Fine crustal structure beneath the junction of the southwest Tian Shan and Tarim Basin, NW China

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ABSTRACT

The geometry of the entire crust from the northern part of the Tarim Basin to the southwestern Tian Shan east of Kashi is imaged on a N-S–directed explosive-source deep seismic-reflection profile. The profile reflects the sedimentary formations in the northern part of the Tarim Basin and the fold-and-thrust belt of the southern Tian Shan. N-dipping reflectors of the lower crust, as well as fluctuations in Moho depth, below which several mantle reflectors were observed, reveal the fine crustal structure beneath the junction of the southwest Tian Shan and the Tarim Basin. Mesozoic–Cenozoic shortening of the southwestern Tian Shan occurred at a crustal scale involving detachment-related folding in the basin directed northward toward the mountains and reverse faulting in the mountains directed toward the basin. In addition, a crocodile fabric developed within the lower crust beneath the basin area. The lithospheric structure revealed by the seismic-reflection section between the Tarim Basin and the Tian Shan Mountains reflects a process of intracontinental collision.

INTRODUCTION

Deep seismic-reflection profiling has been recognized globally as an effective geophysical technique in resolving detailed crustal structures and has been applied in many areas to detect deep structures, leading to many important discoveries (Klemperer, 1989; Bois and ECORS Scientific Party, 1990; Zhao et al., 1993; Goleby et al., 1994; Alsdorf et al., 1996; Brown et al., 1996; Knapp et al., 1998; ANCORP Working Group, 1999; Gao et al., 2000; Balling, 2000; Cook and Vasudevan, 2003; Wit and Tinker, 2004; Cook et al., 2010; Wang et al., 2011) since the pioneering work in the late 1970s and early 1980s (Oliver, 1982). Many large-scale deep reflection profiles, in particular in North America and Europe (Freeman et al., 1988; Wenzel et al., 1991; MONA LISA Working Group, 1997; Knapp et al., 1998; Steer et al., 1998; Balling, 2000; Hammer et al., 2010), have provided high-resolution images of the deepest parts of the continental crust and crust-mantle boundary (Krawczyk et al., 1999; Cook, 2002). Such crustal seismic images are of decisive importance for the interpretation of the ways in which regional tectonic features and structures observed on Earth’s surface are related to structures at depth (Drummond et al., 2006), and may be explained in terms of crust-forming and other tectonic processes (Mooney and Meissner, 1992; Balling, 2000), and so they greatly aid in understanding the composition and evolution of the continental lithosphere (e.g., Cook et al., 2010).

In China, several deep seismic-reflection profiles have been completed in the main orogenic belts since 1992 (Zhao et al., 1993; R. Gao et al., 2000, 2001, 2002, 2011; Liu et al., 2007; Wang et al., 2011), because China occupies a large and geologically complex region of Central and Eastern Asia and holds the key to resolving many basic problems in lithospheric structures and links between these and natural resources (Dong et al., 2011).

As one of the most spectacular and active intercontinental mountain ranges in the world, caused by the convergence of continents, the Chinese Tian Shan, extending from NW China via Kyrgyzstan to Uzbekistan, exhibit complex geologic and tectonic composition and evolution. Since the Neoproterozoic, they have undergone a long orogenetic evolution, culminating in extensive reactivation during the Cenozoic. They have been considered as a classical example of intercontinental orogeny used to understand and explain the geodynamics of mountain-building processes. Today, global positioning system (GPS) data provide present-day shortening rates between the Tarim craton and stable Eurasia reaching a maximum of ~20 mm/yr (Reigber et al., 2001; Wang et al., 2001) between 73°N and 77°N longitude (Fig. 1), i.e., nearly two thirds of the total convergence rate between India and Eurasia (Zubovich et al., 2010). This indicates that crustal deformation in the Tian Shan occurs due to northward push of the India plate, and shortening decreases gradually from south to north (Vergnolle et al., 2007). The rigid Tarim craton, with its overlying sedimentary basin, plays an important role through the transmission of compressive forces from the south. However, the crustal structures of the southwestern Tian Shan and their relationship with those of the Tarim craton are uncertain.

