



Cenozoic tectonic and geodynamic evolution of the Kyrgyz Tien Shan Mountains: A review of geological, thermochronological and geophysical data

M.M. Buslov^{a,*}, J. De Grave^b, E.A.V. Bataleva^c, V.Yu. Batalev^c

^a *United Institute of Geology, Geophysics and Mineralogy, Siberian Branch of the Russian Academy of Science, Novosibirsk, 3 Koptiyuga Ave., Novosibirsk 630090, Russia*

^b *Department of Mineralogy and Petrology, Geological Institute, University of Gent, Gent, Belgium*

^c *International Geodynamics Research Center, Bishkek, Kyrgyzstan*

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Abstract

The complex crustal structure of the Tien Shan has a strong impact on the distribution of strain induced by the India–Eurasia collision, with intracontinental deformation in Eurasia's interior as a distant effect. The northward propagation of the India–Eurasia deformation front is suggested by the rejuvenation of mountain ranges and intermittent intramontane basins. The Tien Shan basement is formed by the rigid, heterogeneous Precambrian blocks (microcontinents) of Tarim, Issyk-Kul (or Central Tien Shan) and Aktyuz-Boordin, surrounded by a 'soft' matrix of Paleozoic accretion–collision belts. The Kyrgyz Tien Shan Mountains are situated between the active structures of the Tarim Plate and the Pamir indenter (south), and the stable Kazakhstan Shield (north). Underplating by the Tarim Plate and thrusting by the Pamirs are responsible for the building of the Cenozoic Tien Shan, the reactivation of its inherited structural fabric and the tectonic layering of the upper lithosphere underlying the area. Large earthquakes ($M > 6$) delineate the northern and southern margins of the Issyk-Kul microcontinent, indicating that crustal heterogeneity influenced the location of active structures in the northern Kyrgyz Tien Shan.

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1. Introduction

Cenozoic tectonic activity in the Tien Shan resulted from the ongoing indentation of India into the Eurasian continent (Molnar and Tapponnier, 1975; Cobbold and Davy, 1988). The collision caused the propagation of deformation to the interior of the continent, resulting in crustal thickening and intracontinental mountain building. The Tien Shan consists of roughly E–W-trending mountain ranges (with peaks exceeding 7000 m), alternating with subparallel sedimentary basins. The E–W-trending boundaries between

ranges and basins are marked by major Cenozoic faults. However, the important Talass–Fergana Fault Zone strikes at an angle to the main structural direction and is oriented NW (Figs. 1 and 2).

The Cenozoic tectonic evolution of a vast part of Asia can be attributed to the continuing convergence between India and Eurasia. After the initial collision between about 52 and 35 Ma ago, India has continued its northward motion at reduced velocity and acts as a rigid indenter, penetrating ~2000 km into Asia, to cause postcollisional underplating (India) and uplift (Tibet) (Molnar and Tapponnier, 1975; Mercier et al., 1987; Cobbold and Davy, 1988; Le Pichon et al., 1992; Dobretsov et al., 1996).

Orogeny in the Pamir and southern Tien Shan regions started after 35 Ma, post-dating the incipient Tibetan uplift

* Corresponding author. Tel./fax: +7 383 333584.

E-mail address: misha@uiggm.nsc.ru (M.M. Buslov).

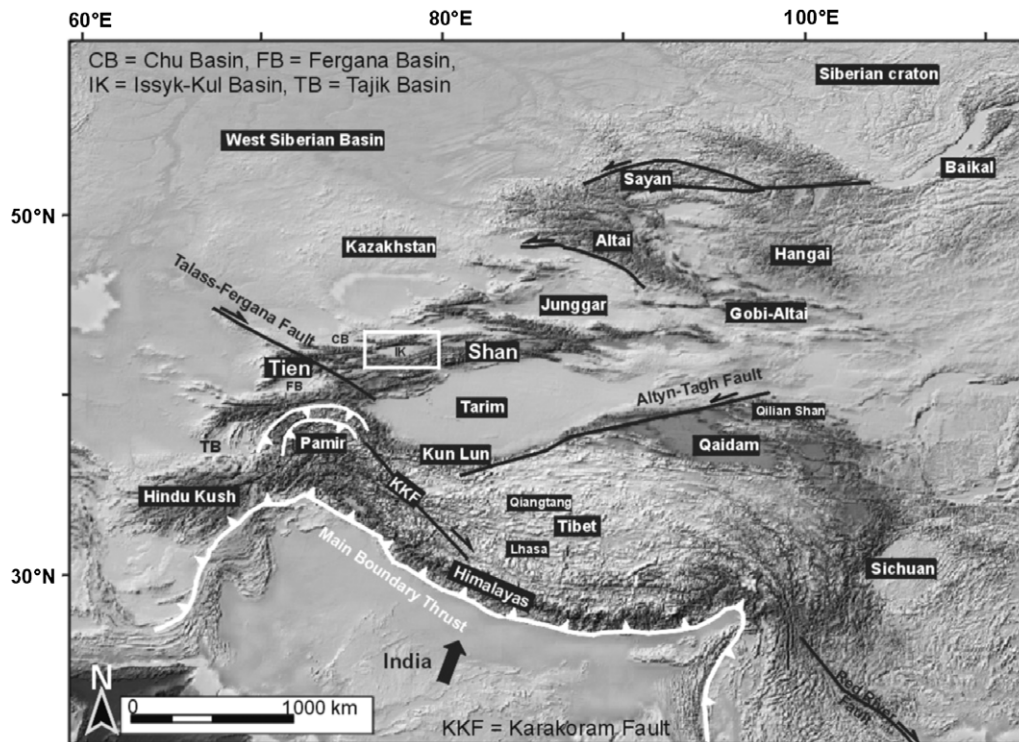


Fig. 1. Digital terrain model of Central Asia indicating major tectonic and structural features and units. The white box indicates the Issyk-Kul Basin (IK).

