuan, are considered earthquake origin (Song and Liu, 2009) (Fig. 6a).

4.4.4. Microscopic flame structure

Earthquake makes unconsolidated sediments liquefied, and pore water with high pressure burst into the upper layers because of differential compaction of overlying sediments. Microscopic flame structure is formed in this process. There is more fine sand debris sediments in T_1j^2, which contain more water than calcareous and argillaceous sediments, and can be easily liquefied during earthquake activities period. Therefore, microscopic flame structure is easy for recognition in T_1j^2 (Fig. 6b).

4.4.5. Microscopic slip

Lumachellas with inverted shells lie in the upper part of some seismites sequences in T_1j^2. These inverted shells probably are related to disturbance triggered by earthquake forcing tsunami (Fig. 6c). Besides, Seilacher (1984) linked their characteristic to paleoearthquake facies.

5. Discussion

5.1. Sedimentary sequence of seismites

Three clear sedimentary sequences of seimites are identified in T_1f^1 at Beibei, Chongqing (Fig. 5). The first sequence in the lower part of T_1f^1 records earthquake activities and earthquake forcing tsunami, which presents a good contrast with seismites sequence of Triassic in British (Simms, 2003). The second sequence in the middle part of T_1f^1 records relative weak earthquake activities comparing with the first sequence, triggering boudinage structures, flame structures and microscopic faults. We have to speculate why tsunami forcing sedimentary structures are almost impossible to detect, is that the second stage of earthquake activities are weaker that the first stage. Similar to the first sequence, the third one in the lower- middle part of T_1f^2 records earthquake activities and earthquake forcing tsunami. But the sedimentary characteristics are different, herringbone cross-bedding is developed in top of the third sequence (Fig. 6d).

Clear sedimentary sequences of seimites from pre-earthquake period (the first sequence), earthquake period (the second sequence) and intense earthquake period (the third sequence), are identified in T_1j^2 at Longdongwan section, Xuyongv, Sichuan (Fig. 7). The first sequence in the lower part of T_1j^2, which deposits before earthquake, develops laminated micritic limestone. The second sequence in the middle part of T_1j^2 records laminated micritic limestone layers with small folds in-situ deposition, representing plastic deformation with a thickness of 10 cm triggered by earthquake activities. The third sequence in the upper part of T_1j^2, with a thickness of 35 cm, records quasi in-situ large-small scale breccia layers of seismites and plastic deformation folds sinking in surrounding rocks. Laminated micritic limestone with ripple surface after the third sequence represents the deadline of earthquake (Fig. 6e). Earthquake has great influence on the marine ecological environment. There are many benthos and a large number of trace fossils in T_1j^2, Xuyong, Sichuan before earthquake period, such as *Palaeophycus* trace assemblage and *Planolits-Helminithopsis* trace assemblage (Liu et al., 2009). The ecological environment is destroyed and not suitable for benthos, and trace fossils are not discovered in layers of seismites during earthquake period. The ecological environment revives again, and benthos emerges gradually after earthquake. There is a certain amount of trace fossils which emerge in the ripple surface (Fig. 6f).

5.2. Mechanism of formation and geological significance of seismites

Earthquake is related to tectonic activities. Seismites of Baimiaozi section in T_1f at Beibei, Chongqing is located near Huaying Moutain fault zone, Seismite sequences is once considered to be related to the activities of fault zone (Luo et al., 2009). However, based on research from Li et al (2002) and lv and Xia (2005), ejective structure in Southeast Sichuan basin, including Huaying Moutain region, experiences three stages, respectively are tensional fractures before fold, initial fold, and shaping after fold. The ejective structure are mainly in Himalayan movement period, and is very weak during T_1f and T_1j, which is impossible for triggering earthquake. Besides, the activities of Longmen-Jinping Moutain tectonics belt is also not the main reason of earthquake in T_1, because the rise of Longmen-Jinping Moutain is related to intracontinental subduction of lithosphere of the Yangtze plate since Cretaceous (Xu et al., 2007). The distribution of seismites in T_1f and T_1j is not only in Chongqing, but other regions in Sichuan Basin as well. Besides, abundant of volcanic debris distributes in the lower part of T_1f^1. The above evidences indicate strong tectonic activities in Upper Yangtze plate, triggering intense volcanic and earthquake activities, and forcing widely deposition of seismites in Sichuan basin.

