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Research paper

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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A B S T R A C T

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.

1. Introduction

The 2500 km 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, 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

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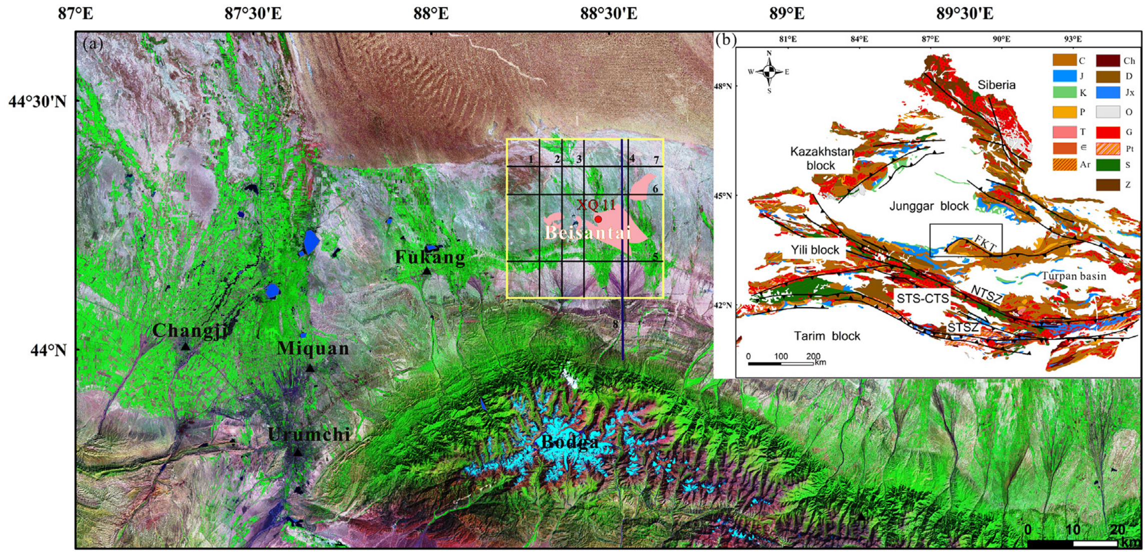

Fig. 1. (a) Topographic map of the Bodga Mountains and the adjacent Junggar Basin. The yellow rectangle shows the 3D seismic data zone and the blue lines represent the typical 2D seismic reflection profiles. The pink area represents the location of the oil field. The inset map (b) displays a geological 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 CAOB 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 filed 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; Fernádez et al., 2004; Ford et al., 2007), which also have major relevance in hydrocarbon exploration and production, well planning and civil engineering (Moretti, 2008; Guzofski 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 Gocad™ 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 et al., 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, 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