Vol. 82 No. 6 pp. 1185–1193 ACTA GEOLOGICA SINICA Dec. 2008

Soft-sediment Deformation Structures Related to Earthquake from the Devonian of the Eastern North Qilian Mts. and Its Tectonic Significance

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Abstracts: Devonian in the North Qilian orogenic belt and Hexi Corridor developed terrestrial molasse of later stage of foreland basin caused by collision between the North China plate and Qaidam microplate. The foreland basin triggered a intense earthquake, and formed seismites and earthquake-related soft-sediment deformation. The soft-sediment deformation structures of Devonian in the eastern North Qilian Mts. consist of seismo-cracks, sandstone dykes, syn-depositional faults, microfolds (micro-corrugated lamination), fluidized veins, load casts, flame structures, pillow structures and brecciation. The seismo-cracks, syn-depositional faults and microfolds are cracks, faults and folds formed directly by oscillation of earthquake. The seismic dykes formed by sediment instilling into seismic cracks. Fluidized veins were made by instilling into the seismo-fissures of the fluidized sands. The load casts, flame structures and pillow structures were formed by sinking and instilling caused from oscillation of earthquake along the face between sandy and muddy beds. The brecciation resulted from the oscillation of earthquake and cracking of sedimentary layers. The seismites and soft-sediment deformations in Devonian triggered the earthquake related to tectonic activities during the orogeny and uplift of North Qilian Mts.

Key words: North Qilian Mts., seismites, soft-sediment deformation, Devonian, tectonics

1 Introduction

After the first discoveries of the deformation and displacement of seafloor sediments and turbidity current triggered by the Grand Bank Earthquake of Canada in 1929 (Heezen and Dyke, 1964) and seismite is defined as redeposited beds disturbed and modified by earthquakes (Seilacher, 1969), the researches on seismites became an important aspect in sedimentology gradually. Special volumes of Marine Geology on seismicity and sedimentation edited by Cita and Ricci Lucchi (1984) and Sedimentary Geology on seismites, tsunamiites and seismoturbidites by Shiki et al. (2000) were issued. Through research on seismites in China started later (Song, 1988; Qiao et al., 1994), much advancement has been achieved. For example, Qiao et al. (1996, 1997, 2000, 2001a, 2007) studied the Mesoproterozoic, Neoproterozoic and Paleozoic earthquake and tsunami deposits of North China, systematically summarizing the diverse lithofacies of seismites and discussing the earthquake distribution and the evolution and tectonic setting of the basin (Qiao et al., 2001b). Recently, extensive studies were performed on the event deposits associated with earthquake by many scholars, investigating the relationship of earthquakes and these tectonic settings (Peng et al., 2001; Du et al., 2001a, 2001b, 2005; Du, 2005; Duan et al., 2002; Zhang et al., 2003; Tian et al., 2003; Yin and Yang, 2005; Lu et al., 2006a, b; Zhou et al., 2006).

Soft-sediment deformation structures resulted from the modifications such as differential compaction, liquefaction, slip and slump of sediments without consolidation. Since these deformations are commonly associated with the vibrations of earth crust, they coexist with seismite frequently. Soft-sediment deformation induced by earthquakes is an important aspect of studies on seismite abroad (Mohindra and Bagati, 1996; Molina et al., 1998; Rossetti, 1999; Ettensohn et al., 2002). Wheeler (2002) made an effort to distinguish the natures of soft-sediment deformations between earthquake cause and non-earthquake cause. The soft-sediment deformations caused by earthquake are accompanied by fractures initiated by earthquake, like seismic micro-fracture and

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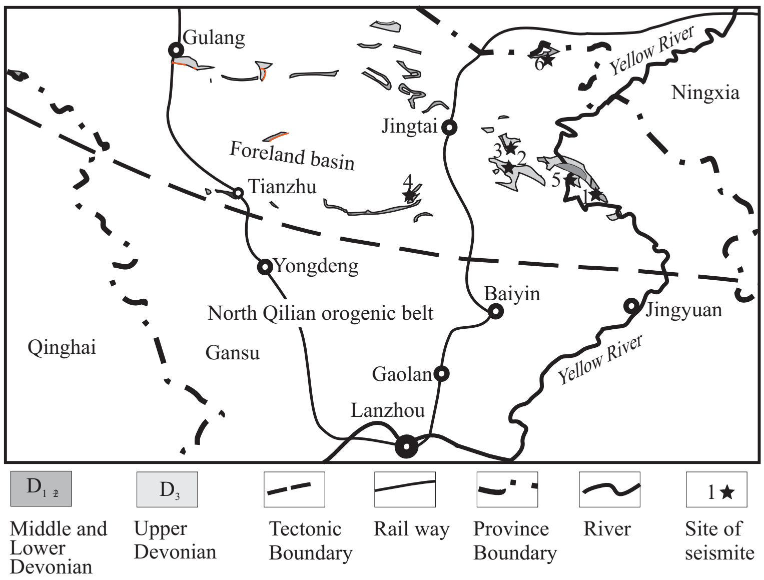

Fig. 1. Devonian outcrops and sites of seismites in the eastern sector of North Qilian Mts.