The thickly and broadly deposition of seismites, with typical soft-sediment liquefied deformation structures and sedimentary layers forced by the tsunami, indicate intense and prolonged earthquake. The inner plate tectonic activities may not have enough power triggering such a large scale seismites deposition. The author argues that the large scale seismites may be related to interaction movements of blocks during Indo-Chinese epoch. The Sanjing tectonic belt, a typical representative of Yidun arc, has a strong tectonic activity at the western margin of Yangtze plate, probably forcing widely deposition of seismites in Sichuan basin during early Triassic. Yidun arc lies between Songpan-Ganzi folds and Qiangtang blocks, where the strongest tectonic deformation and metamorphism occurred emerge in the early Triassic. Ganzi- Litang ophiolite melange belt is the suture zone between Yidun arc and Yangtze blocks, representing the subduction of the Paleo-Tethys. The suture zone is a huge tectonic domain with a few to tens of kilometers wide (Zou., et al., 1994; Zou, 1995; Yao and Lan, 2001; Yang, 2002). The magmatic and volcanic activities occur as the Paleo-Tethys ocean crust subducts eastward along Litang-Batang volcanic arc and subducts westward along the Jinsha suture (Wei et al., 2004; Françoise et al., 2008; Wang, 2009). Anthony et al (2005, 2007) got three groups of age data, representing tectonic movement in Mesozoic through Hf isotope analysis of zircons, respectively were early Triassic - middle Triassic (~ 245 to 229 Ma), late Triassic (~ 219 to 216 Ma) and Cretaceous (~ 105 to 95 Ma). The deformation of Paleozoic strata in the early Triassic originates from the closure of Jinsha suture, while the deformation of Upper Triassic strata in the late Triassic originates from the closure of Songpan-Ganzi-Litang basin. Therefore, the evolution of the Yidun arc is controlled by Litang suture zone and Jinsha suture zone. The evolution of Upper Yangtze plate in Triassic are as follows: aborted rift trough → immature island arc→ mature island arc → remnant basin (Qu et al., 2003; Dai and Sun, 2008).

Earthquake and volcanic activities are frequent and trigger tsunami, with plate collision and ocean crust subduction at the western margin of Yangtze plate in early Triassic. The age of tectonic movement in Mesozoic, obtaining from zircon (Hf isotope analysis) in Songpan-Ganzi regions (Anthony et al., 2005, 2007; Liu et al., 2006; Tang et al., 2017), matches with the age of seismites in Lower Triassic in Sichuan Basin. Meanwhile, volcanic eruptions occur along the volcanic arc as plate collision and subduction of oceanic crust. volcanic ashes erupts into the atmosphere and widely diffuses, depositing not only in Songpan-Ganzi-Litang regions, but Sichuan basin as well. Volcanic ashes in T_1f^1 at Baimiaozi section, Beibei, Chongqing may be related to the volcanic activities of volcanic arc in Litang-Batang. Continuous plate collision and subduction of ocean crust, triggered by tectonic evolution of Yidun arc in the early Triassic, are the main reasons of seismites deposition in the early Triassic in Sichuan Basin (Fig. 8).

6. Conclusions

Seismites are widely discovered in T_1f^1 in Beibei, Chongqing, in southeast of Sichuan Basin, and in T_1j^2 at Longdongwan section in Xuyong, in south of Sichuan Basin. As well as in T_1j^2, Xingwen, Sichuan and Xishui of Guizhou. A series of macroscopic and microscopic sedimentary structures are discovered in seismite senquences, such as soft sediments deformation, breccia of seismites, tabular-pebbles, interformational microscopic faults, representing intense earthquake activities. Seismite senquences in T_1f^2 at Baimiaozi section, Beibei, Chongqing are exposed well, recording the whole course of earthquake activities from intense to weak. The Sanjing tectonic belt, a typical representative of Yidun arc, has a strong tectonic activity at the western margin of Yangtze plate, probably forcing thickly and broadly deposition of seismites in Sichuan basin during early Triassic.

