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STRUCTURAL EVOLUTION AND CONTROLLING FACTS OF PIERCEMENT STRUCTURES IN THE KUQA DEPRESSION, TARIM BASIN, WESTERN CHINA

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Abstract: A piercement structure, as a special type of a diapir structure, requires more complicated triggering conditions than a nonpiercement structure. This study investigates the geometric characteristics, evolution process, formation mechanism, and inducing conditions of piercement structures in the Kuqa depression, Tarim Basin, Western China by using new seismic and drilling data combined with variations in the regional and local stress environments. Results show that the development and distribution of piercement structures in the Kuqa depression are highly localized even in a continuously compressive environment. Piercement structures in the Kuqa depression mainly formed on top of pre-existing basement faults, particularly in the transition zone between uplift and sag, and in relatively narrow salt-bearing basins. The formation conditions for piercement structures in the Kuqa depression are extremely severe and include strong compression stress, reactivation of a pre-existing basement fault, and obstruction of the salt sedimentary boundary. Among these factors, compression stress is the most important dynamics for piercement structures. Pre-existing basement fault and salt sedimentary boundary control the development position. Lastly, a narrow salt sedimentary basin supplies a favorable formation environment.

Key words: Kuqa depression, Diapir structure, Piercement structure, Evolution process, Controlling factor

1. INTRODUCTION

Diapir structures, which are typically induced by the upwelling of plastic strata (e.g., mudstone, salt rock, magma, and high-temperature metamorphic rock) that arise from density inversion and differential compaction, significantly influence the structural deformation of overlying strata. Considering the contact relationship between the diapir nucleus and overlying strata, the formation of diapir structures takes place in two stages as the initial formation of non-piercement structures (domes and pillows) is followed, in some cases, by the generation of piercement structures. As a tectonic form that is closely related to hydrocarbon accumulation, diapir structures are widely distributed in different types of basins worldwide (Jackson et al., 1986, 1994; Buchanan et al., 1996; Rowan, 1996, 1999, 2012; Mcbride et al., 2001; Volozh et al., 2003; Mcclay, et al., 2004; Yin et al., 2006, 2011; Jin et al., 2008; Fetter, 2009; Nikolinakou et al., 2014), including the Bohai Bay Basin in Eastern China and the Kuqa depression located in the Tarim Basin, Western China. Many studies, such as physical and numerical simulations, have been conducted on diapir structures. At present, buoyancy, differential loadings (including sedimentary and structural loadings), gravity expansion, thermal convection, and tectonic stress are regarded as the main triggering factors for diapir structures. These factors vary with different structural environments and evolutionary stages (Jackson & Talbot, 1986; Poliakov et al., 1993, 1996; Hudec & Jackson, 2004, 2007; Li et al., 2012; Li et al., 2015). Confusingly, however, current regional and local seismic and drilling data indicate that the distribution of piercement structures is highly limited in both the offshore Bohai Bay rift basin, which extensively deposits soft mudstone, and the Kuqa rejuvenated foreland basin, which deposits thick salt rock. Physical simulation and numerical simulation experiments also show that salt rocks typically accumulate and thicken in the anticlinal nucleus and then induce overlying layers that form drape anticlines under a strong compressive environment. However, piercement structures are difficult to develop (Duerto & Mcclay, 2009; Wang et al., 2009; Yin et al., 2011; Xie et al., 2012; Li & Qi, 2012). This phenomenon indicates that the formation conditions for piercement structures are more complicated and harsher than those for nonpiercement structures. Research on the formation mechanism and inducing conditions of piercement structures in the Kuqa depression is relatively weak. The Kuqa depression is a typical compressional basin that develops abundant salt diapirs; hence, the study of piercement structures in this depression is highly significant and representative. In view of the aforementioned conditions and on the basis of the latest seismic and drilling data combined with variations in regional and local tectonic environments, this study investigates the geometric characteristics, evolutionary process, formation mechanism and triggering conditions of piercement structures in the Kuqa depression.

2. GEOLOGICAL BACKGROUND

The Kuqa depression, which is situated in the northern Tarim Basin, Western China, is also known as the Kuqa rejuvenated foreland basin or the Kuqa foreland thrust belt. It developed from the Hercynian foreland basin, as a result of the Cenozoic intraplate orogeny. The Kuqa depression can be divided into several secondary tectonic units, including the Wensu uplift, the Kelasu and Qiulitage thrust belts, and the Wushi, Baicheng, and Yangxia sags (Fig. 1). The Cenozoic strata deposited into the Kuqa depression consist of the Kumugeliemu, Suweiyi, Jidike, Kangcun, Kuche, and Xiyu formations. Among which, the Kumugeliemu and Jidike formations are two sets of salt layers that are widely distributed across the entire depression (Fig. 2). The special mechanical properties of salt rocks are the fundamental reasons for the development of various types of salt tectonics and uncoordinated deformations between suprasalt and subsalt layers. The Cenozoic evolutionary dynamics of the Kuqa depression is mainly derived from the southward structural compression triggered by the uplifting of South Tianshan Mountain (Qi et al, 2009a, 2009b, 2013).

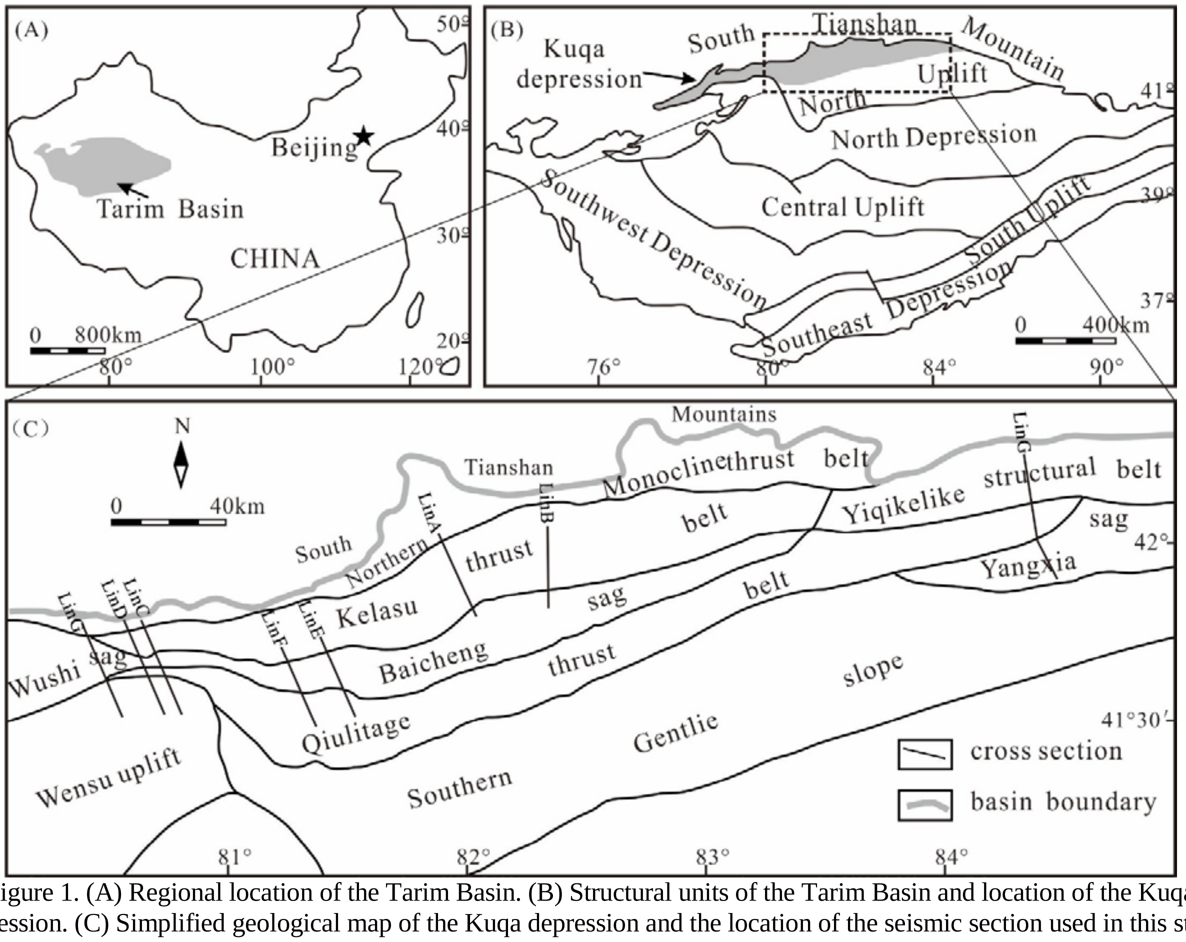

Figure 1. (A) Regional location of the Tarim Basin. (B) Structural units of the Tarim Basin and location of the Kuqa depression. (C) Simplified geological map of the Kuqa depression and the location of the seismic section used in this study

