The stress state of the northern Tien Shan crust based on the KNET seismic network data

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Abstract

In this study we present a detailed analysis of natural stresses in the Northern Tien Shan crust averaged in a window of 10–15 km obtained from seismological data of the local KNET network. The transformation of focal mechanism data into the parameters of the stress tensor was based on the method of cataclastic analysis of rupture displacement elaborated by Yu.L. Rebetsky (Institute of Physics of the Earth, Moscow). The results, including the orientation of the principal stress axes and the reduced stresses, are presented for four depth layers. It was shown that the central part of the study area is dominated by horizontal compression, while multiple domains characterized by horizontal shear and superimposed compression or pure horizontal shear are also present (uppermost layers in the eastern part of the Chuya depression, Suusamyr depression and adjoining regions, in the central part of the Kyrgyz Range). There are also several large domains of high and low effective confining pressure, which defines the corresponding deviator stress, according to the Coulomb–Mohr law. It was shown that relatively strong earthquakes are correlated with zones with low levels of effective pressure where the ruptures are characterized by lower resistance to brittle fracturing, i.e., Coulomb friction stresses. It was also shown that a distinct segment of the ~60 km E–W striking fault on the northern slope of the Kyrgyz Range generates a uniform distribution of stresses, corresponding to a dextral slip along of its edges.

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Introduction

Understanding the distribution of stresses in the Earth’s crust, the main goal of tectonophysics formulated by M.V. Gzovsky, is key for interpreting the mechanisms generating deformation structures. Using this concept as the basis, we attempted to study the stress state of the Northern Tien Shan crust. The goal of this study was to establish the relationship between the crustal stress state, morphology and neotectonics of the study area.

Our previous study (Rebetsky et al., 2013) indicated that the average crustal stresses in seismically active regions of Altai–Sayan and High Asia (Pamir, Tibet, Himalaya, and Kunlun) bear obvious relation to the present topography (mountain ranges and depressions). It was shown that the orientations of the axes of maximum compression in regions of uplifted crust (mountain ranges) and maximum deviatoric tension (minimum compression) in regions of depressed crust (inter- and intramontane basins, valleys and depressions) are generally subhorizontal. The data from a recent study (Rebetsky and Alekseev, 2014) revealed that the axes of minimum compression in plateau-type uplifts (part of the Pamir and Tibet) are also subhorizontal, i.e., the geodynamic regime in these regions was dominated by the combination of horizontal extension with horizontal shear.

Data on the present-day stress state in the upper seismogenic crust (approximately 10 km) of the Northern Tien Shan were reported in the earlier study (Rebetsky et al., 2012). In this paper, we provide the data for the entire seismogenic layer down to 25 km depth.

Brief description of the study area

Geology. The study area is located in the Tien Shan region of the Ural-Mongolian orogenic system between two microplates, Tarim in the south and Junggar in the north (Kazakh platform). This mountainous region extends in a ~N–S direction for a distance of more than 2500 km across
Kyrgyzstan, Kazakhstan, Uzbekistan, Tajikistan, and China (Fig. 1). The Tien Shan folded area comprises the Northern Tien Shan Caledonides, Southern Tien Shan Hercynides, and Central Tien Shan Caledonides and Hercynides (Milanovskii, 1996). The Tien Shan folded area is bounded from the south by the Pamir–Himalayan segment of the Mediterranean orogenic belt, which separates the study area from the Hindustan Platform.

The Tien Shan folded area formed a stable platform since the Mesozoic, and perhaps even the Late Cambrian, which has been leveled into a peneplain. During the Late Cenozoic the area experienced a phase of tectonic reactivation, which produced strong relief contrasts, with high- and mid-elevation mountain ranges separated by intermontane and submontane troughs. The structural framework of the Tien Shan is assumed to have been formed as a result of an N–S horizontal shortening since the Oligocene (Makarov, 1977; Nikolaev, 1988). The Neogene–Quaternary was marked by a pronounced local thickening (to 50–60 km underneath mountain ranges) and thinning (to 40–45 km underneath large depressions) of the crust as well as the development of major gravity and heat-flow anomalies.

The Northern Tien Shan (Fig. 2) encloses the northern segments of the Central Tien Shan, which is separated from the Southwestern Tien Shan by the Talas-Fergana fault (not shown in Fig. 2). The orography of the Northern Tien Shan is dominated by generally E–W-trending mountain ranges and intervening depressions formed as a result of folding and thrusting (Chediya, 1986; Makarov, 2012). The major tectonic features of the study area during the neotectonic phase include the Kyrgyz mega-anticline (Kyrgyz Range) and Chuya depression in the north. The Kyrgyz Range is bounded to the south by the Suusamyr, Kochkor, and Dzhumgol depressions separated by small ranges, to the west by the Talas, Greater and Lesser Karatau Ranges, and to the east by the Kungey-Alatau and Terskey-Alatau Ranges divided by the Issyk-Kul intermontane depression.