Declarations

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary Information

Data will be made available on reasonable request

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Figures

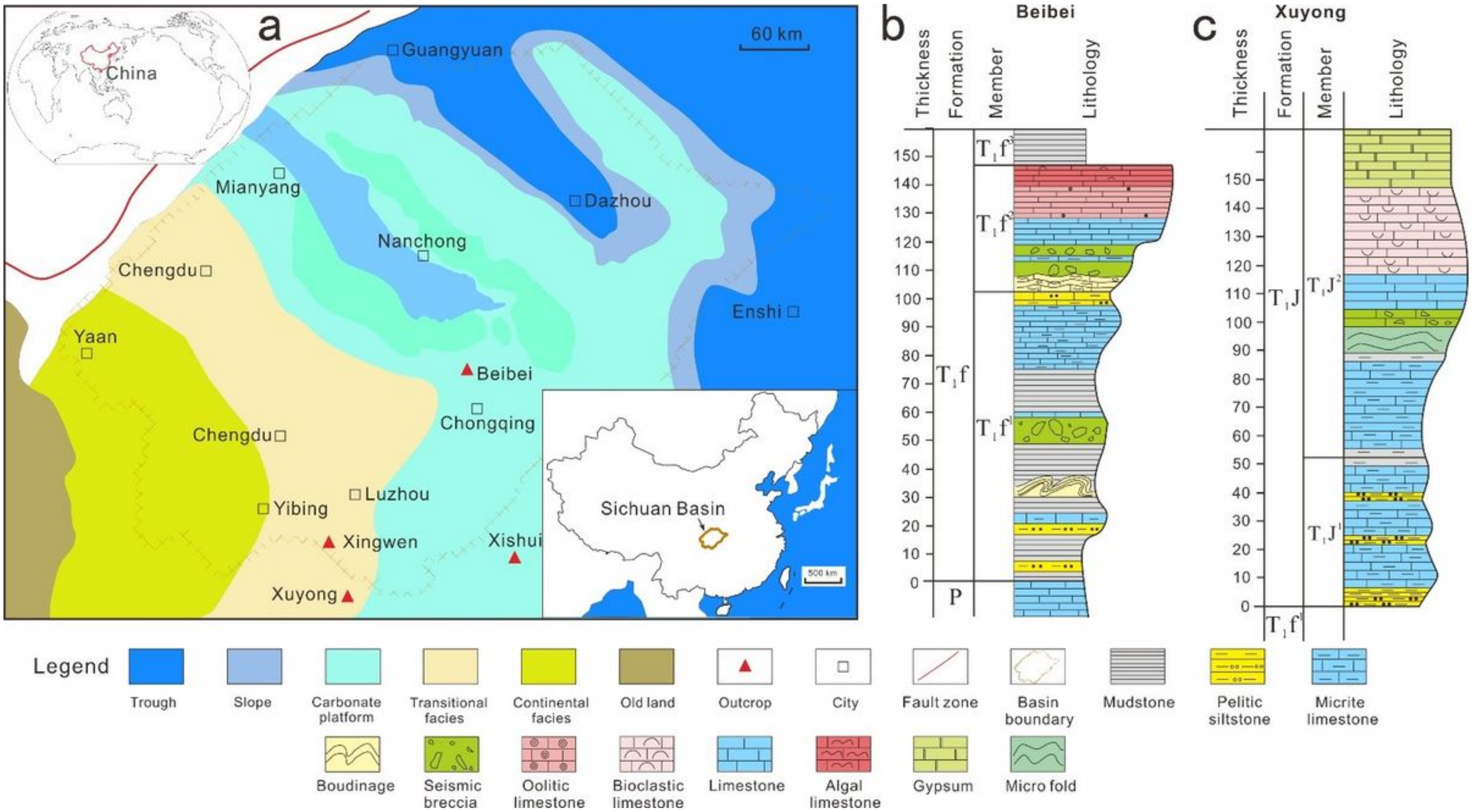

Figure 1

Paleogeographic maps and the distribution of seismites in Sichuan Basin. (a). Paleogeographic maps for the early Triassic in Sichuan Basin. (b). The distribution of seismites in feixianguan formation (T_1f), in Beibei section. (c). The distribution of seismites in Jialingjiang formation (T_1j), in Xuyong section.