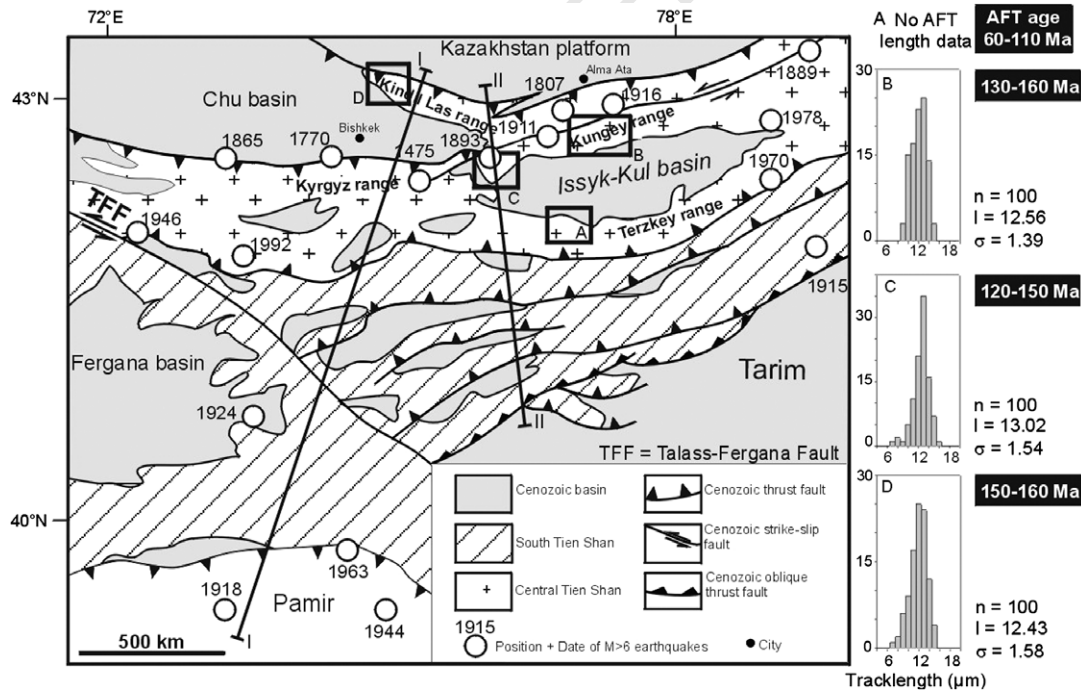


Fig. 2. Tectonic scheme of the Kyrgyz Tien Shan region with general location of apatite fission-track (AFT) sample areas and data (De Grave et al., 2004): (A) Terzkey Range, (B) Kungey Range, (C) West Kungey Range (Boom Canyon area) and (D) Kindil Las Range. For each of these sample areas, except for the Terzkey Range (insufficient number of confined tracks), a representative AFT length distribution (n , number of measured confined tracks; l , mean track length; s , standard deviation) and AFT age range is shown. Major historical earthquake locations are also depicted. Two profiles (I-I and II-II) along which geophysical data were collected are indicated (see text and Fig. 6).

during the collisional stage, and was accompanied in the Late Oligocene by the deposition of coarse-clastic, red continental molasse. The Miocene landscape of the Pamirs and the southern Tien Shan was dominated by <3 km

uplifts and intervening depressions. In the Pliocene red molassic sediments gave way to gray molasse deposits, as a result of climatic cooling, while uplift reached an altitude of 4–5 km. Further Quaternary uplift of the Pamirs and the

Tien Shan produced the current typical glacial landscape (Chedia, 1986; Mikolaichuk, 2000).

The structural pattern of the pre-Cenozoic Tien Shan basement clearly influenced the Cenozoic reactivation of the Tien Shan orogen. This basement is highly heterogeneous and consists of the relatively rigid blocks of the Precambrian Tarim, Issyk-Kul (or Central Tien Shan) and Aktyuz-Boordin microcontinents, enclosed in a 'soft', more easily deformed matrix of Paleozoic accretion–collision belts. It seems that these rigid blocks in the northern Tien Shan were displaced towards each other within the mobile matrix that surrounds them at variable velocities and various directions. These displacements are considered to be active far-field tectonic responses to continued India–Eurasia convergence, and produce large earthquakes at the rigid body boundaries. All the epicenters of these large earthquakes are located within a narrow linear zone between the Aktyuz-Boordin and Issyk-Kul microcontinents, while other epicenters of $M > 6$ earthquakes mark the northern and southern margins of the Issyk-Kul microcontinent (Fig. 2). This indicates that crustal heterogeneity affects the formation of the active structures of the northern Kyrgyz Tien Shan (Buslov et al., 2003, 2004; Buslov, 2004).

The Talass-Fergana Fault Zone, the site of dextral strike-slip movements, divides the Tien Shan into NE and SW parts. Two different tectonic mechanisms are responsible for this characteristic geometry: underthrusting of the Tarim microcontinent beneath the southern Tien Shan and thrusting of the Pamir block onto the southern Kyrgyz Tien Shan, respectively (Buslov et al., 2003). The Tien Shan is situated between these active structures to the south, and the stable Kazakhstan Shield to the north (Figs. 1 and 2). The underthrusting of Tarim and the thrusting of the Pamirs formed the Cenozoic structural pattern of the Tien Shan and caused tectonic layering in the upper lithosphere (Buslov et al., 2003).

Different mechanisms of the Tarim and Pamir convergence were manifested at different times and resulted in strike-slip movements along the Talass-Fergana Fault. During the Late Cenozoic displacement rate along the fault was 10 mm/yr and reducing to 2–3 mm/yr at present (Burtman et al., 1996; Meade and Hager, 2001). This can be explained by convergent forces of the Tarim and Pamir on the southern Tien Shan edges presently cancelling each other resulting in low slip rates. Previously, during the last 10 Ma, indentation by the Pamirs was dominant and resulted in reactivation of the Talass-Fergana Fault as a dextral strike-slip fault with higher rates of displacement.