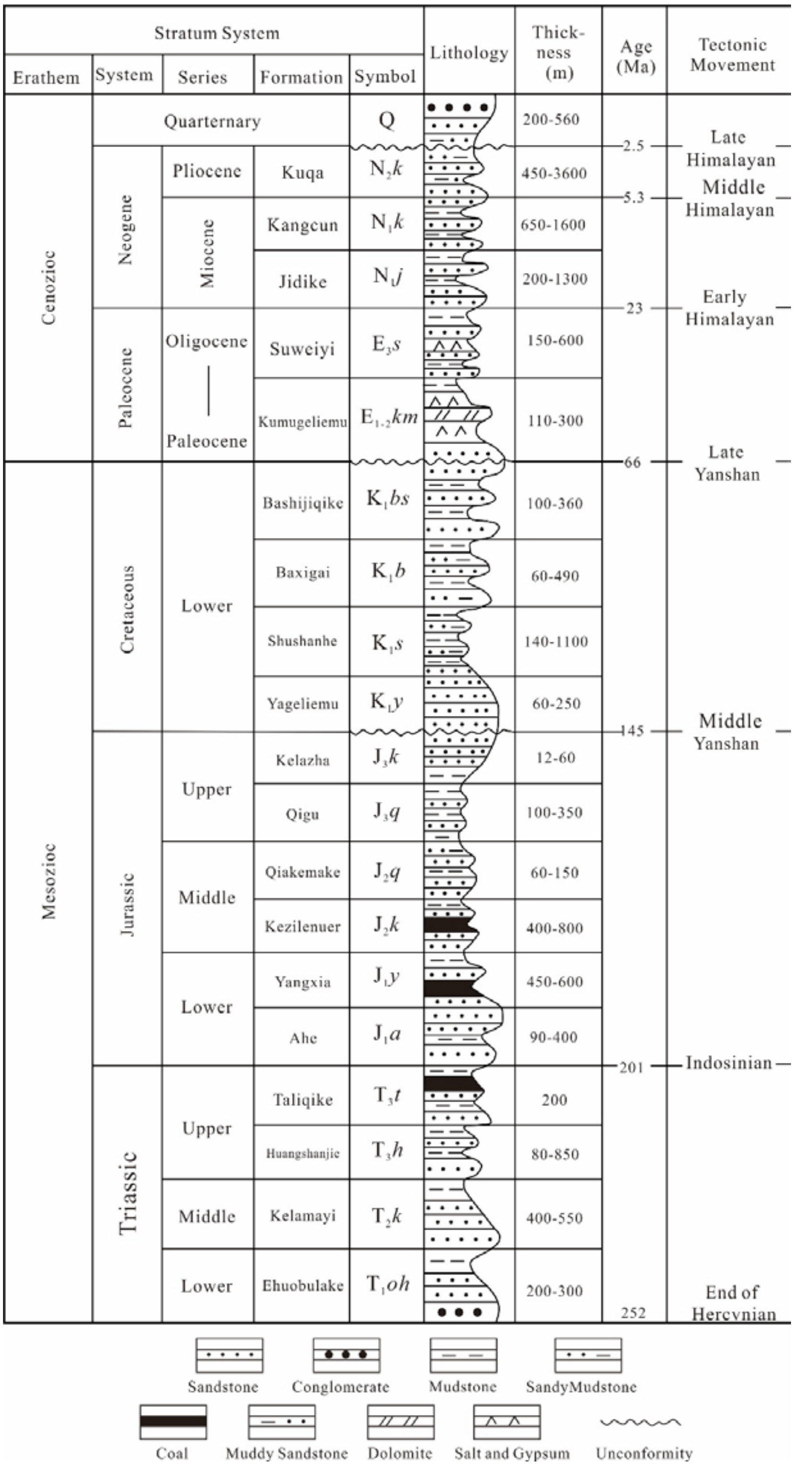

Figure 2. Generalized Mesozoic–Cenozoic stratigraphic column that shows the lithology and major tectonic events of the Kuqa depression.

Current research indicated that the uplifting process of South Tianshan Mountain was pulsatile (Charreau et al., 2006; Guo et al., 2006; Jing et al., 2011); consequently, the extrusion stress exerted on the Kuqa depression from South Tianshan Mountain changed in different evolutionary stages. Influenced by these changes, the tectonic deformations in the Kuqa depression are characterized by evident zonation, segmentation, and stratification differences (Tang et al., 2003a, 2003b, 2004, 2015; Yu et al., 2007).

3. GEOMETRIC CHARACTERISTIC OF PIERCEMENT STRUCTURES IN THE KUQA DEPRESSION

The contact relations between the diapir nucleus and the surrounding rock in a piercement structure have two types: fault contact and intrusive contact. In this study, piercement structure mainly refers to the latter, i.e., a salt rock that directly pierces the surrounding rock without faulting.

Salt structures are widely developed in the Kuqa depression. In addition, salt-related structures, such as salt glaciers and salt karst caves, are also observed in the geological field survey. However, numerous existing seismic and drilling data of the Kuqa depression indicate that salt layers exhibit conformable contact with overlying layers in most diapir structures. Piercement structures are only found locally in the Kelasu and Qiulitage thrust belts, where salt-related structures are magnificent.

The latest seismic interpretation of the Kuqa depression shows that piercement structures are mainly developed in the northern margin of the Kelasu thrust belt and the Awate and Qule zones of the western Qiulitage thrust belt. Seismic sections through the Kelasu thrust belt show that the Kelasu major fault and secondary faults that developed on its footwall exhibit a thrust-imbricated structure. Although subsalt faulting is remarkable, piercement structures have only developed on top of the Kelasu basement fault (Fig. 3). In the junction between the Awate sag and the Wensu uplift, the salt rock in the Kumugeliemu formation significantly thickened and upwardly pierced the Jidike, Kangcun, and Kuche formations (Fig. 4). Numerous basement-involved faults also developed in the subsalt layers of the Awate piercement structure. Influenced by the serious upwelling of salt and fault-block lifting, the overlying strata were thinly deposited and the Jidike formation was uplifted toward the surface of the earth and even locally eroded. In the Quele piercement structure, the number of subsalt faults is relatively less but the scale of the structure is larger. Under strong thrusting actions, salt rocks upwardly pierced the entire overlying strata and formed an exposed salt nappe, as clearly observed on the field outcrop (Fig. 5).

