Multiphase deformation deduced from 3D construction and restoration: Implication for the hydrocarbon exploration in the mountain front of the Northern Tianshan

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Abstract

Three-dimensional (3D) modeling and restoration are powerful in describing the geological characteristics and kinematics which cannot be fully accomplished by the two-dimensional modeling methods. In this study, we applied 3D modeling and restoration to the Beisantai anticline along the mountain front of the Northern Tianshan. The Beisantai anticline shows an EW-trending structure in the shallow layers with NS-trending structures in the deep layers. The 3D seismic reflection data visualize the growth strata well, which record the evolution of the anticline and the influence of Cenozoic India-Asian collision. Our results suggest that a combination of multiple deformations of this anticline on different layers developed during different episodes. In addition, multiphase deformation and strain distribution along the eastern part of the northern Tianshan was implied. Combined with an analysis of the burial and hydrocarbon-generating history from borehole data, we proposed new potential

exploration areas in this region and multistage tectonic effects for hydrocarbon accumulation. This work not only highlights our understanding of the structural decomposition of a multiphase structure associated with growth strata, but also the structural evolution of the northern Tianshan and the adjacent petroleum-producing Junggar Basin.

Key words: Fault-related fold, 3D modeling, Restoration, Tianshan, Hydrocarbon exploration

1. Introduction

The 2500km EW-trending Tianshan mountain belt is part of the Central Asia Orogenic Belt (CAOB) and contains key evidence for the evolution of the CAOB, which extends from the Urals to the Pacific and from the Siberian and East European (Baltica) cratons to the North China and Tarim cratons (Mossakovsky et al., 1993; Khain et al., 2002; Sengör et al., 1993; Sengör and Natal'in, 1996; Yakubchuk et al., 2001). Tianshan Mountain belt is divided into western and eastern segments with its boundary at Urumqi. Bodga Mountain belt is part of the eastern Tianshan, which is convex to the North where it is bounded by the Junggar Basin and the Turpan basin to the South (Fig. 1). This mountain belt has many fault-related folds and strata that originated during the Carboniferous. These complicated structures control the distribution of the mineral deposits and hydrocarbon generation and accumulation (Ma et al., 1997; Zhang et al., 1999; Wei et al., 2005).

The Paleozoic accretion and Cenozoic deformation have been well studied in the Tianshan region (Windley et al., 1990; Avouac et al., 1993; Hendrix et al., 1994; Allen et al., 1991; Sengör et al., 1993; Shu et al., 2000 and 2010; Laurent-Charvet et al.,

2003; Xiao et al., 2003; Wei et al., 2005). However, the deformation and tectonic evolution since the late Paleozoic in Bodga Mountains and the eastern Junggar are still debated. One of the most intense debates focuses on the predominant mechanism for accommodating the convergence and the mechanism of the propagation of the Asian deformation from the Indus-Yalu suture northward where the collision occurred (Molnar and Tapponnier, 1975; Burchfiel and Royden, 1991; Harrison et al., 1992). The key to understanding the Indo-Asian collision is to establish the spatial distribution and temporal variation of the crustal strain in Asia. This in turn has important implications for the paleotopographic and paleoclimatic histories of Tibet and the adjacent regions (Yin et al., 1998). This study focuses on the deformation, strain distribution and tectonic evolution of the northern Tianshan in the CAOBS since the Paleozoic period.

The studies of the deformation and tectonic evolution in this area mostly rely on the field investigations or the low temperature thermochronology (Hendrix et al., 1994; Liu et al., 1994; Shu et al., 2004; Fang et al., 2006). These studies sometimes lead to uncertain, and furthermore, the kinematics of the geological structures is often unknown or, at least, not precisely quantified. One of the advantages of working in 3D is the capability of integrating all available data including the field investigation, 2D/3D seismic, and well in the same framework, so that the data sets complement each other and help to obtain an internally consistent model. 3D reconstructions have proven to be useful for better visualization and understanding of the geometry and property distribution of geological structures (Tanner et al., 2003; Fernández et al.,

2004; Ford et al., 2007), which also have major relevance in hydrocarbon exploration and production, well planning and civil engineering (Moretti, 2008; Guzowski et al., 2009). Therefore, it is important to study the structural geometry, kinematics and tectonic evolution, as well as petroleum exploration through the 3D structural modeling and restoration in the study area.

The Beisantai anticline is located at the mountain front of the Bodga Mountain belt in the eastern Junggar Basin (Fig. 1a); its deformation records the tectonic deformation of the northern Tianshan and Bodga Mountains, as well as the Junggar Basin. This anticline is also an established hydrocarbon field in the Junggar Basin covered by 3D seismic data and much well data, making it a good candidate for the study of the tectonic evolution and kinematics of the northern Tianshan. In this study, on the basis of the interpretation of the 3D seismic data, we constructed a 3D model of the Beisantai anticline, which revealed that the trending of the structure at depth is perpendicular to that of the shallow layers younger than the Cretaceous. In order to study the kinematic and deformation mechanisms, we sequentially restored the structures using the kine-3D in the GocadTM program. The 3D modeling and restoration combined with the growth strata of the 3D seismic data revealed several periods of deformation from the Paleozoic in the southern Junggar Basin along the eastern part of the northern Tianshan, and how the structure developed and superimposed during its tectonic transformation. Combined with a hydrocarbon generation history analysis, the results document the tectonic evolution since the Late Paleozoic and the kinematics of the thrust belt, and also provide insights relevant to

oil and gas exploration.

