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A Large-scale Tertiary Salt Nappe Complex in the Leading Edge of the Kuqa Foreland Fold-Thrust Belt, the Tarim Basin, Northwest China

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Abstract The tectono-stratigraphic sequences of the Kuqa foreland fold-thrust belt in the northern Tarim basin, northwest China, can be divided into the Mesozoic sub-salt sequence, the Paleocene-Eocene salt sequence and the Oligocene-Quaternary supra-salt sequence. The salt sequence is composed mainly of light grey halite, gypsum, marl and brown clastics. A variety of salt-related structures have developed in the Kuqa foreland fold belt, in which the most fascinating structures are salt nappe complex. Based on field observation, seismic interpretation and drilling data, a large-scale salt nappe complex has been identified. It trends approximately east-west for over 200 km and occurs along the west Qiulitag Mountains. Its thrusting displacement is over 30 km. The salt nappe complex appears as an arcuate zone projecting southwestwards along the leading edge of the Kuqa foreland fold belt. The major thrust fault is developed along the Paleocene-Eocene salt beds. The allochthonous nappes comprise large north-dipping faulting monoclines which are made up of Paleocene-Pliocene sediments. Geological analysis and cross-section restoration revealed that the salt nappes were mainly formed at the late Himalayan stage (c.a. 1.64 Ma BP) and have been active until the present day. Because of inhomogeneous thrusting, a great difference may exist in thrust displacement, thrust occurrence, superimposition of allochthonous and autochthonous sequences and the development of the salt-related structures, which indicates the segmentation along the salt nappes. Regional compression, gravitational gliding and spreading controlled the formation and evolution of the salt nappe complex in the Kuqa foreland fold belt.

Key words: salt nappe structure, thrust fault, leading edge of the Kuqa foreland fold-thrust belt, Tarim Basin

1 Introduction

The Kuqa foreland fold-thrust belt is located at the northern Tarim basin, with the south Tianshan Mountains to the north and northern Tarim uplift to the south. The Meso-Cenozoic strata are well developed in the belt and are over 10,000 m thick. With the remote effect of the India-Eurasia continent collision, the fold-thrust belt occurred under an intense compressional stress, resulting in alternate narrow anticlines and wide synclines. Structural deformation of the belt bears a close relationship with the detachment layer and is controlled by the salt sequence of the Paleocene-Eocene Kumglimu Formation. Complex structural styles such as thrust faults, backthrust faults, triangle zones, imbricated thrusts and duplex structures are common in the belt.

Numerous studies (Nishidai et al., 1990; Tang, 1992, 1996; McKnight, 1993; Liu et al., 1994; Zhang et al., 1994; He et al., 1996; Jia et al., 1996, 2000, 2001; Jia et al, 1998; Chen et al., 1999; Lu et al., 2000; Tang et al., 2003) on the structural deformation of the belt have been done. The structural models of fault-related folds (fault-bend fold, fault-propagation fold and fault-slip fold) have been established, and the tectonic characteristics and deformation timing discussed (Yin et al., 1998; Lu et al., 1999; Wang et al., 2002). The salt sequence of the Kumglimu Formation is an important interval to explore oil/gas and potash deposits in the belt. Due to lack of effective research methods, however, the buried salt structural geometry was unknown for a long time. The halite outcropping along the west Qiulitag Mountains was considered to be salt domes or piercement structures (Tang et al., 1986; Wei et al., 1984). Zhang et al. (1998) divided the salt structures into salt dome, salt arch, salt flare, salt ax and salt ridge. On the whole, researches need to be done on the salt structures of the Kuqa foreland fold-thrust belt. The questions to be addressed are: (1) Is the salt structure in the leading edge of the Kuqa foreland fold-thrust belt along the west Qiulitag Mountains a large-scale salt nappe complex, and what are the main characteristics? (2) When was the large-scale salt nappe complex formed, and how much is the nappe distance? (3) If the salt structures are nappe deformation, what is the origin? (4) The west Qiulitag Mountains elongates more than 200 km and its height difference is more than 1300 m. Then is the formation and evolution of the mountains in the leading edge of the Kuqa foreland fold-thrust belt controlled by deep tectonic setting or is it a "rootless mountain" controlled by salt detachment? The questions mentioned above may reveal a new type of nappe structure and mountain genetic model. It will be helpful to understand the characteristics and origin mechanisms of the Kuqa foreland fold-thrust belt. The aim of this study is to discuss this special salt nappe complex based on field investigation, remote sensing, geophysical and drilling data, and restored cross-sections.

2 Geological Setting

The Kuqa foreland fold-thrust belt is located in the northern Tarim basin and elongates east-west approximately. It covers an area of about $2.85\times10^4\ km^2$ and is a foreland depression near the south Tianshan Mountains, neighboring the north Tarim uplift to the south. Take the Kumglimu Formation salt sequence of the Paleocene-Eocene as a marking interval, three main tectono-stratigraphic sequences can be identified: (1) The sub-salt sequence, with a thickness of more than 4000 m, is composed of the Triassic, Jurassic and Lower Cretaceous sediments. It is a series of continental conglomerate, sandstone and mudstone, with coal measures in the Upper Triassic-Middle-Lower Jurassic; (2) The salt sequence, 110–3000 m in thickness and locally thickened, is made up of light grey halite, gypsum, limestone, marl, mudstone, sandstone and conglomerate of the Paleocene-Eocene Kumglimu Formation. From the depositional assemblage and structural deformation it can be seen that a special sequence with obvious plastic flow constitutes the main detachment zone of the Kuqa foreland fold-thrust belt. The sequence outcrops in the west Qiulitag Mountains of the leading edge of Kuqa foreland fold-thrust belt; (3) The supra-salt sequence, with a thickness of more than 5000 m, is composed of the Oligocene-Quaternary continental reddish clastics with gypsum and halite in the Oligocene Suweiyi Formation.