The mountain ranges are composed primarily of Riphean–Paleozoic rocks (metamorphic, sedimentary, and intrusive) and the depressions are filled with Cenozoic continental sediments. The preorogenic peneplain was lowered to its present elevation of 5–10 km within depressions and uplifted to 6–8 km within high mountain ranges (Chediya, 1986; Shul’ts, 1948). Present-day tectonic movement along active faults occurs at a rate of up to 5 mm/yr. The average rate of uplift of mountain ranges in the Oligocene–Quaternary was lower than that in the Quaternary and Late Pleistocene–Holocene, indicating a marked accelerated in mountain building in recent geologic times (Artyushkov, 2012; Chediya, 1986; Krestnikov et al., 1979; Trifonov et al., 2012). The presence of shear zones with both dextral and sinistral shearing in the Tien Shan recent structure (Buslov et al., 2003; Cobbold and Davy, 1988; England and Molnar, 1997; Makarov, 1977) implies a transpressional tectonic regime.

Seismicity. The main factors characterizing a seismic regime in the Northern Tien Shan are the overall geological setting, the intensity of geodynamic processes, and the presence of the ancient North Tien Shan, Kemin, and Kungey...
faults (Fig. 3). The study area was subject to a series of destructive earthquakes: $M = 8.3$ Chilik, 1889; $M = 6.8$ Zhalalnash-Tyup, 1978; $M = 6.8$ Sarykamysh, 1970; $M = 7.3$ Verny, 1887; $M = 8.2$ Kemin, 1911; $M = 6.4$ Balasagun, 1475; $M = 6.9$ Belovodsk, 1885, and $M = 7.3$ Suusamyr, 1992 (Mamyrov et al., 2009). The data presented in Fig. 3 cover a region larger than the study area and are certainly a more exact representation of the character of the seismicity of the Northern Tien Shan relative to the entire Central Tien Shan.

Smaller magnitude events are characteristic of the seismogenic structures confined to areas of continuous uplift during the recent period. Seismically quiescent or aseismic areas are those parts of depressions where negative movements were not translated into positive ones as the width of the uplift region broadened (Bazavluk and Yudakhin, 1993). In the Northern Tien Shan, earthquake foci are located within the Kemin-Chilik or North Issyk-Kul (Kungey Range), Sarykamysh (not shown in Fig. 2), South Issyk-Kul (Terskey Range), and South Chuya zones with broadly similar seismic activity.

The observed seismic structures are interpreted to be marginal faults or their segments. Most of the earthquake epicenters in the Northern Tien Shan lie in a relatively narrow belt along the northern slope of the Kyrgyz Range, which extends eastward to the eastern plunge of the Kungey Range and Trans-Ili Range in the north (Fig. 3). Despite their high density, the earthquake epicenters tend to be clustered in small areas. The seismicity in the Northern Tien Shan is generally restricted to the upper crust or, rather, the pre-Mesozoic base.

The analysis of the earthquake focal depth distribution revealed that all foci in the study area lie in depths ranges 0–5 and 5–10 km. Deep-focus earthquakes are more definitely confined to particular zones. Almost all large earthquakes in the Northern Issyk-Kul zone are confined to the Trans-Ili and Kungey Alatau ranges where focal depths are over 30 km. This is also true for the Sarykamysh and Kadji-Say seismic regions of the South Issyk-Kul zone with focal depths as great as 25–30 km. The only exception within this zone is the western plunge of the Terskey Range where large earthquakes are almost completely absent (Yudakhin, 1983).

The KNET network (Fig. 3), consisting of 10 stations with Streckeisen STS-2 broadband seismometers was deployed in 1991. The earthquake hypocenters were computed using the location program Hypocenter of Lienert et al. (1986) and the velocity model of Roecker et al. (1993). This program is used to determine the epicentral coordinates, depth, and energy class of the event and to generate an ARC-file (phase data archive) for further computation of focal mechanisms. The mean error in the $P$-wave arrival time data is 0.2–0.3 s, which corresponds to location uncertainty of 1200–1800 m. The error in depth of events within the perimeter of KNET stations is not greater than 5 km (Sycheva and Kuzikov, 2012).