2. Geological setting

2.1 Regional tectonics

A series of fold-and-thrust belts developed along the Bodga Mountains, characterized by basement-involved structures in the hinterland and a thin-skinned thrust in the foreland. These structures experienced very complex tectonic events. Many explanations have been proposed for the tectonic evolution of Tianshan since the Paleozoic and the debate focuses on the nature of the Early Permian and Mesozoic basins. Many studies suggest that the Early Permian basins are foreland basins (Liu et al., 1994; Zhang et al., 1999); but some proposed that the basins were extended during this period (Cai et al., 2000; Shu et al., 2005). Furthermore, the Mesozoic basin adjacent to Tianshan has been suggested to be a rift basin (Liu et al., 1994; Li et al., 1998), a sag basin (Chen, 2002), a foreland basin (Chen et al., 2002), a collisional successor basin (Graham et al., 1993) and a craton basin (Cai et al., 2000). Hendrix et al. (1994) considered that the flexurally driven Mesozoic subsidence and the deposition of alluvial conglomerate in the Junggar Basin occurred in response to the periodic deformation of the Tianshan and the associated reactivation of thrust faults in latest Triassic, latest Jurassic and late Cretaceous. The study by Fang et al. (2004 and 2006) suggested that the Junggar Basin and Tarim Basin were not physiographically separated in the Early-Middle Jurassic by the ancestral Tianshan. Basins such as these adjacent to the Tianshan have a similar evolution; an intracontinental rift and sag basin in the Jurassic, an intracontinental basin from the Cretaceous to the Eocene and a rejuvenated foreland basin in the Late Cenozoic. The propagating deformation of

Tianshan that propagates from west to east is related to the extrusion of the Pamir Syntaxis.

2.2 Stratigraphy of the eastern Junggar Basin

Upper Carboniferous to Middle Permian

All the strata sequences in the field and in the borehole in the east Junggar Basin have been found to be since the Carboniferous. The tectonic attribute is unclear in the late Paleozoic. Volcanic arc (Coleman, 1989; Gao et al., 1998; Ma et al., 1997) and continental rift (Han et al., 1997; Han et al., 1999; Gu et al., 2001) are the principal suggested categorizations. The study by Gu et al. (2001) shows that the lower-middle Carboniferous marine volcanic succession in the Bodga Mountains has bimodal features and is dominated by basalts and rhyolites with minor dacites and rare andesitic rocks, which implies that the Bodga Mountain belt was continental rift in the Carboniferous. The sedimentary rocks in the Upper Carboniferous and the lower-middle Jijicaozi Group in the lower Permian are dominated by grey-green quartz sandstone and feldspar sandstone with dolomite (Fig. 2), which suggests a regression marine sedimentary environment during this period.

Upper Permian and Lower Triassic

The upper Jijicaozi Group in the upper Permian reflects the marine-continental transitional facies. The lower Wulabo and Jingjingzigou Formations are dominated by shallow marine and costal deposits. The upper Lucaogou and Hongyanchi Formations are dominated by lacustrine and alluvial deposits. The Cangfanggou Group in the upper Permian and lower Triassic is dominated by red conglomerates, interbedded with argillaceous sandstone (Fig. 2). Large amounts of sandstone and gravel

developed in the mountain front, which implies a high-energy alluvial environment during this period. The study by Shu et al. (2004) suggests that the rift geological setting ended since the Late Permian. It is characterized by red molasse sediments in the study area and a migration of the depocenter towards the center of the basin in the north from the Early to the Late Permian.

Middle Triassic-Middle Jurassic

The lower Kelamayi Formation of the Xiaoquangou Group developed grey-green, greenish yellow graywacke and mudstone. The upper Huangshanjie and Haojiagou Formation of the Xiaoquangou Group developed grey, pale yellow sandstone and dark grey carbonaceous mudstone. The Badaowan, Sangong and Xishanyao Formations in the Early-Middle Jurassic developed grey-green sandstone interbedded with mudstone (Fig. 2). Coal and other carbonaceous materials developed during this period in the study area, even in the hinterland of the Tianshan. Furthermore, the upgrowth-retrogradation of the normal cycle, especially the carbonaceous mudstone and coal line, imply the expansion of the drainage system in this area during the Middle Triassic-Middle Jurassic, and the Tianshan Mountain belt did not obviously experience an uplift during that time.

Middle-Upper Jurassic

The lower part of the Toutunhe Formation in the middle Jurassic is dominated by yellow-green sand, sandstone, fine siltstone and variegated banded mudstone. The purplish-red, brownish-red sandstone and variegated bands increase in an upward direction (Fig. 2), which suggests that the climate became dry and the drainage system shallower. Conglomerates also developed in the Toutunhe Formation, which

unconformably covers the Xishanyao Formation. The Qigu Formation in the upper Jurassic is dominated by purplish-red sandy mudstone and the Kalaza Formation developed a grey-brown sandy conglomerate. The increase of the red clastic rocks indicated an arid sediment environment, which might have arisen from the uplift of Tianshan Mountain belt during this period.

Cretaceous

The Tugulu Group in the lower cretaceous, including the Qingshuihe, Hutubi and Shengjinkou Formations, developed grey-brown mudstone and pale yellow thick mudstone (Fig. 2). The lower Cretaceous layers unconformably overlap the lower deformed strata. The upper Cretaceous layer developed river facies grey-brown, grey-red gravel. The braided-river and alluvial were predominant, which implies an arid climate during this period.

Paleogene

The Paleogene can be divided into the Ziniquanzi and Anjihai Formations, which are composed of brownish-red, reddish-brown sandy mudstone and brownish-red and grey-green/brown gravels of the river and lacustrine facies (Fig. 2). This also implies that a humid climate interrupted the arid climate.