The well-outcropped stratigraphic sequences of the Kuqa foreland fold-thrust belt include the Triassic, Jurassic, Lower Cretaceous, Paleogene and Neogene, which occur from the piedmont toward the basin, forming broad synclines and tight anticlines (Fig. 1). In the leading edge of the mid-segment of the Kuqa foreland fold-thrust belt, there exist the large Qiulitag Mountains elongating more than 200 km. The width of the mountains is 8–20 km and the highest peak is as much as 2300 m above sea level, with a

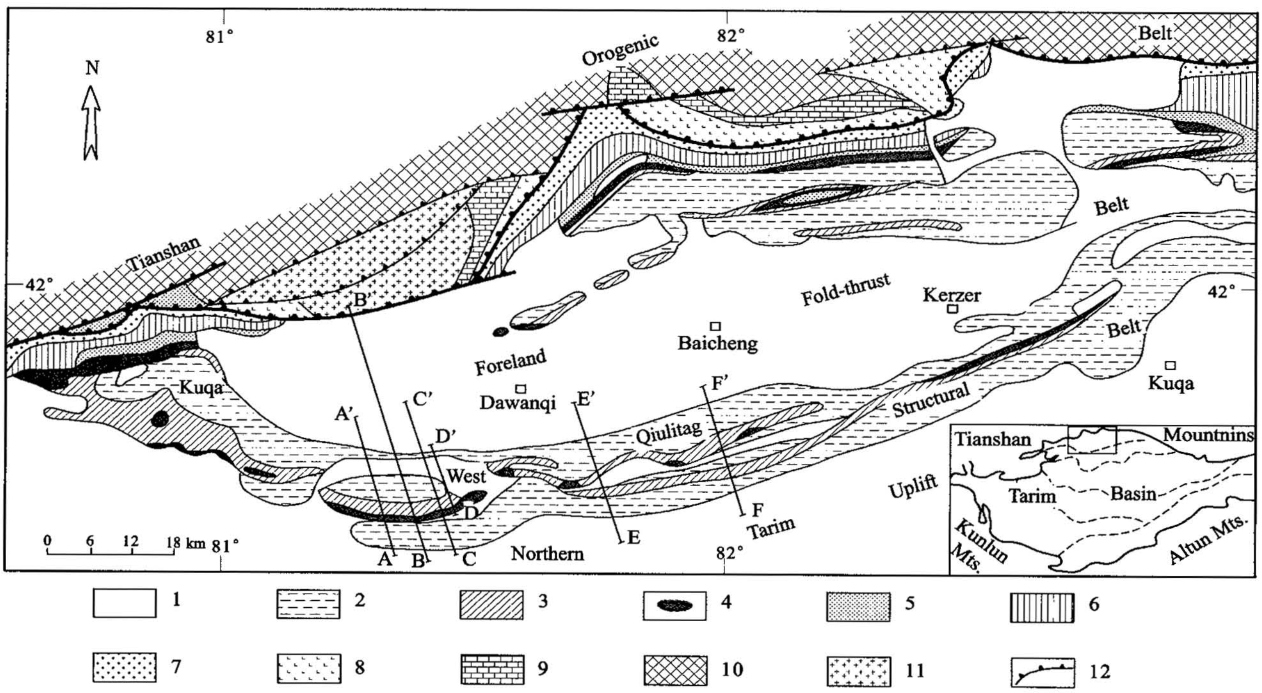

Fig. 1. A sketch geologic map of the mid-segment of the Kuqa foreland fold-thrust belt.

1. Quaternary; 2. Pliocene; 3. Miocene; 4. Paleogene salt sequence; 5. Lower Cretaceous; 6. Jurassic; 7. Triassic-Upper Permian; 8. Lower Permian volcanic rock; 9. Carboniferous; 10. Silurian-Devonian; 11. pre-Sinian basement; 12. thrust fault.

relative elevation difference of 1300 m. In the leading edge and the core of the mountains, the Paleocene-Eocene Kumglimu Formation salt sequence occurs interruptedly. Several salt and gypsum mines are under exploitation along the belt. The salt and gypsum beds are thrust to the surface, forming the special salt nappe complex (Fig. 1).

3 Major Characteristics of the Salt Nappe Complex

3.1 Location, dimension and occurrence of the salt nappe complex

The salt nappe complex is located at the leading edge of the Kuqa foreland fold-thrust belt along the west Qiulitag structural belt, elongating nearly east-west for 200 km and convex towards the southwest (Fig. 1, Plate I). The outcropped stratigraphic sequences include the Paleocene-Eocene Kumglimu Formation, the Oligocene Suweiyi Formation, the Miocene Jidik and Kangchun Formation, the Pliocene Kuqa Formation, and the Quaternary. The Qiulitag structural belt is a complex thrust zone which consists of a series of thrust faults, back-thrust faults, fault-related folds, salt pillows, triangle zones and cuestas. The salt nappe complex constitutes one of the most fascinating structures. The thrust front of allochthonous rocks is composed of the Kumglimu Formation salt sequence. The thrust plane dips northwards and detaches along the salt beds. The magnificent Qiulitag Mountains occur on the south margin of the Kuqa foreland fold-thrust belt, with thick salt beds present in the core of the belt.