Figure 4 shows the distribution ($I_a$, $I_c$) of the number of earthquakes in different magnitude ranges for the earthquake and focal mechanisms catalogues. These two catalogues include events with magnitudes of 1.5 and 2, respectively. The average annual number of events recorded by KNET is 350–400 (Fig. 4, $I_b$). The peaks in the number of earthquakes recorded by KNET occur in 1996 and 1999. Most earthquakes have hypocenters located in the upper 5 km of the crust and no events are recorded at a depth greater than 25 km (Fig. 4, $I_c$). Focal mechanism solutions were computed for earthquakes occurring at a depth greater than 5 km (Fig. 4, $I_c$), the average number of such earthquakes located per year is about 80.
Fig. 3. The distribution of seismic events based on KNET data for 1994–2012 (7720 events). KNET stations are depicted by the triangles. Magnitudes of earthquakes are shown in the upper left corner. Lakes: I, Issyk-Kul; S, Son-Kel; Ch, Chatyr-Kel.

Fig. 4. Characteristics of seismicity from KNET data. Catalogue of earthquakes: Ia, magnitude distribution; Ib, frequency distribution; Ic, depth distribution. Catalogue of focal mechanisms: IIa, magnitude distribution; IIb, frequency distribution; IIC, depth distribution.
The essential requirement for correct fault-plane solution is good station coverage and taking into account the geometry of the network, we evaluated the well-controlled region in the spatial frames 42°–43° N and 73.75°–76.00° E. The FPFIT computer program (Reasenberg and Oppenheimer, 1985) was used to calculate the focal mechanism solutions. The catalogue of focal mechanisms contains over 1056 earthquakes with magnitudes between 1.16 and 5.40 for the observation period 1994–2012 (Sycheva et al., 2003, 2005, 2009). The only focal mechanisms available are for 2, 2, and 9 events occurred within the study area in 1994, 1995, and 1996, and no solutions are present for the study area in 1997. The KNET network began operating efficiently in 1998.

**Catalogue of earthquake focal mechanisms.** The Northern Tien Shan is characterized by events with highly variable focal mechanisms. As seen in Fig. 5a, most of the P-axes representing the direction of compressional stress are subhorizontal and only 10% of the focal mechanisms tend to dip steeply at 55°. The T-axes (Fig. 5b) have a general gentle dip while 33% of them dipping at a higher angle.

The focal mechanism solutions obtained for the study can be divided into six kinematic types (Rebetsky, 2007a), three of which prevail in the crust of the Northern Tien Shan. Type I focal mechanisms have a subhorizontal compressional (P) axis with a NE orientation and a subvertical tensional (T) axis. This type of focal mechanisms accounts for reverse faulting (Fig. 5). Type II has a subhorizontal tensional (T) axis oriented in the NE direction while a compressional (P) axis dips steeply in the SE direction, indicating normal with strike-slip faulting.

In type III focal mechanisms, both axes are subhorizontal, with a NW orientation of the compressional axis and a NE orientation of the tensional axis, indicating a strike-slip faulting regime. As seen in Fig. 5c, with regard to the stress regime, reverse, strike-slip, and strike-slip reverse faulting prevail throughout the region and account for about 27.8%, 34%, and 15.6%. Normal faults and normal with strike-slip faults account for about 10% and 8.5%, while subvertical dip-slip faults account for about 3.9%.

Figure 6 shows the spatial distribution of focal mechanisms. It can be seen that the study area is characterized by a mixture of different faulting types, e.g., the coexistence of reverse and strike-slip reverse faulting, sometimes with a pure strike-slip faulting. Reverse and strike-slip reverse faulting earthquakes are predominant in the study area and normal faulting events are relatively rare but also distributed in the area. It can be seen in Fig. 6 that both normal and normal with strike-slip faults are the common focal mechanisms in the eastern and western parts of the study area and only rarely present in the central part, which is dominated by reverse and strike-slip reverse faulting events. Well-constrained focal mechanisms of earthquakes with magnitudes between 1.5 and 3.5 were used to reconstruct regional stress data.

**Reconstruction of natural stresses**

**Method for reconstructing natural stresses in the crust of the Tien Shan.** Natural stresses were reconstructed from
seismological data on focal mechanisms of earthquakes using
the method of cataclastic analysis (MCA) of fault kinematics,
which was developed in the Laboratory of Tectnophysics of
the Institute of Physics of the Earth (Rebetsky, 1999, 2003,
2005, 2007a, 2009a,b,c; Rebetsky et al., 2012). The MCA
algorithm includes procedures for calculating not only the
parameters of the stress ellipsoid (orientations of three prin-
cipal stress axes and the Lode–Nadai coefficient), but also all
components of the stress tensor using experimental observa-
tions of rock fracture (Byerlee, 1978; and others), additional
data on the stress released during an earthquake, topography,
and intracrustal heterogeneities. The MCA procedures used in
this study include those used in the first two stages of
reconstruction, i.e., for calculating the parameters of the stress
ellipsoid and reduced values of the maximum shear stress and
effective pressure.