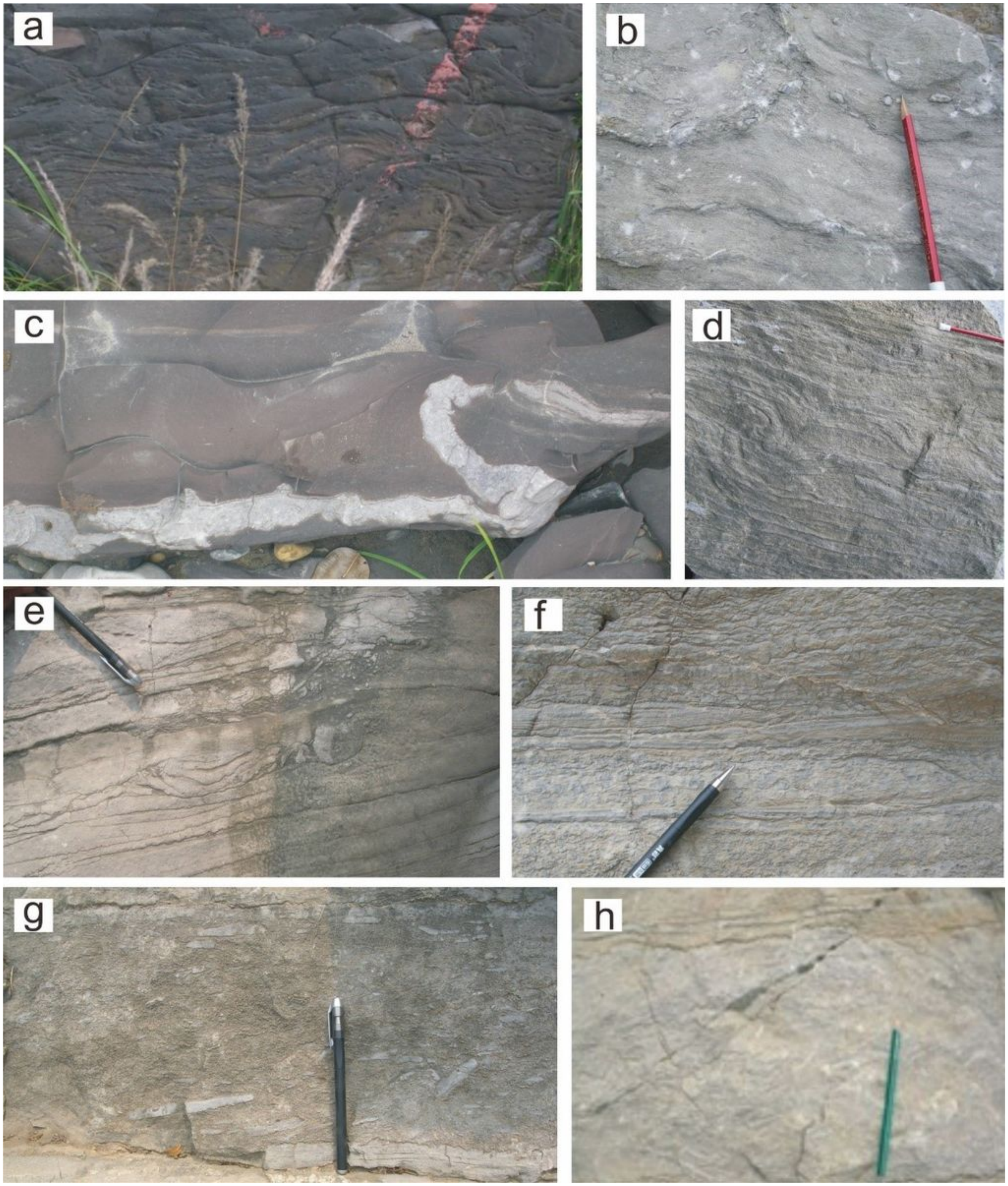

Figure 2

Soft-sediment deformation and Tabular-pebbles in Feixianguan-Jianglingjiang formation during early Triassic in Sichuan Basin. (a). Crimp deformation structure in T_1f^1, in Baimiaozi section, Beibei, Chongqing. (b). Crimp deformation structure with wavy folds in thin micritic limestone layers in T_1f^2, in Longciwan section, Xuyong. (c). Boudinage structure in T_1f^1, in Baimiaozi section, Beibei, Chongqing, composition of gray matter, a few centimeters to more than ten centimeters thick, its folding crankshaft surface is variable, folding morphology is different. (d). Slight folds of laminar plastic deformation in T_1f^2, in Baimiaozi section, Beibei, Chongqing. (e). Slight folds of laminar plastic deformation in T_1j^2, in Longciwan section, Xuyong. (f). Fractured tabular-pebbles distributed along the bedding in T_1f^2, in Baimiaozi section, Beibei, Chongqing. (g) and (h) is disorder fractured tabular-pebbles in T_1f^2, in Baimiaozi section, Beibei, Chongqing.

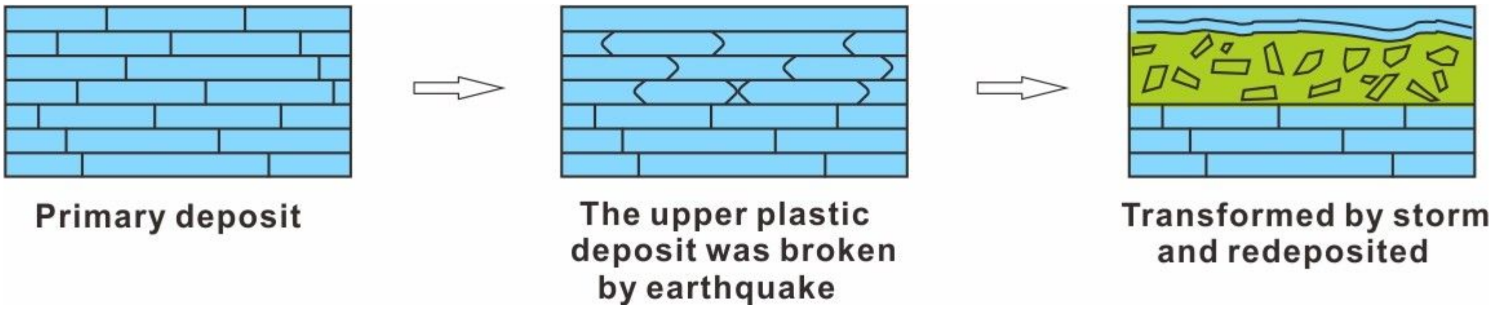

Figure 3

The formation of tabular-pebbles.