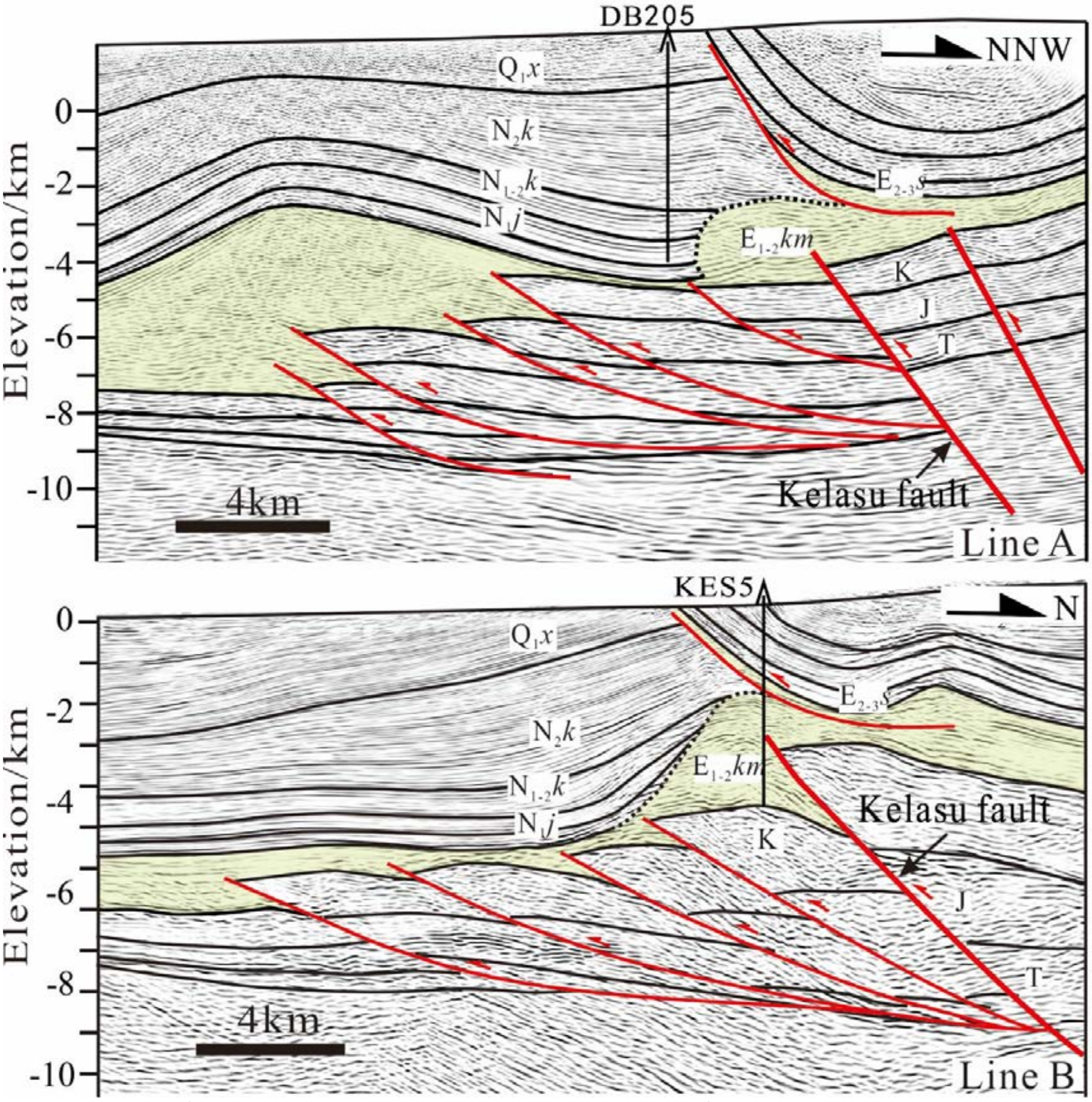

Figure 3. Seismic profile that crosscuts the Kelasu structural zone (profile location shown in Fig. 1). Note that the piercement structures developed on top of the Kelasu basement fault (salt is colored in yellow).

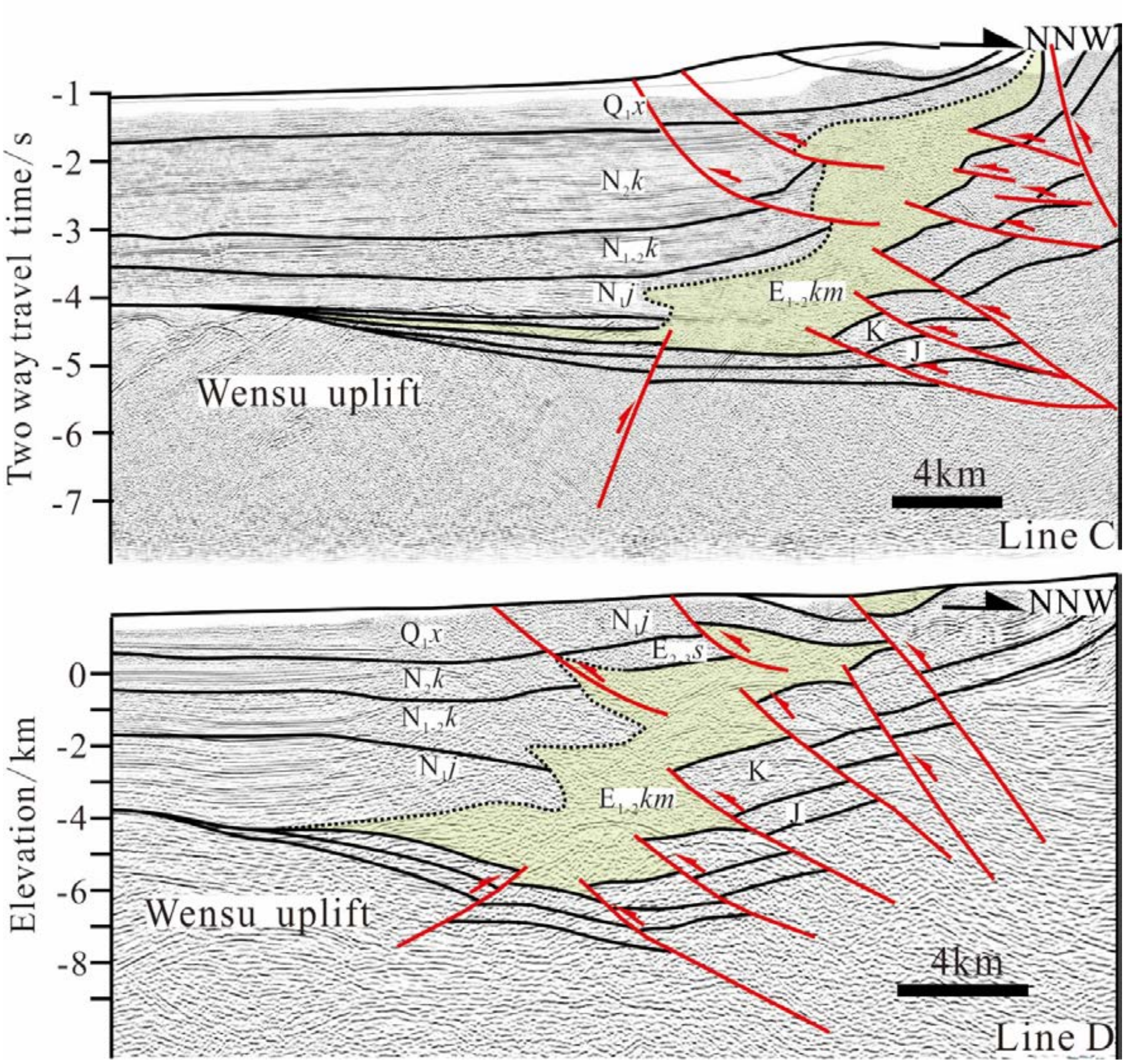

Figure 4. Seismic profile that crosscuts the Awate sag located in the western segment of the Qiulitage thrust belt (salt is colored in yellow); profile location shown in Figure 1.

4. EVOLUTION PROCESS OF PIERCEMENT STRUCTURES IN THE KUQA DEPRESSION

The formation and evolution of piercement structures are slow and are influenced by various geological factors. Throughout the long tectonic history of the Kuqa depression, the evolution process of piercement structures is highly complicated due to variations in compressional stress in different geological stages and the migration of the deposition center toward the foreland direction. Nevertheless, useful clues are available to analyze the evolution of piercement structures. Diapir structures are typically syndepositional structures, and salt rocks interact with surrounding strata during the diapirism period (Reis et al., 2005; Loncke et al., 2006). Therefore, the evolution of diapir structures can be deduced by combining the sedimentary characteristic of growth strata and the evolution of the regional structural and sedimentary environments. We used the piercement structure that developed in the northern margin of the Kelasu thrust belt as an example and analyzed the formation and evolution of the piercement structures in the Kuqa depression, which could be divided into several stages as shown in figure 6.

The Kuqa depression experienced extensive uplifting and erosion during the Late Mesozoic and then began to evolve into a rejuvenated foreland basin. During the Early Paleogene, the uplifting of South Tianshan Mountain was weak and the tectonic activity was accordingly quiescent. The salt layer of the Kumugelimu formation was deposited on the arid–semiarid salt lake environment. During this period, the depositional center was located in the northern margin of the Kuqa depression (Tan et al., 2006), and the salt deposited in the Kelasu structural belt was thick. It slowly accumulated and thickened under its own gravity.