Given total crustal shortening of 200 ± 50 km and the present-day shortening rate of 20 mm/yr, the northern Tien Shan could have been constructed within 10 Ma (Abdrakhmatov et al., 1996). These authors also suggest that the recent rapid uplift of the Tien Shan could be the result of a marked increase in horizontal compressional forces, following the abrupt rise of the Tibetan Plateau, as proposed by England and Houseman (1989). Apatite fission-track thermochronology, structural modeling and

magneto-stratigraphy in the Kyrgyz Range, adjoining ranges, and the Chu Basin in the northern Kyrgyz Tien Shan further show that a strong phase of rock uplift and deformation first affected the northern Tien Shan ~ 10 –11 Ma ago, followed by a second accelerated phase ~ 5 –3 Ma ago (Burbank et al., 1999; Bullen et al., 2001, 2003; De Grave et al., 2004). The latter acceleration is also recorded in the stratigraphy by a marked change in the sedimentary environment in the Late Pliocene–Early Pleistocene, where thick sequences of coarse conglomerate, sedimentary gaps and tectonic unconformities are observed (e.g. Abdrakhmatov et al., 2001).

In this paper various aspects of the tectonic and geodynamic evolution of the northern Kyrgyz Tien Shan are considered, based on geodetic, geological and geophysical data. In particular, attention is directed to basement controls on Cenozoic deformation in the upper crust of the Tien Shan.

2. Present-day basement movements: implications from GPS data

The present northward movement of India with respect to Eurasia (Fig. 1) occurs at a rate of ~ 50 mm/yr. The shortening rate across the Tien Shan (10–15 mm/yr) accounts for a significant part of this total value (Avouac et al., 1993; Avouac and Tapponnier, 1993; Zubovich et al., 2001; Meade and Hager, 2001). Dextral strike-slip displacement along the Talass-Fergana Fault has accumulated to about 100 km since the Late Miocene, i.e. an average of 10 mm/yr (Burtman et al., 1996). Recent GPS data show that the fault is currently not as active and that the maximum rate of displacement is only ~ 2 –3 mm/yr (Abdrakhmatov et al., 1996; Zubovich et al., 2001; Meade and Hager, 2001). Velocity and direction of movement of the basement blocks in the SW and NE Kyrgyz Tien Shan vary greatly. The SW Tien Shan, located between the rigid Kazakh Shield and the active Pamir indenter (Figs. 1 and 2), as indicated by recent geodetic observations, is subject to anticlockwise rotation (Bragin et al., 2001; Meade and Hager, 2001). The NE Kyrgyz Tien Shan is located between the stable Kazakh Shield and the underthrusting Tarim Plate (Figs. 1 and 2). At the present-day, N–S shortening occurs at a rate of about 10 mm/yr in the southern part of the NE Tien Shan Block and up to 2–6 mm/yr in the northern part, and is furthermore occurs along different directions in each part (Figs. 3 and 4). The different rates and orientations of the shortening can be explained by the presence of the rigid Precambrian Issyk-Kul and Aktyuz-Boordin microcontinents. Almost all $M > 6$ earthquakes of the northern Tien Shan are linked spatially with the aforementioned active tectonic zones framing the Issyk-Kul microcontinent (Fig. 5). The epicenters of strong historical earthquakes and their related landslides are located within the Chon-Kemin and Chon-Aksu Fault Zones that separate these Precambrian basement blocks (Fig. 5) (Delvaux et al., 2001; Buslov et al., 2003). This illustrates well the

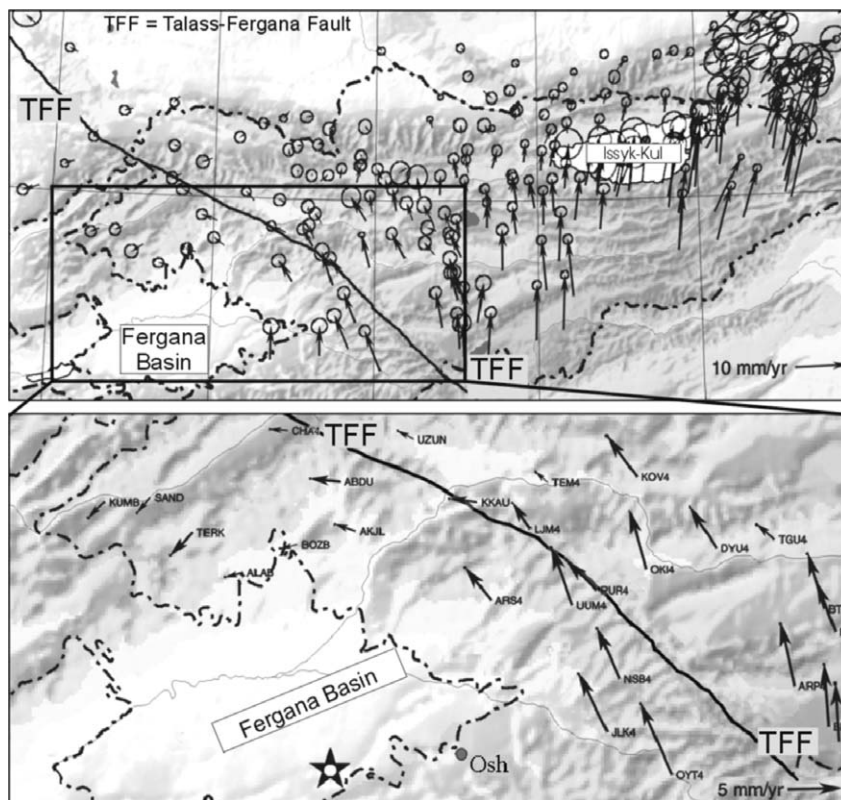


Fig. 3. The vectorial field of active horizontal movements according to GPS measurements in Kyrgyzstan and southern Kazakhstan (modified after Zubovich et al., 2001). Starting points of vectors indicate GPS receiver stations; their length is a measure for the annual average movement at that location (see scale, lower right). Circles at the arrow tips correspond to the 95% (2 s) confidence interval on the direction of movement. Bottom insert shows anticlockwise surface rotation in the Fergana Basin area around a supposed rotation pole (star, Zubovich et al., 2001).