In order to investigate the fine crustal structure as well as the relationships between deep and shallow structures beneath the junction between the western part of the south Tian Shan and the northwest margin of the Tarim craton, a 121-km-long active-source deep seismic-reflection profile, TT2007, was completed in 2007. The goal of this effort was to establish a framework for interpreting the evolutionary processes that occurred within this complex region.
BACKGROUND

TECTONIC AND GEOLOGIC BACKGROUND

Collision of the Indian subcontinent with the Eurasian plate has led to a wide range of intercontinental deformation (Zhang et al., 1996), especially in the Central and Southeast Asian regions, where convergence and tectonic escape between the two plates continue (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977; Tapponnier et al., 1986). The Tian Shan (Fig. 1) in central Eurasia are regarded as a Paleozoic orogen rejuvenated in the Cenozoic (Fig. 1) in central Eurasia are regarded as a Paleozoic orogen rejuvenated in the Cenozoic (Yin et al., 1998; Allen et al., 1999, 2001; Tapponnier et al., 1986). The Tian Shan fault (Heermance et al., 2008), the Muz- iduke fault, and the Kashi Basin thrust (Fig. 2) make up three subparallel fold sets that trend east-west from the northeastern corner of the Pamir Mountains to the western end of the Kepingtage thrust belt (Fig. 1) of the Chinese southwest Tian Shan (Chen et al., 2007; Heermance et al., 2008). The Talas-Ferghana fault (TFF in Fig. 1) in the western part of the Tian Shan is one of the world’s most prominent strike-slip faults (Burman et al., 1996). Exploratory research on the lithospheric relationships among the South Tian Shan orogen, the West Kunlun (Pamir) orogen, and the Tarim craton has recently been undertaken (Qian et al., 2009). Thus, the western Tarim Basin forms a large topographic low between these two bounding orogenic belts (Fig. 1).

SEISMIC DATA ACQUISITION

In view of the mountain topography and the existing road network, our survey line has a somewhat crooked form (Fig. 2). Explosions were recorded using a SERCEL 408 Seismic Data Acquisition System. The shot points included charges of three sizes. The nominal 40 kg charge was placed in 25-m-deep boreholes with 250 m spacing, and additional shots of 80 kg were placed in one 35-m-deep or two 25-m-deep holes with a 1 km spacing, and also four several-hundred-kilogram charges were fired to provide high-energy signals from the deepest parts of the crust. Recording was at 2 ms sample rate to a total two-way traveltime (TWT) of 30 s and at 4 ms sample rate to a 60 s length for big shots with a minimum of 1000 channels. The smallest offset was 25 m. The seismic-reflection data averaged 100-fold common midpoint (CMP) stacking recorded using SM 24 (10 Hz) geophones and 50 m receiver-group spacing. The data acquisition parameters are listed in more detail in Table 1.

DATA PROCESSING AND SEISMIC SECTIONS

The seismic data were mainly evaluated using the seismic processing package ProMAX and...
the CGG processing system, following the processing steps listed in Table 2. Preparation of the CMP geometry was based on the crooked-line design. The projection of the individual CMP scatter points from the original receiver line onto a smooth reference line led to a reduction of the true profile length from 121 to 110 km with 4433 CMP gathers. Typically 25 m, half of the receiver spacing, was used as a binning distance, or CMP space.

After the geometry design, the data set underwent trace editing (top mute, kill traces), amplitude recovery, multidomain noise elimination, and band-pass filtering. Velocities and thicknesses of the surface velocity were computed by a tomographic method, based on the first arrival times of the common shot point gathers. These velocities varied from 1500 m/s to ~4000 m/s. The application of static time shifts computed by the tomography method significantly improved the results, compared to a simple elevation static correction (Hou et al., 2010). Detailed interactive velocity analyses were performed, and stacking of the data was achieved during application of normal moveout (NMO) corrections (for more information on these procedures, see Yilmaz, 2001). To obtain a good velocity model (supplemental material 1) for the depth conversion, we employed several methods to estimate velocities: (1) tomographic for the very shallow crust, (2) the CMP velocities, and (3) the crustal velocity structure inverted from wide-angle reflection and refraction data (Zhang et al., 2002) to constrain the Moho morphology. By meticulous

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1GSA Data Repository Item 2013224, supplemental material 1: velocity model; and supplemental material 2: upper 30 s of the seismic reflection section, is available at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

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Figure 2. Geologic map of the study area (after the work of Heermance et al., 2008) and deep seismic-reflection common midpoint (CMP) line. Major thrust faults and anticlines are indicated. Along CMP line from north to south, deformation controlling factors are different: to the mountain side, it is mainly by a forward-propagating thrusting system, and to the basin side, it is dominated by a décollement fault-propagation fold. KBT—Kashi Basin thrust.
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RESEARCH

processing, a 0–30 s stack (supplemental material 2 [see footnote 1]), depth-converted profile (Fig. 3) was obtained and yielded numerous coherent reflectors.