Neogene and Quaternary

The Changjihe Group in Neogene consists of reddish-brown sandy mudstone, grey-red sandstone and gravel of the river and lacustrine facies. The Xiyu Formation, Wusu Group, Xinjiang Group and Holocene develops dark-grey and grey-green massive sandstone, gravel, as well as loess, silicate weathering sediments (Fig. 2), which reflect the alluvial and braided-river facies.

3. Methods

Fault-related folds are very common geological features in the fold-and-thrust belt (Suppe, 1983; Shaw et al., 2005). Several different deformation mechanisms control the structures in the mountain belts, such as fault-bend fold, fault-propagation fold, and detachment folds, etc. After multiphase deformation develops in the mountain belts, the structures become very complex. Interpretation of seismic reflection data provided direct constraints for the subsurface structures. Geologists used a balancing technique to verify the length coherence along cross-sections by hand (Bally et al., 1966). Two dimensional (2D) balance cross sections have been widely used during the last decades because they can visualize the structural deformation episodes and reveal the kinematics of the mountain belts and the amount of shortening. The increased development of computers encouraged the appearance of several commercial programs in the 1990s, such as Geosec, 2D_move, etc. (Kligfield et al., 1986; Moretti and Larrère, 1989). However, 2D structural interpretations and balanced cross sections cannot reveal the structures along the strike nor three dimensional structural characteristics. New technology allows the study of the fault-related folds progressing from 2D to 3D, from geometric to kinematic and geodynamic (Gratier and Guillier, 1993; Mallet and Massot, 2001; Moretti, 2008). 3D modeling can integrate many different kinds of data in a numerical platform, such as seismic reflection cross sections, well data, geological maps, seismic data, satellite images, remote sensing images etc., which can synthesize all the surface and subsurface data to guarantee that the model approaches the natural geological

condition. 3D modeling has proven to be useful in earthquake hazard assessment (Shaw and Shearer, 1999; Carena and Suppe, 2002; Shaw et al., 2002; Carena et al., 2004; Plesch et al., 2007; Hubbard et al., 2009; Li et al., 2010 and 2014), hydrocarbon exploration and production, and well design (Moretti, 2008; Guzowski et al., 2009). As a consequence, new surface and volume restoration applications are continuously emerging, such as Geosec_3D, Kine_3D and the structural modeling workflow implemented in the Gocad application (Moretti et al. 2006 and 2007; Moretti, 2008). Furthermore, 3D restoration methods have been used to study strain distribution (Plesch et al., 2008; Guan et al., 2012; Li et al., 2013), as well as the kinematics of folds or thrusts (Sanders, 2004; Maerten and Maerten, 2006).

In order to determine the 3D structural geometry and the strain distribution of the Beisantai anticline, we applied 3D structural modeling and restoration in this study. The interpretations of the 3D seismic volume were used to develop a 3D horizon and fault model by generating surfaces via the computer-aided design application *Gocad* (Mallet, 1992). These interpretations were used to generate evenly meshed triangular surface meshes (Tsurfs) for the major faults and horizons by discrete smooth interpolation (Mallet, 1992). The structural modeling workflow implemented in *Gocad* allows for iterative improvement of the surfaces through a variety of methods. The generated tsurfs were modified by adjusting the mesh triangle size to properly sample the existing data constraints, and subsequently smoothed by a Kriging interpolation while assuring the consistency of the faults and horizon cutoff relationships.

This model serves as the basis for the strain restorations. We used KINE3D in the Gocad program to perform the 2.5 dimension restoration in this study. The 2.5D restoration refers to surface balancing, which allowed us to unfold or unfault the horizon. The study by Moretti (2008) summarized the various deformation modes for the upper crust: a flexural slip is characterized by a shear occurring along the inter-bed weak layer (shale or slit) surface of the horizon with the thickness being preserved. The competent layers in the upper crust are better modeled with a flexural slip model (Suppe, 1983; Moretti and Larrère, 1989). We used a flexural slip deformation model in this paper that followed the rule of global area conservation. The restoration can calculate the dilatation of the horizons during the restoration, and the result represents the strain distribution on the horizon. It is known that structures are commonly deformed by multi-stage events. Via this method, we can eliminate the structural effects in a later stage to help analyze the primary strain distribution, which might help constrain the tectonic history and dynamic processes that occurred during different geological evolutionary periods.

4. Structural interpretation and strain restoration

The high quality 3D seismic data of the Beisantai anticline used in this study covers about $\sim 1225 \text{ km}^2$ in the southern Junggar Basin (Fig. 1a). The two way travel time (TWTT) for the seismic volume reached 5s, which means that the depth was approximately 10 km if we assume that the average velocity is 4000 m/s on the basis of the borehole data from this area. In order to ascertain the 3D structural characteristics and strain distribution, detailed seismic cross section interpretations

and 3D structural modeling as well as restoration were performed in this study.