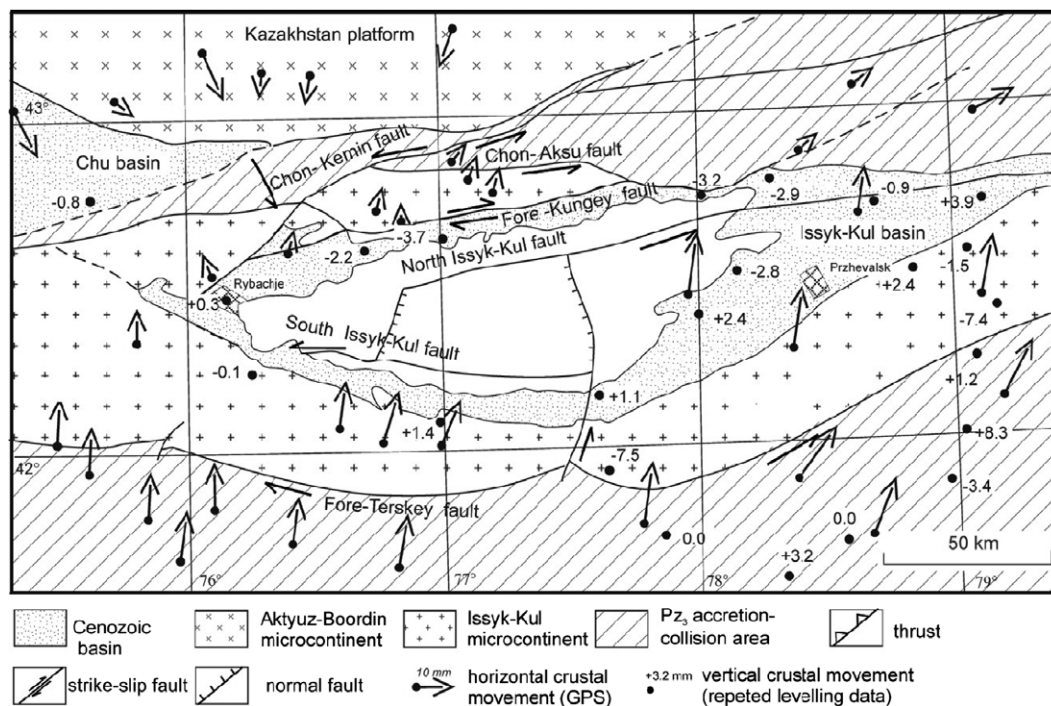


Fig. 4. Sketch map of active strike-slip deformation in the Issyk-Kul region, northern Kyrgyz Tien Shan (from GPS and other geodetic data, Buslov et al., 2003). See text for discussion and interpretation.

basement control on active tectonic movements and the reactivation of the area.

GPS data show that the present structure of the Tien Shan consists of three blocks: northern; central; and southern Tien Shan (Fig. 5), each characterized by a different displacement velocity and direction. The southern Tien Shan has the highest velocity of 6–10 mm/yr. The displacement vectors describe a fan, with a NNW trend in the western part, north in the central part, and NNE in the eastern part. The Issyk-Kul Basin is located in central, and partly in southern Tien Shan. Central Tien Shan is characterized by 4–6 mm/yr active lateral movement in a NE to N direction. Northern Tien Shan, north of the Chon-Kemin Fault, is moving with a velocity of 4–10 mm/yr to the SE. The eastern part of this area (Zaili Range and part of the stable Kazakh Shield – Alma Ata region) is moving to the SW, while the mountain ranges framing the Chu Basin are moving to the SSW (Fig. 5).

3. The Cenozoic structure of the Tien Shan: basement control

The Cenozoic tectonic evolution of the Kyrgyz Tien Shan is evidently influenced and directed by the inherited structural fabric acquired from its pre-Cenozoic evolution. The lens-shaped Issyk-Kul and Aktyuz-Boordin microcontinents, surrounded by vast zones of strike-slip deformation, are the significant features (Fig. 2). The basement is composed mainly of Archean metamorphic rocks and Early Proterozoic quartz-schists and carbonate rocks. The basement is covered by Ediacaran and Cambrian–Ordovician volcanic and sedimentary rocks. The entire assemblage has been intruded extensively by Ediacaran–Middle Paleozoic plutonic rocks. Remnants of a Late Devonian–Early

Carboniferous active margin sequence and a Late Carboniferous–Permian passive margin sequence are also found in the area.

Small intramontane Tien Shan basins, as well as larger adjoining basins (e.g. Tarim), record a strong phase of Mesozoic reactivation within the Tien Shan (e.g. Hendrix et al., 1992).

In the Paleogene, about 4 km of lacustrine sediments accumulated in the Issyk-Kul Basin. This basin is a prime example of a fast subsiding intramontane basin in the Cenozoic Tien Shan. It developed on the rigid basement of the Issyk-Kul microcontinent (Fig. 2 and 5). The onset of uplift of the southern Tien Shan started in the Neogene, when clastic and proluvial sediments, transported from the rising southern ranges, were deposited in the Issyk-Kul Basin. For a long time during the Cenozoic, deformation was concentrated mainly in a distinct zone surrounding the Issyk-Kul microcontinent, while the interior remained a more or less stable platform. In the Quaternary the propagating deformation reached the central part of the Issyk-Kul Basin and affected the more rigid interior. At the present time deformation has resulted in an intricate system of strike-slip faults surrounding the microcontinent (Buslov et al., 2003).

