Recent strike-slip deformation of the northern Tien Shan

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Abstract: The paper presents a geodynamic interpretation of the deep structure and active tectonics of the northern Tien Shan, with particular emphasis on strike-slip motions, which produced a pull-apart in the centre of the Issyk-Kul basin. The study is based on a detailed interpretation of satellite imagery, fault plane solutions of earthquakes, seismic, and geodetic data.

Seismic and magnetotelluric studies show tectonic layering of the Tien Shan lithosphere, with several nearly horizontal viscoelastic layers and the lower layer underthrust northward in the northern Tien Shan. This active process may be responsible for the intricate present-day tectonic framework of the northern Tien Shan.

The recent tectonics of the northern Tien Shan inherits the earlier structure: The lens-shaped Issyk-Kul microcontinent comprising Precambrian–Palaeozoic metamorphic and magmatic rocks is surrounded by thick shear zones which have been involved in the activity over most of the Cenozoic. In the Quaternary the strain propagated as far as the central part of the Issyk-Kul basin.

The Tien Shan is a unique example of an active intracontinental mountain belt whose origin and evolution have been interpreted as responses to processes at remote plate boundaries. The mechanisms invoked to explain the formation of the present-day Tien Shan alternate between ductile coupling of a tectonically layered lithosphere over a mantle diapir (Gubin 1986; Bakirov *et al.* 1996; Dobretsov *et al.* 1996) and lithospheric folding (Burov *et al.* 1993).

The present-day Tien Shan is a system of several ranges trending roughly west–east and almost parallel sedimentary basins separated with active faults. The intracontinental tectonics of the Tien Shan is apparently a consequence of the India/Eurasia collision (Fig. 1), and the recent activity is assumed to be controlled by the penetration of the rigid indenter of India into Asia (Molnar and Tapponnier 1975; Cobbold and Davy 1988; Molnar *et al.* 1993).

The active tectonics of the Tien Shan has been best documented in the region of the Talas-Fergana fault, a major strike-slip zone of the region. The cumulative right-lateral offset along it since the Late Miocene approaches 100 km, with a 10 mm a^{-1} of average slip rate (Burtman *et al.* 1996), but GPS data obtained since 1992 do not show ongoing motions (Abdrakhmatov *et al.* 1996, 2001; Meade and Hager 2001; Zubovich *et al.* 2001). The highest slip rate in the southern Tien Shan, near the Tarim plate, was 2–3 mm a^{-1} (Meade and Hager 2001). The velocities and directions of motions of crustal blocks in the northern Tien Shan have been greatly variable through its history. The present-day left-lateral strike-slip reaches 8 mm a^{-1} (Meade and Hager 2001).

We studied the northern part of the Tien Shan range, a major active shear zone at the transition between the Tarim plate and the stable Kazakhstan platform (Figs 1 & 2), with a special focus on the processes that control the Issyk-Kul pull-apart basin near the northern limits of the mountain belt (Fig. 2). The structural pattern of the northern Tien Shan (Kyrgyzia) and the Issyk-Kul basin records

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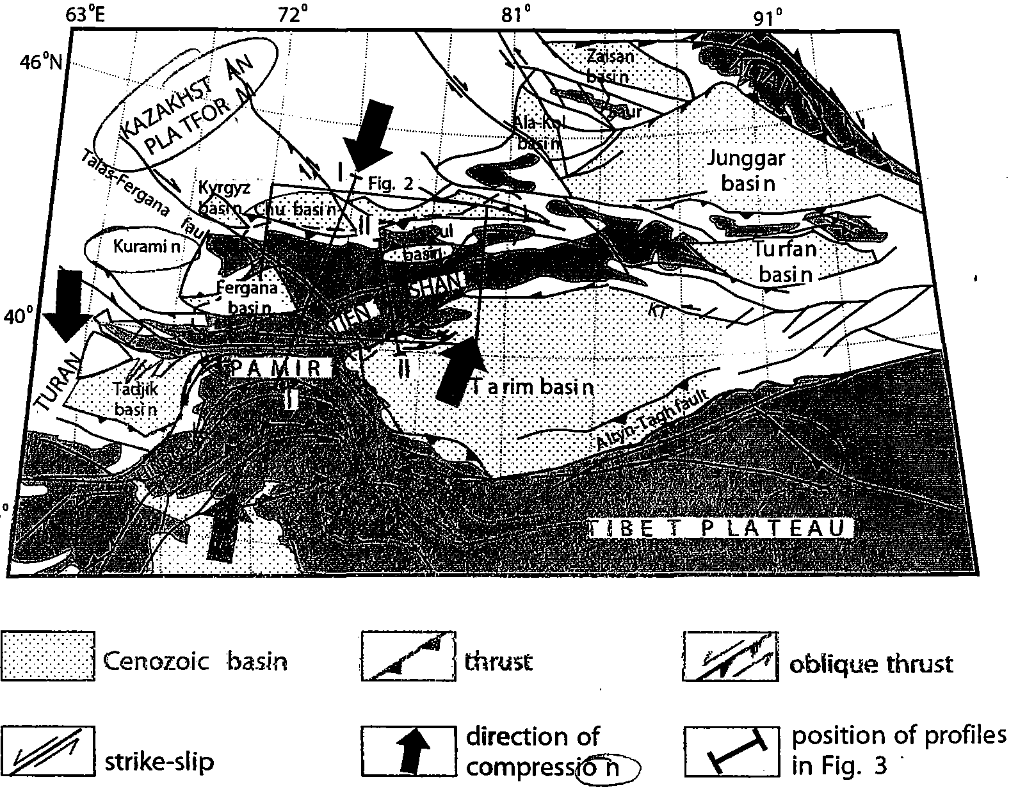

