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Tectonophysical Paleostress Reconstructions: Interpretation Challenges and Possible Solutions

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Abstract—Paleostress inversion may be ambiguous when several markedly different local stress states are inferred for a group of outcrops. Attempts of reconstructing regional stress regimes (compressional, extensional, or strike-slip) by selecting local principal stresses of proximal directions turn out to have poor grounds. Each stress permutation (e.g., extension to compression) attendant with buildup of large irreversible strain (fault slip) requires a 5–6 kbar change in middle-crust horizontal stress and at least 50 Myr stable and uniform loading. Tectonophysical stress reconstructions for present active intracontinental orogens show heterogeneous patterns: Stress directions in uplifts are different from those in large intermontane basins and even in relatively subsided parts of mountain ranges or in adjacent uplifted zones (e.g., a plateau and a range). Paleostresses should be interpreted with reference to present stress fields in the respective areas. It is suggested to reconstruct regional stresses using the approach of L. Sim implying search for "common stress fields". Another important technique is to trace stress changes in specific structures (large folds etc.) in the course of their evolution. The available data indicate correlation and bipolarity of stress states in large basins and uplifts.

Keywords: slickensides, stress, tectonophysics, shear, fold, deformation phase, paleostress

INTRODUCTION

Major lithospheric structures, such as zones of subduction, collision, and rifting, which Dobretsov et al. (2013) discussed in terms of plate and plume tectonics, originate and evolve under regional-scale principal stresses of extension or compression in horizontal planes depending, in their turn, on the interplay of external and internal forces. Studies of regional stress patterns are indispensable for understanding global mechanisms of deformation.

Knowledge of regional deformation mechanisms stems from crustal stress data collected over large areas of hundreds or even thousands of kilometers. In this respect, it is important to properly constrain the spatial limits of affected areas. Many case studies focus on specific uplifts, basins, or foredeeps and thus overlook the fact that positive and negative geological structures often form dynamic couples. Separate consideration of these structures may lead to misinterpretation of their deformation mechanisms, as we found out from field stress studies (Rebetsky et al., 2013, 2016; Rebetsky, 2015). It was noted long ago (Karpinsky, 1919) that a rapidly growing uplift exposed to erosion always borders a subsiding basin that accommodates sediments shed from its slopes. In this context, zones of intracontinental orogens and intermontane basins correspond to zones of plate convergence and spreading, respectively.

In tectonophysics, crustal stress is studied using seismological (earthquake focal mechanisms) and geological (fault slip) data. The former represent the current state while slickenside and striation patterns are used for paleostress inversion and allow insights into the geological past.

However, paleostress reconstructions are challenging because they refer to past events of brittle failure followed by prolonged post-failure deformation. In this paper we discuss possible ways of interpreting reconstructed paleostresses which differ in direction or geodynamic type in several nearby sites or even within the same outcrop. In these cases, the problem is solved for spatially and/or temporally heterogeneous regional stress and strain, and the solution quality influences the idea of regional tectonic history.

PALEOSTRESS ANALYSIS: DATA INTERPRETATION

After the studies by Anderson (1951) and Gzovsky (1954), fault slip data sets have been used for estimating the parameters of the causative stress and surface slickenside lineations have implications for slip geometry and direction. The two types of data are used, respectively, in two ways of paleostress inversion.