Due to regional N–S compression induced by the India–Eurasia collision, the structural features of the Precambrian–Paleozoic basement and the Cenozoic cover of the northern Kyrgyz Tien Shan show signs of complex deformation involving and strongly controlled by the heterogeneous crust underneath the area. Cenozoic deformation, with tectonic reactivation and mountain building, propagated inside the continent along ancient fault zones of the inherited regional structural fabric. Remnants of Cenozoic

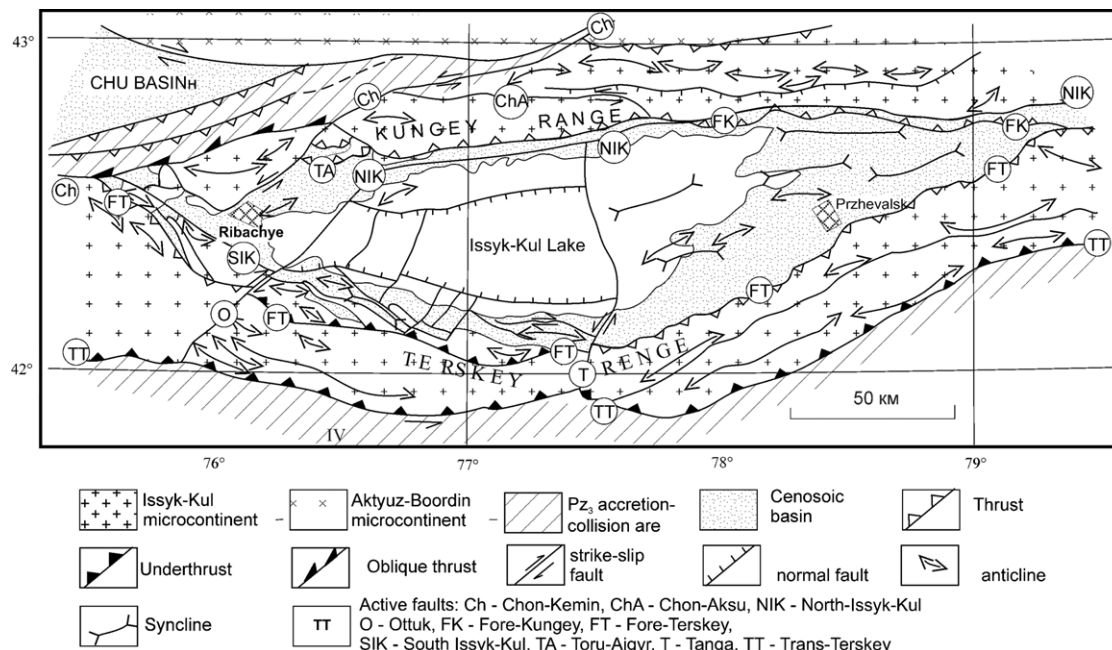


Fig. 5. Sketch map of active tectonics in the Issyk-Kul region, northern Kyrgyz Tien Shan (after Buslov et al., 2003). See text for discussion and interpretation.

basins (e.g. Tarim, Tajik and Fergana) are preserved where stable, rigid crust occurs. This pattern largely coincides with the outline of Precambrian (microcontinental) basement, as is clearly the case for the Issyk-Kul area, for example. The Issyk-Kul microcontinent is an E-W-striking, lens-shaped structure, up to 110 km wide and 350 km long (Figs. 2 and 4). As in other examples, the microcontinent is bounded by wide zones of strike-slip deformation: the Kyrgyz-Terzkey zone in the south, and the Kemin zone in the north. The Pred-Terzkey and Chon-Kemin are active faults coinciding with these deformation zones (Buslov et al., 2003). During much of the Cenozoic the interior, rigid part of the Issyk-Kul basement remained unaffected and deformation was largely restricted to the aforementioned fringing fault zones.

Tectonic reactivation of the Kyrgyz Tien Shan reached its peak in the Pliocene–Early Quaternary and resulted in the formation of the present-day topography and the strong deformation of the Issyk-Kul basement and its Cenozoic cover (Delvaux et al., 2004). The direction of regional compression changed from NW–SE in the Late Miocene to a predominant N–S direction in the Pliocene–Early Quaternary, which continues to the present day. During this evolution, the southern and northern margins of the Issyk-Kul microcontinent gradually became involved in the deformation and were thrust over the edges of the Issyk-Kul Basin. The areal extent of the basin was reduced and ramp structures formed at the western and eastern ends. The thrusting of these mountain ranges over the basin was accompanied by strong erosion and the deposition of molasse. Underthrusting along the Kyrgyz-Terzkey Zone resulted in the disruption of the southern margin of the microcontinent to form several blocks, separated by oblique thrusts and strike-slip faults (Buslov et al., 2003). Further strike-slip movement along the Chon-Kemin Fault resulted in thrusting and reverse faulting along the northern margin of the microcontinent (Figs. 2, 4 and 5).

In the central part of the NE Kyrgyz Tien Shan, the structural scheme is different. In the north of this area, the Pred-Kungey oblique thrust joins with the Taldy-Sui Thrust through the Aksu Graben that constitutes the boundary between the eastern and central part (Fig. 2). However, the most important structure of this region is the NE-striking Chon-Kemin Fault Zone, discussed earlier. Recently a significant sinistral strike-slip component has been observed in the kinematics of the Chon-Kemin Fault Zone (Delvaux et al., 2001; Buslov et al., 2003).

4. Tectonic layering of the Kyrgyz Tien Shan lithosphere and seismicity

There are three main seismically active regions in the western Tien Shan and Pamirs: the north Tien Shan (NTS), the south Tien Shan (STS) and the Pamir-Hindu Kush (PHK) (Fig. 7). The NTS generally is a low-activity seismic zone, although large historical earthquakes have occurred such as the 1885 Belovodskoye ($M=6.9$), the 1887 Vernen

($M=7.3$), the 1889 Chilik ($M=8.3$), the 1911 Kebin (Kemin) ($M=8.2$), the 1946 Chatkal ($M=7.5$), and the 1992 Suusamyr ($M=7.5$). The 1902 Kashgar ($M=7.8$), the 1907 Karatag ($M=7.3$), the 1949 Khait ($M=7.4$), and the 1974 Markansui ($M=7.3$) earthquakes in the STS zone occurred against a background of high seismic activity. The PHK is the most seismically active zone in Central Asia (e.g. Pavlis and Das, 2000). It can be traced along the Pamir indenter front and has a characteristic S-shape. The PHK zone generated the 1909 Hindu Kush earthquake ($M=8.0$) with hypocenter at 230 km depth, several dozen $M 7.0 < 7.5$ tremors with shallower focal points, and thousands of weaker events. The lithosphere beneath the PHK zone is unstable and is continuing to subside into the upper mantle, providing very deep seismic sources at depths of up to 300 km. The seismic sources of the STS and NTS zones on the other hand are a lot shallower and are located in the upper crust, mostly at a depth of 15–20 km, as they are constrained at depth by visco-plastic layering in the Tien Shan crust and the underlying lithosphere.