Fig. 1. Generalized tectonics of Central Asia (Tarim, Turfan, and Junggar basins and surrounding mountains). Modified after Cobbold and Davy (1988).

complex Cenozoic deformation associated with the India/Eurasia collision and related strain propagation inwards into the continent, crustal shortening and thickening, and mountain building. The present-day N–S crustal shortening in the southern and northern Tien Shan occurs in different directions and at different rates (10–15 mm a^{-1} and up to 2–6 mm a^{-1}, respectively), possibly because the northern Tien Shan encloses a Precambrian microcontinent which may control the Neogene–Quaternary evolution of Cenozoic basins and active strike-slip deformation processes.

The geodynamics of the northern Tien Shan is investigated using published and original geological and geophysical data. Deep structure is described from seismic and magnetotelluric evidence; the Cenozoic structural evolution is inferred from interpretation of satellite imagery and field structural and geomorphological studies; stress and strain distribution in the crust is reconstructed from fault plane solutions of earthquakes; recent crustal movements are revealed by geodetic surveys (GPS for horizontal movements and repeated levelling for land uplift).

Geological and tectonic background

As was first shown by Molnar and Tapponnier (1975, 1978), the Cenozoic tectonics over a broad territory of Asia can be explained in terms of the continuing convergence between India and Eurasia. After the initial collision between 60 and 35 Ma (Mercier *et al.* 1987; Le Pichon *et al.* 1992) India has continued its northward motion at reduced velocity and acts as a rigid indenter penetrating (for ~2000 km) into Asia to cause post-collisional underplating (India) and uplift (Tibet) (Molnar and Tapponnier 1978; Cobbold and Davy 1988).

Orogeny in the Pamir and southern Tien Shan regions started later than the Tibet uplift and was accompanied in the Late Oligocene by deposition of coarse-clastic red-colour continental molasse. The Miocene landscape of the Pamirs and the southern Tien Shan was made up of ≤3 km uplifts and depressions between them. In Pliocene time, red molasse gave way to grey ones as a result climatic cooling, and the uplifts reached 4–5 km high. Further Quaternary uplift of the Pamirs produced the typical glacial landscape (Chedija 1986).

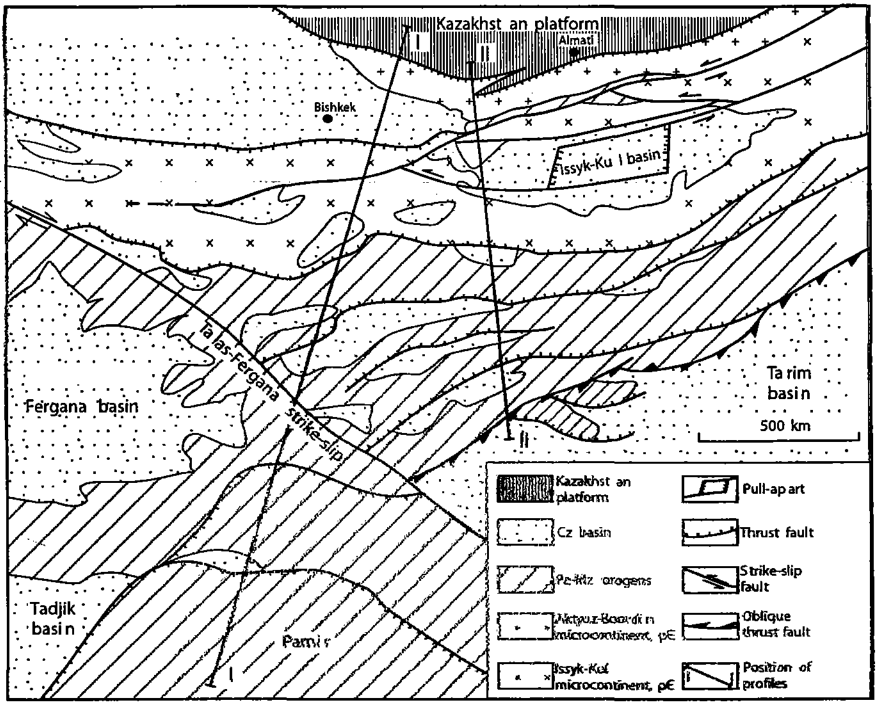

Fig. 2. Generalized tectonics of Tien Shan.

The northern Tien Shan became involved in orogeny in the Late Miocene under tangential compression which caused linear folding, reverse and thrust faulting, seismic activity, and crustal thickening up to 60 km in the north and 75 km in the south (against 40–45 km in the Kazakhstan platform) (e.g. Gubin 1986; Sadybakasov 1990; Burov *et al.* 1993). The growth of mountains was likewise accompanied by molasse deposition in the Issyk-Kul and other basins (Chediya 1986; Sadybakasov 1990).