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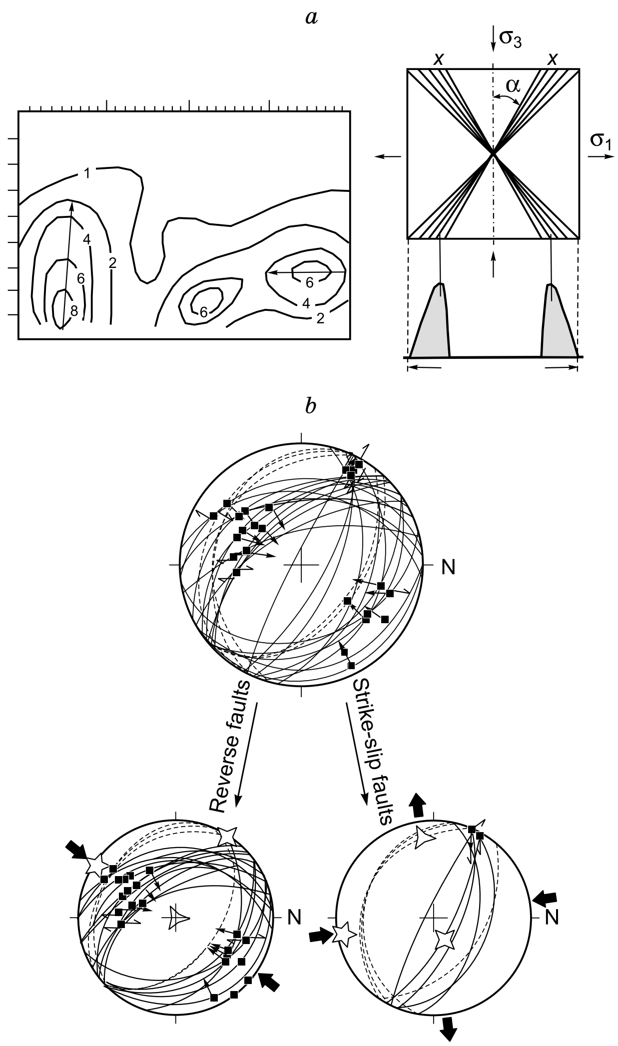

Fig. 1. Examples of stress events distinguished by the methods of Nikolaev (*a*) and Angelier (*b*). In the method of Nikolaev (1992), stress states are identified based on maximum density of fracture poles (density contour lines are from 1 to 8 for (*a*) in the left), which have long "tails" along low density gradient (on the right). σ_3 is maximum compression. In the method of Angelier (1984), stress events are distinguished according to slip geometry.

We analyze paleostresses reconstructed using orientations of slip planes and striation (slickenside data) by the methods of Gushchenko (1975) and Angelier (1984) largely used in Russia and abroad. The new STRESSgeol software is based on cataclastic analysis of slip data (Rebetsky, 2003) and is applied to slickensides as indicators of deformation (Rebetsky et al., 2017a).

Historic background. The methods of Gushchenko (1975) and Angelier (1984) differ in ways of distinguishing stress states from a set of slickensides. Both approaches postulate that new fractures predominant in a mass of previously deformed rocks correspond to conjugate slip planes under active stress. This hypothesis is basically reasonable, unlike another one in the method of Angelier that stress states can be reconstructed from a group of slickensides if it includes at least two sets of fractures with prevalent normal, reverse, and strike slip components. In fact, the method of Angelier, as it was implemented by him and his followers, is a certain modification of Gzovsky's conjugate pairs (Gzovsky, 1954) with two fracture sets rather than two individual fractures.

Different deformation events in Gushchenko's kinematic method are identified assuming that stress states are identified in rocks that were fractured before the onset of the current event. Therefore, deformation events are distinguished by selecting slickensides that fit a certain stress state while the remaining slickensides are tested for evidence of another stress state. If possible, two or more stress states can be determined at a single site. The algorithm of Rebetsky et al. (2017a) is close to Gushchenko's approach, but it additionally can evaluate the quality of identifying homogeneous subsets of slickensides in a larger sample. The subsets and the stress states that show the maximum dissipation of mechanic energy are found by iteration.

Ambiguity of stress inversion in a single outcrop. Paleostress inversion often yields several principal stress directions (with difference of 45° to 90°) for a single outcrop, when fractures in a nearby or the same outcrop differ in slip plane orientation or in slip geometry measurable in slickensides (Fig. 1). Or, sometimes a single slip plane includes slickensides of two or more directions corresponding to reverse, normal or dextral/sinistral strike slip geometries.

Note that principal stress orientations obtained for past events of millions or tens of millions years ago require correction (Bergerat et al., 2007) as any specific local slip or slickenside originally formed 1–3 km or deeper under the surface and the deformed rocks were then exhumed, not necessarily by a simple vertical motion but rather experienced rotations during tectonic flow and later denudation. The original position of rock mass at the time of deformation can be inferred from bedding angles and parameters of local folds (hinges) assuming horizontal bedding at depths.