4.1 Structural geometry of the Beisantai anticline and Fukang system

Seven seismic reflection profiles were generated in this research, including four NS-trending cross sections (Fig. 3) and three EW-trending sections along the strike (Fig. 4). Cross sections 1-4 show that the structure of the Beisantai anticline is characterized by a paleo-high before the Cretaceous and a deformation led by a fault-bend fold F1 in the shallow layers (Fig. 3). Four unconforming surfaces were revealed in the study area (Fig. 5d). The most obvious one lies at the bottom of Cretaceous, which was widely developed along the Bogda Mountain belt and the southern Junggar Basin. This implies that a strong deformation occurred before the Cretaceous. The seismic reflection of the Carboniferous strata in the cross sections is discontinuous and discordant, which is consistent with the volcanic rocks during this period but the seismic profile also shows stratifications and deformations in these cross sections. We thought that these might reflect the deformation of the volcanic tuff in the Late Carboniferous during the later era. The Wutonggou Formation in the Late Permian lies unconformably on these deformed layers (Fig. 5d). Another two unconformity surfaces are located at the bottom of the Eocene and Neogene. Although the truncation of the strata is not very obvious, it is easy to distinguish that the thickness of these strata obviously changes on different parts of these cross sections (Fig. 5d).

The EW-trending sections show that a fault-propagation fold cutting runs from the Permian to the upper Jurassic layers on section 7 (Fig. 4). Comparing the

thickness of the strata in the hanging wall and the footwall in this seismic section, we find that the growth strata thin onto the fold crest and the lowermost growth units show the greatest changes in thickness. The layers before Jurassic are pre-growth strata and the Jurassic layers are growth strata. This fault-propagation fold with Jurassic growth strata only developed on the NE corner of the 3D seismic volume (Figs. 6 and 7). Although the F9 fault is local, it also provides evidence for a syntectonic deformation in the Jurassic. The strike of this structure as revealed by the 3D structural modeling will be discussed in the next section. As previously discussed, dark rocks with carbonaceous mudstone and coal widely developed during the early Jurassic and the color of the rocks in the Middle-Late Jurassic became purplish-red, brownish red and the amount of conglomerate increased. This Jurassic lithology leads us to infer that the initiation of this deformation continued from the Middle-Late Jurassic.

The Beisantai anticline is located at the mountain front of the Bodga Mountain belt (Figs. 1 and 5). The Fukang fault system is the main fault system along the Bodga Mountain belt. The Fukuang fault (F2) is the largest fault-propagation fault, which thrusts the strata from Permian to Jurassic onto the Cenozoic layers in the basin (Fig. 5a). We can calculate that the slip of this fault is larger than 7 km if we assume that the average velocity is 4000 m/s. Several imbricated faults and folds developed in the Fukang system and accommodated considerable shortening. The regional cross section 8 (Fig. 5a) shows that the Jurassic layer was strongly deformed in the hanging wall of the Fukang fault, which suggests the time of the deformation is later than the

Jurassic. Many blind fault-propagation faults transfer the deformation in depth from the mountain front into the Basin. These structural activities deformed the layers from the Permian to the Cenozoic in the footwall of the Fukang fault (F2), which reflects the latest deformation in the Cenozoic in the southern Junggar Basin.

Although the Carboniferous strata are volcanic, the seismic reflection also shows deformation beneath the Beisantai anticline. According to the relationship between the deformation pattern and the truncation of the seismic reflection, we inferred a north-dipping thrust fault (F3) thrusts on the south-dipping fault F4, solving to a deeper detachment at about 6s depth. The Late Permian strata and Jurassic strata thin towards the crest of the fold, which is characteristic of a drape or growth strata. Fig. 5b shows the theoretical model of the drape sequence above a rigid model, which thins toward the crest of the structure, and younger strata have less relief than older units. Fig. 5c shows a growth stratum above a fold developed by progressive limb rotation. The two stratigraphic patterns are similar, and sometimes difficult to distinguish. According to fault-related fold theory (Suppe, 1983; Shaw et al., 2005), drape and growth strata can be distinguished by the orientation of the axis. Axial surfaces in drape sequences often are vertical or dip away from the structural crest (Fig. 5b), reflecting a state of tension and are due to compaction in some cases. In contrast, in axial surface models the growth strata generally dip toward the structural crest (Fig. 5c), reflecting the compression state (Shaw et al., 2005). In our model, the strata of Late Permian to Triassic and Late Jurassic thin towards the crest of the fold. According to our interpretation, the axial surfaces of these strata dip toward the crest, which implies

that these strata are growth strata rather than drapes. This suggests that the syntectonic structural activity of F3 and F4 beneath the Beisantai anticline occurred during the Late Permian to the Late Jurassic.

In order to ascertain the deformation time in detail, we did a combined analysis of the lithology and sedimentary environment. Previous studies have indicated that the red molasse sediments became widely developed since the Late Permian. The unconformity of the Toutunhe Formation in the Middle Jurassic with the lower strata and an increase of red rocks in the Late Jurassic imply a dry climate during that period. Together, these data imply that the syntectonic deformation occurred from the Late Permian-Early Triassic to the Middle-Late Jurassic.

Another F5 thrust fault ramped up from this deeper detachment and linked with the back thrust fault F6 with a structural wedge. In summary, the fault system along the Bogda Mountain belt and the mountain front is characterized by several fault-related folds that deformed during several different periods since the Late Paleozoic. They are Late Permian-Early Triassic, Middle-Late Jurassic, Late Cretaceous, Eocene, and Neogene.