Abdrakhmatov *et al.* (1996) estimated that the evolution of the northern Tien Shan belt lasted 10 Ma, on the basis of 200 ± 50 km of total crustal shortening and its interpolated present-day rate of 20 mm a^{-1}. They attributed the origin of the belt to a notable increase in horizontal compression in response to the abrupt rise of the Tibetan plateau reported by England and Houseman (1989) and Molnar *et al.* (1993). Apatite fission track thermochronology, structural modelling and magnetostratigraphy in the Kyrgyz range and the Chu basin (Burbank and Bullen 1999) further showed that the uplift and strain rate in the northern Tien Shan first increased 10–11 Ma ago, and then after 3 Ma. The latter episode is expressed in the stratigraphy by a marked change in Late Pliocene–Early Pleistocene deposition environments, thick sequences of coarse conglomerates, sedimentary gaps, and tectonic unconformities (Abdrakhmatov 1993).

Tectonic layering of the lithosphere of northern Tien Shan

The following implications for tectonic layering in the upper lithosphere of the Tien Shan are based on geological, seismic, and magnetotelluric evidence, including published *P*- and *S*-wave seismic data for the Tien Shan and neighbouring territories (Sabitova 1989; Roecker *et al.* 1993; Sabitova *et al.* 1995; Roecker 2001; Sabitova and Adamova 2001), data from 250 magnetotelluric profiles recorded by the IVTAN station (Bishkek) since 1983 and processed by a method reported by Trapeznikov *et al.* (1997), as well as synthetic seismic and magnetotelluric data correlated on two profiles from the Kazakhstan platform to the Pamirs (Profile I–I) and Tarim (profile II–II) (Figs 2 & 3).

P- and *S*-wave seismic profiles (cross section I–I in Fig. 3) image 10–20 km thick nearly horizontal waveguides in the lower (35–50 km) and upper (10–20 km) crust throughout the region except for the Fergana basin and the neighbouring flat areas. The upper crust waveguide is at depths of 10–20 km north of the Pamirs; the lower-crust waveguide abruptly rises to 15–20 km beneath the Talas-

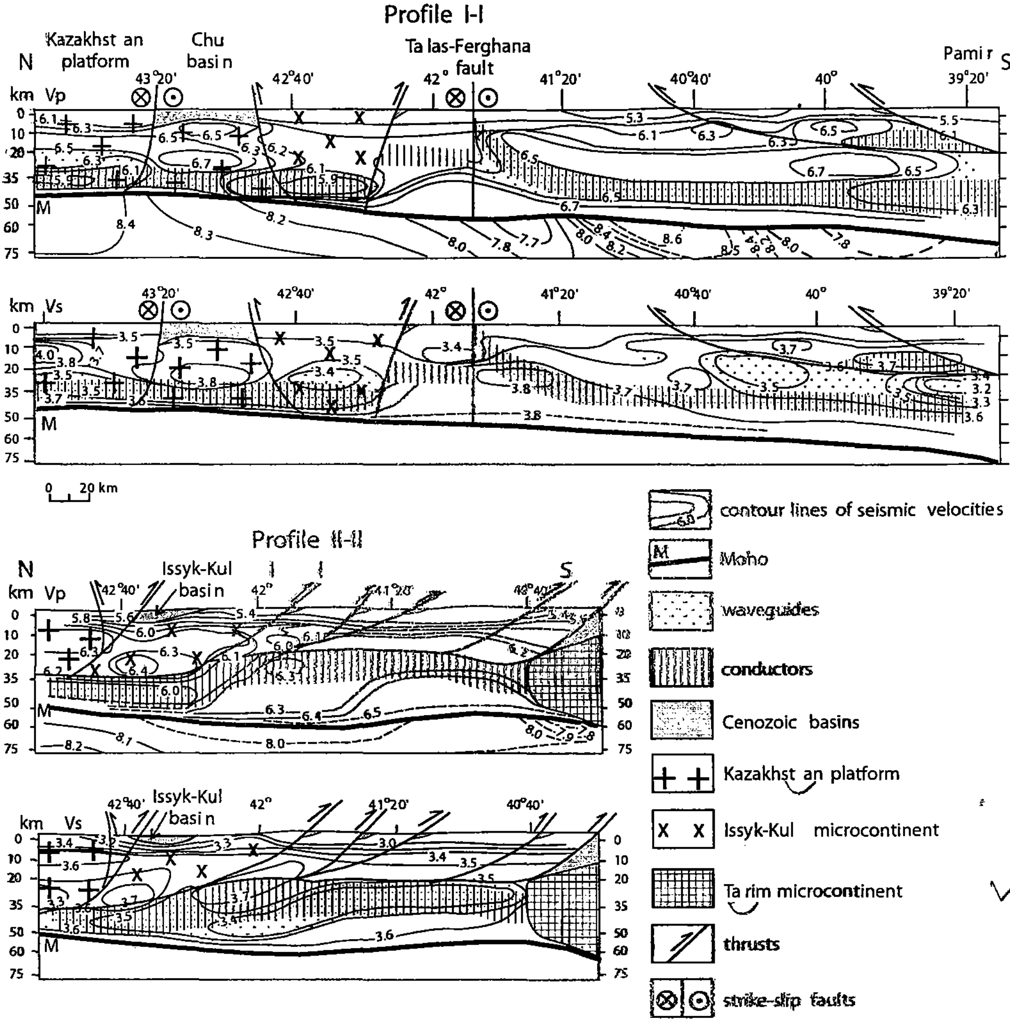

Fig. 3. Cross section of crust and upper mantle beneath Tien Shan, from P (Vp) and S (Vs) seismic velocities, along profiles Aktyuz-Torugart (I) and Kindiktas-Karakul (II) (see Figs 1 & 2 for location). After Bakirov *et al.* (1996).