Seismic S- and P-wave studies (profile I-I; Fig. 6) show horizontal wave-guide layers, 10–20 km thick, in the lower (35–50 km) and upper (10–20 km) crust (Bakirov et al., 1996; Sabitova and Adamova, 2001). These thick seismic wave-guide layers are absent beneath the Fergana Basin and adjacent flat areas. Wave-guide lenses are found in the upper crust at a depth of 10–20 km, to the north of the Pamirs. The lower layer abruptly rises to a depth of 15–20 km near the Talass-Fergana Fault. The southern part of the lower wave-guide is 20 km higher than the northern part. Near the Tarim Plate and NE of the Talass-Fergana Fault, the wave-guide occurs at a depth of 20–40 km (profiles I-I and II-II; Fig. 6). Near the southern margin of the Issyk-Kul microcontinent the northern extremity of the wave-guide is also located deeper, some 15 km lower than its shallow southern part (profile II-II; Fig. 6).

Magneto-telluric (MT) studies in the Tien Shan (Trapeznikov et al., 1997; Rybin et al., 2001) also indicate the presence of layers and lenses. Together with seismic wave-guide characteristics discussed above, these layers and lenses exhibit a high electrical conductivity. Profiles in Fig. 6 show the position of the low seismic wave area obtained by seismic data and the high conductivity layers based on magneto-telluric data. These profiles show a good correlation between results from these different methods. A 15–25 km thick layer identified by MT, is located at a depth of 35–50 km to the north of the Issyk-Kul microcontinent, and at a shallower depth of 20–35 km to the south. Oblique wave-guides mark the southern border of the Issyk-Kul microcontinent. Towards the south, the wave-guide is located at the same depth as the basement of the Tarim microcontinent (20–50 km).

The occurrence of these viscous layers would restrict the depth of faulting, and consequently the depth of earthquake hypocenters; hypocenters of all Tien Shan earthquakes, are limited to a depth of less than 10–20 km (Sabitova and Adamova, 2001; Bragin et al., 2001). A

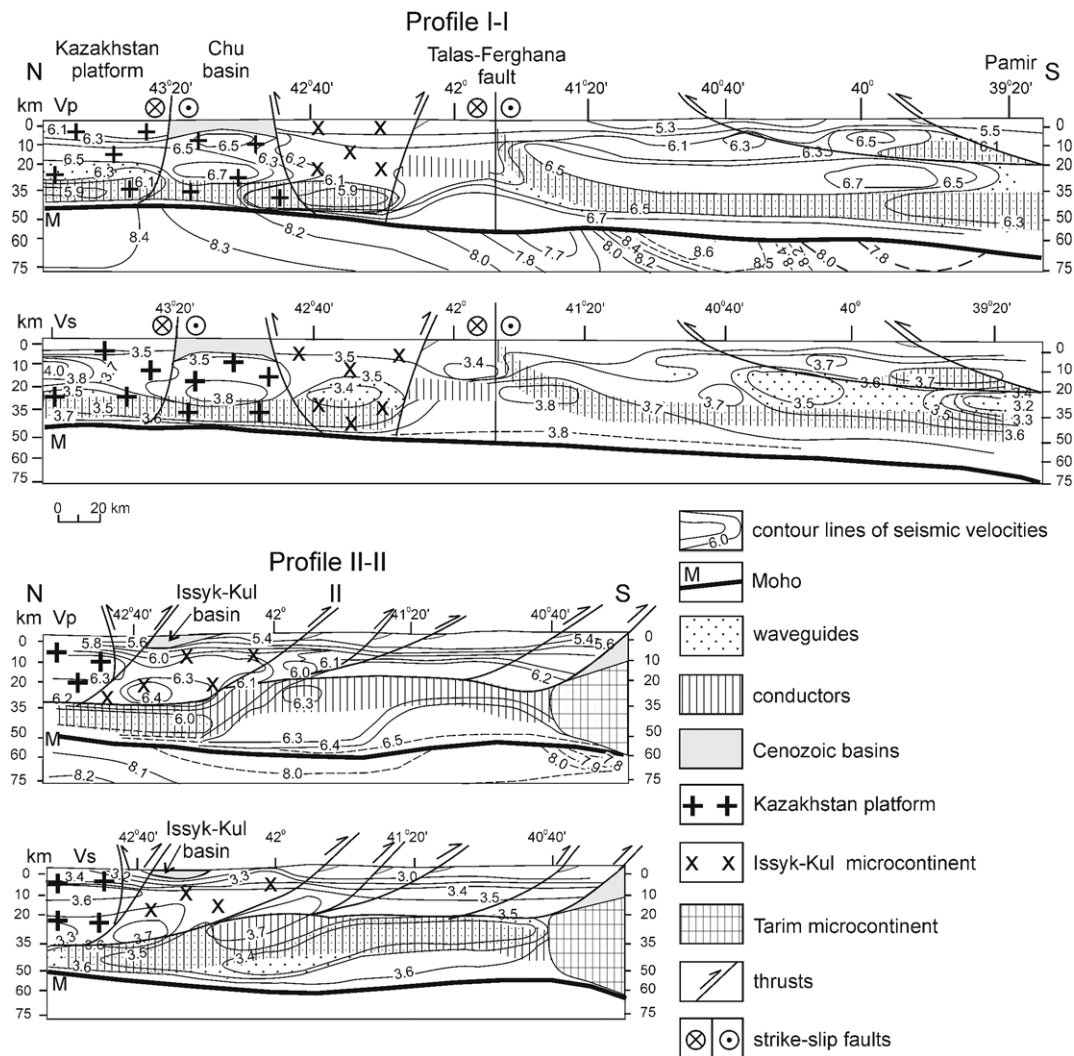


Fig. 6. Geological and geophysical profiles (I-I and II-II) of the crust and upper mantle beneath the Kyrgyz Tien Shan (see Fig. 2 for location). Based on seismic and magneto-telluric profiling. See text for discussion and interpretation.

visco-plastic medium, identified by the geophysical techniques, cannot retain tectonic strain. Tectonic layering of the Kyrgyz Tien Shan lithosphere with visco-plastic layers 20–30 km thick may permit the fast slip and deformation of the upper crustal section including the rotation of the SW Tien Shan Block, the underthrusting of the Tarim Plate, and the indentation of its basement into the middle crust of the Tien Shan.