Preliminary analysis of the catalogue focal mechanisms
showed that the distribution of earthquake density and mag-
nitudes allowed stress reconstruction with a lateral averaging
size of 10–15 km at a 0.05° × 0.05° grid. The calculation was
performed for horizontal lines up to 10 km thick, the mid-
points of which are located at depths of 5, 10, 15, and 20 km
(i.e., these lines have depth intersections). As a result, the
stress parameters were determined for 286, 467, 407, and 142
domains, corresponding to crustal depths of 5, 10, 15, and
20 km.

Each homogeneous sample of earthquake focal mechanisms
included at least six events, which allowed us to determine
the directions of principal stresses and the Lode–Nadai
coefficient to an accuracy of 10°–15° and 0.2, respectively.
Homogeneous samples generated at the first stage of stress
ellipsoid calculations (directions of three principal stress axes
and Lode–Nadai coefficient) can be used to calculate the
relative magnitudes of the stresses at the second stage of the
MCA.

It should be emphasized that we present here some new
results, which were not discussed in previous studies (Rebet-
sky et al., 2009, 2010, 2012). The earlier reconstruction used
the catalogue of focal mechanisms for the period 1998–2008,
which includes 889 events. This enabled the calculation of
283, 384, 328, and 176 domains for four crust layers,
respectively. The increasing number of focal mechanisms (by
9%) allowed us to obtain stress data for midcrustal depths,
which make the reconstruction to comply with more tight
requirements for the generation of homogeneous samples of
earthquakes using a smaller size of the averaging window. For
example, we assumed the minimum number of events in a
homogeneous sample to be 5 in the previous calculations and
6 in this study. The practice of stress reconstruction demon-
strates that that an increase in the number of events in the
homogeneous sample of earthquake focal mechanisms might
reduce the spatial variability in the parameters of the stress
state.

Parameter of the stress ellipsoid. The reconstruction
shows that the axes of the algebraically minimum principal
stress (maximum compressional stress) \( \sigma_3 \) have a ~N–S trend
and are oriented at 330°–360° N and 150°–180° S (Fig. 7a).
These axes are always north- and northwest-dipping at a depth
of 0–10 km. In deeper layers, the south-dipping orientation of
these axes is observed for about 30% of the crust domains.
The average dip angle is 0°–20° for about 50% of determina-
tions. In the uppermost layer, the orientation of the \( \sigma_3 \) axes
is subvertical for 10% of the domains, as can be seen in rose
diagrams in the upper left corner of Fig. 7a. Similar domains
are found to be rare at a depth of 5–15 km and completely
absent at depths of 10–20 and 15–25 km.

The upper crust domains with subvertical \( \sigma_3 \) axes largely
correspond to the eastern part of the Chuya depression,
northern and southern slopes of the Kyrgyz Range to the
northeast of the Suusamyr depression.

The axes of the algebraically maximum stresses \( \sigma_1 \)
(mini-
mum compressional or tensional stress) vary considerably
compared with those of the maximum compressional stresses.
Fig. 7 (to be continued).
In the upper two layers, they have a ~E–W trend and are oriented at 240°–270° W and 60°–90° E (Fig. 8a, b). The west-dipping orientation becomes predominant at depths of 10–20 and 15–25 km (Fig. 8c, d). At depths of 0–10 and 5–15 km, the subhorizontal dip (about 20°) of the $\sigma_1$ axes prevails over a steep dip (about 50°–70°). In deeper layers, both high and low dip angles of the $\sigma_1$ axes tend to be dominant. The domains with dominant subvertical $\sigma_1$ axes are found at depths of 10–20 and 15–25 km in the central part of the study area. Such changes in the principal stress orientation from subhorizontal to subvertical can be explained by the evolution of the surface topography of the crust rather than differences in the rock properties.

Based on the types of geodynamic or stress regimes (Fig. 9) the study area is dominated by the combination of horizontal shear and compression. In addition to these two types of stress regimes, there are three areas of localized horizontal extension with subvertical maximum and subhorizontal minimum compressional stress (deviatoric tension) axes, two of which occur in the western segment of the Kyrgyz Range, and the third in the eastern portion of Chuya depression. In the first two areas, the axes of the maximum deviatoric tension are oriented in the ENE direction and in the ~E–W direction in the third area.