4.2 3D structural construction and restoration of the Beisantai anticline

The 3D structural model (Figs. 6 and 7) reveals three main faults beneath the Beisantai anticline. They are the EW-trending fault-bend fold F1 and the related breakthrough fault F8 in the forelimb (Figs. 6a and 6b) and the NW-SE-trending fault-propagation fault F9 (Fig. 6c) that is also shown on Fig. 4. The layers from the Triassic to the Jurassic are eroded to different degrees beneath the Beisantai anticline

and the Cretaceous layer unconformably covers these strata. The contour map of Neogene shows that an EW-trending structure is predominant in the study area (Figs. 7a and 8). The EW-trending structure decreases gradually with an increase in depth and disappears beneath the Cretaceous layer. The structural contour maps of the area beneath the Cretaceous strata suggest a NS-trending structure on these layers. However, the denudation surfaces of the layers from the Triassic to the Jurassic show EW-trending in the study area (Fig. 8). In many cases, the strike of the structure is always perpendicular to the structural shortening orientation but the primary structure trending of the multistage deformations may change in some cases. Therefore, restorations of these complicated structures are necessary to reveal the primary structural geometry.

In order to study the historical structural geometry and the strain distribution during the Cenozoic deformation, we restored the layers of the Wutonggou Formation (P3w), the bottom of the Triassic (T1) and the Jurassic (J1) layers using the Kine3D module in the *Gocad* application. The Cretaceous layer is flattened and this can restore the structural deformation after the Cretaceous and reveal the strain distribution of the target layers under the deformation in the Cenozoic. The second column in Fig. 9 shows the primary structure contour of P3w, T1 and J1 before the Cenozoic. Compared with the first column in this figure, we can see that the contours turned from NS-trending to almost EW-trending, which is consistent with the strike of the denudation surface of these layers. This implies that the NS-trending structural shortening led to the deformation before the Cretaceous, which might be related to the

dynamic processes from eastern part of the Northern Tianshan in the Late Paleozoic rather than to other tectonic processes. The calculated dilation in column 3 shows the strain orientation is distributed predominantly EW with a local NE-trending strain to the NW boundary of the denudation surface, which implies that the strain distribution was not only caused by the dynamic process, but also controlled by the primary structural geometry.

5. Discussion

5.1 Highlights of the tectonic evolution

As previously discussed, the tectonic processes from the Late Paleozoic to Cenozoic were still under debate. On the basis of the new evidence from 3D structural modeling and strain restoration of an anticline adjacent to the Bogda Mountains, we attempted to provide some insights in this paper for the tectonic evolution and dynamic processes for the eastern part of the Northern Tianshan.

The Tianshan Mountains began its growth at c. 1.0 Ga (Khain et al., 2002) and continued to c. 250 Ma, when the Palaeo-Asian Ocean closed and the Solonker suture formed (Xiao et al., 2003). Two late Paleozoic collisions produced the ancestral Tianshan and two sutures. The southern suture was created by the collision of a passive continental margin on the northern side of the Tarim block with an active continental margin to its north in the Devonian (Fig. 1b) (Windley et al., 1990; Allen et al., 1991). The second collision led to the southward subduction of the North Tianshan Ocean beneath the Yili and Central Tianshan terrane in the early Carboniferous (Fig. 1b) (Windley et al., 1990; Charvet et al., 2007; Han et al., 2010). Under this extensional tectonic setting, volcanic arcs developed in the northern

Tianshan and the rift basin in the southern Junggar block in the Late Carboniferous (Fig. 10a). From the above interpretation of the Beisantai anticline in the mountain front, we can infer the tectonic processes in the eastern part of the northern Tianshan since the Permian in this study. We think that the foreland basin developed during the Late Permian. The marine sedimentary environment turned into the continental setting, which might reflect the original uplift of the Bogda Mountains and the marine regression process during this period (Fig. 10b). The thrust belts progressively propagated into the basin in sequence.

From the Middle Triassic to the Middle Jurassic, the coal and carbonaceous material became widely developed with the expansion of the drainage system. This implies that tectonic setting was relatively quiet during this period (Fig. 10c). In the Middle-Late Jurassic stage, the Bodga Mountains experienced another uplift, with dominate NS-trending shortening (Fig. 10d) and local NE-SW-trending shortening. This is consistent with the result from Yang et al. (2015). Compared with the whole Northern Tianshan Mountains, this tectonic deformation was widely distributed along the mountain belt. Wang et al. (2013) suggest that the Junggar Basin shows an extensional tectonic setting in the Middle Triassic to the Middle Jurassic and a switch from an extension to a compression state in the Middle-Late Jurassic in the western part of the northern Tianshan. Although large normal faults are not evident on the seismic reflection profiles in the eastern part, we can infer that some extension events occurred in this period because of the presence of coal-bearing Jurassic and Triassic strata in the hinterland. Compared with the western part, the extension deformation

from Middle Triassic to Middle Jurassic is not very obvious in this area, whereas the Middle-Late Jurassic compression deformation is a regional tectonic event (Fig. 10c). Because of the amount of erosion beneath the unconformity surface, this might possibly be the largest deformation event before the Cenozoic. River facies and alluvial red gravel developed in the Late Cretaceous, implying an arid climate during this time. Combined with the unconformity surface between the Cretaceous and Paleogene, we infer that a compressive tectonic event occurred during this period. In summary, the periodic deformation in the Late Permian, Middle-Late Jurassic and Late Cretaceous might have been preceded by the tectonic accretion of the island-arc system onto the small blocks in the south Asia margin.