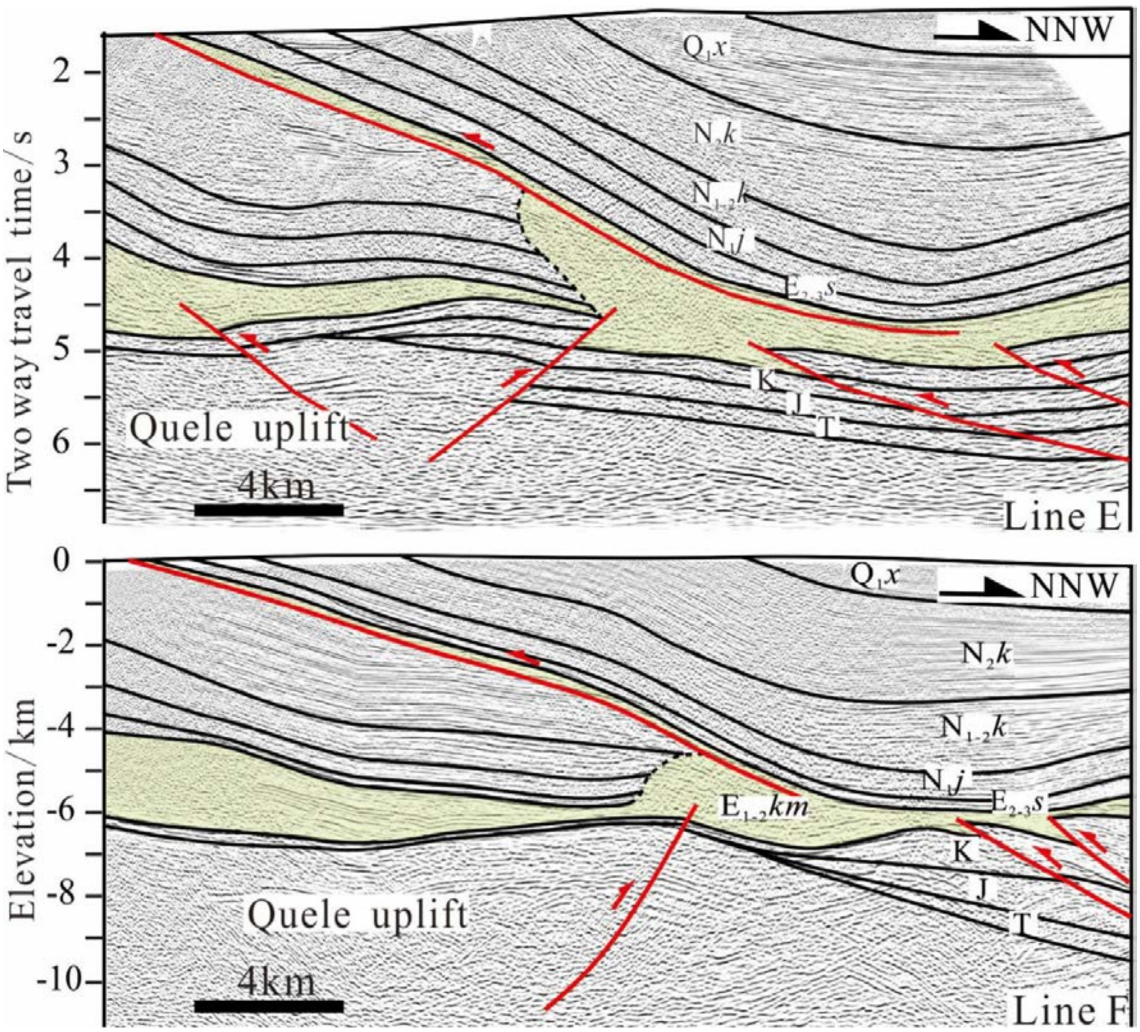

Figure 5. Seismic profile that crosscuts the Quele piercement structure located in the western segment of the Qiulitage thrust belt (profile location shown in Fig. 1). Note that salt nappes developed on the northern edge of the Quele paleo-uplift (salt is colored in yellow).

The thicknesses of the suprasalt Suweiyi and Jidike formations are relatively uniform, thereby indicating that a relatively quiescent structural environment has persisted into the Early Miocene and that the salt has not yet upwelled and affected the deposition of overlying strata in this stage. During the deposition period of the Kangcun formation, the long-distance effect of the collision between the Indian Plate and the Eurasian Plate transferred to the northern margin of the Tarim Landmass, thereby causing South Tianshan Mountain to experience tectonic compression and to begin uplifting. These phenomena exerted compressional stress to the Kuqa depression from nearly north to south. During this period, the uplifting of South Tianshan Mountain was relatively weak and compressional stress was slight. Consequently, salt diapirism and thickening were slow and the overlying Kangcun formation did not exhibit apparent synsedimentary features. No new fault developed in this stage, but the Kelasu fault, which was regarded in previous studies as a pre-existing normal fault that developed in the Jurassic extensional environment (Qi et al., 2009a, 2009b, 2013), might have been preferentially activated and even suffered slight compressional stress. As a structural weak zone, the pre-existing basement fault significantly influenced the subsequent deformations of salt structures (Giambiagi et al., 2003; Zanchi, 2006).

The upward propagation of pre-existing major faults resulted in the formation of fault propagation folds by overlying strata, and salt rocks in the Kumugeliu formation accumulated in the anticline nucleus and formed a salt dome. Thickened salt generated large buoyancy on overlying layers, which, in turn, strengthened fold amplitude. During the deposition of the Kuqa formation in the Pliocene Epoch, South Tianshan Mountain began uplifting violently and compressional stress exerted on the Kuqa depression was significantly enhanced (Zeng et al., 2004).

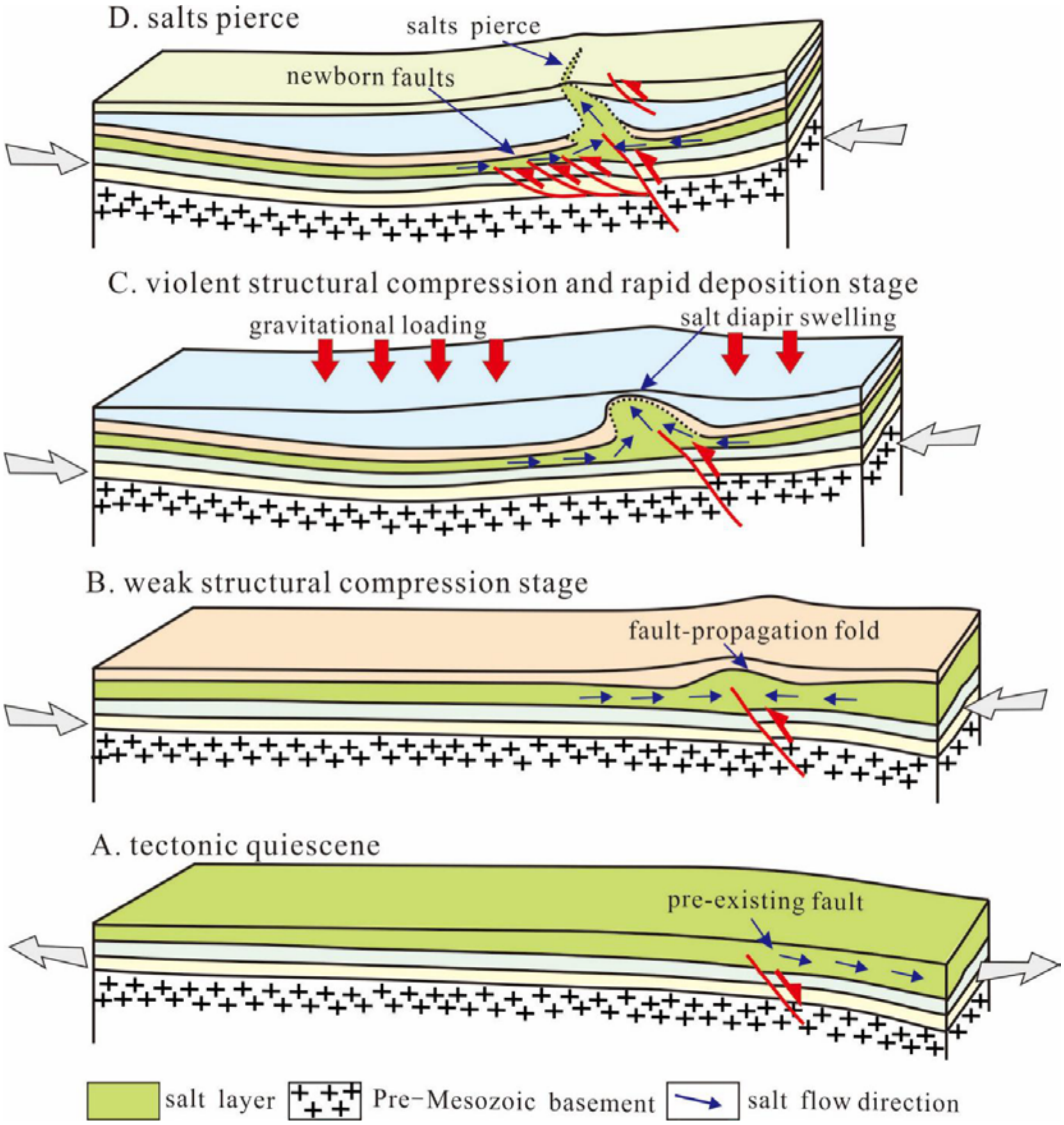

Figure 6. Diagram of the evolution model for the piercement structure in the Kelasu thrust belt.