The central part of the Northern Tien Shan is dominated by horizontal compression. The crust in this region is bounded by areas dominated by the combination of horizontal shear, compression and extension.

The values of the Lode–Nadai coefficient ranging from –0.2 to 0.2 calculated for the entire Northern Tien Shan region correspond to the stress tensor of pure shear (Fig. 10). At the same time, there are large spatial domains where the Lode–Nadai coefficient is close to +1 and –1, indicating regimes of uniaxial compression and tension.

Characteristic parameters of the stress state in a geographic coordinate system. As noted above, the reconstruction of natural stresses using the algorithm of the first stage of the MCA makes it possible to compute the components of the stress ellipsoid. The major and minor axes on a horizontal plane of the ellipsoid indicate the orientations of maximum and minimum compressive stresses (or tensile stress in some cases) acting in a horizontal direction. Zoback (1992) referred these axes to as $S_{H_{\text{max}}}$ and $S_{H_{\text{min}}}$ (maximum and minimum horizontal compression). The orientation of these axes correlates with the stress field, which can be obtained from geodetic (GPS) measurements.

Figure 11 shows that the maximum horizontal compressional stresses are often in a ~E–W direction and trend 150°–170° S or equivalently 330°–350° N. The most frequent deviations are observed in the upper 0–10 km. In the Chuya depression, ~E–W orientations of the maximum compressional stresses are reported not only for the upper 0–10 km but also for 5–15 km depth.

The results in Fig. 11 can be used in addition to the data on the types of geodynamic regimes (Fig. 9) to determine the direction of maximum shortening in domains with a horizontal compression regime or the direction of minimum shortening in domains with a horizontal extension regime.

Possible stresses exerted by the underlying mantle on the crust can be illustrated in a geographic coordinate system as a depth difference of horizontal motions. The difference in the rates of horizontal displacement of the crust relative to the mantle produces shear stresses. The maximum shear stresses would act on subhorizontal planes and their magnitudes would reflect the difference in the rates of horizontal motions of crustal layers relative to the mantle. The directions of shear stresses would reflect the direction of the relative displacement.

Fig. 7. Horizontal projections of plunges of the principal stress axis $\sigma_3$ for different depth layers: a, 0–10 km; b, 5–15 km; c, 10–20 km; d, 15–25 km. The open circles in the middle of the axes mark subhorizontal orientations (the angle of plunge is less than 7.5°). Rose diagrams (upper left corner) show the predominant trends (averaged over 20°) and plunges (over 10°) of this stress axis.
Fig. 8 (to be continued).
of individual crustal layers or the crust as whole with respect to the mantle. Because such motions could be manifested as underthrusting, the shear stresses acting on horizontal planes should be also referred to as underthrusting shear stresses.

Figure 12 shows the directions and relative magnitudes of underthrusting shear stresses acting on horizontal planes oriented normal to the center of the Earth. As can be seen, these stresses have a mosaic orientation and there are only few domains with a general northward orientation of underthrusting shear stresses at all depths layers. The most uniform stress orientations are observed in the upper 0–10 km. The lower crustal layers here exhibit a south-directed displacement with respect to the uppermost crustal layer. An alternative explanation is that the uppermost crustal layer is displaced to the north with respect to the lower layers. The deeper layers are dominated by the SSW direction of shearing and display a larger scatter of orientations. The number of domains with a ~E–W orientation of shear stresses can essentially increase. At a depth of 10–20 km, the domains where shear stresses are oriented in the east, south, and west directions are present in almost the same proportions. At a depth of 15–25 km, the representative stress orientations are to the south and west. Such a change in the stress orientation in deeper layers suggests that the main concentrator of inhomogeneous horizontal motions occurs in the midcrust and its impact should diminish with depth.

The accuracy of the determination of the orientation of shear stresses acting on a horizontal plane depends on proximity of this plane to the plane of maximum shear stresses. The lighter color in Fig. 12 shows less-constrained orientations of shear stresses.

It should be noted that in the case of the predominance of south and SSW directions of underthrusting shear stresses, the field of these vectors is less uniform than that of subduction zones (Rebetsky, 2009c; Rebetsky and Marinin, 2006a,b; Rebetsky and Tatevosian, 2013). Chaotic orientations of the underthrusting shear stress field are evident, as indicated by a large number of domains with east-, west-, and even north-directed stresses. This stress field persists with depth at all grid levels.