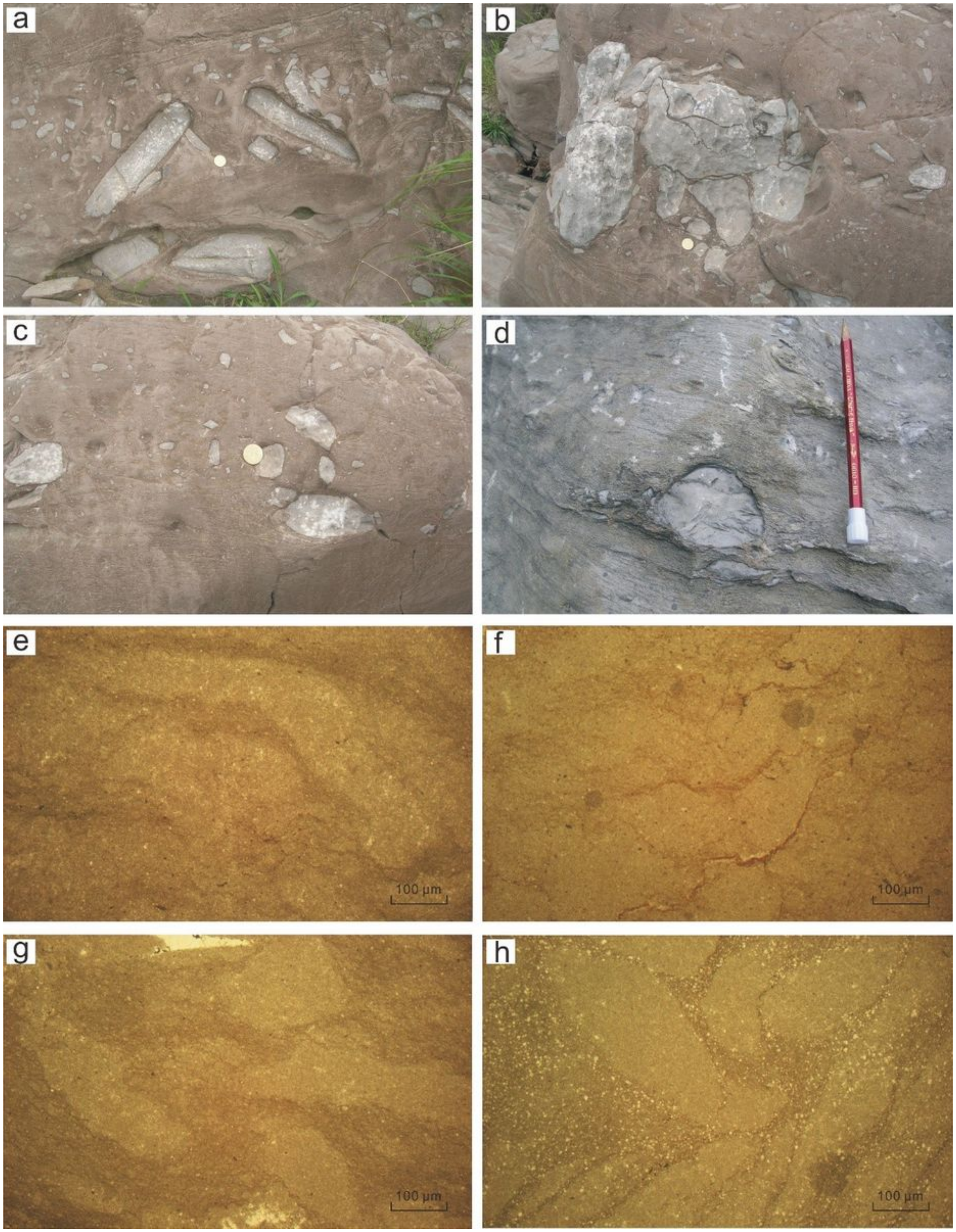

Figure 4

Breccia of seismites in Feixianguan-Jianglingjiang formation during early Triassic in Sichuan Basin. (a). Tabular seismite breccia in T_1f^1, in Baimiaozi section, Beibei, Chongqing. (b) and (c) are mixed size seismite breccias with a certain degree of roundness in Baimiaozi section, Beibei, Chongqing. (d). Seismite breccias in T_1j^2, in Longciwan section, Xuyong. (e) and (f) are microscopic liquefied curled deformation structure in T_1j^2, in Longciwan section, Xuyong. (g) and (h) are microscopic tabular gravels, arranged in millimeter-scale laminated micritic limestone thin layer, (g) is in T_1j^2 in Dali Village section, Xingwen, and (h) is in in T_1j^2 in Huangmuping section, Xishui.