Location of sections: 1 – Shaliushui, Pingchuan, Baiyin City; 2 – Xiakoujing, Jingtai County; 3 – Huangtuya, Jingtai County; 4 – Fulushui, Jingtai County; 5 – Yellow River Cross, Xiaokou, Pingchuan, Baiyin City; 6 – Kongdonggou, Jingtai County.

synsedimentary fracture, generally. In contrast, there are no such structures developing with generic soft-sediment deformation. Additionally, soft-sediment deformation is usually formed by intense external forces, which contains volcanic activity, tsunami, gravity landslide and slump, besides earthquake. Even so, the soft-sediment deformation coexisting with typical seismite should be related to earthquake.

2 Geological Setting

North Qilian Orogenic belt was formed by the collision among Qaidam microplate, Median Qilian block and North China plate in the Late Caledonian to Early Hercynian. The Paleozoic North Qilian ocean succeeded the breakup of Rodinian Supercontinent, experiencing an evolution of non-united rift in Sinian-Cambrian and archipelagic ocean in Ordovician, foreland basin in Silurian-Devonian. The transformation of sedimentary basin in North Qilian area took place during late Caledonian and early Hercynian (Silurian and Devonian). The collision of median Qilian block, Qaidam microplate and North China plate ended the evolution of Ordovician archipelagic ocean, and resulted in a sedimentary sequence of typical foreland basin, including inchoate flysch in Early-Middle Silurian foreland basin, terminal marine molasses in Late Silurian and terrestrial molasses during Devonian (Du et al., 2003, 2004).

In North Qilian-Hexi Corridor area, the Silurian consists of the Lower Silurian Angzanggou and Lujiaogou formations, Middle Silurian Quannaogoushan Formation, and Upper Silurian Hanxia Formation in ascending order. All of above formations found in the west sector of North Qilian-Hexi Corridor area and in eastern sector only developed the Angzanggou Formation. The lower part of Angzanggou Formation contains green, grayish-green mudstones and medium-thick-bedded sandstones, sandy conglomerates, and interbedding grayish-green thick-bedded sandstones, siltstones and mudstones in the upper part. This formation overlaid unconformably on Ordovician volcanic rocks, limestones and siliceous rocks. In Sunan-Yumen subarea of western sector, the bottom of Silurian is constituted by grayish-green conglomerates, sandy conglomerates and pebbly sandstones, intercalated with sandstones, siltstones, mudstones with a maximum thickness of 350 m, named as the Lujiaogou Formation. The Quannaogou Formation, in a maximum thickness of 2109 m, consists mainly of grayish-green, purplish-red medium-thin-bedded fine-grained sandstones, siltstones, silty shales, with dark gray medium-thick-bedded limestones. The Hanxia Formation contains purplish-red fine-grained sandstones, siltstones, sandy shales and mudstones with a maximum thickness of 1930 m.

The Devonian in North Qilian and Hexi Corridor area is subdivided into two parts, the Laojunshan Formation and Shaliushui Formation. The former is mostly distributed in the junction area between the Hexi Corridor and the northern edge of North Qilian Mts. The latter mainly appears in Jingtai-Jingyuan area of east part of Hexi Corridor. Laojunshan Formation, with a maximum thickness of 3750 m, mainly consists of purplish-red thick-hugely thick-bedded conglomerates, sandy conglomerates. In the Shaliushui Formation with a maximum thickness of 595 m, the changes of lithology are from conglomerates and pebbly sandstones at bottom to sandstones and interbedded siltstones, mudstones at upper parts. The Laojunshan Formation covers above the Silurian unconformably, which is covered by the Upper Devonian Shaliushui Formation disconformably.

Both Silurian and Devonian seismites develop in North Qilian foreland basin, and the former has be reported by the author (Du et al., 2001a). This thesis emphasizes on Devonian soft-sediment deformations related to earthquake in eastern Qilian area (Fig.1).