Fergana fault and is as deep as 20–40 km northeast of it and near the Tarim plate (profiles I–I and II–II). Near the southern margin of the Issyk-Kul microcontinent, the northern end of the waveguide is 15 km deeper than the southern one (profile II–II in Fig. 3).

Magnetotelluric data (Trapeznikov *et al.* 1997; Rybin *et al.* 2001) indicate the presence of crustal conductors nearly at the same depths as the waveguides (see Profiles I–I and II–II in Fig. 3). A 15–25 km thick conductor is located at a depth of 35–50 km north of the Issyk-Kul microcontinent and at 20–35 km south of it. A sloping conductor marks the southern border of the Issyk-Kul microcontinent. Southwards, the conductor is located at the same depth as the basement of the Tarim microcontinent (20–50 km).

Therefore, geophysical data provide evidence for the tectonic layering of the present-day crust beneath the Tien Shan, possibly associated with high-temperature metamorphism and migmatization: the lower waveguide is attributed to partial melting in the amphibolite-facies P–T conditions (Bakirov *et al.* 1996). The intermediate and upper waveguides may correspond to magmatic chambers with plastic migmatites squeezed out towards the surface.

The occurrence of an asthenospheric upwarp beneath the Tien Shan is marked by abnormal heat flux (twice that beneath Kazakhstan) (Yudakhin

1983; Yudakhin and Belonovich 1989) and low seismic velocities (1–3% ΔVp). High ΔVp was recorded northeast of the Talas-Fergana fault, with the maximum of 3% south of Lake Issyk-Kul (Roecker *et al.* 1993).

The hot anomalous mantle hypothesized beneath the northern Tien Shan, northeast of the Talas-Fergana fault, may be responsible for magma generation and lithospheric layering. Magma layers serve as a lubricant facilitating movements of upper crust blocks over them.

The viscous plastic layers in the crust may constrain the depth of faulting, and consequently the origin depth of most earthquakes. Taking into account that tectonic strain cannot exist in a viscous medium, this may explain why the hypocentres of all Tien Shan earthquakes are restricted to <10–20 km.

Thus, the recent orogenic stage has acted upon a thinned or weak lithosphere. Strong compression from Tarim and Pamir is accommodated in horizontal movements facilitated by the presence of subhorizontal zones of weakness in the crust where the hypocentres of almost all regional earthquakes cluster (Gubin 1986; Abdrakhmatov 1993).

The tectonic layering of the Tien Shan lithosphere and the heterogeneous composition of the crust (granite–metamorphic microcontinents, accretionary complexes, shear zones) may be responsible for the discordant behaviour of its constituent blocks under general W–E compression (Figs 2 &3). The direction of block motions primarily depends on the geometry of the border faults, which are most often Late Palaeozoic faults reactivated in the Cenozoic (Bakirov and Maksumova 2001; Maksumova *et al.* 2001). Recent tectonic movements follow the earlier Cenozoic structure (Tapponnier and Molnar 1979; Mikolaichuk 2000), and the geometry of faults is controlled by the position of their planes relative to the direction of compression.

The basement structure of the northern Tien Shan

The basement of the Kyrgyz Tien Shan includes the Issyk-Kul and Aktyuz-Boordin microcontinents composed of Archean high-grade metamorphics and Early Proterozoic quartz schists and carbonates overlain by Late Riphean and Cambrian–Ordovician volcanosedimentary rocks. These, together with Late Riphean–Middle Palaeozoic intrusions, are covered by Devonian–Carboniferous volcanosedimentary and sedimentary deposits.

The Issyk-Kul microcontinent with the Issyk-Kul basin in its centre is a miniature model of the Tarim and Junggar microcontinents that contain basins of the same name reduced through the Cenozoic. It is a W–E-striking southward convex lens *c.* 110 km wide and 350 km long (Fig. 4) bounded in the south and in the north by the Kyrgyz-Terskey and Chon-Kemin shear zones, respectively.

According to geophysical data, the microconti-

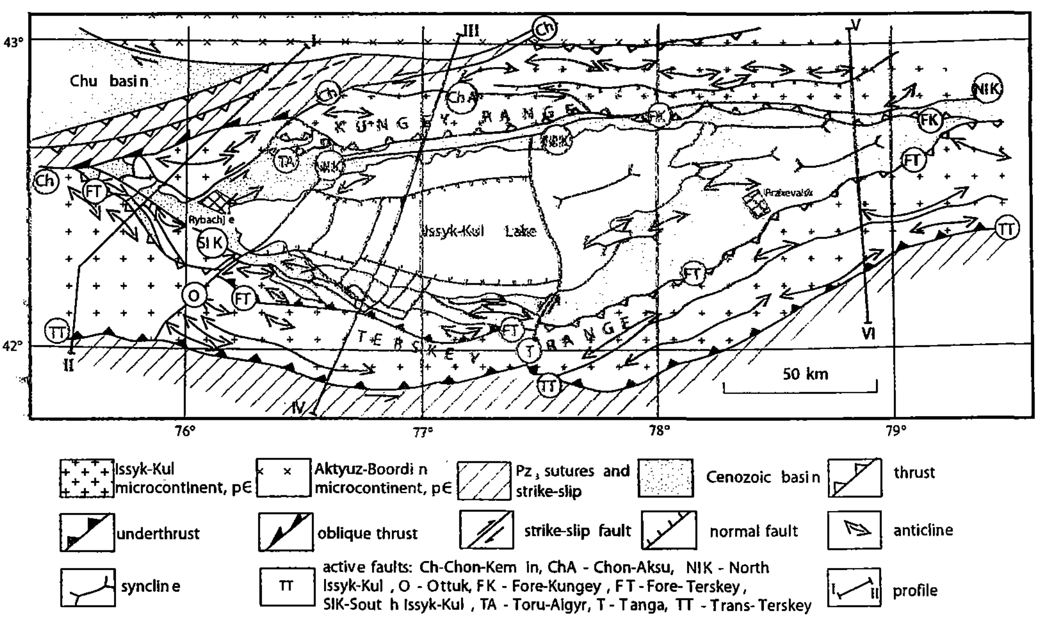

Fig. 4. Active tectonics of the northern Tien Shan around the Issyk-Kul basin.