Several listric thrust faults that slipped downward in the unconformity between the basin basement and the Mesozoic cap layer were produced on the footwall of the Kelasu fault. During this stage, the depositional center migrated from the piedmont zone to the Baicheng sag accompanied by the orogenic wedge moved toward the foreland direction, and the depositional rate was significantly increased. The strong differential loading induced by the thick deposition of the Baicheng sag impelled the salt to continuously flow northward. By contrast, tectonic compression from north to south and terrain elevation incurred by the uplifting of Tian Shan promoted salt to flow southward. Under the joint functions of the aforementioned factors, the top of the Kelasu fault became a favorable position for tectonic deformation, in which the continuous influx of salt resulted in the swelling of the pre-existing salt dome. The salt eventually pierced the overlying layers and formed the piercement structure on top of the Kelasu fault, whereas the Baicheng sag developed salt-withdrawal sag and welded structures due to salt outflow and depletion. The violent tectonic compression derived from South Tianshan Mountain lasted until the deposition of the Quaternary Xiyu formation, which exhibited evident synkinematic characteristics. During this period, compressional stress reached its peak (Zeng et al., 2004), which intensified the development of the piercement structures, with new thrust faults developing on the suprasalt layers. The occurrence of new faults might have intensified salt diapirism. The interactions between fault formation and salt diapirism promote the growth of piercement structures.

5. COMPARISON WITH PIERCEMENT STRUCTURES IN AN EXTENSION ENVIRONMENT

As an important petroliferous rift basin located in Eastern China, the offshore Bohai Bay Basin also developed piercement structures, although their quantity and scale were limited. Piercement structures were only found in the Liaozhong and Laizhouwan sags. The two piercement structures represent uplifts developed in the sag center, and thus, they tend to be mistakenly interpreted as negative flower structures triggered by local transpression actions. However, they were eventually proven to be piercement structures through drilling data. The diapir nucleus of the piercement structure in the Liaozhong sag is Shahejie-3 member mudstone, whereas that of the piercement structure in the Laizhouwan sag is Shahejie-4 member salt rock. The seismic data show that the piercement structure in the Liaozhong depression is intersected by the Liaozhong no. 1 fault, which is the most important branch of the Tan–Lu strike–slip fault zone, and the piercement structure in the Laizhouwan depression is close to the eastern branch of the Tan–Lu fault zone (Fig. 7).

Extensional faulting is pervasive in the offshore Bohai Bay Basin, and the widespread thick Shahejie-3 member mudstone and Shahejie-4 member salt layer supply abundant source rocks. All the aforementioned factors are propitious to the development of piercement structures. However, the two discovered piercement structures in the Liaozhong and Laizhouwan sags only developed in or near the locations where the branch fault of the Tan–Lu strike–slip fault zone crosscuts. We believe that the strike–slip activities of the Tan–Lu fault zone play important roles in the formation of piercement structures based on the features of strike–slip faults and the piercement structures combined with the results of previous studies (Yu et al., 2009). Those studies showed that the Tan–Lu fault zone experienced multi-stage strike–slip movements during its tectonic history due to the variations in the subduction direction and velocity of the Pacific Plate. Consequently, the branch faults of the Tan–Lu fault zone are prone to inducing local transtensional and transpressional stresses in the turning position along fault strikes.

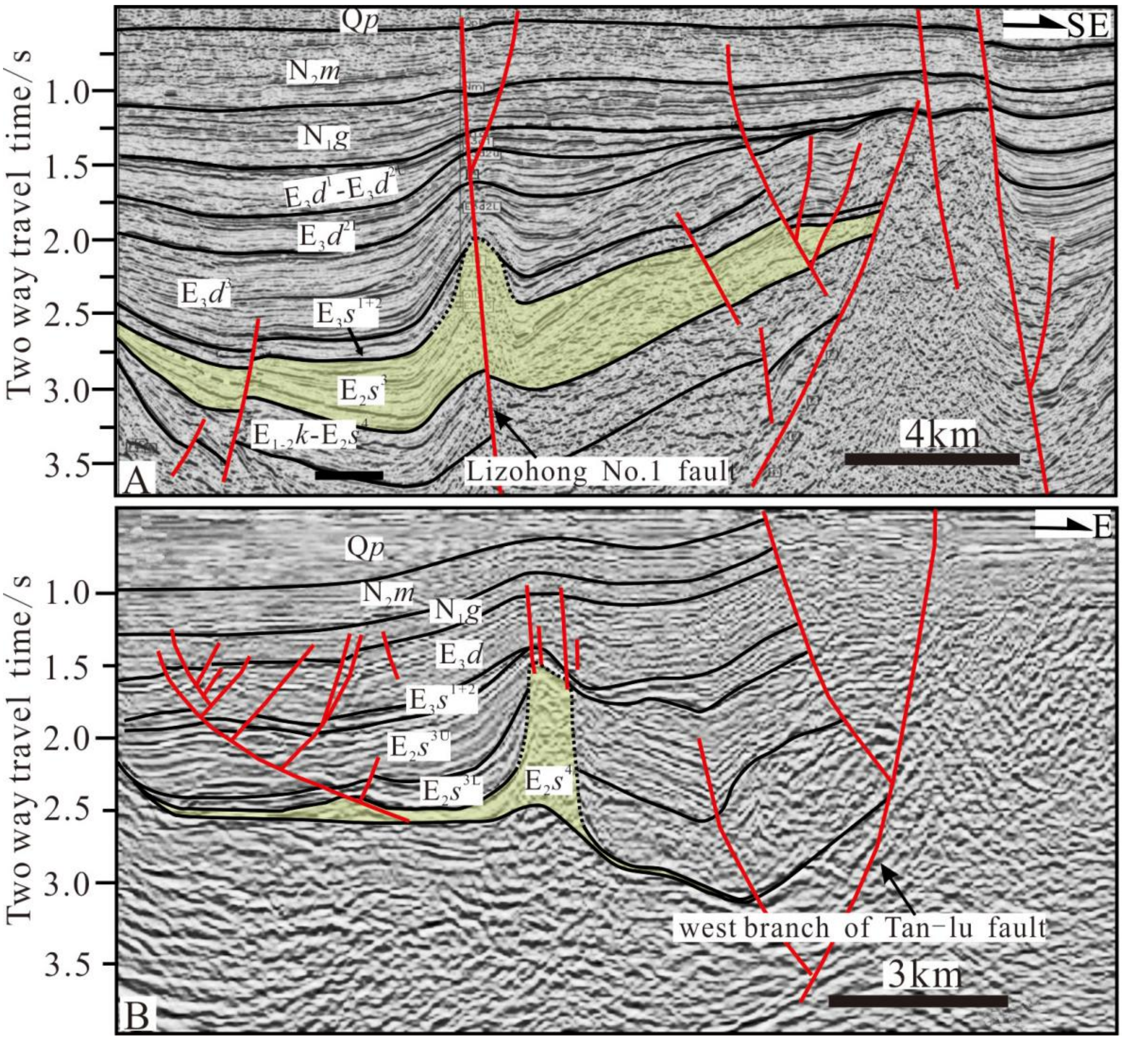

Figure 7. Seismic profile that crosscuts the piercement structures in (A) the Liaozhong depression and (B) the Laizhouwan depression. Note that both piercement structures developed in positions where the Tan–Lu fault passed through (salt is colored in yellow).