3 Soft-sediment Deformation Related to Earthquake

Devonian in eastern North Qilian (Jiangyuan-Jingtai region) deformed weakly and the stratigraphic layer is stable unicline except that close to fracture zone with disarrangement. Although soft-sediment deformation caused by earthquake is frequently developed, in the bottom conglomerates of the Laojunshan Formation are difficult to be identified. Typical soft-sediment deformations, including crack and sandy dyke, liquefied vein, synsedimentary fault, micro-corrugated lamination, load structure and pillow structure and brecciation, develop well in the upper sandstones of Laojunshan Formation and Shaliushui Formation.

3.1 Cracks and depositional sandy dykes or veins

Description: The typical crack can be seen in the Shaliushui Formation in Shaliushui of Pingchuan, Baiyin City and Kongdonggou of Jingtai County. The cracks in Shaliushui Formation in the northwest of Shaliushui village are wedge-shaped in profile, and zonal on depositional surface, wedged into stratum vertically and inclined to strata trend. The width of the top of cracks is from 20 cm to 30 cm, filled by fine sandstone dykes which are distinct with the country rocks showing a markable boundary between light sandstones and purplish-red muddy sandstones (plate I-1). The cracks of Shaliushui Formation in another place in Shalishui are quite small, only showing some proximally lattice-like sandstone veins with a width range of 0.3 cm–3 cm and presenting obvious circumscription between pale-red sandstone veins and purplish-red country muddy rocks (Plate I-3). The mudstone dykes of Laojunshan Formation in Kongdonggou of Jingtai County, in a width of about 5 cm, are planar in vertical profile and wedged into the layers perpendicularly, filled with purplish-red muddy rocks that is similar to the country rocks which is less muddy (Plate I-2).

Interpretation: Cracks are typical sedimentary structures in seismite. The micro-fractures induced by earthquake are usually perpendicular to layers, with varied width from a few to tens centimeters generally. Cracks are mostly wedge-shaped in profile, and banded (single fracture) or irregular network-shaped (multiple fractures) on the layer surface, showing distinct differences with the conjugated joints formed from faults in the late period. Cracks are filled with the sediments at depositional time immediately, with sandy fillers in sandstone dyke or thinner sandstone vein, and muddy fillers in mudstone dyke (vein). The component of sedimentary dyke or vein depends on the composition of filling sediments, keeping distinct boundary with country rocks. These sandy mudstone dykes are perpendicular to layers and unconjugated, and support their earthquake origin undoubtedly.

3.2 Liquefied veins

Description: Sandstone veins formed by liquefaction appear in Kongdonggou of Jingtai County, Shaliushui of Pingchuan in Baiyin City and some other places. The sandstone veins in Kongdonggou develop among the red-gray silty mudstones of the Shaliushui Formation with a width range of 1 cm–2 cm, and are perpendicular to the layers. The veins are shaped like prolate ellipsoid, bowling or irregular forms. The filler in the veins is pale-gray siltstones and distinct with pale-red muddy-rocks (Plate I-4). The sandstone veins of the Shaliushui Formation in Shaliushui are discovered in the purplish-red muddy-rocks and silty-mudstones with a width of about 3 cm, and perpendicular to the layers. The veins are shaped irregularly, but planar in local. The component of filler in the veins is pale-grey fine-grained sandstones, showing a clear boundary with the country-rocks (Plate I-5).

Interpretation: The aquiferous sandy layers are liquefied by the compaction of the covering layers commonly in the nature. When cracks occur, the liquefied sandy layers will overflow into the cracks, then form sandstone vein, which is called as liquefied vein (Qiao et al., 1994). This liquefied vein can present in both calstic rocks and carbonate rocks. After the micro-fracture is caused by earthquake, the liquefied sandy mud is pushed in and liquefied vein is formed. When the liquefied veins extrude out of layers and on the surface of sedimentary layer, sandy volcano or muddy volcano is shaped (Du et al., 2005). Liquefied vein is different from depositional vein (dyke) formed in the cracks mentioned above, which usually is formed within depositional layer, and is bent, enteroid or irregular in form but no wedge-shaped with vertical flowing-marks. In addition, the liquefied vein is also different from the vein filling in the anaphase structural joints. The joints formed by anaphase structure are conjugated generally, and filled by quartz or calcite during the digenetic period; while the liquefied veins are non-conjugated and filled with sandy and muddy sediments. The liquefied veins without conjugation described here, whose filler is fine-sands and silts and shows flowing-marks inform, should be caused by earthquake.