INTERPRETATION AND DISCUSSION

The interpretation (Fig. 4) for the upper crust of this profile is in accordance with previous work employing an oil industry seismic line that crossed the Kashi anticline (Xiao et al., 2000; Heermance et al., 2008). In the upper portion of the interpreted section in Figure 4, the division of subsurface zones is consistent with the geological data (Fig. 2). First, the structure of the upper crust will be described, and we then depict the fold and fault system within it. This is followed by some interpretations of lower-crustal features. Then, we discuss Moho reflection and mantle reflectors. Finally, based on these reflectors observed from this section, we discuss the tectonic-structural models proposed for this region and provide a summary tectonic cartoon with a sequence of proposed tectonic events.

Structure of the Upper Crust

We define the upper crust to be the reflective region between TWT of 0 and 7 s on the time section (supplemental material 2 [see footnote 1]); on the depth section (Fig. 4), its base varies from 12 to 20 km in depth, since the velocity of the upper crust under the Tian Shan is much higher than the velocity of the basin upper crust. Heermance et al. (2008) provided a detailed description of the upper-crustal reflectivity of interpreted late Cenozoic deformation of the active Kashi foreland using TWT 7 s (~14 km) record sections from industry. On the basis of their three balanced sections, shortening decreases from west to east across the foreland and is consistent with the gradient predicted by the clockwise rotation of the Tarim craton with respect to the Tian Shan. The patterns of reflectivity vary from layered and subhorizontal in and beneath the basin to inclined reflectors beneath the mountains. We interpret the lowermost reflections (D in Fig. 3) to represent the top layer of the Tarim Basin cratonic crystalline basement, and we interpret the change in reflectivity (E in Fig. 3) to represent pre-Tertiary to Early Tertiary strata. The Miocene Wuqia Group lies between reflections E and F (Fig. 3), and the Pliocene Atushi Formation (Fig. 4) conformably overlies the Wuqia Group and consists of up to 4000 m of interbedded tan sandstone, siltstone, mudstone, gypsum, and rare pebble conglomerate (Heermance et al., 2008) that are related to erosion and uplift of the Cenozoic Chinese Tian Shan (Yin et al., 1998). Pleistocene Xiyu Conglomerate lies

TABLE 1. DATA ACQUISITION PARAMETERS

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<th>Recorded</th>
<th>July 2007</th>
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<td>By</td>
<td>No. 6 Geophysical Prospecting Team, East China Petroleum Bureau</td>
<td></td>
</tr>
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<td>Number of CMPs, 4433</td>
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TABLE 2. BASIC PROCESSING STEPS AND PARAMETERS

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<td>Surface consistent amplitudes recovery</td>
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<td>Velocity analysis</td>
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<td>Residual statics correction</td>
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<td>Poststack filter</td>
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<tr>
<td>Trace equalization</td>
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<tr>
<td>Time-to-depth conversion</td>
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unconformably above the Atushi Formation along the northern margin of the Tarim Basin.

Continuous D reflections can be easily traced beneath the basin, but they deepen in the Tian Shan and display discontinuous reflectivity. E reflections can be traced continuously from a depth of 7 km under the basin to the edge of the deformed belt beneath CMP (common midpoint) 2501 (Fig. 2) down to a depth of 14 km under the deformed belt. F reflections in Figure 3 can be traced continuously at a depth of 4 km from the basin to the front of the Atushi-Keketamu anticline (Fig. 4). These three sets of reflections (D, E, F) from bottom to top can be traced from the basin through the anticline belt (Fig. 2), showing the effective extent of the thrusting process and the reverse faults and décollement-related folds in the belt between the south Tian Shan and Tarim Basin, discussed in the following section.