3.2 Characteristics of salt nappe complex based on field investigation

On the basis of field investigations, it can be seen that the major thrust faults have developed along the salt detachment zones of the Kumglimu Formation. The allochthonous nappes on the major thrust faults are composed of the Kumglimu Suweiyi, Jidik, Kangchun and Kuqa Formations, which constitute north-dipping monoclinal fault sheets or cuesta. The oldest outcropped strata are the Kumglimu Formation salt sequence and Suweiyi Formation saliniferous clastics, with linear or string distribution along the west Qiulitag structural belt (Fig. 1). The allochthonous salt strata were thrust upon the autochthonous rocks of the Quaternary (Plate II-1). The "salt glacier" (Plate II-2) and "salt creek" (Plate II-3) were formed in the leading edge of the belt where a series of salt and gypsum mines occur. A lot of solution collapse and cave were formed because of dissolution (Plate II-4).

3.3 The salt nappe complex revealed by seismic profiles

The geometry of the salt nappe complex was revealed by seismic profiles (Fig. 2). As illustrated in Fig. 2, a major detachment fault occurs along the salt sequence of the Kumglimu Formation. The allochthonous supra-salt nappes on the detachment fault appear as monocline fault-sheets. Within the detachment zone, a thin sheet-like salt with a thickness from several meters to hundreds of meters occurs.

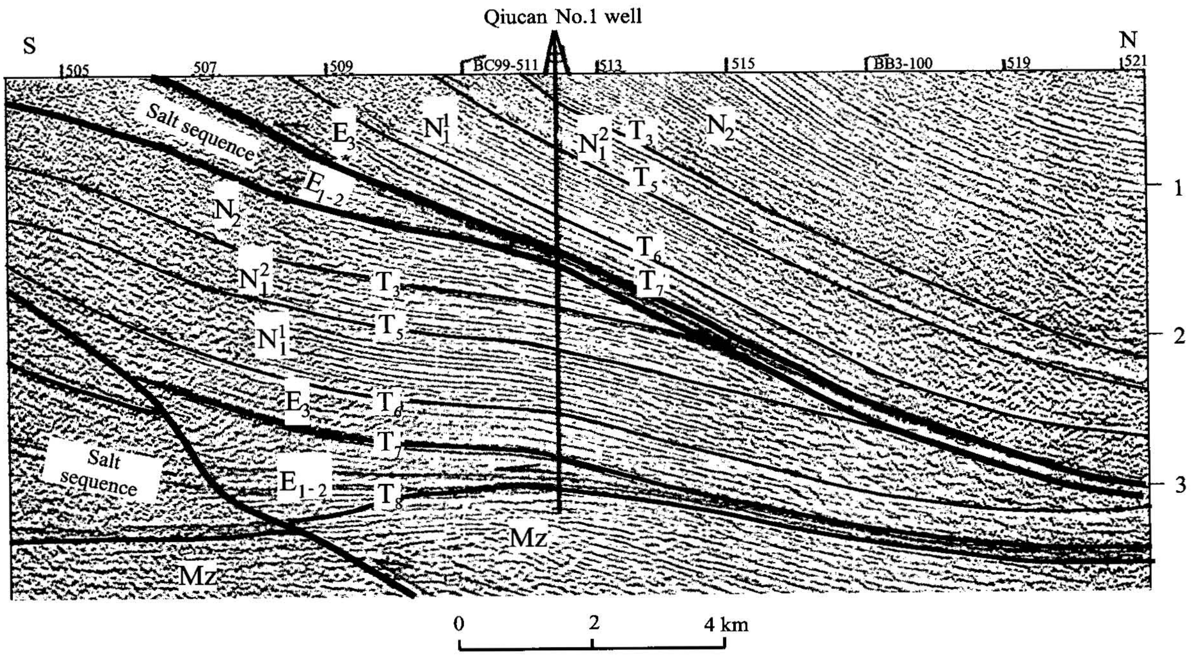

Fig. 2. Seismic profile of the salt nappe complex on the leading edge of the Kuqa foreland fold-thrust belt (see Fig. 1 for its location).

The halite and gypsum in the fault zone were derived from the deep salt sequence in the nearby Baicheng sag to the north. The autochthonous sequences thrust by salt nappes are Oligocene-Pliocene clastics which are transected by the thrust zones (Fig. 2).

3.4 Drilling data

The Paleocene-Eocene salt sequence is penetrated by Qiucan No.1 well at a depth of 2635 m. The well located at the leading edge of the salt nappe complex and drilled through the salt sequence into the footwall of the Miocene Jidik Formation clastics at a depth of 3550 m. A total of 915 m salt sequence was encountered by the well from 2635 m to 3550 m, indicating that the older halite sequence of Paleocene-Eocene is thrust upon the newer supra-salt sequence (Fig. 2).