3.3 Synsedimentary faults

Description: Synsedimentary faults develop in the Shaliushui Formation exposed in Shaliushui of Pingchuan of Baiyin, the Yellow River Crossing of Xiaokou and other places. The synsedimentary faults in Shaluishui region show intralayer faults which is constrained between the upper and lower layers and the sedimentary layer is cut by inclined faults. The faults are small-size with a height of about 25 cm and filled with purplish-red sandy and muddy sediments with non-flat fault planes (Plate I-8). At the Yellow River Crossing in Xiaokou region, the sedimentary faults develop in the layers of purplish-red sandstone, mudstone and are intralayer faults too, which display a broken sandstone block slipped into the underlying mudstones and laterally is adjacent to the muddy rocks obviously with a fault-throw range of 30 cm–60 cm (Plate II-1, 2).

Interpretation: Synsedimentary fault is the typical synsedimentary structure related to seismite. This type of fault is different from post-sedimentary fault, which are illustrated as following: (1) synsedimentary fault belongs to intralayer fault without crossing the overall beds, while post-sedimentary fault cross through the layers commonly; (2) the plane of synsedimentary fault is not flat, along which the fault is filled with sediments, while post-sedimentary fracture is filled with quartz vein or calcite vein along its planar fracture plane. The faults described above are intralayer faults with sediment filler, which are caused by earthquake during penecontemporanous period.

3.4 Micro-corrugated lamination

Description: Micro-corrugated lamination is mainly presented in Xiakoujing and Kongdonggou of Jiangtai County. The micro-corrugated laminations in Xiakoujing develop in pale-red fine-grained sandstones of the Shaliushui Formation with distorted and irregularly undulant laminas. The micro-corrugated laminas are not cross into upper and lower lamination and constrained within the laminated fine sandstones, in a thickness of about 18 cm. Different phases can be distinguished between corrugated-laminas (Plate I-6). The micro-corrugated lamination of Kongfonggou is discovered in the purplish-red fine-grained sandstones of the Laojunshan Formation and the thickness of the corrugated laminas is about 10 cm. They are intralayer folds too that develop between the unfolded upper and lower layers. The laminas are deformed as chest-like or irregular shapes, and folded laminas are uncontinued in interrupted form (Plate I-7).

Interpretation: The micro-corrugated lamination is formed by deformation of unconsolidated sediments under the forces of vibration in earthquake. Because of the poor consolidation of the surface sediments, the micro-corrugation mainly develops in the surface sediments, and form intralayer fold, when earthquake takes place. The micro-corrugated lamination is different from the fold originated from post-sedimentary structure. The fold from post-sedimentary structure is accompanied by all of the layers involved in the fold. Additionally, the fold caused by post-sedimentary structure is continuous and coordinated with large dimension and the same phase in different folded horizons. The micro-corrugated lamination is small in size, poorly continuous and uncoordinated. Consequently, the fold described above is micro-corrugated lamination, which is triggered by earthquake, and does not remain with the folded structure of post-sedimentary structural origin.

3.5 Load structures, flame structure and pillow structure

Description: Load structure, flame structure and pillow structure are the most well developed soft-sediment deformation of Devonian in the North Qilian. Three types of structures occur under the influence of vibration during earthquake. The load structure was formed as sandy sediments sank into unconsolidated muddy layers; and the flame structure was formed as muddy sediments wedged upwards into sandy layers and the pillow structure as the sandy body dropped within the muddy layers in a pillow form. The load and flame structures of the Shaliushui Formation in Shaliushui are in irregular rod-form in a range of 20–35 cm. The sinking of sandstone into the underlying muddy layers result in load structure, the piling of muddy layers into sandy layers forms flame structure (Plate II-3). The load and pillow structures from the Shaliushui Formation in the Yellow River-Crossing of Xiaokou occur at the bottom of sandstone layer and the load bodies in a width of about 75 cm sink in the muddy layers. The pillow bodies with a length of 50 cm sink within the mudstone layers (Plate II-4). Various load structures develop in the Shaliushui Formation in Huangtuya, Xiakoujing and other places of Jingtai County (Plate II-5-7). These load structures are about 10 cm in width and shaped in discoid, hummocky form and irregular gibbosity, sinking into the underlying muddy layers.