**Fold and Fault System**

According to geological survey results and seismic-reflection profiles reported by Herrmane et al. (2008), the northernmost part of our seismic section is in the south Tian Shan thrust belt, which includes the South Tian Shan fault, also called Maidan fault (Chen et al., 2001; Schärer et al., 2004), the Muziduke fault, the Kashi Basin thrust, previously called the Tuotegongbaizi/Aerpaleike fault (Allen et al., 1999; Schärer et al., 2004), and the Atushi fault. The first three reverse faults (South Tian Shan fault, Muziduke fault, and Kashi Basin thrust in Fig. 4) were observed dipping north with high angle and originated from a décollement surface we named the Southwest Tian Shan décollement (SWTSD in Fig. 4). Below the Southwest Tian Shan décollement, two south-dipping reverse faults and two north-dipping reverse faults were observed to cut through the top layer of basement of the southwest Tian Shan; these are named southwest Tian Shan basement faults (SWTSBFS in Fig. 4), and they developed during Paleozoic mountain building. The Atushi fault (AF in Fig. 4) cuts the southern flank of the Atushi fold but not out to the surface, while to the west, near Kashi, the Atushi fault accommodates at least 4–5 km of displacement at the surface (Atushi fault in Fig. 2). These reverse faults are the main factors that led to the deformation of the southwest Tian Shan within the upper crust and reflect the thrusting process that

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**Figure 3.** Depth-converted seismic section. Vertical scale approximately equals horizontal scale. Zero depth represents datum at sea level.
propagated the Cenozoic deformation to the south, forming the Atushi and Kashi anticlines.

The Atushi and Kashi anticlines form the striking geomorphic features that trend east-south, forming the Atushi and Kashi anticlines. The Atushi and Kashi anticlines are defined by the décollement levels in seismic section TA 9402 introduced by Heermance et al. (2008), interpreted décollement levels in seismic section of the Wuqia Group. This décollement (KAD in Fig. 4), which is the bottom level is interpreted here, the Kashi-Atushi décollement; AF—Atushi fault; KBT—Kashi Basin thrust; MF—Muziduke fault; STSF—South Tian Shan fault; SWTSD—southwest Tian Shan décollement; SWTSBFS—southwest Tian Shan basement faults.

**Figure 4.** Interpretation of seismic section. Vertical scale approximately equals horizontal scale. Zero depth represents datum at sea level. KAD—Kashi-Atushi décollement; AF—Atushi fault; KBT—Kashi Basin thrust; MF—Muziduke fault; STSF—South Tian Shan fault; SWTSD—southwest Tian Shan décollement; SWTSBFS—southwest Tian Shan basement faults.

**Features in the Lower Crust**

We define the lower crust as the area between reflections B and C (Fig. 3). Before interpreting the reflectivity patterns of the lower crust, a short review of the most important types of reflecting signals will be discussed. Three main types of reflection signatures (Fig. 5) have been used to relate certain types of reflecting signals to specific tectonic structures (DEKORP Research Group, 1990). Type I reflectors, lower-crust lamellae (Fig. 5A), are related to high-heat-flow areas, i.e., young, mostly extensional zones. Type II reflectors, the so-called “crocodile” (Fig. 5B) i.e., diverging reflectors, indicate an interwedging of layers with crustal shortening and are more common in the older flanks and cores of the Variscan orogenic belt in Europe and other zones of tectonic compression. The type III diffractions (Fig. 5C) seem to originate preferably in the lower or middle crust from small-scale inhomogeneities or strong curvature of reflectors showing strong impedance contrasts (DEKORP Research Group, 1990; Sadowski et al., 1989).

The classification of these three types of reflecting signals leads us to look back at the record section presented here (Fig. 3), where type II fabric, i.e., crocodile reflections, can be observed beneath the Tarim Basin area (Fig. 4).
We interpret the reflection beneath the crystalline basement within the lower crust as the northward wedging of the middle and lower crust of the Tarim craton beneath the south Tian Shan, and this wedging ends beneath the Kashi anticline. These imaged reflection fabrics record the ancient compression polarity from the Tarim Basin to the south Tian Shan, although the age of this event and the structure south of our seismic profile are not clear.