Thrusting of the Tarim Plate under the southern Tien Shan and of the Pamirs onto the SW Kyrgyz Tien Shan, has a maximum velocity of 10–15 mm/yr, whereas the Indian Plate is moving to the north with a velocity of 50 mm/yr, resulting in the compression of the upper crust (Avouac et al., 1993; Avouac and Tapponnier, 1993). We suggest that a part of this convergence was accommodated by flow of the viscous layer in the middle of the Tien Shan crust. Deformation in the upper crust occurred mainly along the Talass-Fergana Fault and in the strike-slip belts around the microcontinental fragments (Figs. 1 and 6) as already described for the Issyk-Kul microcontinental fragment.

The relationship of the STS and NTS seismic zones to the mountain ranges bordering the Precambrian Issyk-Kul microcontinent is important to the mountain building process. Strong earthquakes (NTS) and high-velocity active fault movements are connected to the building of these mountain ranges. These events are clearly indicate basement control as they are concentrated at the margins of the rigid microcontinent. We can view the seismic events in the STS in the same context, with the Tarim microplate acting as a rigid body thrusting beneath the Tien Shan.

5. Apatite fission-track analysis

An apatite fission-track (AFT) study (De Grave et al., 2004) was performed on crystalline rocks from the Kyrgyz Tien Shan (Figs. 2 and 8). The samples come mostly from the Paleozoic basement of the Issyk-Kul. Samples were also collected along profiles in the Kungey and Terzkey ranges. These ranges are formed primarily of Ordovician granites and are thrust onto the northern and southern margins of

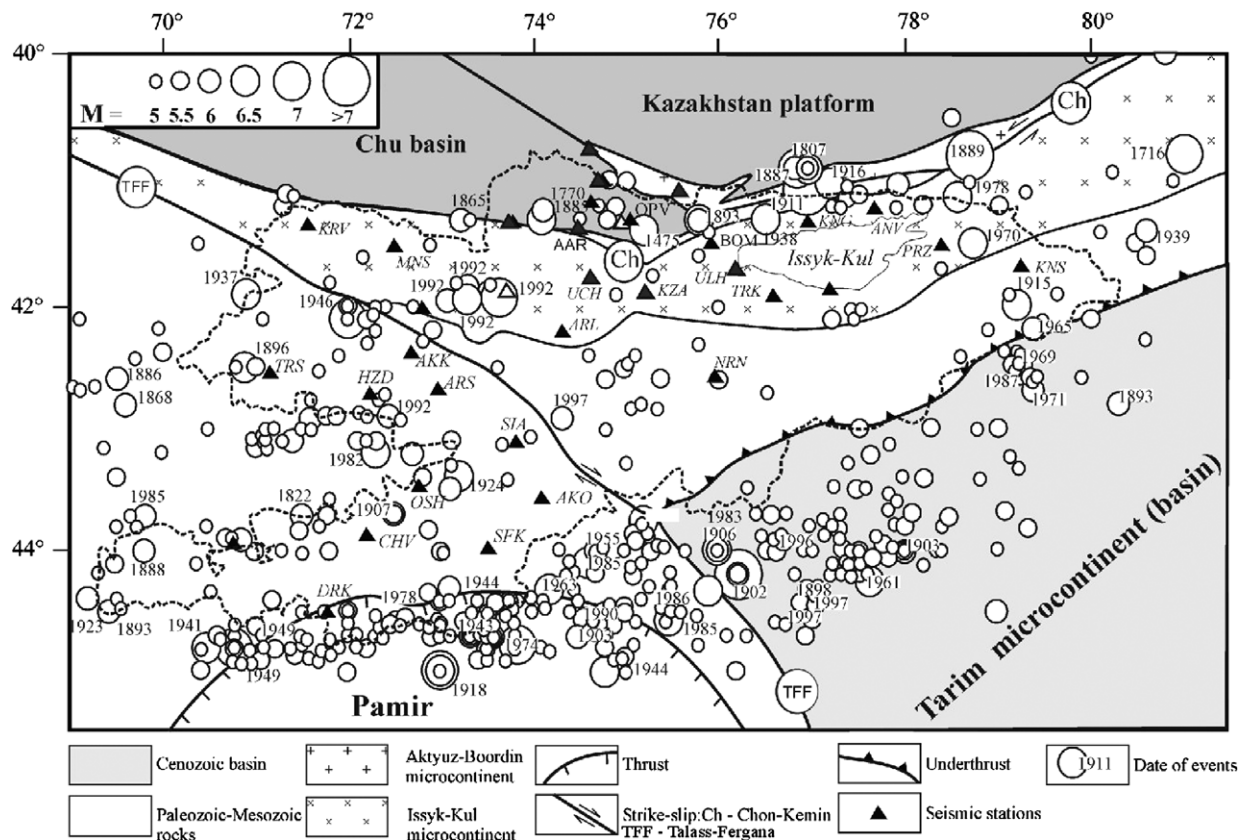


Fig. 7. Map of seismicity and tectonics of the Kyrgyz Tien Shan and adjoining regions (after Buslov et al., 2003).