nent is located in the upper crust above the plastic layer (Fig. 3) formed under the pressure from the Tarim microcontinent thrusting under the Tien Shan. The Issyk-Kul microcontinent has behaved as a rigid bock during the Cenozoic and has played an important role in the regional distribution of strain induced by the India/Eurasia collision and transmitted to inner Asia along old faults.

The Cenozoic structure of the Issyk-Kul region

In Palaeogene–Miocene time, the Issyk-Kul microcontinent remained more or less stable and was an area of continuous lacustrine deposition in the Palaeogene. Neogene and Quaternary clastic sediments record the onset of tectonic activity, especially clastic transport from the growing southern and, possibly, northern Tien Shan. The tectonic activity in the northern Tien Shan culminated in the Pliocene–Early Quaternary as compression changed to N–S from NW in the Late Miocene. This episode strongly deformed the Issyk-Kul microcontinent and its Cenozoic cover and produced the present-day surface topography. The southern and northern margins of the microcontinent were gradually involved into uplifting, the area of the Issyk-Kul basin strongly reduced, and ramp structures formed in its western and eastern margins. Thrusting of mountains over the basin was accompanied by molasse deposition. As a result of underthrusting along the Kyrgyz-Terskey zone, the southern margin of the microcontinent split into several blocks separated by oblique thrusts and strike-slip faults. Strike-slip motions along the Chon-Kemin fault induced thrusting and reverse faulting along the northern margin of the microcontinent (Fig. 4). In the Holocene, the deformation reached the centre of the microcontinent and the Issyk-Kul basin (Buslov *et al.* 2001).

The Issyk-Kul basin has been studied in some detail (Chedija 1986; Sadybakasov 1990; Trofimov 1990; Mikolaichuk 2000) but its recent tectonics and evolution remain a subject of discussions. The basin formed in the Early and Middle Pleistocene along W–E and transverse normal faults and has accumulated about 4 km thick basin fill. Its origin was interpreted in terms of a pull-apart structure formed in response to right-lateral strike-slip faulting under N–S compression (Klerkx *et al.* 1999). At its early evolution stage the basin was larger than now, especially in the east. Now it has a trapezium-shaped geometry and is bounded by W–E, NE, and NW faults (Fig. 4). Trofimov (1990) interpreted the evolution of the basin as successive centreward collapse of blocks from the west and from the east while the faults in the south and in the north remained stable. In Early and Middle Pleistocene time the basin floor subsided for 30–50 m along the border faults. Reactivation of normal faults in the Late Pleistocene produced an offset of 50–100 m. In the Middle Holocene the central part of the lake underwent a catastrophic collapse and subsided for 200 m to form an over 700 m deep lake in 10 000 years. The collapse may have been responsible for the Middle Holocene regression and a 100 m fall of water level (Trofimov 1990).

The western, central, and eastern parts of the basin have different structural styles (Fig. 4). In the western part (Fig. 5, profile I–II), the basin has a well-defined ramp structure which grades into a half-ramp eastward where the Kungey range is thrust over the basin along the Toru-Aigyr fault in the north, and sediments are conformable to the basement in the south (Korzhenkov 2000; Mikolaichuk 2000). In the eastern part of the basin (profile V–VI in Fig. 5), Cenozoic sediments are involved in brachiform and linear folds and are separated from the basement by thrusts and reverse faults in the north and in the south.

The particular structural style of the basin's cen-

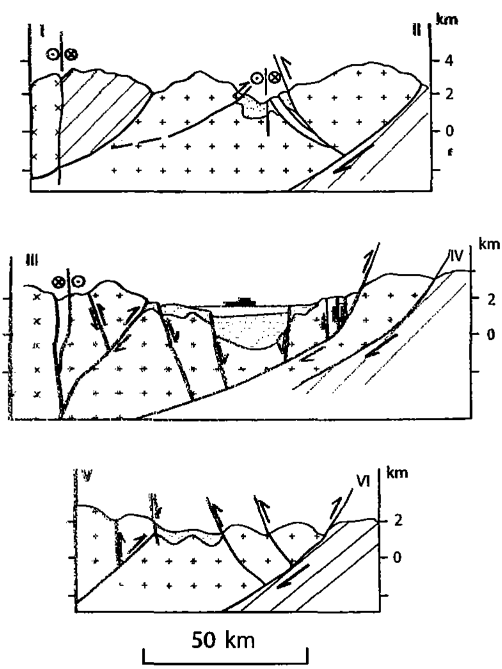

Fig. 5. Geological cross sections of different segments of northern Tien Shan around Issyk-Kul basin (for location of profiles see Fig. 4). Profile I–II (western Issyk-Kul microcontinent): Cenozoic sediments overthrust by basement rocks in a ramp structure. Profile III–IV (central Issyk-Kul microcontinent and Lake Issyk-Kul): reverse faulting at southern extremity of microcontinent. Profile V–VI (eastern Issyk-Kul microcontinent): basin fill is more strongly deformed in a half-ramp structure.