The Cenozoic India-Asia collision reactivated the Paleozoic orogenic belt in the early Tertiary period and produced the present Tianshan Mountains (Tapponnier and Molnar, 1977; Avouac et al., 1993; Yin et al., 1998; Burchfiel et al., 1999). Modern crust shortening along the Tianshan Mountain belt is accommodated by the active thrust fault systems within the range and the adjacent basins (Tapponnier and Molnar, 1979; Burchfiel and Royden, 1991; Avouac et al., 1993). The 2D cross section (Fig. 5) and 3D models (Figs. 6 and 7) show that the strata from the Permian to the Neogene were deformed accordingly by the imbricated fault-related faults in depth between the Fukang fault to the Beisantai anticline. This implies the main deformation occurred after the Neogene period (Fig. 10e). Apatite fission track analysis suggests that a rapid cooling occurred at about 20-25 Ma in the Tianshan Mountains, which might be attributed to a tectonically induced uplift in this region (Sobel, 1995; Sobel and

Dumitru, 1997). Additionally, the Oligocene conglomerates unconformably cover the lower units. Therefore, we infer the main deformation of these imbricated structures might have happened during this period. The seismic reflections also show a weak unconformity between Eocene-Oligocene and Neogene (Figs. 3-5), so we infer weak deformation may accommodate some shortening in the Eocene-Oligocene before the large amount of shortening occurred in the Neogene. The 2D regional cross section (Fig. 5) shows that the Late Jurassic strata are strongly deformed along the Fukang fault system, which implies that the strongest shortening occurred after the Late Jurassic, possibly including the Middle-Late Jurassic and the reactivated Cenozoic deformation.

Thermochronology history results by the method of fission-track dating of apatite have been employed in many studies. The study by Zhu et al. (2006) shows that four exhumation periods in the Bogda-Harlik mountains occurred in the Early Cretaceous (119 - 105 Ma), late Cretaceous (67 - 65 Ma), Early-Middle Cenozoic (47 - 31 Ma) and Late Cenozoic (12-7 Ma). Liu et al. (2004) postulated four major uplift ages; 66 - 45 - 33 Ma, 25 - 16 Ma, 7 - 0.7 Ma, and < 0.7 Ma. Another four stages since the late Jurassic-Cretaceous were provided by Shen et al. (2006): 150 - 106 Ma, 75 - 65 Ma, 44 - 24 Ma, and 13-9 Ma. Wang et al. (2008) hypothesized three obvious uplifting stages of the Bogda Mountains during the Cenozoic; 5.6 - 19 Ma, 20 - 30 Ma, and 42 - 47Ma. The 150 - 106 Ma period is consistent with the deformation in the Late Jurassic and the ~ 60 Ma age is in accordance with the Late Cretaceous deformation in this study. In the Cenozoic, we infer the main uplift in the Cenozoic

might have occurred in the Oligocene and the Latest Cenozoic. It is known that many large earthquakes occurred along the Northern Tianshan Mountain belt, such as the 1906 Mw 7.4 – 8.4 Manas earthquake (Avouac et al., 1993; Deng et al., 1996; Burchfiel et al., 1999; Stockmeyer et al., 2014), and the 1812 Magnitude 7 – 8 Nilk earthquake in the western part of the northern Tianshan (Lee et al., 1976; Yang et al., 1985). These earthquakes are the manifestations of the recent structural activity along the Northern Tianshan (Fig. 10e). The Cenozoic deformation in the Junggar Basin led to greater than a 4% local internal strain on the Beisantai anticline, especially concentrated in the primary uplift zone. The minimum shortening amount of the Triassic layer between the Fukuang fault system and the Beisantai anticline on the cross section 8 is about 12.4 km, which includes the deformations since the Late Jurassic. Because of the erosion of the Cenozoic data in the hinterland, it is difficult to discern the amount of shortening in the Late Cenozoic.

5.2 Comparison with the Tarim basin

After the collision in the Paleozoic period, both the Tarim basin to the south of Tianshan and the Junggar basin to the north of Tianshan encountered several stages of deformation in the Mesozoic-Cenozoic periods. The sedimentary records and structural deformation pattern record the evolution of the Tianshan and the adjacent basins. In the Late Permian, the molasse sediments developed both in the Tarim and Junggar basin, which indicate that the foreland basin developed in the two basins. From Triassic to Middle Jurassic, the coal-bearing sediments in the reductive environment were widely distributed in the Tianshan and the adjacent basins, which

imply that the whole Tianshan area was under the peneplain condition. The sedimentary environment in the northern Tarim and southern Junggar is totally different in the early Cretaceous. The red clastic sediments with anhydrite cement developed in the Tarim basin, which reflects the arid and hot environment (Fang et al., 2004). In contrast, the lacustrine mudstones developed in the Junggar basin during this period, which are much thicker than those in the Tarim basin. This might reflect the uplift of the Tianshan in the Late Jurassic separated the two basins and that the amount of deformation occurred in the Junggar basin was much larger than that in the Tarim basin.

In the late Cenozoic, the India-Asia collision reactivated the structures and led to thick upper Neogene sediments. Three rows of thrust belts developed in the Junggar basin and four rows of thrust belts developed in the Kuqa thrust belt (North Tarim). In the west segment of the northern Tianshan, thin-skinned thrust nappes characterized by gentle dip (Avouac et al., 1993; Liu et al., 1994; Deng et al., 2000) propagated into the Junggar basin about 40-50km. The detachment located in the Eocene units composed of siltstones and mudstones (Stockmeyer et al., 2014) in the basin and stepped down to the south into Mesozoic and Paleozoic layers (Fu et al., 2003). It is studied by Callot (2013) that the Kuqa thrust belt in the northern Tarim is mainly controlled by the two major detachment levels. Thin skin deformation and Mesozoic thrust sheet develop above the Triassic coal measures. The Paleogene and Neogene foreland synclines developed detached above the stacked thrust sheets through the Eocene salt layer. The geometry of the salt layers and backstop plays an important

role on the structural style. In the east segment of Tianshan, this study revealed that thick-skinned nappes developed in the Bodga Mountain belt, rather than propagated into the basin. Strong deformation was accommodated by the thrusts along the Bodga Mountain belt. In summary, although the tectonic evolution is similar along the Tianshan, the structural deformation patterns are totally different. It is obvious that several rows of thrust belts propagating into the basin accommodated larger amounts of shortening than the thick-skinned thrust nappes along the Bodga Mountain belt. The deformation and thickness since the Middle Miocene decreased gradually to the east of Tianshan, which might be related with the northward compression of the Pamir plateau (Zhang et al., 1996).