During the violent strike–slip movement period, local transpressional stress provides crucial dynamics for the development of special structural styles, such as flower, diapir, and piercement structures. Evolutionary model for the piercement structure in the offshore Bohai Bay Basin is shown according to regional and local stress environments and variations in syndepositional strata thickness in figure 8.

During the Paleogene rift stage of the Bohai Bay Basin, the Tan–Lu fault zone and its branch faults were dominated by extensional activities and structural weak zones were formed in the vertical direction. Meanwhile, soft salt was slowly flowing toward the sag center along the slope under its own gravity; however, gravity flow remained insufficient to form a diapir structure. When faulting was dominated by strike–slip movements, which provided local transpressional stress, soft rocks began to migrate upward along the pre-existing weak fault zone, thereby causing the overlying synkinematic layers to exhibit a drape anticline shape characterized by a thin top and thick flank. If the strike–slip activity declined, then the upwelling and diapirism of salt rocks (or mudstone) would be accordingly suspended.

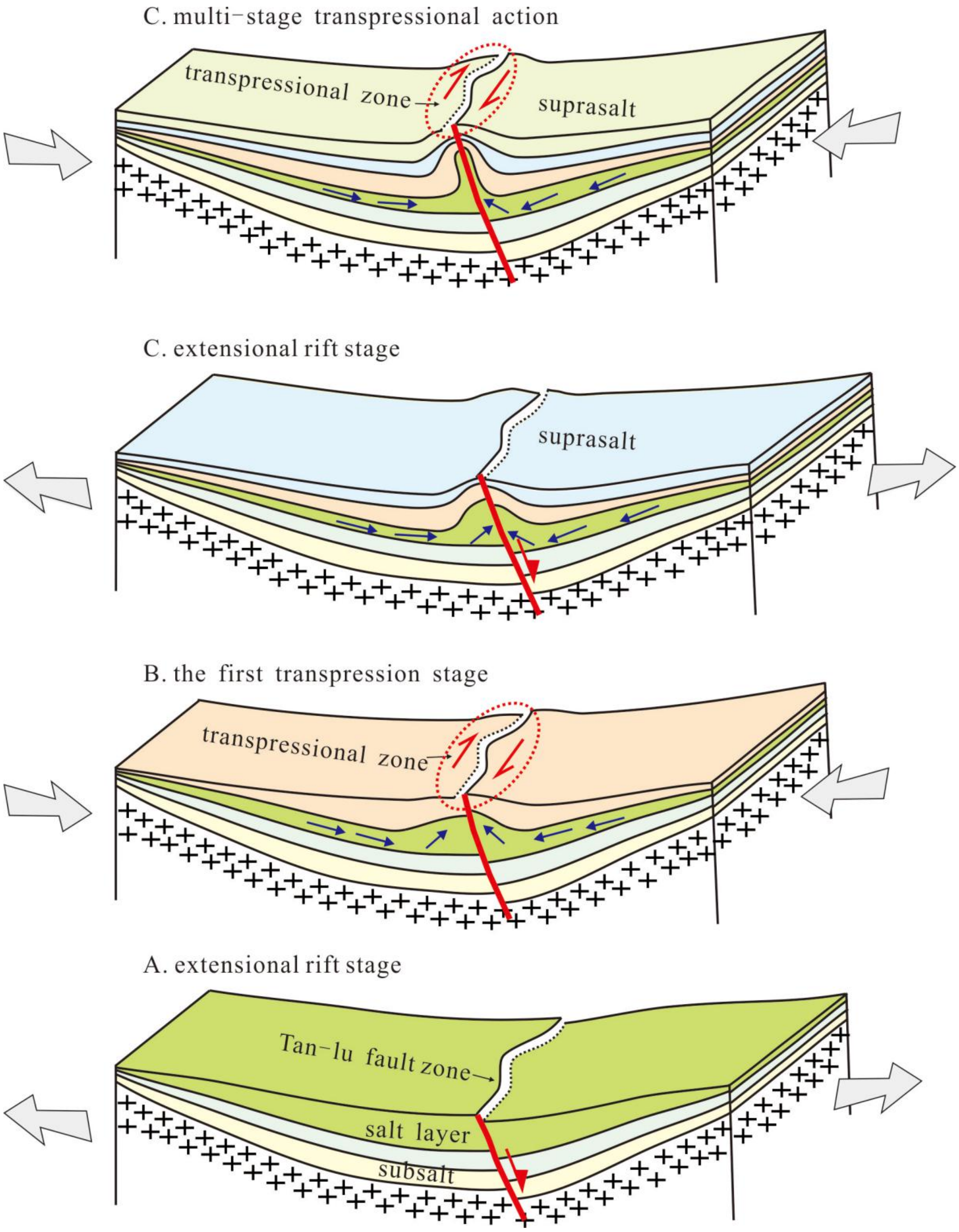

Figure 8. Diagram of the evolution model for the piercement structure in the offshore Bohai Bay Basin.

Under the multi-stage rebuilding of the strike–slip activity of the Tan–Lu fault zone, piercement structures were ultimately developed in the local position of the Liaozhong and Laizhouwan sags.

In addition, the magmatic diapirism observed in the southern segment of the Liaodong uplift, the Weibei sag, and the Huanghekou sag of the Bohai Bay area is also closely related to the strike–slip activities of the Tan–Lu fault. In general (Jiang, 2008), strike–slip faults played important roles in the development of the piercement structures in the offshore Bohai Bay Basin. These faults did not only directly control formation location but also supply fundamental dynamic sources.

6. FORMATION CONDITIONS OF PIERCEMENT STRUCTURES

From the preceding contrastive analysis of the piercement structures in the Kuqa depression and the offshore Bohai Bay Basin, a conclusion can be drawn that regional or local structural compression is the most important dynamics in the formation of piercement structures. However, the upwelling and diapirism of salt are dominated by various composite factors and the major controlling factor varies with different evolution stages. During tectonic quiescence, compressional stress is weaker and the depositional rate is lower, and thus, salt mainly accumulates and thickens to form a salt pillow (or a salt dome) under its own buoyancy and gravity. A previous study calculated the critical condition for buoyancy to form a salt diapir in the western segment of the Kuqa depression based on thin sheeting theory. On the basis of this theory, a diapir structure will not develop because the buoyancy effect will be restrained if the wavelength of the salt anticline is less than 33 km (Yu et al., 2008). From this viewpoint, the contribution of buoyancy to the formation of piercement structures will be reduced with the amplitude intensification and wavelength shortening of the salt anticline. Correspondingly, the gradually enhanced compressional stress gradually becomes the main factor that drives salt to pierce upward. Simultaneously, the differential loading triggered by the increasing depositional rate plays a substantial role. Undoubtedly, gravity, buoyancy, differential loading, and compressional stress significantly influence the formation and evolution of piercement structures. However, the highly limited distribution of piercement structures in the Kuqa depression also indicates that their formation process is extremely difficult to explain based only on the aforementioned factors. The development conditions for piercement structures are further analyzed in the following sections. Many basement-involved faults, which cut downward into Paleozoic metamorphic rocks, were developed under the piercement structures in the Kuqa depression. Among these faults, the Kelasu major fault was determined as a pre-existing fault that formed in the Jurassic extensional environment and that experienced tectonic inversion under Cenozoic structural compression.

On the basis of the comprehensive analysis, including those of regional and local stress environment and seismic data, we attribute the basement faults developed in the transition zone between the Awate and Northern Monoclinic structural belts to be the same inversion fault system. For the subsalt basement faults developed in the Qule piercement structure, current seismic and geological data are insufficient to prove that they are pre-existing faults developed in the Jurassic extensional environment, similar to the Kelasu fault. However, regional seismic data show that subsalt faults, which have been induced by compressional stress from north to south, have failed to get across the Baicheng sag and transmit to the Qiulitage tectonic belt. Moreover, the Upper Paleozoic layer of the hanging wall of these thrust faults was seriously denudated. Through the aforementioned aspects, we infer that these faults may have been produced before the Mesozoic Era. These pre-existing subsalt faults would be preferentially reactivated even under slight compressional stress. On the other hand, the hanging walls of these faults were uplifted to form structural highs, which resulted in the decrease of the overlying gravity loading. Accordingly, differential loading was enhanced and the top of pre-existing faults became favorable positions for salt accumulation and diapir formation. The basement fault was then propagated upward, thereby inducing the overlying layers forming fault-propagation folds. Salt accumulated in the anticlinal nucleus and formed salt domes, which were the most advantageous locations for subsequent tectonic deformations. In addition, strongly uplifted fault blocks provided resistance to salt flow from south to north. Piercement structures were eventually formed under the sustained differential loading and tectonic compression, along with new secondary thrust faults that developed in the suprasalt layers of the anticlinal nucleus. The reactivation of pre-existing faults is crucial during the evolution history of piercement structures. By contrast, salt pillows located in the western part of the Kelasu thrust belt failed to evolve into piercement structures because of the absence of pre-existing faults, although salt had remarkably thickened.