tral part is controlled by the Chon-Kemin and Fore-Terskey master faults, the Fore-Kungey oblique thrust joining the Taldy-Su thrust, North and South Issyk-Kul faults, and the transversal Tanga and Ottuk faults (Fig. 4). The NE-striking Chon-Kemin fault bordering the Issyk-Kul microcontinent on the north was interpreted as a reverse fault (Chedija 1986) before a significant left-lateral strike-slip component was recently revealed (Delvaux *et al.* 2000). The Fore-Terskey fault that borders the Issyk-Kul microcontinent on the south is split by the Tanga and Ottuk faults into three segments with different kinematics of fault planes. The segment east of the Tanga fault is a thrust in which the Terskey range is thrust over Cenozoic sediments, the western segment is also a thrust, and the segment between the Tanga and Ottuk faults is an underthrust. Cenozoic sediments and Quaternary terraces south of the lake are folded into linear folds or E–W-striking flexures. Many flexures and folds have gently sloping northern limbs and steep and short southern limbs, often cut with reverse faults.

The changes in kinematics along the basin axis are various expressions of the impact of the N–S compression on the Issyk-Kul microcontinent. The underthrusting of the Terskey range apparently caused uplift of the southern flank of the microcontinent and subsidence of its central part, which is confirmed by northward dipping erosion surfaces of the range and the Cenozoic sediments. The boundary between the uplifted and subsided parts of the microcontinent (western Terskey range) runs along the southern shoreline of the lake.

Active crustal movements

Seismicity

The seismicity of the northern Tien Shan and neighbouring areas is shown in the map of M>5 epicentres in Fig. 6 (Vvedenskaya 1964–1973; Gorbunova *et al.* 1975–1981; Kondorskaya 1978–1991; Starovoit 1998–2001). In the period of historic seismicity (*c.* 120 years), the region was shocked by a series of great earthquakes which started with the 1887 M_s = 7.3 Vernen earthquake in the vicinity of Alma-Aty; then followed the 1889 M_s = 8.3 Chilik event and the M_s = 8.2 Kemin (Kebin) earthquakes in 1911, which were among the strongest historic catastrophes in the northern Tien Shan. The 1938 M_s = 6.9 Kemin-Chu earthquake was obviously the final event of this series. The earthquakes record westward stress release along the Kemin-Chilik fault (Fig. 6). They produced an intricate pattern of surface rupture and numerous landslides and rock avalanches within an area of 10 000 square kilometres (200 km from east to west along the fault and 70 km from north to south) (Delvaux *et al.* 2001).

The epicentres of all great earthquakes in the northern Tien Shan are located within a narrow strip between the Aktyuz-Boordin and Issyk-Kul microcontinents. Other M>6 epicentres mark the

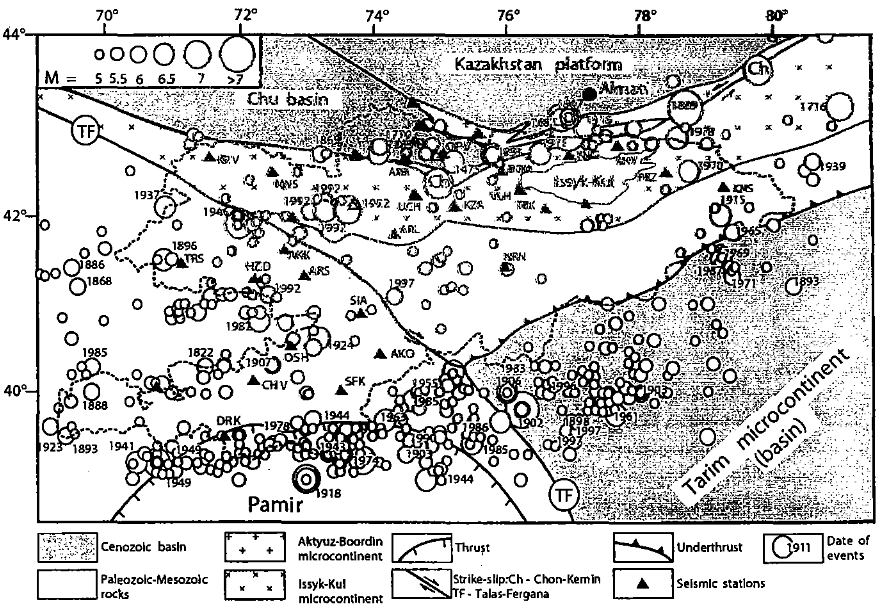

Fig. 6. Seismicity and tectonics of northern Tien Shan and neighbouring territories.

northern and southern margins of the Issyk-Kul microcontinent (Fig. 6) indicating the effect of crustal heterogeneity on the active structure of the northern Tien Shan.

Seismotectonics

The distribution of stress and strain in the crust of the northern Tien Shan was inferred from fault plane solutions of 780 M = 3–7 earthquakes between 1962 and 1995 (Vvedenskaya 1964–1973; Gorbunova *et al.* 1975–1981; Kostrov 1975; Kondorskaya 1978–1991; Yunga 1990; Starovoit 1998–2001), using only first motions of P-waves (Vvedenskaya 1969) and focal mechanisms within 0.1° from fault planes.