Having obtained two different principal stress directions for one point in a specific outcrop, a geologist has to time each stress state. In the method based uniquely on slip plane orientation (methods of Gzovsky, Parfenov, and Nikolaev), strain and stress are assumed to be synchronous. In this case, the age of deformed rocks can provide only the lower time constraint for the obtained paleostress. Fractures can be timed unambiguously if they have geological markers on their surfaces. If stresses are reconstructed from striation, one has to bear in mind that fracture surfaces may experience deformation during later stress events, and the ages of striation and slip may be different. To interpret paleostress inversion results, it is sufficient to determine a succession of stress states without precise dating.

According to our experience, an outcrop or a local structure can expose signatures of no more than two or three stress states. The number of events may be greater in the reports that use data from several distant parts of a region.

Stress field. The results of paleostress inversion are presented as maps showing trends of principal stress axes. Tectonic settings are often analyzed proceeding from directions of maximum and minimum compression (Gushchenko, 1975; Rebetsky, 2003). They are often defined, respectively, as principal compression and principal extension or simply compression and extension, because their deviators are the maximum deviatory compression and extension. Otherwise, mapping uses directions of maximum horizontal compression (Zoback et al., 1992) or special variables that provide integrate characteristics of principle stresses and the respective regime (Delvaux et al., 1995).

The stress field concept means an assemblage of coeval stress states at different points of the geological space that represent uniform or nonuniform deformation of the given crust volume (Rebetsky, 2003) rather than data from one outcrop. The behavior of spatial changes in stress tensor is limited by the requirement of satisfying the equilibrium equations (Rebetsky, 1991).

A reconstructed paleostress field consisting of stress states quite uniformly distributed in space appears reasonable, even if principal stresses differ slightly in directions (Delvaux et al., 2013) because of faults. However, the lack of integrity in a stress field comprising several states with markedly different principal stress directions (Bergerat et al., 2007; Delvaux et al., 2013; Gonchar, 2017) would mean a complex stress history of several events. Below we check whether this approach is justified by the potentiality of the methods for paleostress studies.

As we noted above, original fracture and striation in slickenside data often have different ages, which requires additional assumptions on deformation models for specific regions for interpretation of paleostresses reconstructed with the methods of Gushchenko and Angelier. Since the 1980s, such results have been interpreted with reference to plate tectonic postulates of horizontal compression caused by plate convergence and horizontal extension associated with spreading (Turcotte and Schubert, 1982) (Fig. 2). According to the modern views, plate motions of this kind produce the respective stresses in zones of interaction (convergence or spreading) which propagate to long distances, as in the case

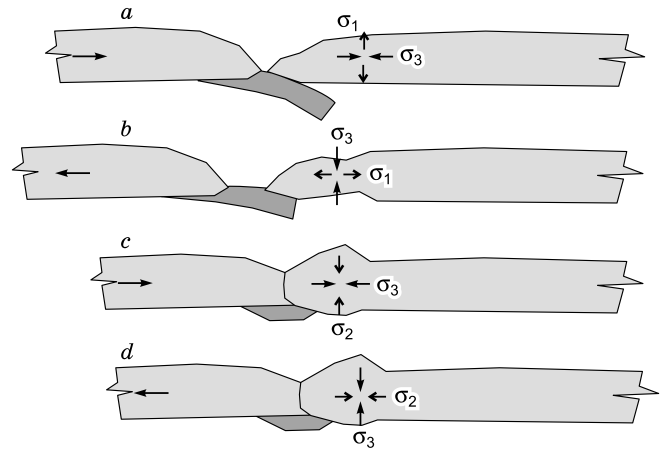

Fig. 2. Geodynamic changes at convergent boundaries. *a*, Horizontal compression (vertical maximum extension) at the onset of subduction (oceanic plate subducting beneath continental plate); *b*, horizontal extension at inverse motion of oceanic plate; *c*, horizontal compression; minimum compression along convergent boundary (vertical intermediate stress) at another convergence event: collision and mountain growth; *d*, horizontal extension; horizontal compression reduced to intermediate principal stress at another inversion event.

of the India–Eurasia collision (Molnar and Tapponnier, 1975) invoked to explain crustal compression in Asia over thousands of kilometers off the main suture.