3.5 Remote sensing data

A satellite photograph (Plate I) shows that the Paleocene-Eocene salt sequence outcrops in the leading edge of the

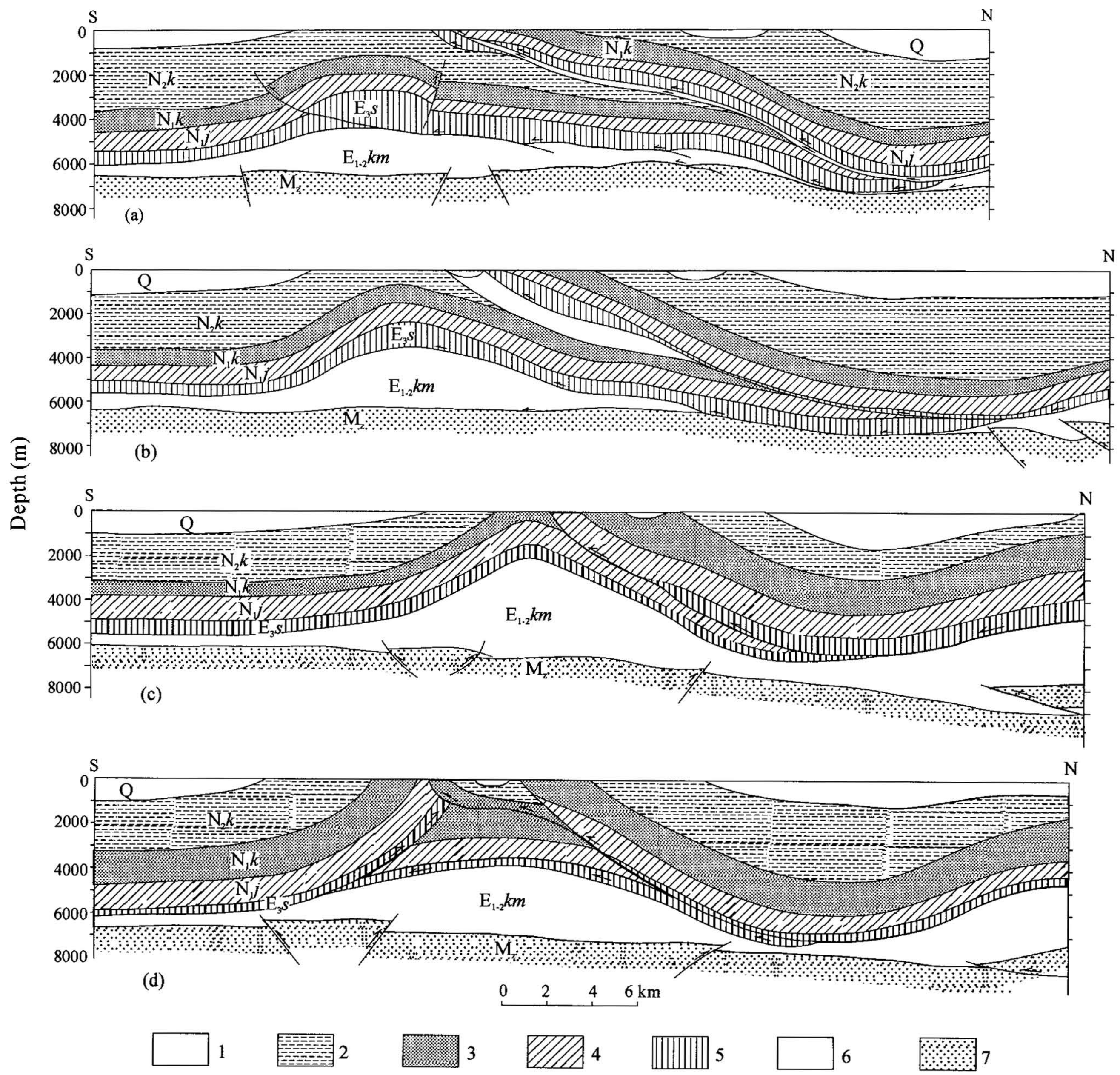

Fig. 3. Cross-sections of the salt nappe complex on the leading edge of the Kuqa foreland fold-thrust belt (see Fig. 1 for line locations).

1. Quaternary; 2. Pliocene Kuqa Formation; 3. Miocene Kangchun Formation; 4. Miocene Jidik Formation; 5. Oligocene Suweiyi Formation; 6. Paleocene-Eocene salt sequence; 7. Mesozoic.

Kuqa foreland fold-thrust belt. Distribution of the grey-white images along the Qiulitag Mountains is linear or ribbon-like and does not resemble a salt dome with a perfectly round shape.

3.6 Segmentation of the salt nappe complex

The thrust distance is variable along the strike of the salt nappe complex of the Kuqa foreland fold-thrust belt. In the west segment, the thrust distance is greater and the salt sequence is thrust to the surface. The nappe is composed mainly of salt sequences of the Kumglimu Formation (Fig. 3a,b). The thrust distance becomes smaller eastwards and the salt sequence is not thrust to the surface. The nappe is composed mainly of gypsum and halite of the Suweiyi Formation, forming behind the salt nappes (Fig. 3c, d). The segmentation of the salt nappe structures is probably controlled by transcurrent faults shown clearly on the satellite photograph (Plate I).

4 Deformation Stage and Estimation of Thrust Distance of the Salt Nappe Complex

A series of discussions on deformational time of the Kuqa foreland fold-thrust belt have been made. The