Strain estimates were obtained by the method of Riznichenko (1977, 1985), which implies slip measurements along seismic ruptures of different orientations and calculation of tensor components by summation of contributions from all earthquakes. The tensor components were then used to estimate the amount and direction of principal stress for each 0.4 × 0.4° averaging cell by formulas of elasticity. This averaging cell size was chosen because of uneven aerial distribution of seismicity. Depths of all events were assumed to be in the upper 20 km of the crust.

Our implications proceed from the basic assumptions that movements in earthquake sources and on the causative long-living faults result from the same tectonic forces and that coseismic slip follows the orientation of the fault plane (e.g. slip on a left-lateral strike-slip fault must be left-lateral as well).

Figure 7 shows the obtained distribution of stress in the crust of the northern Tien Shan divided into

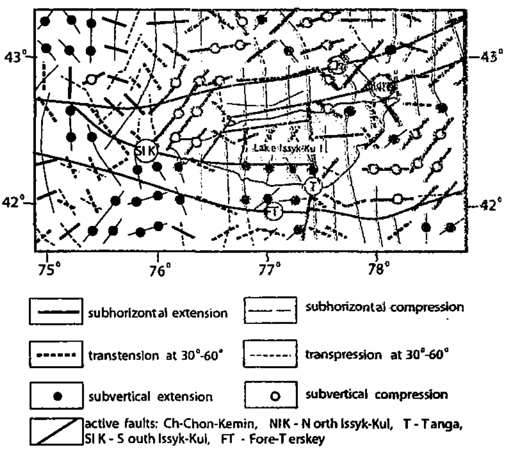

Fig. 7. Principal stresses in northern Tien Shan, from tensor analysis (see text for explanation).

the northern, central, and southern blocks with different tectonic styles, especially contrasting around the Issyk-Kul basin. The northern block is bounded in the south by the Chon-Kemin Fault, the central block is located west of the North and South Issyk-Kul faults, and the southern block is east of them.

The northern block evolves mostly under N–S compression. In the central block, the strain patterns indicate NE extension in its centre (Lake Issyk-Kul), NW extension in the west, and roughly N–S compression in the northern and eastern parts. The southern block experienced roughly N–S compression in its western part and mostly NE extension in the east.

The directions of principal horizontal axes are well defined against the mosaic background and reflect a regional-scale N–S compression. The vertical axes show positive motions, i.e. relative surface uplift throughout the northern Tien Shan but with minor subsidence southeast and northeast of the Issyk-Kul basin.

The obtained seismotectonic data were used to analyse the kinematics of the Chon-Kemin, North and South Issyk-Kul, and Fore-Terskey faults (the available solutions are insufficient for reliable simulation of other faults), using the method of Kuchai (1978, 1990).

The western and eastern segments of the Chon-Kemin fault were considered separately. The western segment shows both left- and right-lateral strike-slip faulting and the eastern segment is dominated by left-lateral motions, which confirms the geological evidence (Delvaux *et al.* 2000). Sixty mechanisms along the North Issyk-Kul and South Issyk-Kul faults suggest sinistral movements. The Fore-Terskey fault shows an intricate slip pattern, with left-lateral strike-slip in the east (from 31 mechanisms) and right-lateral slip in the west (from 23 mechanisms).

Geodetic data

The available geodetic data on horizontal crustal movements were obtained from a network of GPS stations run between 1992 and 1999 (Abdrakhmatov *et al.* 1996; Meade and Hager 2001; Zubovich *et al.* 2001). High-precision measurements of crustal movements have been carried out at 9 permanent and over 300 temporary stations (station POL/2 belongs to the world GPS network) by a joint Russia–Kyrgyzstan–Kazakhstan–USA project. The data are processed in the Institute of High Temperatures, Russian Academy of Science (former IVTAN RAS), using the GAMIT/GLOBK software designed at the Technological Institute of Massachusetts. The uncertainty of the measurements is within <2 mm a^{-1} (Zubovich *et al.* 2001).

The GPS data support the division of the northern Tien Shan into the northern, central, and southern blocks (Fig. 8) with different rates and directions of movements. The southern block moves at the highest rate (6–10 mm a^{-1}), in the NNE direction in its central part, N in the western part, and NE in the east. The central block experiences 4–6 mm a^{-1} active horizontal movements in N and NE directions. The northern block moves at 4–10 mm a^{-1}, predominately in the southern direction.

Recent vertical crustal movements are inferred from annual repeated geodetic levelling between 1937 and 1980 (Gubin 1986). These data, with the rms error no more than 0.2 mm a^{-1}, show 3 mm a^{-1} subsidence east (Rybachje) and west (Przhevalsk) of Lake Issyk-Kul, whereas the southern shore is subject to uplift at 2 mm a^{-1} (Fig. 8).

The GPS data and land uplift calculated relative to the Azor mark across the Kazakhstan platform (Abdrakhmatov *et al.* 1996) likewise indicate a N–S compression and recent strike-slip movements in the northern Tien Shan.

Discussion

The fault plane solutions of earthquakes and the geodetic (GPS and repeated levelling) data made a basis for two schemes of the active tectonics of the northern Tien Shan (Figs 7 & 8). The schemes show the crust of the region divided into several blocks with different tectonic styles. The western and eastern parts of the territory experience nearly horizontal N–S compression and nearly vertical extension. In the central part of the Issyk-Kul basin, extension is nearly horizontal and compression is nearly vertical. The mountain ranges around the Issyk-Kul basin are compressed in the N–S direction. The strain axes are oriented northward in the western part and northeastward in the central and eastern parts of the region.