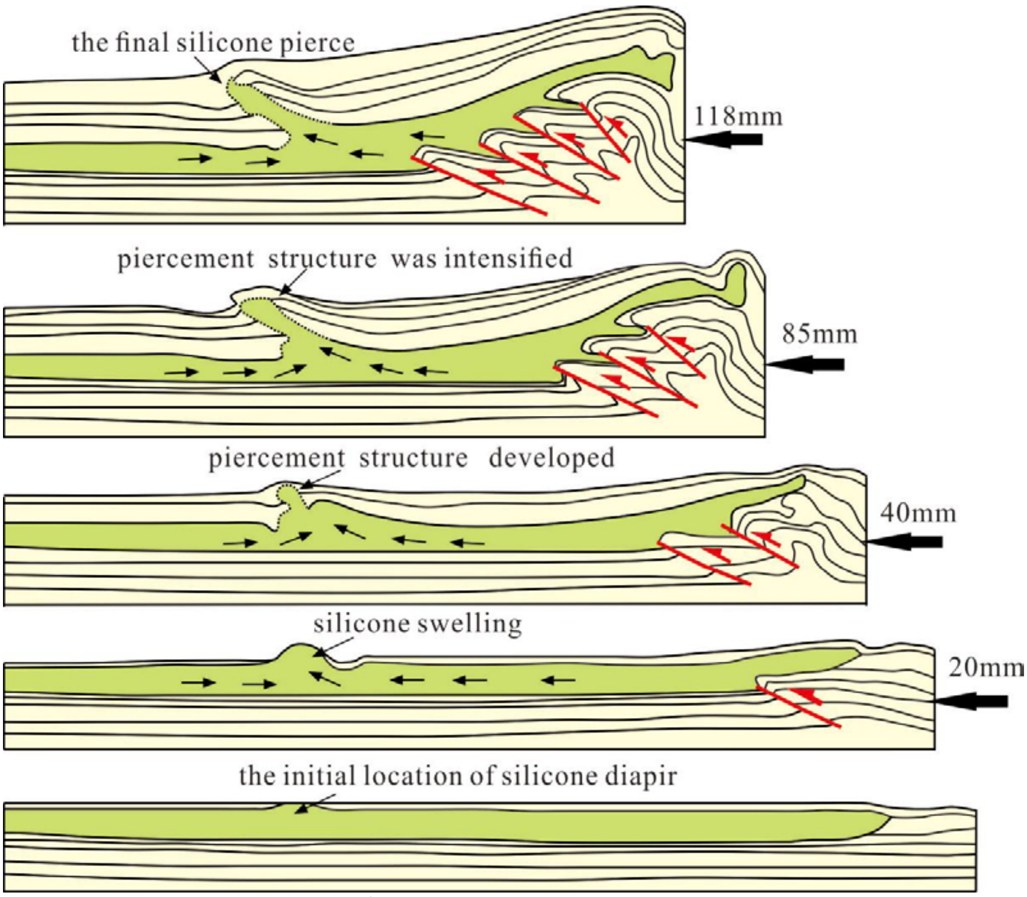

Figure 9. Structural physical simulation of the Quele salt nappe in the Qiulitage thrust belt, which attributes the formation of the nappe to an existing early salt diapir (adapted from Wu et al., 2013)

The Quele salt nappe was studied through physical simulation experiments (Wu et al., 2013), and the results suggested that the pre-existing salt diapir was the main controlling factor for the development of the Quele salt piercement structure (Fig. 9). However, another study proposed that the evidence for the existence of an early salt diapir was insufficient (Cheng et al., 2014).

The current study mainly focuses on the inducing factors of the Quele piercement structure, apart from the pre-existing salt diapir. From the comprehensive analysis of the seismic data of the Quele and Awat areas, we found that the two piercement structures with disparate size and geometry are developed on the uplift edge. The Quele piercement structure is located in the northern edge of the Quele paleo-uplift, whereas the Awate piercement structure is located in the northern edge of the Wensu paleo-uplift. Similarly, the salt layer of the Paleogene Kumugeliemu formation gradually pinched out toward the margin of the Quele and Wensu paleo-uplifts. The hard basement strata (pre-Mesozoic) of the paleo-uplifts deformed slightly under Cenozoic compressional action, which played a role of pine-line and restricted the southward expansion of thrust deformation. Moreover, the frictional resistance between the subsalt and suprasalt layers was increased by the thinning or pinching out of salt on the uplift edge, which prevented the southward flow of salt. On the other hand, the terrain elevation difference on the north flank of the piercement structure induced by the serious thrust and the uplift of the Northern Monoclinic structural belt prevented salt from flowing northward. The bilateral boundary barriers are significant in forming the piercement structure. Consequently, salt had nowhere to go to and could only deform within a limited space under increasing differential loading and tectonic compression. Finally, a magnificent piercement structure was formed in the junction position between the uplift and the depression. By contrast, the piercement structure located in the Kasangkaituo anticline of the Kelasu thrust belt is smaller than the Awate and Quele piercement structures because of the absence of a southern boundary barrier. Similarly, in the eastern segment of the Kuqa depression, the Yiqikelike structural belt (the salt layer was the Miocene Jildike formation), which was sandwiched between the Northern Monoclinic tectonic belt and the Yangxia depression, experienced strong compressional stress from North Tian Shan but did not develop a piercement structure (Fig. 10A).