Interpretation: Load structure, flame structure and pillow structure are the ubiquitous soft-sediment deformation in clastic rocks. The formation of these structures is commonly influenced by the following conditions: (1) unconsolidated sediments, (2) a certain context of intergranular water trapped in the sediments, (3) vibration of sedimentary layers caused by structural activity. The above soft-sediment deformation coexists with the typical structures with earthquake origin (such as cracks, liquefied vein, micro-corrugation, and synsedimentary-fracture). Therefore, they are considered to be related to earthquake.

Except the main soft-sedimentary structures stated above, brecciation caused by earthquake also develop in Devonian, which are associated with seismites (Plate II-8). This breccia is seldom sorted and sharp-shaped, with

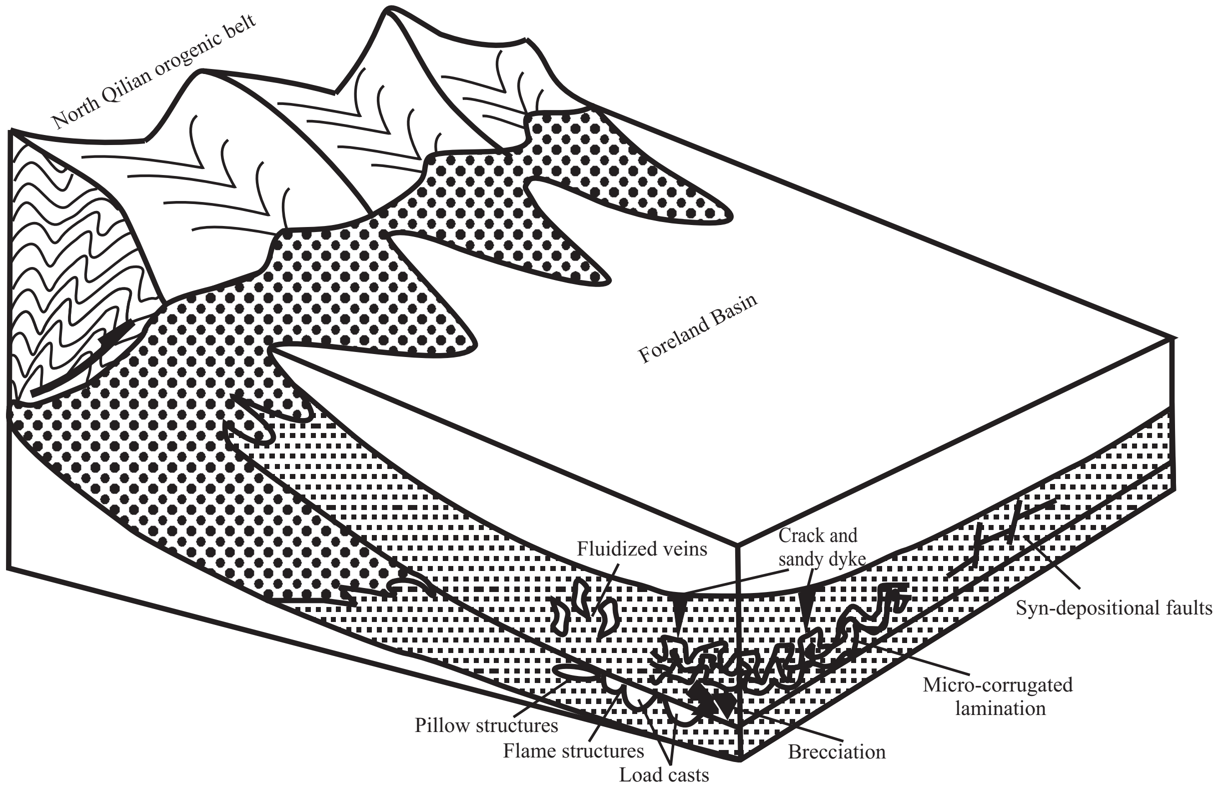

Fig. 2. The model of Devonian seismites and earthquake-related soft-sediment deformation in North Qilian foreland basin.

unorderly arrangement and without preferential direction. It is visible that the original layer is tensile and broken. The breccia is different from the sediments of debris flow and alluvial fan in fabric characteristics, but similar to autoclastic breccia of seismites.