Moho Reflection and Mantle Reflectors

The geologic development of the crust-mantle transition is an evolutionary process, thermally, petrologically, and structurally, such that an image as viewed today may be a snapshot taken at any stage in that process (Cook, 2002). Previous estimates of Moho depth of this survey area beneath the Tarim Basin are consistently ~50 km (Shao et al., 1997; Zhang et al., 2002; Li et al., 2006; Zhang et al., 2015), and the crustal thickness beneath the Tian Shan has been estimated by P and S receiver functions to be 45–65 km (Kosarev et al., 1993; Oreshin et al., 2002; Vinnik et al., 2004; Kumar et al., 2005). From the southern rim of the Tian Shan southward to the Tarim Basin, the Moho was observed to vary from depths of 60–76 km to 40–52 km (Liu et al., 2000). On our depth-converted section, the reflection Moho (B, Fig. 3) is well defined and is at a depth of 50–52 km to the south; it then rises a little to 49 km below the Kashi and Atushi anticlines; and it then deepens again toward the Tashipike anticline, attaining a depth of 54 km. It shallows slightly to 52.5 km beneath CMP 1601 and then deepens to 57 km in the northernmost part of the section. There are offsets of the Moho beneath CMP 2101–2701, maybe related to the event during development of the southwest Tian Shan basement faults (SWTSBFS in Fig. 4). This Moho depth derived from our reflection section provides more detailed variation than the wide-angle reflection and refraction data (Zhang et al., 2002).

Reflections from the continental mantle lithosphere have been reported from CMP profiles at numerous sites around the world (Ahsdorf et al., 1996; Knapp et al., 1996; Steer et al., 1998; Balling, 2000; Krawczyk et al., 2002; Yang, 2003; Okure and McBride, 2006; Hammer et al., 2010). The deepest events imaged thus far in a controlled source CMP survey are the “super-deep” mantle reflections of the URSEIS project that were identified at ~135–165 km (35–43 s TWT) (Knapp et al., 1996; Steer et al., 1998). Of special note are the various reports of specific reflections at ~80–100 km (22–24 s TWT) in the North Sea (Warner et al., 1996), eastern Europe, eastern China (Yang, 2003), and the Urals (Knapp et al., 1996), which suggest a more ubiquitous mantle horizon (Steer et al., 1998).

Interpreting the tectonic significance of these mantle reflections is difficult for even the most well-studied examples. The geological interpretations of many mantle reflections globally are based on structural information obtained from reflection data and are highly variable and largely speculative (Posgay et al., 1990; Best, 1991; Calvert et al., 1995; Warner et al., 1996). Interpretations include intraplate thrust faults or shear zones (Smythe et al., 1982), normal faults (Reston, 1990), igneous intrusions (Warner and McGearry, 1987), active (Clowes et al., 1987) and relict (BABEL Working Group, 1990) subduction zones, a relict Moho (Snyder, 1991), and structures within the asthenosphere (Posgay et al., 1990).

What we can see from Figure 4 is the continuous subhorizontal reflector (A, Fig. 3) with small north-dipping reflections beneath the basin side under a depth of 90 km with a stretch length of 48 km (CMP 5433–3501). Connecting the dipping lower-crustal to upper-mantle reflections (A’ in Fig. 3) with the deeper mantle reflectors (A in Fig. 3), we conclude that they are most likely related to late Paleozoic subduction processes (Allen et al., 1993; Gao et al., 2009).

Discussion

The combined descriptions of reflection fabrics and spatial relationships discussed herein allow us to reconstruct the structural evolution of the deformed belt along the junction between the north Tarim Basin and southwest Tian Shan in the pre-Cenozoic and main deformation since 25 Ma. Most of the age constraints are after the study of Heermance et al. (2008).

Stage 1: Pre-Cenozoic basement faulting beneath the southwest Tian Shan (Fig. 6A) occurred as the result of compression related to the Tarim craton wedging into the south Tian Shan above the north-driving upper mantle.

Stage 2: The initiation of the south Tian Shan deformation (Fig. 6B) occurred ca. 20–25 Ma, according to apatite fission-track cooling ages in the hanging wall of the South Tian Shan fault and Muziduke fault (Sobel et al., 2006). These ages are similar to the suggested initiation of uplift for the southern Tian Shan at the Keptingate fold-and-thrust belt (Allen et al., 1999; Yin et al., 1998) and the Kuaqi Basin (Avouac et al., 1993; Sobel and Dumitru, 1997) to the east.