Several explanations exist for the observed dominant orientation of underthrusting shear stresses. The first explanation is that the ~N–S-directed force exerted by the Pamir block allows the crust of the Northern Tien Shan to move north with respect to the more stable mantle and produces the underthrust shear stresses directed to the south along the boundary between the crust and the mantle, which tends to resist this movement. Another explanation is that a ~N–S mantle flow from the Eurasian side is a sufficient mechanism to drag the crust of the Northern Tien Shan and to pile it up over the more stable Pamir. Our data are not adequate to establish which of the two mechanisms operated in reality. Moreover, it is even not clear what kind of data would be most useful to unambiguously answer this question.

The results of our reconstruction are related only to the crust of the Northern Tien Shan, which is affected by the above two loading mechanisms. Comparison of the proposed interpretations with the horizontal displacement models based on surface GPS data (Kostyuk, 2009; Kuzikov and Mukhamediev, 2010; Zubovich et al., 2010) allows us to conclude that both of them are possible. For example, Figure 13a shows crustal movements consistent with the first interpretation, which invokes pressure exerted by the Pamir block to allow the crust of the Northern Tien Shan to move north with respect to the more stable mantle. In this case, a specified location on the Kazakh platform (northern boundary, Fig. 13a) will become a reference point (zero horizontal displacement), with respect to which the displacement vector field is defined. If the horizontal displacement velocity vectors are redrawn to tie a reference point to the southern boundaries of the Central
Fig. 9 (to be continued).
Tien Shan (Fig. 13b), then the maximum southward displacement will be located at the northern boundaries of the Tien Shan region. These displacement velocities will decrease approaching to the southern boundaries of the Tien Shan. This case is consistent with the second interpretation of geodetic data in Fig. 12.

Because both interpretations of geodetic data are possible, they cannot be used to distinguish the genesis of horizontal displacements and identify the cause behind the vector field of underthrusting shear stresses in Fig. 12.

It is worth noting another possible interpretation of geodetic data. Assuming that the zero reference point is located within the Northern Tien Shan (Fig. 13c), then the values of the vectors of displacement velocities will reach their maximum magnitude at its northern and southern boundaries and have opposite directions. Such deformation mechanism is not consistent with the observed directions of underthrusting shear stresses in Fig. 12.

There is another point which it seems necessary to mention and which follows from the geodetic data in Fig. 13. The observed GPS velocities of surface motions in the Northern Tien Shan allow us to draw an important conclusion. The largest variations in velocities occur within intramontane depressions, which is consistent with evidence from geological observations that the piling up of mountain ranges over intramontane and intamontane depressions causes their eventual collapse (Belousov, 1976; Sorskii, 1962).

It should be noted that the horizontal displacement vector field (Fig. 13) has a uniform orientation compared to stress field orientations in Fig. 11. However, this apparent uniformity is deceiving. The stress field should be compared not with the horizontal displacement vector field, but with the incremental strain field calculated from it. The calculation of such deformations for the Northern Tien Shan in the previous study (Kostyuk, 2008; Kostyuk et al., 2006), show that a small averaging window may lead to a noticeable variation in the orientation of the principal incremental strain axes, resulting in the coexistence of lateral triaxial compression and extension domains.

Reduced stress. The results of the second stage of the MCA reconstruction for the crust in the Northern Tien Shan showed that the relative magnitudes of maximum shear stresses and effective confining pressure (the difference between the rock pressure and the fluid pressure in the pore space $p^* = p - p_{fl}$ at $p = -(\sigma_1 + \sigma_2 + \sigma_3)/3$) is nonuniformly distributed in the study area. As seen in Fig. 14, the reduced effective pressure $p^*/\tau_f$ ($\tau_f$ is the strength of cohesion of rocks) has quite a mosaic distribution. In the upper 0–10 km, the domains with the maximum effective pressure correspond to the Kara Moynok Range and southern slope of the central Kyrgyz Range (Fig. 2). However, in deeper layers, such domains are observed in the north of the central segment of the study area (northern slope in the central part of the Kyrgyz Range and Chuya depression).

Large domains (100×100 km) with a relatively high effective pressure adjoin domains where these values are half as high. Figures show that strong earthquakes occur in regions with moderate to low effective pressure.