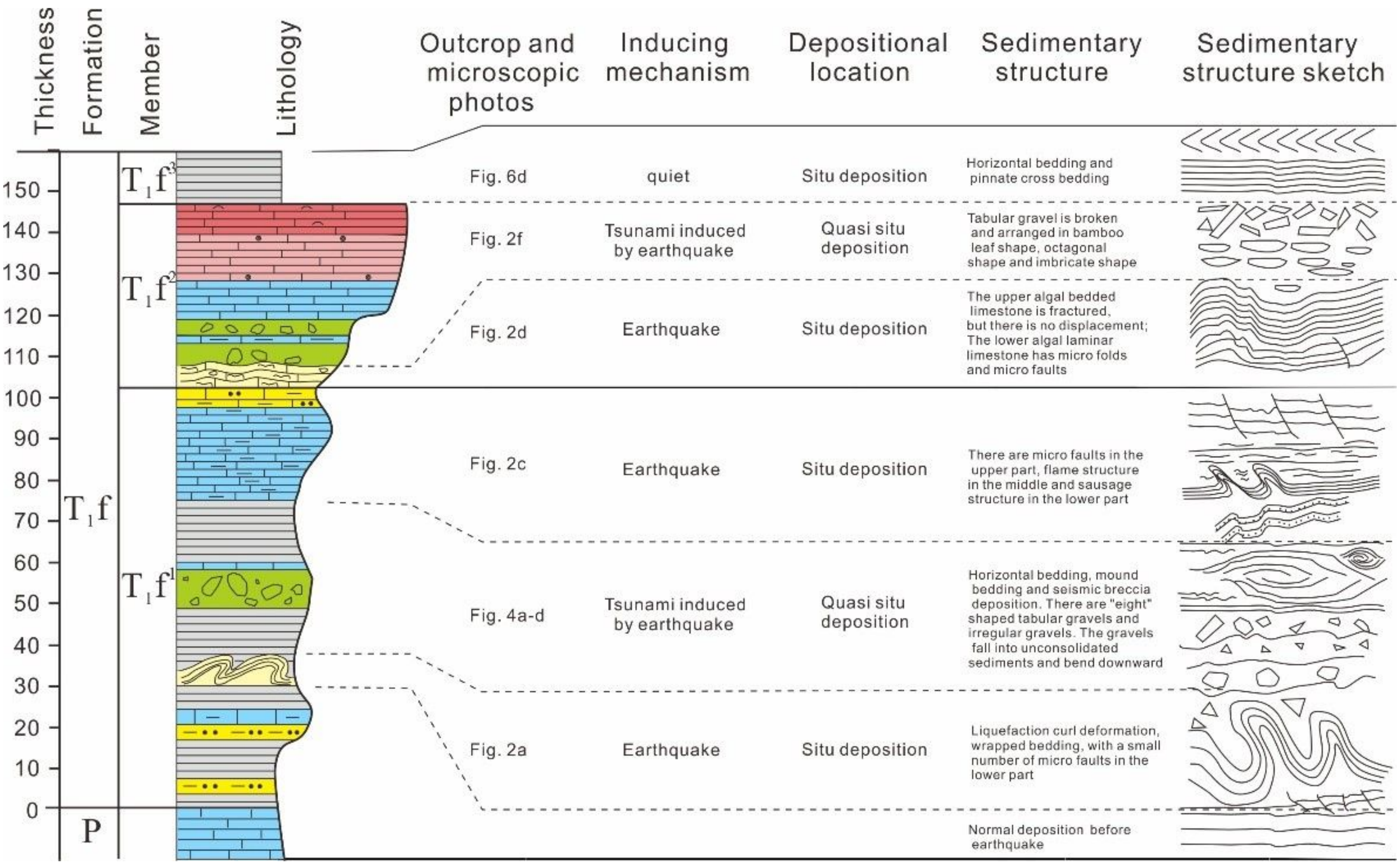

Figure 5

The sedimentary sequence of seismites in Feixxianguan Fm., Chongqing.