Stage 3: As shortening increased, deformation moved south to the Kashi Basin thrust (Fig. 6C) at 16 Ma (Heermance et al., 2008).

Stage 4: Décollement slip progressed south onto the Atushi fault (Fig. 6D), and growth of the Keketamu, Atushi, and Kashi anticlines has continued since ca. 4 Ma.

Various studies (Schärer et al., 2004; Vinnik et al., 2004; Makarov et al., 2010) have presented data indicating that the Tarim crust is thrust under the Tian Shan (Fig. 6E) and that an increase in the lower crust thickness at the Tarim Basin northern margin is likely associated with this process (Vinnik et al., 2006). Another model (Fig. 6F) interprets a magmatic intrusion in the lower crust to illustrate mechanisms of shortening. While one can easily derive a tectonic model (Fig. 6G) based on the reflections introduced in this paper, and one can easily say there is no zone of midcrustal flow observed on the seismic-reflection section beneath the southwest Tian Shan, there is no firm justification for underthrusting of the Tarim craton beneath the Tian Shan, as we just determined a fine structure of southern half of the models E and F. Our model also suggests mantle flow and crust wedging of lithospheric deformation during the early stages of continental plate collision that is comparable with numerical experiments (Pysklwyc et al., 2002) and the observation of a V-shaped reflection pattern from a deep seismic-reflection profile across the juncture zone between the Tarim Basin and the West Kunlun Mountains (Gao et al., 2000).

CONCLUSIONS

The high-fold explosive-source deep seismic-reflection profile across the junction of...
Fine crustal structure beneath the junction of the southwest Tian Shan and Tarim Basin

STAGE 1 (pre-Tertiary)

A

STAGE 2 (25-19 Ma)

B

STAGE 3 (19-4 Ma)

C

STAGE 4 (4-0 Ma)

D

E

F

G

Figure 6. (A–D) Cartoons showing the schematic structural evolution of the southwest Tian Shan. Syntectonic deposition and erosion are not shown. New structures that initiate in a given stage are labeled. Thick black lines indicate active faults; thin dotted lines are future faults. (E–F) Cartoons showing the tectonic-structural models proposed for this region. Dashed black lines show north end of G. (G) Final model based on this study. KAD—Kashi-Atushi décollement; AF—Atushi fault; KBT—Kashi Basin thrust; MF—Muziduke fault; STSF—South Tian Shan fault; SWTSD—southwest Tian Shan décollement; SWTSSBS—southwest Tian Shan basement faults.
the southwest Tian Shan and the Tarim Basin (craton) imaged a series of tectonic segments in this area during Cenozoic intercontinental orogenesis and showed that the deep structure within lower crust and mantle may be related to Paleocontinental mountain building.

Syntectonic sedimentation to the south of the Kashki Basin thrust produced 10–12-km-thick, subhorizontal stratigraphy in the late Cenozoic. The deformation along the northern margin of the Tarim Basin is dominated by folding but not faulting. This huge sedimentary basin provides the basic conditions for oil and gas accumulation.

One décollement level and a series of décollement layers are interpreted under the Tarim Basin within ~7–17 km depths in the seismic section. Series of forward-propagating thrusting faults within the upper crust of the southwest Tian Shan lead to the southward propagation of deformation while caught by the rigid Tarim craton. This thrusting has also created a fault-propagation fold at the junction of the mountain and the basin. The complex tectonic activity and imbricate structures are well developed due to multiple tectonic contractions.

The observed “crocodile” reflection fabrics within the lower crust indicate an interwedgeing of layers with crustal shortening and are interpreted to be related to compression during the late Paleozoic stage of Tian Shan mountain building.

The Moho reflection indicates that the crust thickness varies from 50 km beneath the Tarim Basin to 57 km across the anticlinal belt toward the Tian Shan. An upper-mantle reflector occurs at the same depth level compared with many CMP profiles at numerous sites around the world. All these reflections provide evidence of the tectonic process of intercontinental mountain building and basin formation at a lithospheric scale.

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