Thus seismotectonic and geodetic analysis shows that the Issyk-Kul microcontinent is currently subject to left-lateral strike-slip motions, well pronounced around the microcontinent (eastern segments of the Chon-Kemin and Pred-Terskey faults) and in its centre where left-lateral slip on the North Issyk-Kul and South Issyk-Kul faults is consistent with the formation of a pull-apart.

The epicentres of great earthquakes and related land sliding are attributed to the Chon-Kemin and Chon-Aksu faults separating Precambrian microcontinents (Delvaux *et al.* 2001). Almost all M>6 earthquakes in the northern Tien Shan are spatially associated with active tectonic zones around the Issyk-Kul microcontinent (Fig. 6).

As a result of recent crustal movements at variable directions and rates, the southern shore of Lake Issyk-Kul is subject to uplift, and there are indications for subsidence in the eastern and western shores, with a risk of collapse. Activity of the mountains around the Issyk-Kul microcontinent and reactivation of fault borders of the Aktyuz-Boordin microcontinent is expected to continue in the future. We suggest that reactivation of faults and the related seismic and geological hazard can

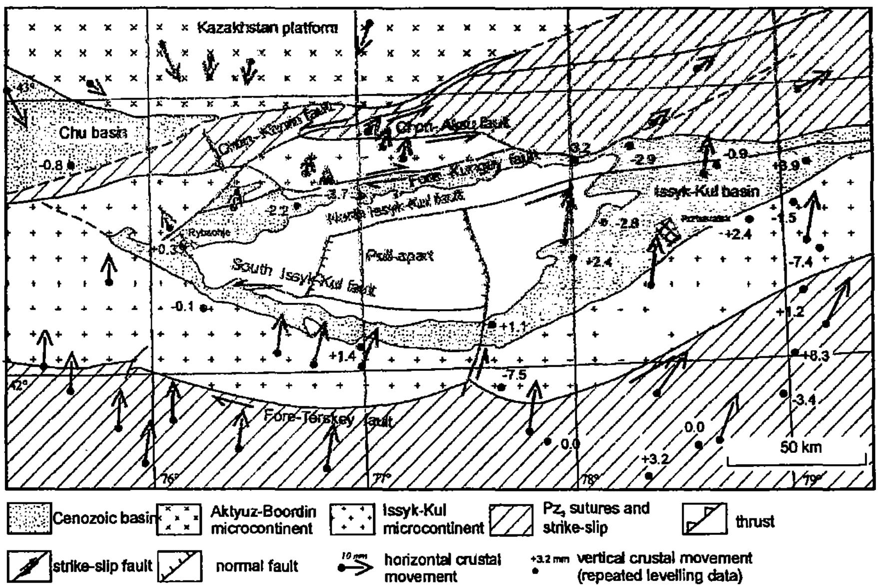

Fig. 8. Active strike-slip movements in northern Tien Shan (after geodetic surveys).

be predicted from changes in direction and rate of block movements.

Conclusions

We investigated the relationships between the present-day structure, reactivation of ancient faults, and interaction of old granite–metamorphic blocks (microcontinents) within relatively mobile orogenic belts in the region of Tien Shan, on the basis of geological information, detailed interpretation of satellite imagery, analysis of seismicity and fault plane solutions, and geodetic measurements.

The tectonics of the Tien-Shan evolves in response to the convergence between India and Eurasia since their collision in the Eocene (Molnar and Tapponnier 1975; Tapponnier and Molnar 1979, etc.), as India continues its northward motion at 50 mm a^{-1} (Avouac and Tapponnier 1993; Avouac *et al.* 1993). The propagation and distribution of strain induced by the collision is controlled by the complicated structure of the crust and lithosphere. Geophysical data indicate tectonic layering of the lithosphere beneath the northern Tien Shan. The presence of horizontal viscoelastic layers may influence the rotation and underplating of the Tarim plate and indentation of its basement into the middle crust of the Tien Shan. The thrusting of the Tarim plate under the northern Tien Shan has caused the shortening of the upper crust at a rate of <10–15 mm a^{-1} and related rapid movements and failure to depths of 20–30 km. A part of the strain may have been accommodated by the viscoelastic layer in the middle crust of Tien Shan.

The Issyk-Kul microcontinent plays an important role in redistribution of upper crustal stress and strain in the northern Tien Shan. The lens-shaped microcontinent is surrounded by thick shear zones which have been involved in the activity over most of the Cenozoic. In the Quaternary the strain propagated as far as the central part of the Issyk-Kul basin. It has produced a piano-key fault pattern in its inner part and favours further subsidence of the lake bottom.

The movements in the upper crust are best illustrated by the Fore-Terskey active fault bounding the Issyk-Kul microcontinent in the south, with south-dipping reverse faults and thrusts in its eastern segment and a series of underthrusts in the western segment that borders Lake Issyk-Kul. All these faults have a strike-slip component. The underthrusting of the Kungey range resulted in the uplift of the southern part the Issyk-Kul microcontinent and subsidence of its central part. The present-day activity in the region of Lake Issyk-Kul is dominated by left-lateral strike-slip faulting along the Chon-Kemin, Chon-Aksu, Fore-Kungey, and North and South Issyk-Kul faults. Strike-slip faulting may be responsible for the formation of a pull-apart structure in the central part of the basin.

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