In these approaches, a study region as a whole is assumed to experience similar stress regimes at different evolution stages, i.e., to have the same geodynamic type of stress in its different parts, with minor variations in strike and dip of principal horizontal stress axes. It is also assumed by default that such regime covers the whole crust or at least the upper seismogenic crust (Zoback, 1992).

Paleostress interpretation: a case study of Northwestern Caucasus. Paleostresses in the Northwestern Caucasus and Crimea regions, along the Black Sea shore and in the mountains, were reconstructed (Saintot and Angelier, 2002) using brittle structural data. Inversion of 2000 structural data by the method of Angelier (1984) allowed 124 local stress states which are presented as upper hemisphere projections of principal stress axes in Fig. 3. The maximum

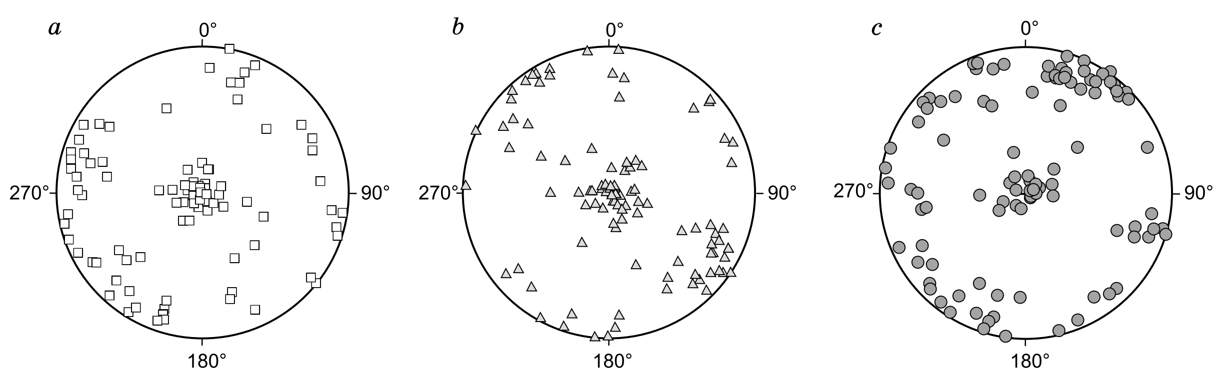

Fig. 3. Stereoplots (upper hemisphere projection) of principal stress directions for all local stress states in NW Caucasus (Saintot and Angelier, 2002). *a*, Maximum extension; *b*, intermediate principal stress; *c*, maximum compression.