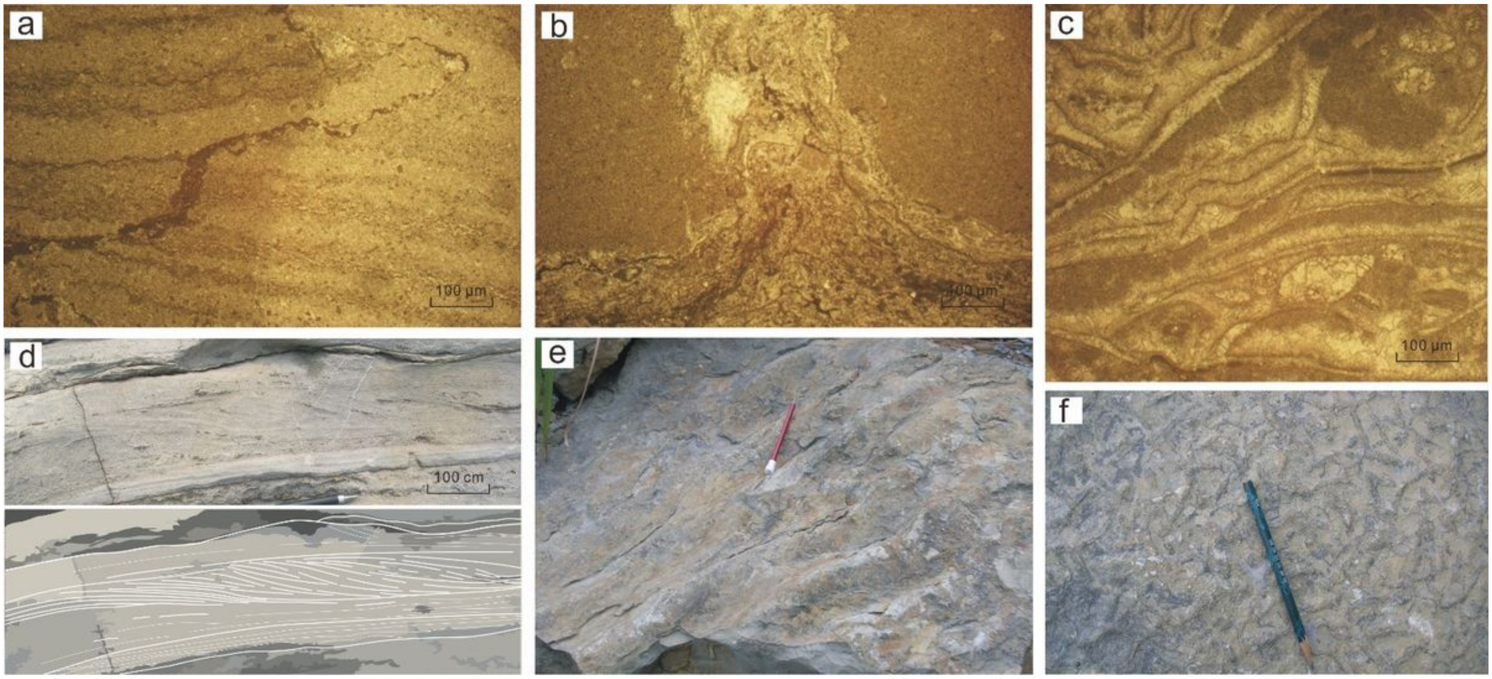

Figure 6

Microscopic slip, flame structure and other sedimentary structure in sequence of seismites, in Feixianguan-Jianglingjiang formation during early Triassic in Sichuan Basin. (a), (b) and (c) are respectively microscopic slip, flame structure and lumachella in T_1j^2, in Longciwan section, Xuyong. (d). Herringbone cross-bedding in T_1f^1, in Baimiaozi section, Beibei, Chongqing. (e) and (f) are laminated micritic limestone with ripple surfaces in T_1j^2, in Longciwan section, Xuyong, a certain amount of trace fossils emerges in layer with ripple surface in (f).