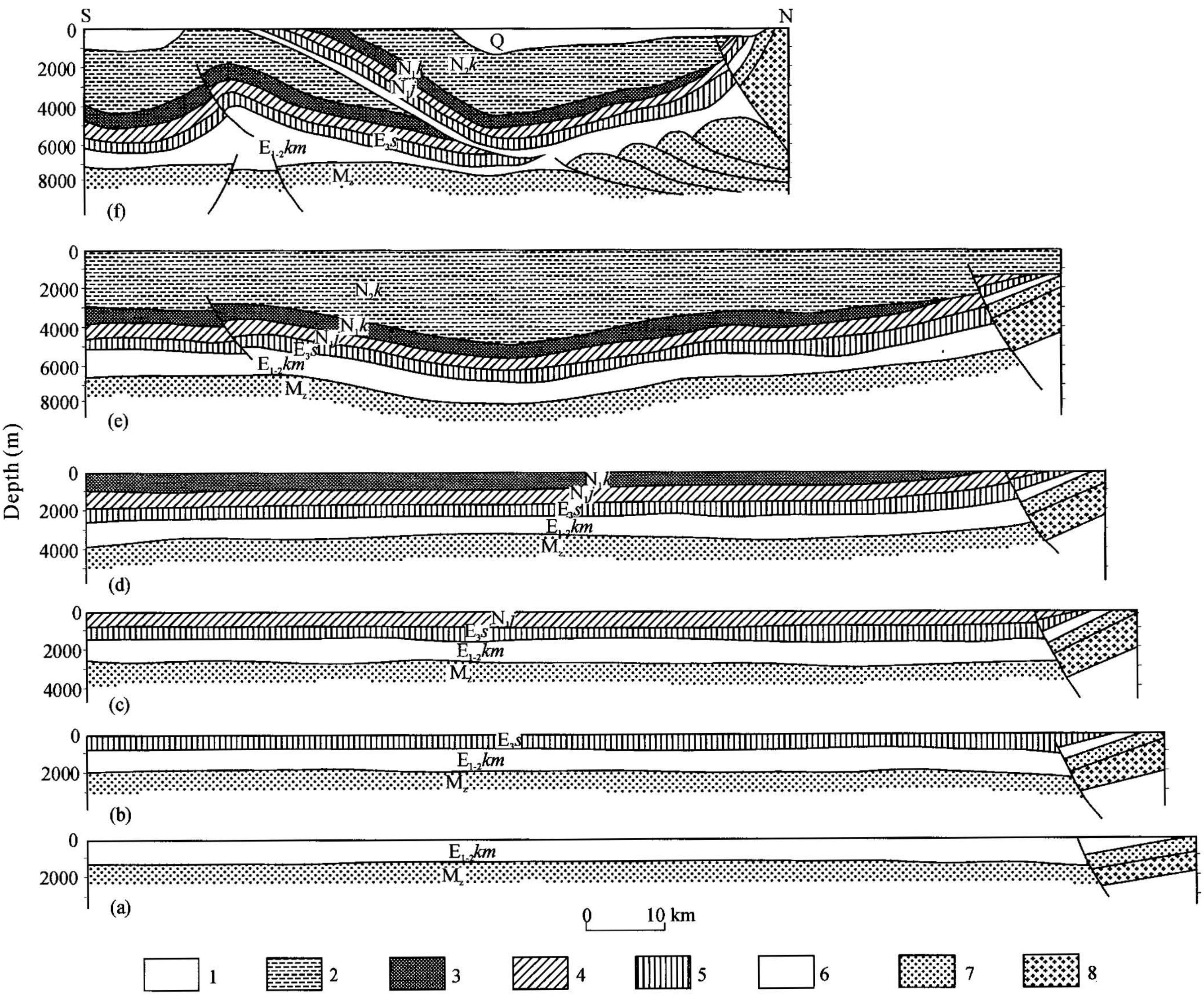

Fig. 4. Restoration of the cross-sections of the salt nappe complex in the west segment of the Kuqa foreland fold-thrust belt.

1. Quaternary; 2. Pliocene Kuqa Formation; 3. Miocene Kangchun Formation; 4. Miocene Jidik Formation; 5. Oligocene Suweiyi Formation; 6. Paleocene-Eocene salt sequence; 7. Mesozoic; 8. Paleozoic

(a) End of the stable deposition epoch of the Kumglimu Formation ($E_{1-2}km$); (b) end of the stable deposition epoch of the Suweiyi Formation (E_3s); (c) end of the stable deposition epoch of the Jidik Formation(N_1j); (d) end of the stable deposition epoch of the Kangchun Formation(N_1k); (e) end of the rapid deposition epoch of the Kuqa Formation (N_2k); (f) intense folding-thrusting epoch of the Quaternary.