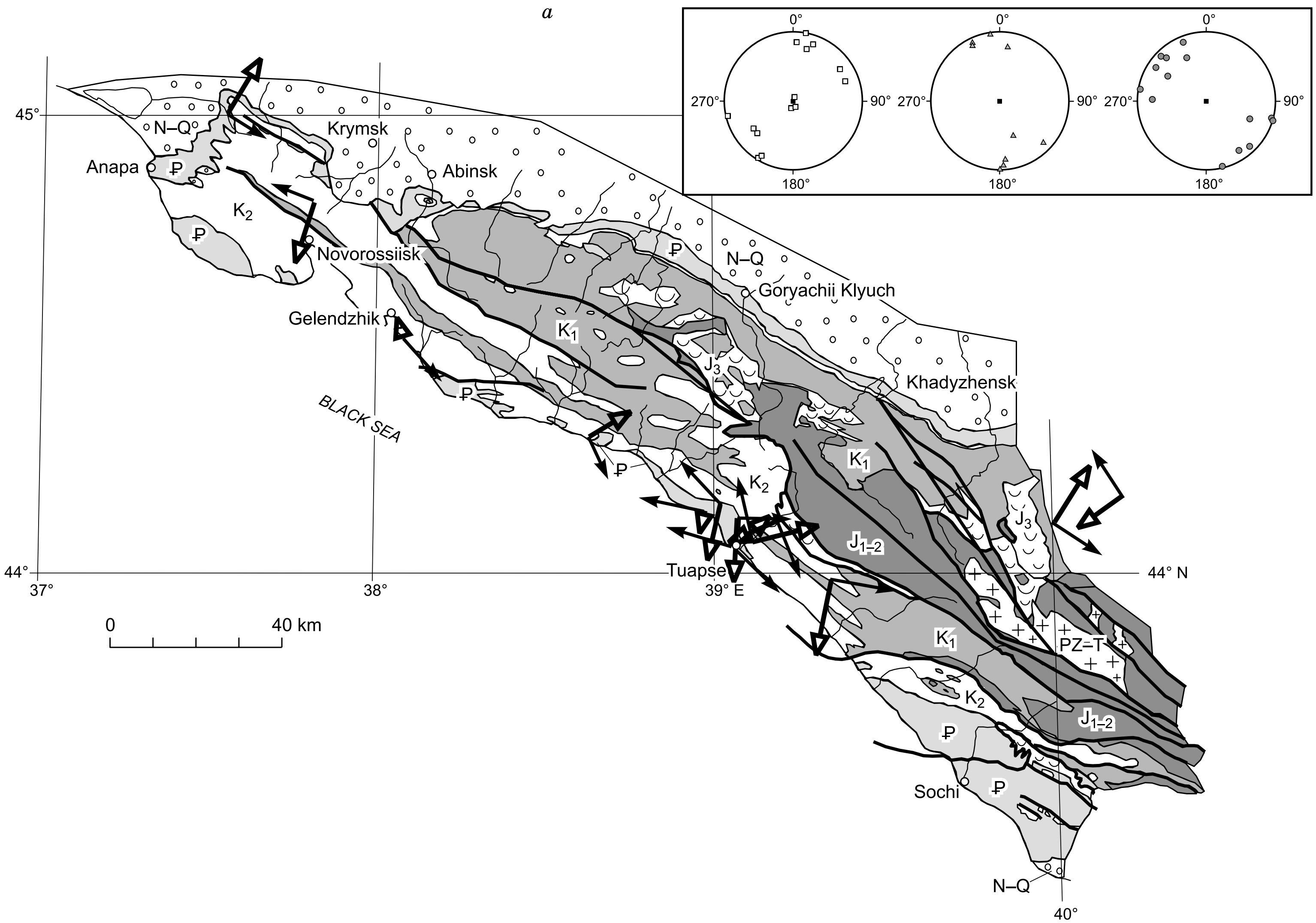

Fig. 4. Maximum compression directions for two stress events: horizontal strike slip (*a*) and compression (*b*), according to (Saintot and Angelier, 2002), with additionally analyzed three principal stress directions in stereoplots (upper hemisphere projections). *1–7*, sediments of different ages: Neogene–Anthropogene (*1*), Paleogene (*2*), Upper Cretaceous (*3*), Lower Cretaceous (*4*), Upper Jurassic and Callovian (*5*), Lower and Middle Jurassic (*6*), Paleozoic (*7*); *8*, faults; *9*, *10*, maximum compression (*9*) and extension (*10*) directions (dip projections). Inset in right top corner shows projections of maximum deviatoric extension (squares) and intermediate (triangles) and maximum (circles) compression.