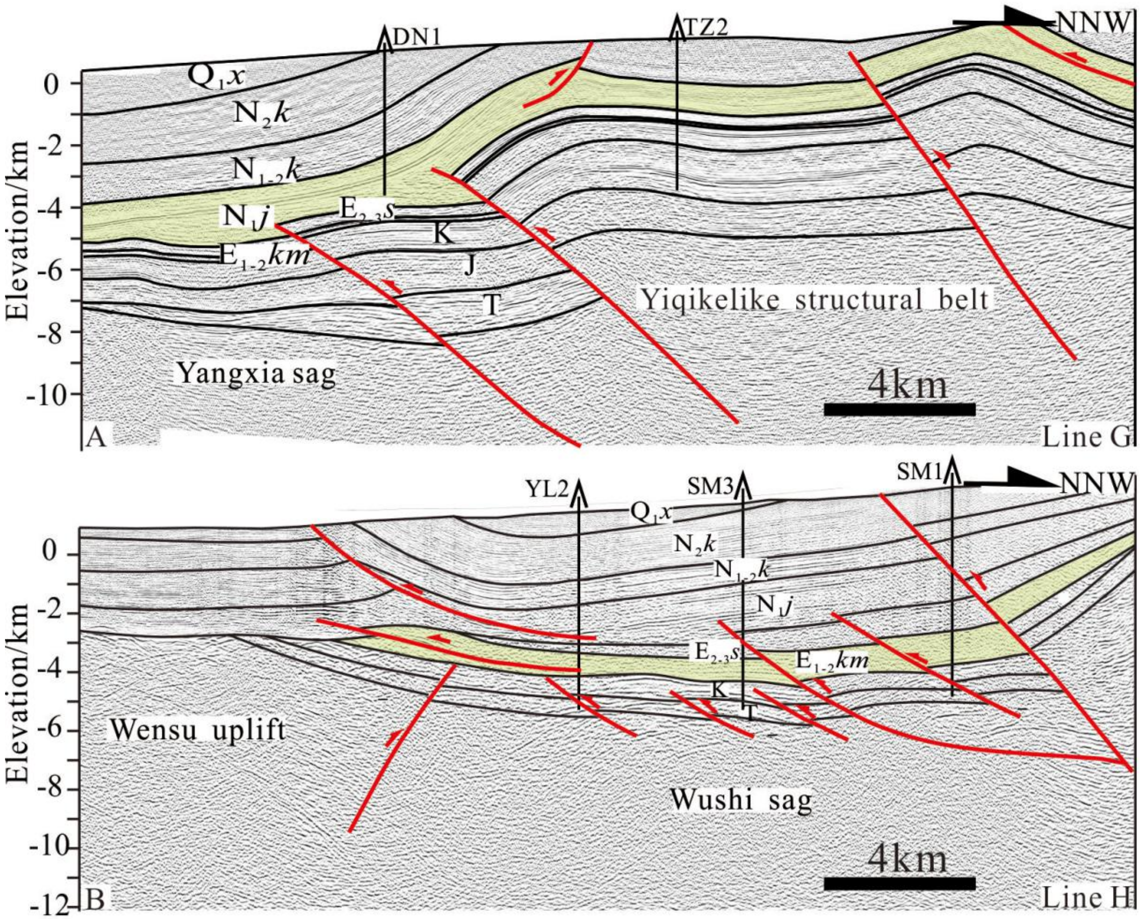

Figure 10. Seismic profile that crosscuts (A) the Yiqikelike structural belt and (B) the Wushi sag. Neither of these structural belts developed a piercement structure, the former because of the absence of a boundary barrier and the latter because of the relatively extensive salt-bearing range (salt is colored in yellow).

In addition, the comparison of the seismic data of the Awate and Wushi sags showed that although both structural belts were sandwiched between the South Tianshan Mountain orogenic belt and the Wensu uplift, they exhibited disparate deformation characteristics i.e. the Awate area developed magnificent piercement structures whereas the Wushi sag had no piercement structure (Fig. 10B). After analyzing the seismic data of the two areas, we attributed their varying deformation characteristics to the different widths of the salt-bearing basins (sags). The structural belts of the Awate and Wushi sags are adjacent, and thus, we assume that the compressional stresses exerted on the two sags by the uplifting of South Tianshan Mountain are approximately equal. Under the action of equal structural compression, the Awate and Wushi sags experienced disparate deformation processes. In particular, the basement of the Awate sag was strongly uplifted and salt was significantly thickened due to the narrow space. These conditions are beneficial to the formation of piercement structures. Meanwhile, the compressional stress from north to south of the Wushi sag was triggered by the uplifting of South Tianshan Mountain, was gradually absorbed and decreased via brittle basement faulting and plastic salt layer folding. Consequently, basement uplifting and caprock deformation were mainly concentrated in the northern part of the Wushi sag, whereas the structural deformation in the southern part was weaker because of stress attenuation. Therefore, the Wushi sag failed to develop piercement structures although the southward flow of salt was obstructed by the Wensu paleo-uplift. Hence, a narrow salt-bearing basin (sag) is more conducive to the development of piercement structures under the same compressional stress.

From the preceding analysis, we determine that the formation of piercement structures in the Kuqa depression requires a strict structural environment that results from the combined actions of various factors. During the evolution history of a piercement structure, regional or local compressional stress provides the fundamental dynamics, the pre-existing tectonics (e.g., fault, paleo-uplift or salt dome) dominates the development position, and a narrow salt-bearing basin (sag) is more advantageous for the

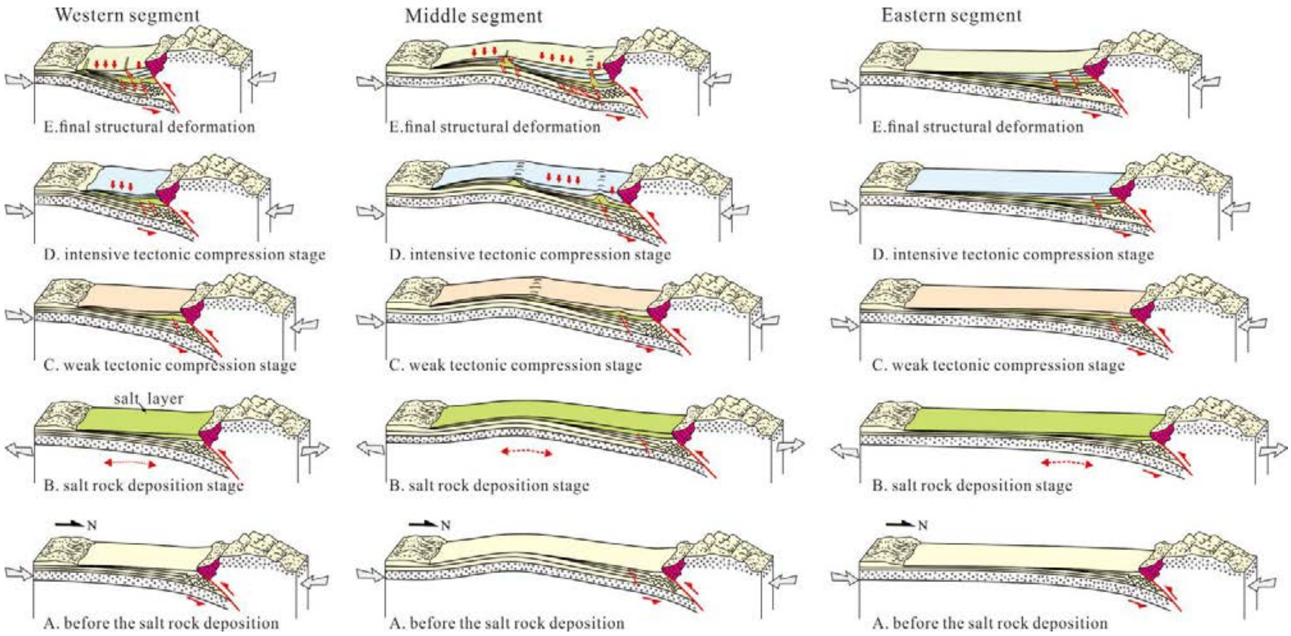

Figure 11. Diagram of the evolution models for piercement structures in different parts of the Kuqa depression. In the western segment of the Kuqa depression, the salt layer was deposited thickly within a narrow range, thereby supplying a beneficial environment for the development of piercement structures. A pre-existing basement fault and paleo-uplift are located in the middle segment of the Kuqa depression. The piercement structures were mainly developed on top of the pre-existing fault and the northern edge of the paleo-uplift. By contrast, the eastern segment of the Kuqa depression, where the salt layer was deposited thinly within a wide range and where a pre-existing fault or paleo-uplift was absent, had no piercement structure.

development of piercement structures under lateral compressional stress. The evolution models for the piercement structures influenced by various factors in different parts of the Kuqa depression are shown in figure 11.

7. CONCLUSION

1. The development of piercement structures is highly localized in the Kuqa salt-bearing depression located in the Tarim Basin. These structures are mainly distributed in the northern margin of the Kelasu thrust belt and the western segment of the Qiulitage thrust belt. The Kelasu piercement structures primarily developed on top of the pre-existing Kelasu basement fault due to the reactivation of a pre-existing fault. By contrast, the Qiulitage piercement structures mainly developed in the northern margin of the Quele paleo-uplift and the junction between the Awate sag and the Wensu uplift as a consequence of the boundary barrier and the relatively narrow salt-bearing range.

2. The formation and evolution of piercement structures in the Kuqa depression are controlled by many factors that vary in different evolutional stages and are generally dominated by the pulsant uplifting process of South Tianshan Mountain. During tectonic quiescence, salt mainly accumulates and thickens under its own gravity flow. In the weak structural compression period, pre-existing faults are preferentially reactivated and cause the suprasalt layers to form fault-propagation folds, which significantly dominate the development location of piercement structures. When the uplifting of South Tianshan Mountain was accelerated, compressional stress and differential loading became the most important dynamics. These factors result in the swelling of salt domes, which eventually evolve into piercement structures.

3. The formation conditions for piercement structures in the Kuqa depression is extremely strict and include comprehensive factors such as tectonic compressional stress, reactivation of a pre-existing fault, boundary barrier arising from a paleo-uplift, differential terrain elevation triggered by the uplifting of a thrust fault block, and narrow salt-bearing basin (sag). Among these factors, regional or local tectonic compression is the principal dynamics, the top of a pre-existing fault and the sedimentary boundary of salt are the preferred development positions, and narrow salt-bearing sag provides an advantageous environment.

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