Because yielding state of rocks is defined by the Coulomb–Mohr equation relating effective normal and shear stresses over the brittle fracture plane, the effective confining pressure is correlated with maximal shear stresses (Fig. 15). Higher values of $p^*/\tau_f$ are found in regions characterized by high
Fig. 10 (to be continued).
values of $\tau/\tau_f$. The regions with low values of $p^*/\tau_f$ are characterized by low values of $\tau/\tau_f$. Such stress distribution can be related to the assumption of the MCA method that the stress state is close to the limiting state in regions of high seismicity and that the cohesive strength $\tau_f$, averaged over a few tens of kilometers, shows little variability within the same region. Figure 15 shows the results of stress monitoring in each individual crust domain, the stress parameters for which are shown in Figs. 6–11. This monitoring provides stress parameters for each domain at different time intervals. Therefore, the number of determinations of the stress state shown in Fig. 15 is much greater than those in the preceding figures.

As seen in Fig. 15, relatively strong earthquakes with $M_w \geq 4.5$ occur in the domains characterized by low effective confining pressure and maximum shear stresses (Rebetsky, 2007b, 2009c; Rebetsky and Marinin, 2006a,b; Rebetsky and Tatevosian, 2013), in which frictional forces over rupture are smaller and brittle failure is developed most effectively.

To consider the stress magnitudes let us return to Fig. 1, which shows the orientations of maximum and minimum effective compression stresses (tectonic stress minus fluid pressure) acting in a horizontal direction and their reduced values, which were normalized to the values of the cohesive strength (the results of the second stage of the MCA). These data show that the maximum lateral compression in the uppermost layer (0–10 km depth) is observed in the Kara Moynok and Sandyk ranges, where both stresses are high and approximately equal in magnitude. The strongest inhomogeneity in the compressive stress acting in the lateral direction is found within the Kochkor depression. The maximum lateral compression here is much larger than the minimum compression. In deeper layers (10 and 15 km depths), the crust of the Kyrgyz Range is subjected to relatively high, uniformly distributed lateral compression.

Assuming that the cohesive strength of the rock remains unchanged with depth, the analysis of the three-dimensional field of the reduced lateral compression shows that the moderate to high compression levels can be achieved at greater depths. Therefore, with increasing depth, lateral compression becomes more differentiated as the overall compression becomes higher.

Conclusions

To summarize, we can conclude that the stress state in the crust of the Northern Tien Shan is not as simple as it may look from a preliminary analysis of GPS observations of surface motions (Fig. 13a). The complexity of the stress state is not visible only from the orientation of the compressive principal stress axes, which has a stable position in the region (Fig. 7) and defines a preferred NNW and SSE dip direction, corresponding to GPS velocity vectors. The complexity of the stress state in the study area is manifested in the areal distribution of the most important parameters characterizing the deformation of a rock massif.

It was shown that the central part of the study area is dominated by horizontal compression, while multiple domains characterized by horizontal shear and superimposed compression or pure horizontal shear are also present. To the west and east, the stress regimes is dominated by horizontal shear, superimposed shear and extension, or pure extension, while the combinations of horizontal shear with compression or pure horizontal compression are rarely observed (Fig. 10).

Understanding the mechanisms for generation of tectonic stresses in the Earth’s crust of mountainous regions has important implications for geodynamic modeling of the evolution of the lithosphere. Measurements and modeling of in situ rock stresses are critical for studying the effects of loads.
Fig. 11 (to be continued).
acting on the lithosphere and lithospheric response to its tectonic loading. A detailed investigation of natural stress fields has been recently made for the crust of the Altai–Sayan (Rebetsky et al., 2012, 2013) and High Asia (Rebetsky and Alekseev, 2014). The results revealed a relationship between the type of the crustal stress state and surface topography (uplifts manifested as mountain ranges and plateaus or depressions).

The results of the new tectonophysical reconstruction for the Northern Tien Shan show that the crust in the central part of the study area where the topography is represented by high-elevation mountain ranges is dominated by horizontal compression. The crust of the Suusamyr and Kochkor depressions is characterized by a horizontal shear regime. The eastern termination of the Chuya depression and the western segment of the Kyrgyz Range are dominated by horizontal extension. These data are consistent with the previous results. Of special interest are the two crust domains dominated by horizontal extension, which were identified within the Kyrgyz Range in the northwestern segment of the study area (Fig. 9a). These domains are located in opposite sectors of a ~E–W-trending fault, which is situated south of the Chonkurchak fault and dips to the north crosscutting the spurs of the northern slope of the Kyrgyz Range. This unnamed fault is shown on many local maps (Kal’metyeva et al., 2009; Mikel’chuk, 2000). Because this fault is known to traverse the upper reaches of the river catchments, we suggest it to be named “Verkhovoy” (Fig. 2). This fault segment with a highly inhomogeneous stress state reaches some 60 km in size. Because the ~15 km averaging scale was chosen for the reconstruction of natural stresses, the fault length of about 60 km makes it possible to identify the inhomogeneity of the stress state.