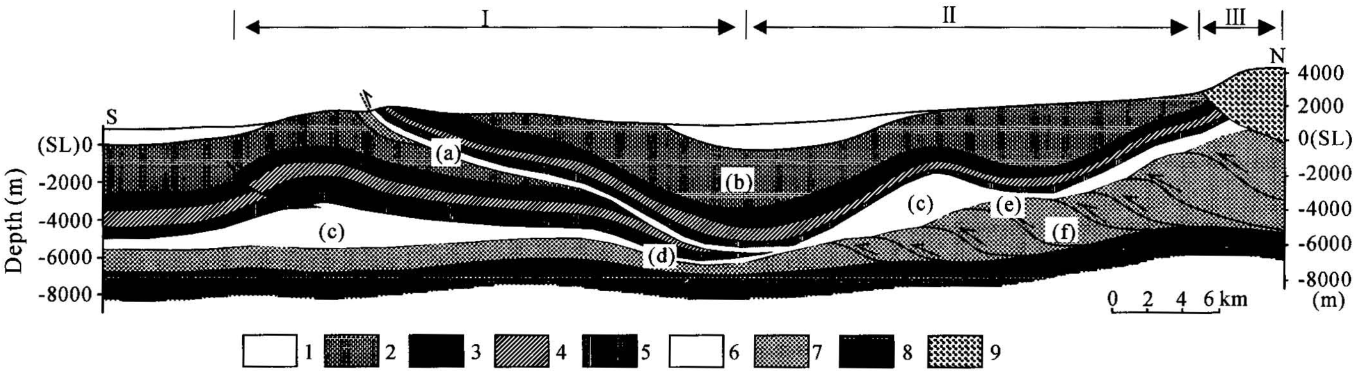

Fig. 5. A sketch map showing the formation mechanism of the salt nappe complex in the Kuqa foreland fold-thrust belt. 1. Quaternary; 2. Pliocene Kuqa Formation; 3. Miocene Kangchun Formation; 4. Miocene Jidik Formation; 5. Oligocene Suweiyi Formation; 6. Paleocene-Eocene salt sequence; 7. Mesozoic; 8. Paleozoic; 9. sequence of the orogenic belt: I. salt nappe complex; II. gravity gliding and spreading belt; III. Tianshan orogenic belt. (a) salt nappe; (b) Baicheng sag related to gravitational spreading and salt necking; (c) salt pillow; (d). salt necking or salt welding associated to gravitational spreading; (e) regional gravitational sliding plane; (f) subsalt duplex structure accommodating the salt bed shortening.

deformation might begin in the Miocene and is probably active up to the present (Yin et al, 1998; Lu et al, 1999; Wang et al, 2002). By means of the layering restoration method of salt structures in a compressional region, the supra-salt and sub-salt sequences may be restored by the layer length balance with flexural-slip mechanism. The salt sequence can be restored by the area balance. We can combine the respective restoration results of supra-salt, sub-salt and salt sequences, and let the length of the salt sequence be equal to the lengths of the supra-salt and sub-salt sequences on the basis of the area balance. Thus, a balanced cross-section of the salt nappe complex is constructed and it is shown in Fig. 4. The formation and evolution of the salt nappe complex can be divided into three stages: (1) The stable sedimentary stage of Paleogene-Miocene Kangchun Age. The salt sequence and lower supra-salt sequence were deposited and salt deformation were very weak at this stage (Fig. 4a, b, c, d); (2) The initial deformation stage of the Pliocene Kuqa Age (Fig. 4e). The deformation mechanism is related to gravitational sliding and buoyant force owing to differential loading. Shortening was still insignificant at this stage; (3) The intense deformation stage of the salt structure since the end of Neogene. The formation mechanism has a bearing upon the compression and uplifting of the south Tianshan mountains, and gravitational gliding and spreading towards the foreland. As a result, thrust nappes are confined to the leading edge of the fold-thrust belt (Fig. 4f). It can be seen that the large-scale salt nappe complex in the leading edge of the Kuqa foreland fold-thrust belt mainly formed in the late Himalayan orogeny at the end of Neogene and is still very active at present. The thrust distance is as much as 30 km in the Kuqa foreland fold-thrust belt from balanced cross-section analysis. Allowing for salt solution, plastic flow and erosion, the real thrust distance is probably much greater than 30 km. Since the end of Neogene, the shortening is more than 24 km, accounting for over 80% of the total shortening. Tang et al. (2003) has indicated that the late Himalayan movement plays an important role in salt deformation since the end of Neogene.

5 The Origin of the Salt Nappe Complex

Several drive mechanisms responsible for salt structural deformation have been proposed (Jackson, 1995; Letouzey et al, 1995): (1) buoyant force, depending on density difference between salt sequence and supra-salt sequence, (2) differential loading, (3) heat convection, and (4) gravitational gliding and spreading. Compressive forces and gravitational sliding play an important role in the origin of nappe tectonics in general. From Fig. 5 it can be seen that the hanging-wall ramp has outcropped or been eroded on the north flank of the leading belt of the salt nappe complex, while the hanging-wall flat has extended to the north flank of the Baicheng sag. The salt sequence is elevated rapidly northwards further more. It is proposed that the formation of the salt nappe complex in the Kuqa foreland fold-thrust belt is related to the uplifting of the Tianshan orogenic belt (see Fig. 5). The uplifting of the Tianshan Mountains resulted in elevation of the piedmont, forming a slope dipping southwards along a decollement layer of the salt sequence. The supra-salt sequence slid along the slope under gravitation, resulting in slide structure on the salt detachment slope (see gravity gliding and spreading belt in Fig. 5). Southwards the sliding system was converted into a thrust movement in the leading edge, forming the salt nappe structure along the west Qiulitag Mountains (see salt nappe complex in Fig. 5). Evidence of gravitational sliding can be found in the piedmont of the south Tianshan Mountains in field investigations. On the steep slope about 2700 m above sea level, a series of large-scale gravity-glide surfaces and gliding tectonics have been observed. The elevation of the salt marker horizon near the mountains is higher than that in the Baicheng sag where the salt marker horizon is at a depth of 6000 m below the sea level. The distance from the foothill to the Baicheng sag is less than 30 km and the elevation difference of the salt marker horizons of these two places is more than 8000 m. The slope of the regional gravitational gliding plane is up to 20°. Under the impact of the gravity potential energy, salt and overlying sequences would be subjected to gravitational gliding in the rear and intense thrusting in the front (Fig. 5, Tang et al., 2003).

The other factor resulting in the salt nappe complex is gravitational spreading owing to differential loading. The thick sediment on the Baicheng depocenter forced the salt bed to move both northwards and southwards in a plastic fashion, which is one of the trigger mechanisms of salt structure formation. The flowing salt could be accumulated in the Klasu and Qiulitag structural belt to form salt pillows. As a result of gravity spreading, salt necks and related sags occurred. A salt-weld structure may occur where the salt sequence thinned or vanished because of gravitational spreading (Fig. 5, Tang et al., 2003).