5.3 Implications for the hydrocarbon exploration

As previously discussed, several deformation events shaped the Beisantai anticline, some of which play an important role in the processes of hydrocarbon accumulation. It is known that the independent NS shortening event led to the EW trending structure. However, the superimposed tectonic events, even if they share the same shortening directions, may cause different structural styles. For instance, this study suggests that the multistage tectonic shortening events occurred along the NS orientation. However, the structures beneath the Cretaceous layer turn to NS-trending to some extent rather than to EW-trending, which might lead to an alteration of the hydrocarbon migration directions. A study by Zeng et al. (2008) suggests that the oil migration effect at the southern slope of the Beisantai anticline is relatively strong. These hydrocarbons did not come from the mountain front depression, but migrated

from the Jurassic source rocks in the Fukang depression from the west.

According to borehole data and the oil-source correlation analysis, the hydrocarbons in the study area mainly arose from the river flood plain - lacustrine source coal rocks with 0.33-1.32% TOC in the Toutunhe, Sangonghe and Xishanyao Formations in the Jurassic; the mudstone with 5.02% TOC in the Jiucaiyuanzi Formation in the Triassic; the lacustrine argillaceous rocks with 0.08-5.09% TOC in the Wutonggou Formation in the Permian and the volcanic rocks in the Carboniferous (Fig. 2). In this paper, a Lopatin diagram was used to model the post-Carboniferous burial and maturation history of the source rocks in the Xiquan 11 well in the study area (Figs. 1 and 11).

The model shows that the Carboniferous, Permian and Triassic layers entered the oil window maturation cycle by the Late Triassic and Early Jurassic periods, and that the Jurassic source rocks did not enter the oil window until the Late Cretaceous (Fig. 11). Two obvious tectonic uplift events occurred in the Middle-Late Jurassic and the Late Cretaceous periods, which is consistent with the results in the preceding discussion. In these two periods, many fault-related folds were developed or reactivated, which led to the structural trap build up in the source rocks. We think that most of the generation of hydrocarbons occurred in these periods. Combined with the hydrocarbon generation history, we think that the primary reservoirs in the Middle-Late Jurassic come from Carboniferous, Permian and Triassic source rocks. The Ro value of Triassic rocks is generally between 0.5 – 0.7 %, which is in the early mature stage, and the Carboniferous and Permian source rocks are approximately 0.7

– 1.0 %, in the middle mature stage. Therefore, oil is anticipated to be the main hydrocarbon in this scenario.

Recently, exploration has been concentrated in the structural high and the southwestern slope of the Beisantai anticline in the Mesozoic layers (Fig. 1a). However, the fault related folds with opposite thrust orientations in depth constrain the structural geometry and the evolution of the Beisantai anticline, which led to the structural high in the Permian and rejuvenated it in the Jurassic period, even in the Cretaceous and Cenozoic time. Therefore, the structural high and the footwall of F3 and F4 in the Carboniferous layer might be the new potential hydrocarbon site in this area. The Jurassic source rocks entered the early mature stage in the Late Cretaceous and the hydrocarbon-generation peak stage in the Eocene. Furthermore, the Cenozoic activity along the Tianshan Mountain belt might rejuvenate the structures in the frontal zone, which could cause secondary hydrocarbon accumulation. The NW-trending structure in the Jurassic layer at the northeastern corner of the Beisantai area was demonstrated in this study (Fig. 6c). This structure might be reactivated by the deformation in the Cenozoic, consistent with the hydrocarbon-generation peak stage in this period, which implies that this NW-trending structure may also be a new potential exploration zone.

6. Conclusion

The Bogda Mountain belt mainly encountered compressive deformation in the Late Permian, Middle-Late Jurassic, Late Cretaceous, Oligocene, and the latest Cenozoic. The Mesozoic deformations are related to the accretion onto the southern

margin of Asia and the Cenozoic deformations are in accordance with the India-Asia collision.

The deformation in the Permian and Jurassic led to two fault-propagation fold thrusts of opposite orientation beneath the Beisantai anticline, the limb rotation of the Beisantai anticline and the corresponding growth strata. Another syntectonic NW-SE-trending structure also occurred in the Late Jurassic. The Cenozoic deformation led to the imbricated thrust from the hinterland to the foreland in depth. The largest deformation occurred in the Jurassic and Cenozoic, with a total shortening amount greater than 12.4 km during these periods.

Although the 3D structural models in Beisantai show the NS-trending of the strata, the restoration results suggest that this was preceded by a multiple stage of primary NS-trending compression. The strain distribution is controlled by the tectonic stress, as well as the primary structural geometry. The local internal strain caused by the Cenozoic deformation is larger than 4% on the Beisantai anticline.

This study suggests that the primary hydrocarbon generation mainly developed during the Middle-Late Jurassic and Late Cretaceous periods, and that the Cenozoic activity might lead to secondary hydrocarbon accumulation. The superimposed tectonic events might change the strike of the original structure styles and the hydrocarbon migration direction. The structural high and the footwall of the faults F3 and F4 in the Carboniferous strata, as well as the NW-trending structure in the Jurassic layers, might be new potential exploration areas in the study area.