4 Discussion

The soft-sediment deformations genetically related to earthquake include crack and sandy dyke, synsedimentary fracture, micro-corrugated lamination, liquefied vein, load structure, flame structure, pillow structure, brecciation and so on in Devonian, North Qilian area. The crack, synsedimentary fracture and micro-corrugated lamination are the fracture and fold caused by earthquake directly; sandy dyke or vein is formed as the sediments fill into the fractures formed by earthquake. The liquefied vein is formed as the liquefied sandy layers rip into the fractures with earthquake origin. The load structure, flame structure and pillow structure are formed as the sandy layers sinking downwards into mudstone layers, and muddy layer wedging upwards into sandy layer triggered by the vibration of earthquake. The brecciation results from the rapture of sedimentary layers triggered by the earthquake vibration. These soft-sediment deformations coexist with each other and constitute the typical soft-sediment deformation associated with autochthonous seismites (Qiao et al., 1994) originated from earthquake (Fig. 2).

Modern earthquakes are regionally confined to active continental margin (both sides of trench-subduction zone), plate-suture belt (both sides of continental subduction zone), and secondly the continental rift valley and oceanic rift valley (oceanic central rift valley). On the analogy of this, ancient earthquakes are able to be inferred. Similarly to the Alps-Himalaya-Indonesia earthquake belt today, North Qilian was on a background of a deuteric foreland basin which is filled with terristrial molass in Devonian, experiencing the collision and orogeny of Qilian from the Late Caledonian to the Early Hercynian (Du et al., 2003, 2004). The Early-Middle Devonian Laojunshan Formation comprises typical terristrial molass sedimentation in North Qilian-Hexi corridor, and mainly consists of purplish-red conglomerates of debris-flow and alluvial-fan along Sunan-Minle-Jingyuan, forming a quite huge fan body in the plane (Du et al., 2003). The Late-Devonian Shaliushui Formation is predominated by the sedimentation of distal underwater-alluvial fan and lacustrine facies. The sedimentation in the foreland basin was surely impacted by the earthquake activities triggered by the abduction and uplifting of North Qilian orogenic belt, and recorded the earthquake event sediments. Accordingly, the seismites and soft-sediment deformations related to earthquake in Devonian are the record of tectonic activities during the orogeny and uplift of North Qilian Mts.

5 Conclusion

The Early Paleozoic Qilian Ocean resulted from the breakup of Rodinia supercontinent and evolved later to oceanic rift from Sinian to Cambrian, Ordovician archipelagic ocean and foreland basin in Silurian-Devonian. The Silurian-Devonian is the key period for the transformation of sedimentary basin and tectonic evolution in Qilian. The Ordovician archipelagic ocean is closed by the collision among the Mid-Qilian block, Qilian micro-plate and North China plate, forming the flysch sedimentation representing the early stage of the foreland basin in the Early-Middle Silurian, the marine molasses sedimentation in the Late Silurian and the terrestrial molasses in Devonian representing the late stage of the foreland basin, which compose the sedimentary sequence in a typical foreland basin.

During the formation and evolution of the foreland basin, the intense overthrusting of the orogenic belt onto the foreland results in the violent earthquake activity by continent-continent collision. The typical deposits of earthquake event and a series of soft-sediment deformations related to earthquake are recorded in the foreland basin. Emblematical Silurian seismites develop along Yumen-Minle-Tianzhu region of North Qilian (Du et al., 2001a). The conglomerates of the Laojunshan Formation dominate the Devonian with intense deformation in the west sector of North Qilian; while, the typical soft-sediment deformation develops well in Jingyuan-Jingtai region in the east sector of North Qilian. It is confirmed that the North Qilian foreland basin is in the stage of intense tectonic activity from Silurian to Devonian.

In the North Qilian area the soft-sedimentary deformation associated to earthquake includes cracks and sandy dykes, synsedimentary-faults, micro-corrugated laminations, liquefied veins, load structures, flame structures, pillow structures, brecciation and so on. All of the deformations are the sedimentary structures implying the existence of synsedimentary earthquakes.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (NO, 40672080, 40621002), the Program for Innovative Research Team in University of the Ministry of Education of China (IRT00546) and “111 Project” (Grant No. B08030). The authors are grateful to Prof. Yan Jiaxin for discussion and revision to this paper.

Manuscript received Oct. 9, 2007
accepted May 4, 2008
edited by Jiang Shaoqing

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Plate illustration

Plate I

I-1, 3 Sandstone veins formed in the cracks discovered in Shaliushui Fm., Shaliushui, Pingchuan of Baiyin.

I-2 Mudstone veins formed in cracks within Laojunshan Fm., Kongdonggou, Jingtai County.

I-4 Sandstone veins formed by liquefaction in Shaliushui Fm., Kongdonggou, Jingtai County.

I-5 Fine-sandstone veins formed by liquefaction in Shaliushui Fm., Shaliushui, Pingchuan of Baiyin.