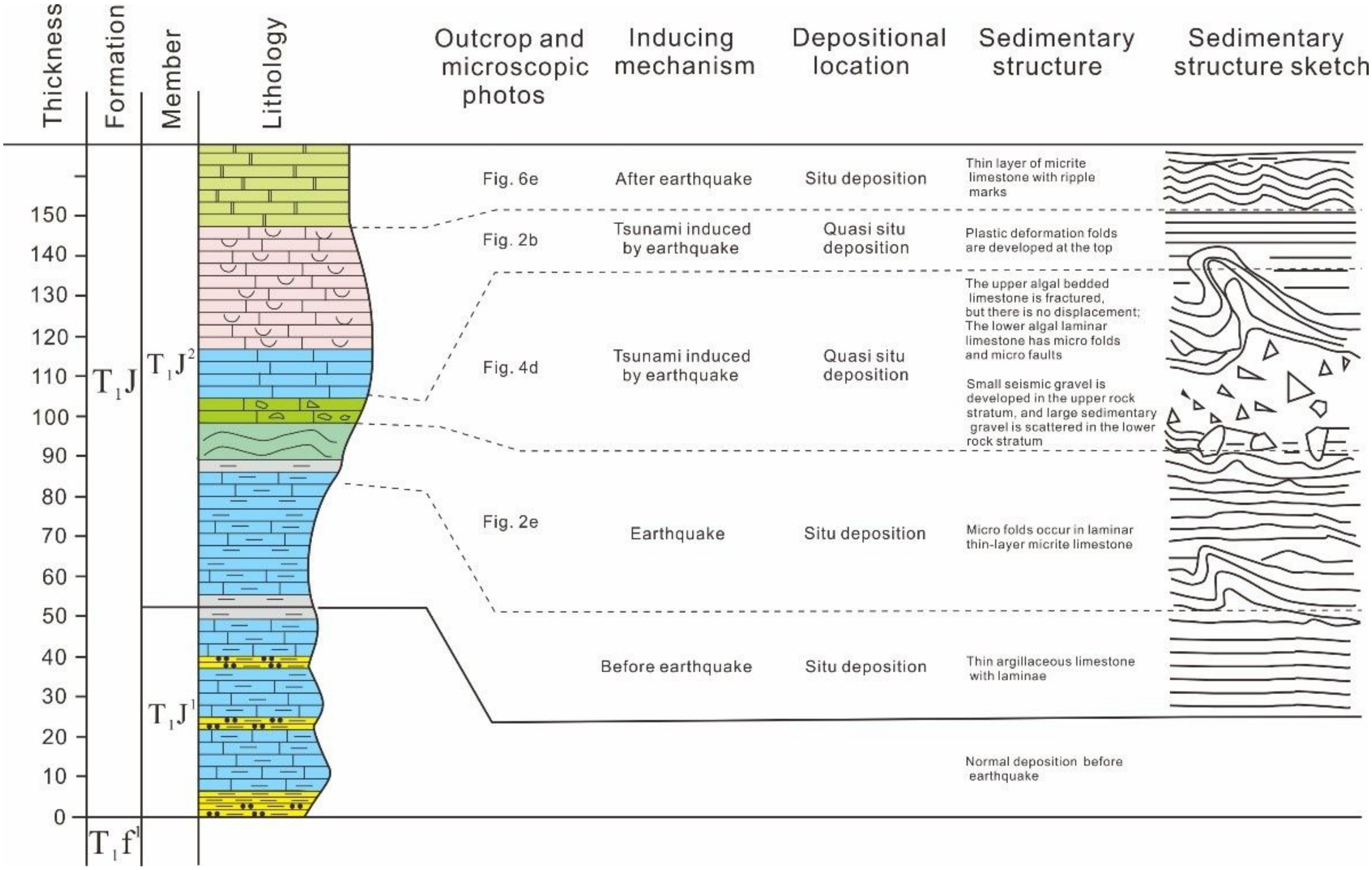

Figure 7

The sedimentary sequence of seismites in Jialingjiang Fm. at Xuyong, Sichuan.

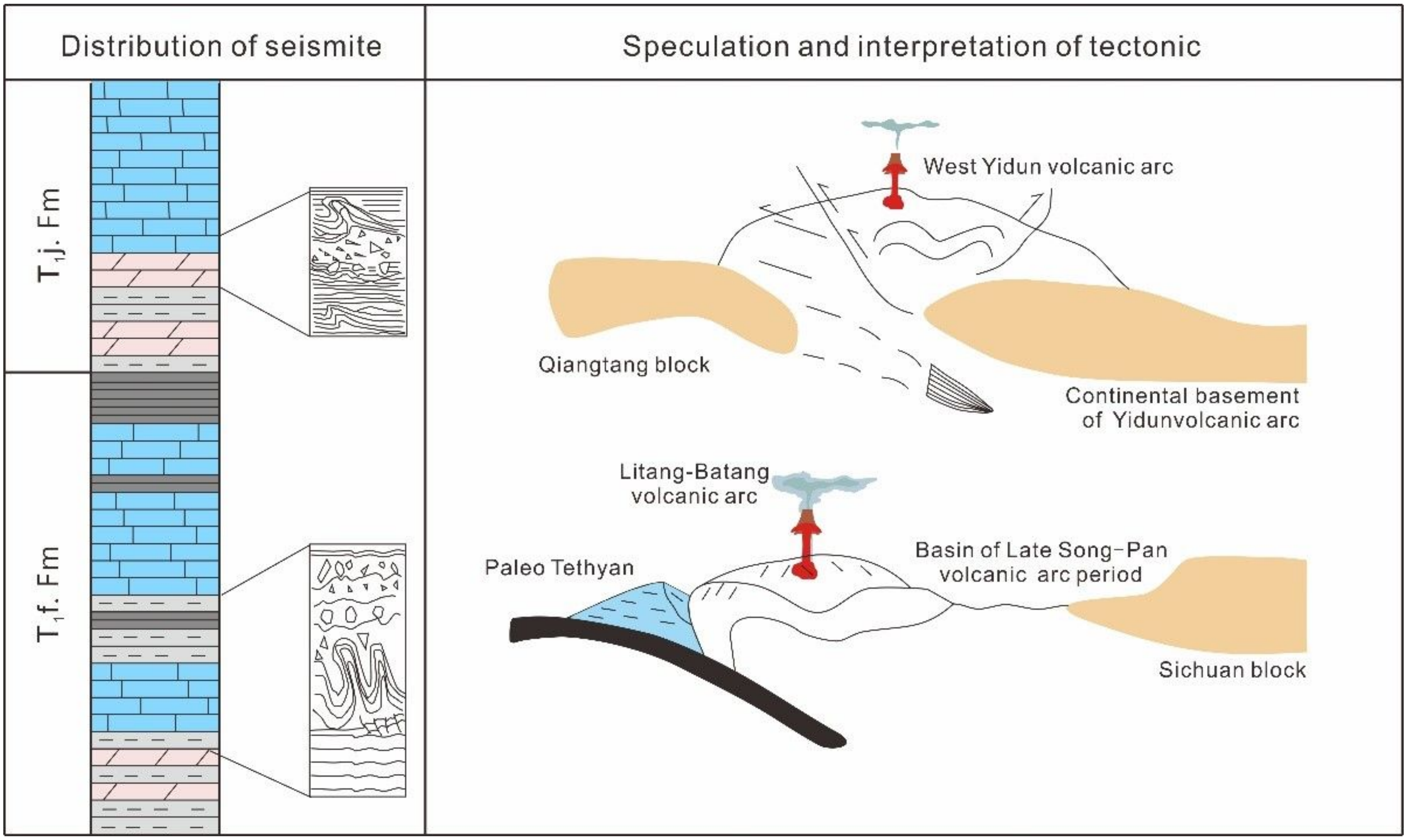

Figure 8

The Jinshajiang tectonic belt evolution at the west margin of the Upper Yangzi plate and the relationship with seismites development during the early Triassic.