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Figure captions

Fig. 1 (a) Topographic map of the Bodga Mountains and the adjacent Junggar Basin. The yellow rectangle shows the 3D seismic data zone and the blue lines represent the typical 2D seismic reflection profiles. The pink area represents the location of the oil

field. The inset map (b) displays a geological map of Northwestern China; the black rectangle designates the study zone in (a). NTSZ = North Tianshan suture zone, STSZ= South Tianshan suture zone, STS= South Tianshan, CTS= Central Tianshan, FKT = Fukang thrust belt, XQ 11=Xiquan 11.

Fig. 2 Stratigraphic column of the Bodga Mountains and the adjacent Junggar Basin. This figure is modified from Chen et al. (2012).

Fig. 3 The interpretations of the cross sections 1-4 extracted from the 3D seismic data of the Beisantai anticline. N = Neogene, E = Eocene, K = the bottom of Cretaceous, J2t = the Toutunhe Formation, J1s = the Sangonghe Formation, J1 = the bottom of Jurassic layer, T1 = the bottom of Triassic layer, P3w = the Wutonggou and C = Carboniferous Formation.

Fig. 4 The interpretations of the seismic reflection profiles 5-7 along the strike. The abbreviations are the same as in Fig. 3.

Fig. 5 (a) The regional cross section 8 across the Fukang fault system. (b) The theoretic model of the drape sequence. Note that the axial surfaces dip away from the crest. (c) The growth fold is characterized by the axial surfaces dipping toward crest of fold. Figs. 5b and 5c are revised from Shaw et al. (2005). (d) The unconformity surfaces revealed by the seismic data. The closeups in Fig. 5d are shown in the white rectangle in Fig. 5a.

Fig. 6 The 3D model of the Beisantai anticline in different perspective views.

Fig. 7 (a) The contour map the Neogene layer. (b) The 3D model of the Beisantai anticline with a contour map of the Neogene layer.

Fig. 8 The contour maps of the N, E, K, J2t, J1s, J1, T1 and P3w layers. The abbreviations are the same as in Fig. 3.

Fig. 9 The first column shows the contour maps of J1, T1, P3w. The abbreviations are the same as in Fig. 3. The second column displays the contour map of the structures after eliminating structures after the Cretaceous. The third column shows the dilation parameters, which reflects the local internal strain distribution during the restoration.

Fig. 10 The tectonic evolution in the period of (a) Late Carboniferous, (b) Late Permian, (c) Middle Triassic – Early Jurassic, (d) Middle – Late Jurassic, and (e) Late Cretaceous and Cenozoic.

Fig. 11 The Lopatin diagram showing the burial and maturation history of the source rocks in the Xiquan 11 well. The paleo-geothermal gradient refers to Qiu et al. (2002).

Figure 1

Figure 2

System				Lithology	Source	Reservoir	Sedimentary Facies	Legend	
Cenozoic	Quaternary	Holocene	GP / FM				Alluvial and braided-river facies	<div> Reservoir</div> <div> Source</div>	
		Upper Pleistocene	Xinjiang GP Q ₃ xn						
		Middle Pleistocene	Wusu GP Q ₂ ws						
		Lower Pleistocene	Xiyu FM Q ₁ x						
	Neogene	Pliocene-Miocene	Changjihe GP Nch				River and lacustrine facies	<div> Loess, soil, alluvial deposit</div>	
		Paleogene	Oligocene - Eocene	Anjihai FM E ₂₋₃ a					Lacustrine facies
Paleocene - Eocene	Ziniqianzi FM E ₁₋₂ x					River and lacustrine facies	<div> Gravel</div>		
Mesozoic	Cretaceous	Upper	Donggou FM K ₂ d				Braided-river and alluvial facies	<div> Sandstone</div>	
		Lower	Tugulu GP	Shengjinkou FM K ₁ s					Lacustrine facies
				Hutubi FM K ₁ h					
				Qingshuihe FM K ₁ q					
	Jurassic	Upper		Kalazha FM J ₂ k				Braided-river and lacustrine facies	<div> Mudstone</div>
				Qigu FM J ₂ q					
		Middle	Shuixigou GP	Tougunhe FM J ₂ t				River and swamp facies	
				Xishanyao FM J ₂ x					
				Sangonghe FM J ₂ s					
		Lower		Badaowan FM J ₂ b					
	Triassic	Upper-Middle	Xiaoqiangou GP	Haojiagou FM T ₂ h				River, alluvial and lacustrine facies	<div> Coal</div>
				Huangshanjie FM T ₂ hs					
				Kelamayi FM T ₂₋₃ k					
		Lower	Upper Cangfanggou GP	Shaofanggou FM T ₂ s					
	Jiucuiyuanzi FM T ₂ j								
Paleozoic	Permian	Upper	Lower Cangfanggou GP	Wutonggou FM P ₂ w				Terrigenous facies	<div> Siltstone</div>
				Quanzijie FM P ₂ q					
			Upper Jijicaozhi GP	Hongyanchi FM P ₂ h				Marine-terrigenous facies	<div> Dolomite</div>
				Lucaogou FM P ₂ l					
				Jingjingzigu FM P ₂ j					
				Wulabo FM P ₂ w					
		Middle-Lower	Lower Jijicaozhi GP						

Figure 3

Figure 4

Figure 5

Seismic reflection profile 8

Drape sequence Axial surfaces dips away from crest

Growth fold Axial surfaces dips toward crest

Unconformity surfaces

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11