The third factor controlling the formation of the salt nappe complex is associated with intense compression at the late Himalayan movement. Not only the uplifting of the Tianshan Mountains, but also the regional compressive stress field is related to the movement, resulting in folding, faulting, thrusting, and formation of the salt nappe complex (Fig. 5). The formation of the west Qiulitag Mountains is clearly related to the salt nappe complex on the leading edge of the Kuqa foreland fold-thrust belt. From Figs. 3 and 5 it can be seen that the formation of the west Qiulitag Mountains with a relative elevation of over 1300 m is probably not controlled by deep tectonic settings. It probably belongs to a "rootless mountain system" subjected to thrusting-napping, plastic flowing, accumulating and thickening of the salt sequence.

6 Conclusion and Discussion

Field investigation, geophysical probing and remote sensing data have revealed that a large-scale Paleogene salt nappe complex occurs on the leading edge of the Kuqa foreland fold-thrust belt. Napping took place in the major thrust fault along the salt sequence of the Paleocene-Eocene Kumglimu Formation. The allochthonous nappes are composed of the Paleogene Kumglimu and Suweiyi Formations, and the Neogene Jidik, Kangchun and Kuqa Formations, elongating more than 200 km. Based on the balanced cross-section analysis and structural restoration, it is estimated that the thrust distance is more than 30 km and the deformation started to occur mainly in the Himalayan orogeny at the end of Neogene. The formation of the "rootless" west Qiulitag Mountain on the leading edge of the Kuqa foreland fold-thrust belt is probably related to the salt nappe complex. The origin of the salt nappe complex has a bearing upon the gravitational gliding and spreading as well as the intense compression in the Himalayan orogeny.

The salt nappe complex is a unique structural type in the Kuqa foreland-thrust belt. Its formation and evolution is related to the development of the salt sequence and a specific regional compressional regime. Because of inhomogeneous nappe-thrusting, a great difference exists in different places as regards the thrust distance, occurrence of thrust faults, superposition of allochthonous and autochthonous systems and salt-related structures. In addition, the formation of the salt nappe complex has changed the structural features of the region to a great extent, which will undoubtedly affect the formation, migration and accumulation of hydrocarbon reservoirs.

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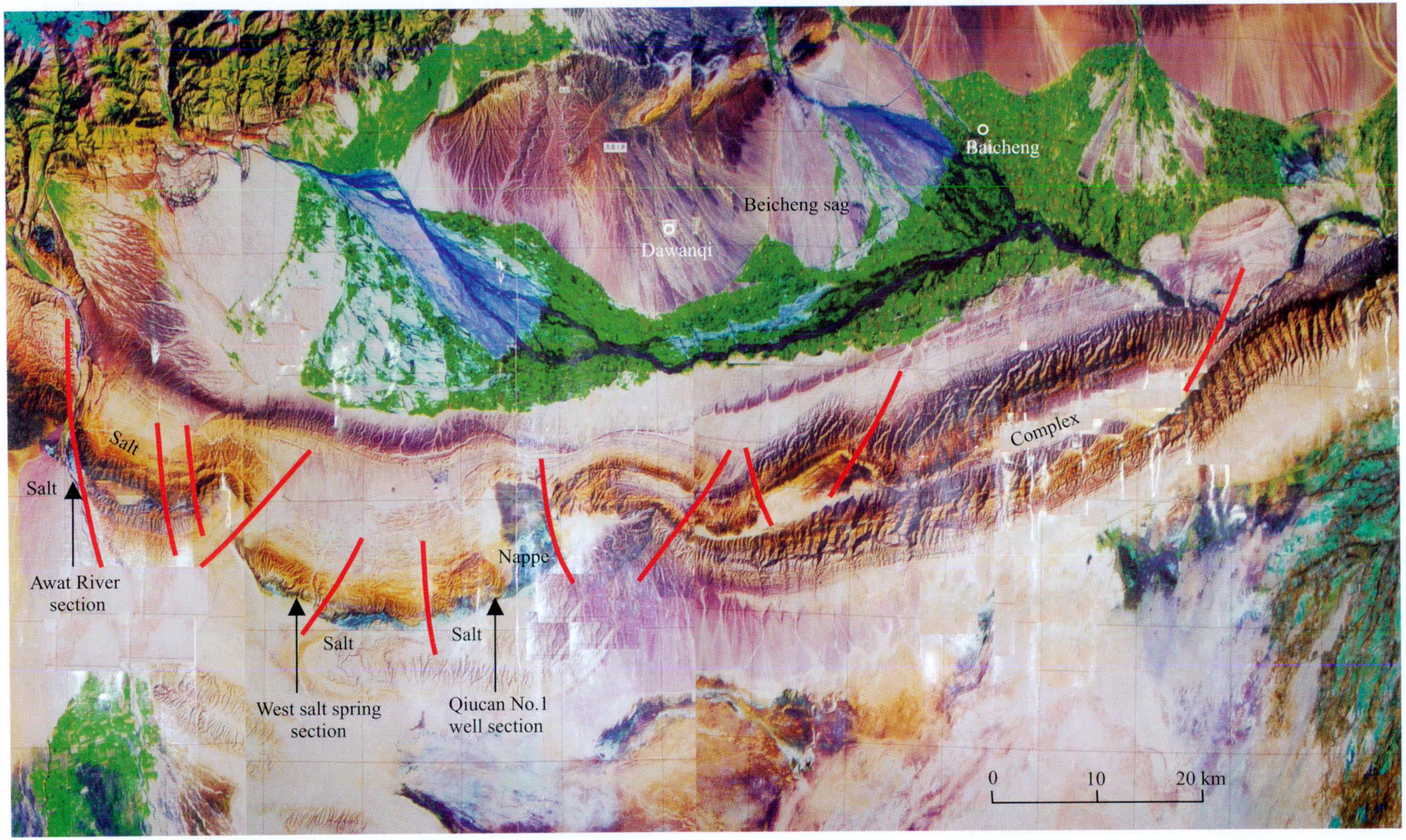

Plate I. Satellite image showing the salt nappe complex on the leading edge of the Kuqa foreland fold-thrust belt.