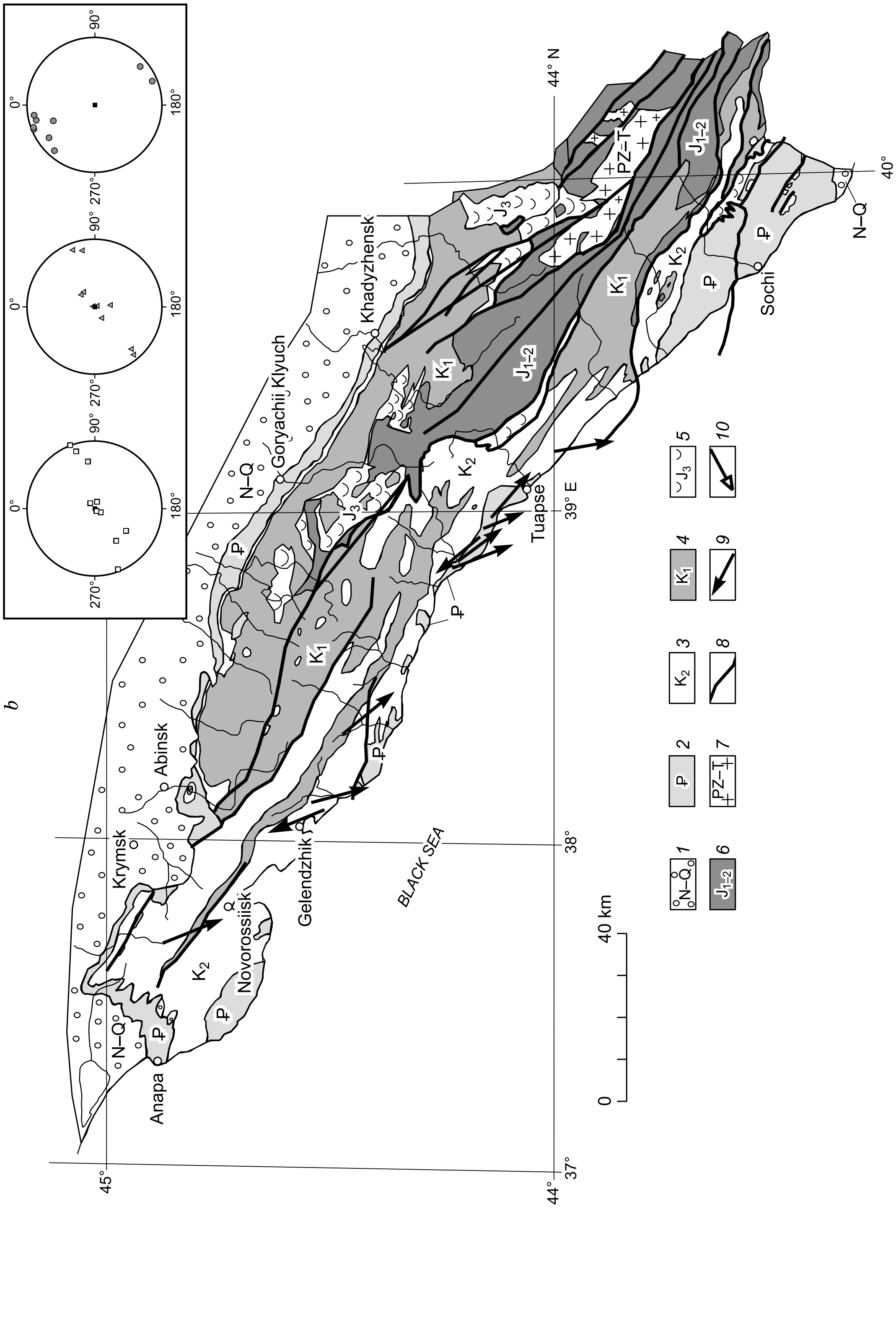

Fig. 4 (*continued*).