The orientations of the principal stress axes in the vicinity of the Verkhovoy fault (Figs. 7a and 8a) suggest that this fault is probably affected by dextral shear. This is consistent with evidence on the dextral component of strike-slip reverse slip along a major E–W fault that crosscuts the southern slope of the Kyrgyz Range and dips to the south similar to the Verkhovoy fault. This is clearly seen in Fig. 11 presented in the study of Kal’metyeva et al. (2009).

As suggested by Osokina (1987), there are two domains with uniform compression (resulting in horizontal shearing) and two domains with uniform extension or higher and uniformly oriented compressive stresses that are expected near strike-slip fault terminations. If this interpretation of the results of stress reconstruction is consistent with the real process, this fault segment can be regarded as an active fault showing a tendency to dextral slip either due to creep or seismotectonic flow.

The predominant south-southwest orientation of underthrusting shear stresses acting on horizontal planes can be explained by the action of pressure exerted on the Northern Tien Shan from south to north. However, this explanation is not the only possible one and requires further investigations. It is important to note that there are large domains or crustal blocks, which are characterized by differently oriented stresses (underthrusting shear stresses) exerted by the mantle on the crust (Fig. 12). This fact is possibly related to the absence of a uniaxial shearing motion of the crust near the Moho or may result from a rotation of crustal blocks. The rotation is hypothesized to result in shearing stresses of opposite directions and signs acting on horizontal planes at the deep crustal level.

In addition, large domains of high or low effective confining pressure have been detected in the crust of the

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**Fig. 11.** Orientations of maximum ($SH_{max}$, thick lines) and minimum ($SH_{min}$, thin lines) compressive stresses acting on a horizontal plane and their reduced values (different shades of grey) normalized to the cohesive strength, $SH_{max}/\tau_f$ and $SH_{min}/\tau_f$, for different depth layers: a, 0–10 km; b, 5–15 km; c, 10–20 km; d, 15–25 km. The rose diagram in the bottom right corner shows the dominant trend of the maximum horizontal compressive stress; the diagram in the top part of the figure shows the reduced values of stresses (left $SH_{max}/\tau_f$, right $SH_{min}/\tau_f$).
Fig. 12 (to be continued).
Fig. 12. Orientations of underthrusting shear stresses $\tau_z$ on the horizontal plane with the normal to the center of the Earth and their relative values (different shades of gray) normalized to the values of the maximum shear stresses, $\tau_z / |\tau|$, for different depth layers: $a$, 0–10 km; $b$, 5–15 km; $c$, 10–20 km; $d$, 15–25 km. The rose diagram in the bottom part of the figure shows the predominant azimuths of the maximum horizontal compressive stress; the diagram in the top part of the figure shows the distribution of values of $\tau_z / |\tau|$.

Fig. 13. GPS velocity vectors of horizontal displacement in the Northern Tien Shan for different reference point (zero displacement) locations (asterisk): $a$, at the northern boundary of the figure; $b$, at the southern boundary of the figure; $c$, in the center of the figure. Tight vector clustering denotes the location of local GPS scientific stations of the Russian Academy of Sciences, Bishkek.
Fig. 14 (to be continued).
Fig. 14. Areal distribution of the relative component of the effective pressure normalized to the internal cohesion $p^*/\tau_f$ for different depth layers: a, 0–10 km; b, 5–15 km; c, 10–20 km; d, 15–25 km. the diagram in the top part of the figure show the distribution of values of $\tau_f/\tau_f$ and $p^*/\tau_f$.

Fig. 15. Relationship between reduced effective pressure and maximum shear stresses for different depth layers: a, 0–10 km; b, 5–15 km; c, 10–20 km; d, 15–25 km. The asterisks mark the domains of earthquakes with magnitudes greater than 5.
Northern Tien Shan. It was shown that relatively strong earthquakes are correlated with zones with low levels of effective pressure. This is in good agreement with the present-day stress state of other seismically active regions (Rebetsky, 2007b).

As noted above, this contribution represents a second attempt to reconstruct the pattern of the crustal stresses (Rebetsky et al., 2012), by assembling most of the KNET seismic network data on earthquake focal mechanisms collected over a four-year period. An updated focal mechanism catalogue was used to refine the results of the previous stress reconstruction and obtain the parameters of the stress state for vast crustal domains where such data were missing. The stable operation of the KNET operations will enable the development of the MCA algorithms for a more accurate determination of the strength parameters of rocks.

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