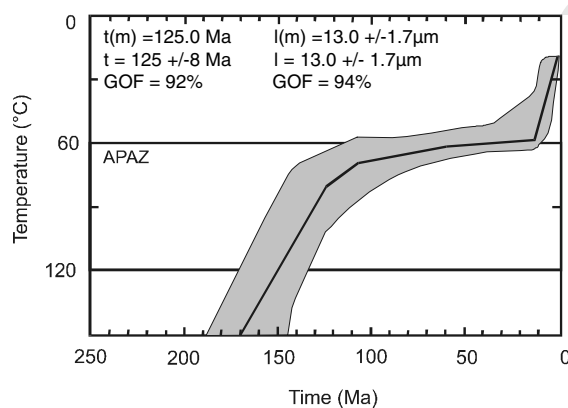


Fig. 8. A representative thermal history model obtained from AFT age and length data (AFTSolve, Ketcham et al., 2000) from a granite sample from the Kungey Range (Issyk-Kul region, northern Kyrgyz Tien Shan; from De Grave et al., 2004). APAZ, Apatite Partial Annealing Zone; $t(m)$, modeled AFT age, t , observed AFT age, $l(m)$, modeled mean track length, l , observed mean track length; GOF, Goodness of fit. The best statistical cooling-path is shown as a single line within a statistical good fits envelope. See text for discussion and interpretation.

the Cenozoic intramontane Issyk-Kul Basin, respectively. Based on AFT age and length data and using the appropriate modeling software thermal history models for the study area were reconstructed (Ketcham et al., 2000). These models (Fig. 8) reveal a three-stage Meso-Cenozoic cooling history throughout the investigated area.

Firstly, the thermal history models show a cooling of the Issyk-Kul basement in the Jurassic–Early Cretaceous (~180–110 Ma). De Grave et al. (2004) interpret this cooling as due to the denudation of the Issyk-Kul basement, associated with the tectonic reactivation of the ancestral Kyrgyz Tien Shan, possibly related to the Cimmerian orogeny and associated collision of various Cimmerian (Tibetan) blocks with the Eurasian margin; discussion of which is beyond the scope of this paper. At the cessation of Mesozoic cooling, the Issyk-Kul basement reached upper Apatite-Partial Annealing Zone (APAZ) temperatures (~60–80 °C). After Mesozoic cooling, a second stage in the cooling history is reflected by Late Cretaceous–Paleogene, near-horizontal modeled, cooling paths. These can be attributed to a period of tectonic quiescence and peneplanation. At the end of this period, before onset of rapid Late Cenozoic cooling, the investigated apatites remained at upper APAZ temperatures, or just reached lower AFT retention temperatures (~50–60 °C). This long period of APAZ-residence is reflected in the AFT length data. Low mean track lengths (~11–14 μm) and negatively skewed distributions are exhibited by all samples (De Grave et al., 2004).

The present neotectonic reactivation of intracontinental Central Asia as a whole and the Tien Shan in particular is shown by a final cooling stage described by the AFT thermal history models. The models exhibit this feature from ~15–10 Ma onwards, with a specific acceleration after ~5–

3 Ma ago (Fig. 8). This young cooling down to ambient surface temperatures is interpreted as denudation and exhumation of the studied rocks to their present outcrop positions.

Together with results from similar studies (Hendrix et al., 1994; Van der Beek et al., 1996; Sobel and Dumitru, 1997; Burbank et al., 1999; Bullen et al., 2001, 2003; De Grave and Van den haute, 2002; De Grave et al., 2004), these observations seem to suggest that reactivation and deformation in the interior of the Eurasian continent is gradually rejuvenating northward through Central Asia since the Miocene as a distant effect of the ongoing indentation of India into Eurasia. This deformation resulted in transpressive mountain building and roughly 2 km of denudation of the northern Kyrgyz Tien Shan since the Late Miocene.

6. Discussion and conclusions

The structure of the Tien Shan is formed by isometrically outlined Precambrian microcontinents (Tarim, Issyk-Kul, Aktyuz-Boordin) surrounded by accretion–collision zones. This complex crustal structure of the Tien Shan has a strong impact on the distribution of stress induced by the India–Eurasia collision. This stress is propagated northward through Central Asia and is expressed as strain in the rejuvenation of intracontinental mountain ranges and intramontane basins. In a first collisional stage (35–20 Ma ago), India was thrust under Tibet and the Pamir, resulting in incipient growth of the Himalayan–Karakoram orogen, the embryonic uplift of the Tibetan Plateau, and subsidence of the Tarim and Fergana depressions. Also, the Pamir Block was thrust onto the SW Kyrgyz Tien Shan and the Tien Shan Block was rotated anticlockwise as a direct result. In a second stage (20–11 Ma ago), the Tarim microcontinent was thrust under the central and eastern parts of the southern Tien Shan, resulting in the additional uplift of the southern Tien Shan ranges. While thrusting of the Pamirs continued, the tectonic load on the SW Tien Shan increased further. A third stage (10–3 Ma) saw the reactivation of the Issyk-Kul microcontinent and its surrounding accretion–collision mobile belt in the northern Kyrgyz Tien Shan, where mountain ranges also started to develop. Anticlockwise rotation of the Tien Shan Block continued and dextral strike-slip displacement along the Talass-Fergana Fault Zone occurred at rates of about 10–15 mm/yr. Finally, the interplay of the Tarim and Pamir convergence with the Tien Shan (~3 Ma ago to the present) gave rise to the maximum uplift and formation of the modern Tien Shan as they occur today, while dextral strike-slip displacement along the Talass-Fergana Fault Zone reduced to ~1 mm/yr.

The thrusting of the Tarim Plate underneath the Tien Shan resulted in the shortening of the upper crust at a rate of ~10–15 mm/yr, whereas India moves northward at 50 mm/yr. A certain amount of the stress induced by the ongoing convergence may have been accommodated by

flow within the viscous, plastic layers in the Tien Shan crust and lithosphere. Stress in the upper crust was buffered to a large extent by the Issyk-Kul microcontinent and taken up by strain in the surrounding mobile belts. It is clear that the recent tectonics of the northern Tien Shan is controlled by its pre-Cenozoic structure. Earthquakes of $M > 6$ clearly mark the northern and southern margins of the lens-shaped Issyk-Kul microcontinent, indicating that crustal heterogeneity affected the formation of the active northern Kyrgyz Tien Shan structures. Seismic and magneto-telluric studies show that the Tien Shan lithosphere contains tectonic layering, with several nearly horizontal viscous layers. The lower layer is underthrust northward into the northern Tien Shan middle crust, as indicated by seismic data shown in this paper. The viscous layers in the lithosphere beneath the Tien Shan possibly permitted the rotation of the SW Tien Shan Block, the underthrusting of the Tarim Plate, and the indentation of its basement into the middle Tien Shan crust. This caused high slip rates with failure in the upper crust to depths of 20–30 km.

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