Grey image near the Awat River, west salt spring and Qiucan No.1 well sections shows narrow salt sequence outcrops, elongating along the leading edge of the west Qiulitag Mountains. There are a series of strike-slip faults truncating the salt nappe complex.

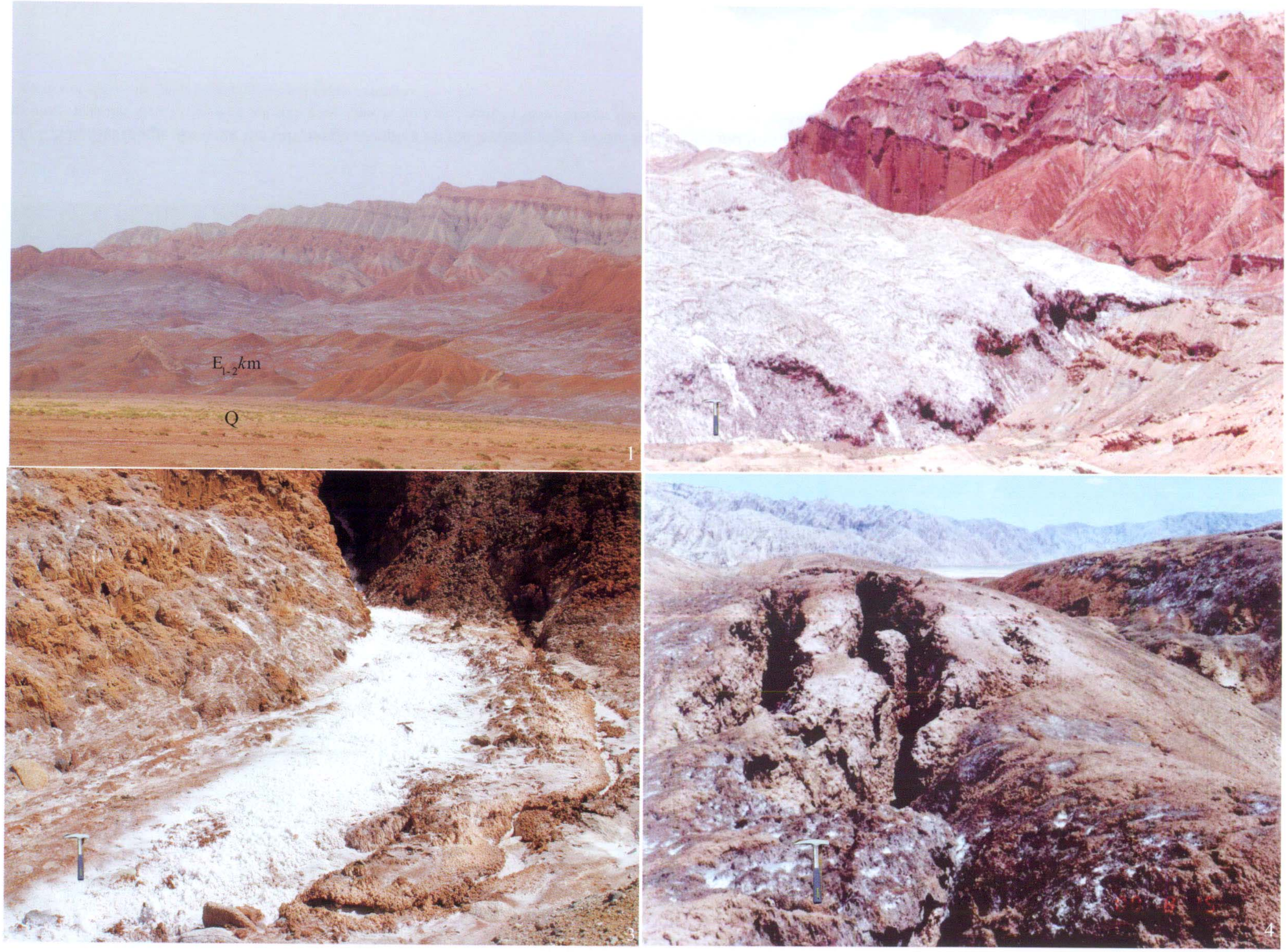

Plate II. Field photography showing salt-related structural styles on the leading edge of the Kuqa foreland fold-thrust belt.

1. Paleogene salt sequence thrust over the Quaternary on the leading edge of the salt nappe complex (camera lens pointing to 350°, near the west salt spring section shown in Plate I); 2. salt glacier (camera lens pointing to 46°, near the Awat River section shown in Plate I); 3. salt stream stretching about several kilometers (camera lens pointing to 15°, near the Awat River section shown in Plate I); 4. salt solution trench (camera lens pointing to 80°, near the Qiucan No.1 well section shown in Plate I).