I-6 Micro-corrugated lamination in Shaliushui Fm., Xiakoujing, Jingtai County.

I-7 Micro-corrugated lamination in Laojunshan Fm., Kongdonggou, Jingtai County.

I-8 Synsedimentary-fractures in Shaliushui Fm., Shaliushui, Pingchuan of Baiyin.

Plate II

II-1, 2 Synsedimentary-fracture in Shaliushui Fm., the Yellow River crossing of Xiaokou, Pingchuan of Baiyin.

II-3 Load structure in Shaliushui Fm., Shaliushui, Pingchuan of Baiyin.

II-4 Load structure and pillow structure in Shaliushui Fm., the Yellow River crossing of Xiaokou, Pingchuan of Baiyin.

II-5 Load structure in Shaliushui Fm., Huangtuya, Jingtai County.

II-6, 7 Load structure in Shaliushui Fm., Xiakoujing, Jingtai County.

II-8 Autoclastic breccia and load structure in Shaliushui Fm., Fulushui, Jingtai County.

Plate I

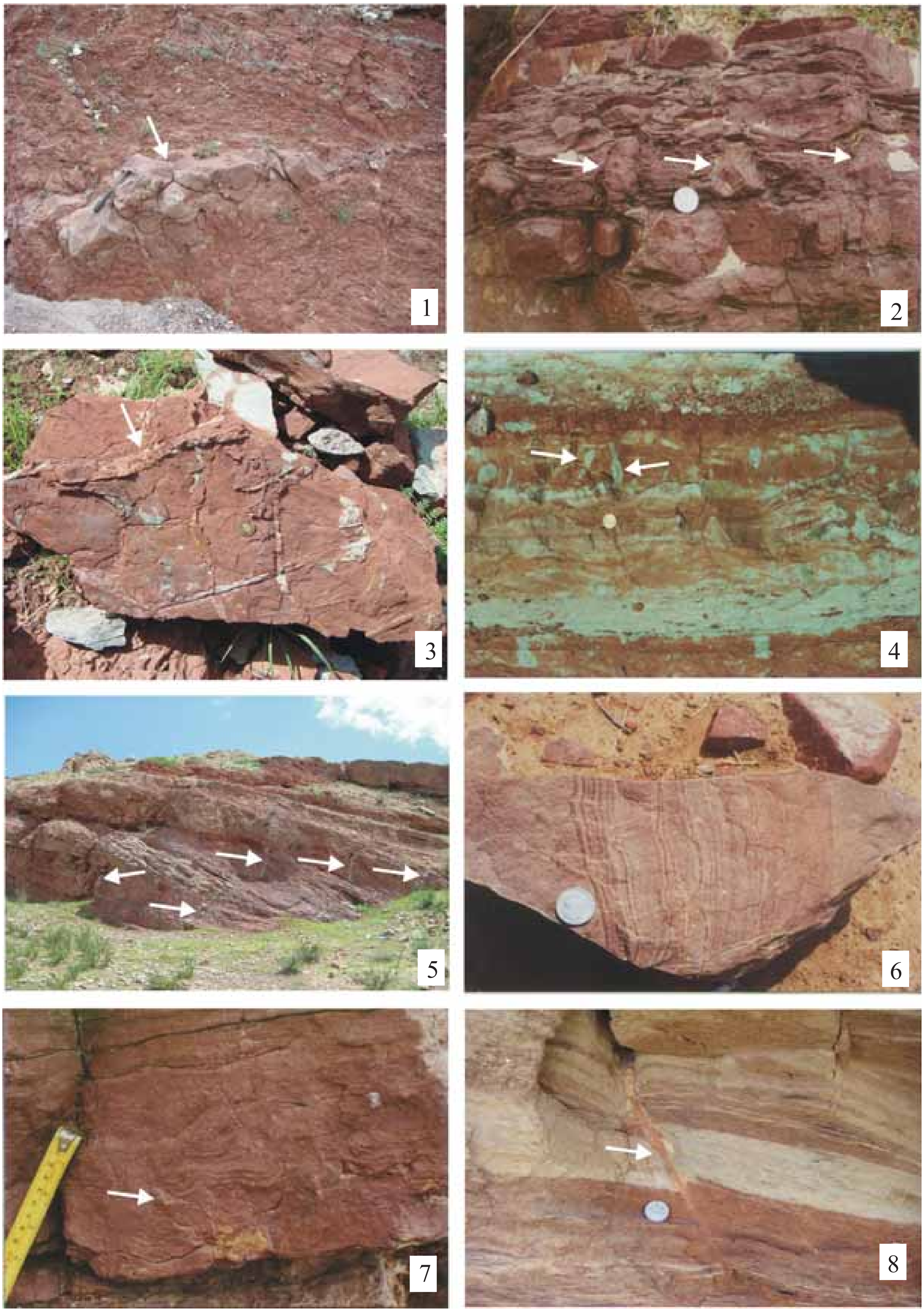
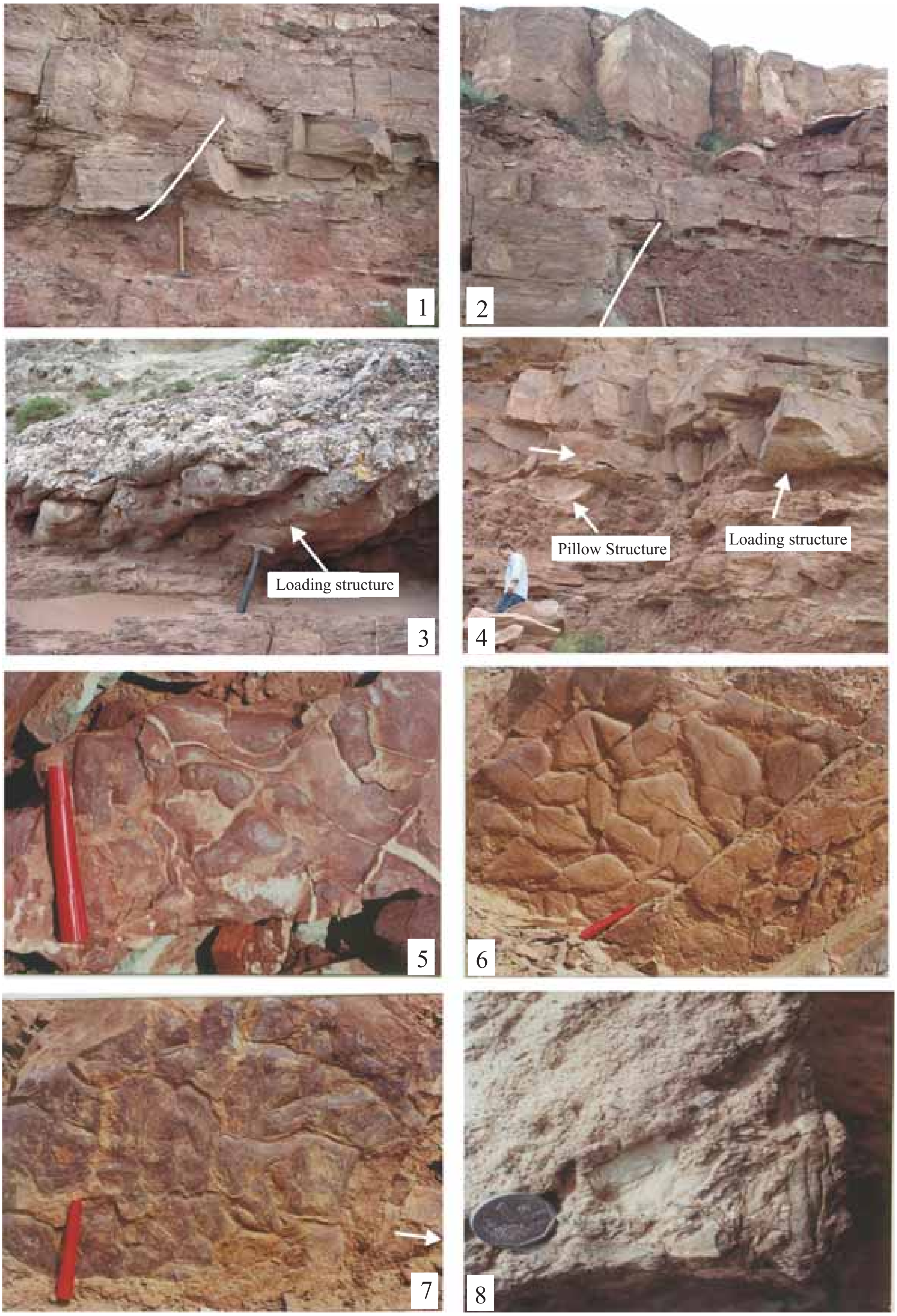


Plate II


1
2
Loading structure
3
Pillow Structure
Loading structure
4
5
6
7
8