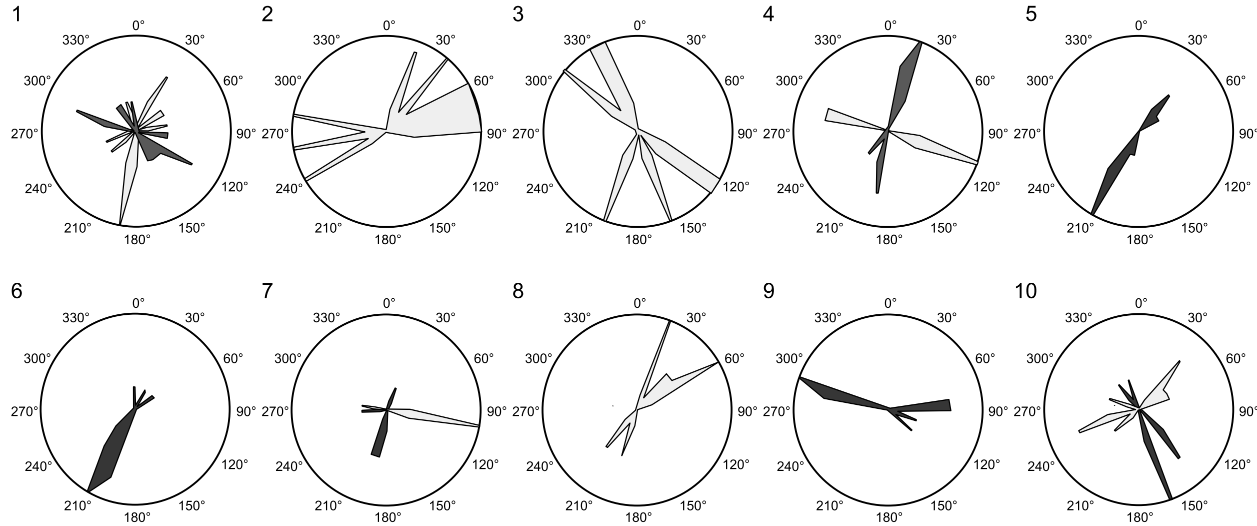

Fig. 5. Rose diagrams of principal stress directions for ten stress states of (Saintot and Angelier, 2002). 1, strike slip (stress change to horizontal compression), σ_3 (dark gray) trending NW and SE; 2, horizontal extension, σ_1 (light gray) trending ENE and WSW; 3, horizontal extension, σ_1 trending SE and NW; 4, strike slip, σ_3 mainly trending NNE; 5, horizontal compression, σ_3 mainly trending SW; 6, horizontal compression, σ_3 trending SW; 7, strike slip, σ_3 trending SSW; 8, horizontal extension, σ_1 trending ENE; 9, transpression, σ_3 mainly trending WNW; 10, transpression, σ_3 mainly trending SSW. σ_1, maximum extension; σ_3, maximum compression.

compression and extension, as well as the intermediate principal stress axes, make up two groups: an almost isometrical one in the center of the hemisphere (about 20°–30°) and a concentric group at the bottom (30°–35°); few stress states fall between the two groups.

The inversion results were interpreted in terms of plate tectonics. All stress determinations were grouped into time intervals according to directions of principal horizontal stresses which made up ten stress states corresponding to compression, strike-slip, and extension in the horizontal plane (Saintot and Angelier, 2002). See two examples in Fig. 4.

The approach of Saintot and Angelier (2002) was based on the assumption that principal stress directions in a stress filed, which show the least spatial variance and are regionally continuous, are related to a certain tectonic event. Specific events were attributed to certain stress fields proceeding from agreement between the filed parameters and the local setting. Note that the stress field concept in rock mechanics refers to spatial change in stress parameters which satisfy the equilibrium equations. This requirement limits spatial variations in both direction and magnitude of principal stresses. However, equilibrium equations can be satisfied, i.e., stress field remains the same, also when stress directions change and even become opposite (see below).

All stress regimes obtained by Saintot and Angelier (2002) are presented in Fig. 5 as stereoplots of average maximum compression or extension directions in a succession based on plate tectonic considerations. In the course of tectonic history, at least one principal stress axis in NW Caucasus changed from nearly horizontal to nearly vertical and back. The maximum compression and extension axes permuted four times, and each changed direction laterally, for angles about 90°, at least once.

Given such permutation of stress directions, the magnitude of horizontal stress can be expected to change as well (vertical stress approaches the overburden pressure), which would require some time (Markov, 1977; Goodman, 1980; Brade and Bzown, 2004). According to Saintot and Angelier (2002), the stress state would change ten times within a time span of 70–100 Ma (from Late Cretaceous to Present). The question arises whether the stress magnitude can change as much as to convert maximum compression into maximum extension in the same direction (Fig. 5, events 1–4).

A change from horizontal extension to compression or back within 20 km of crust would require additional stress of 5–6 kbar (Rebetsky, 2015), because the maximum shear stress has to reach the yield value rather than simply change the principal stress direction (for which 2–3 kbar would be enough). Each event of this kind would last at least 10–20 Myr, as one may estimate assuming that the strain rates for the past 100 Myr were about the present values ($n\ 10^{-9}\ yr^{-1}$) and that all strain caused brittle failure (actually, only 10–30% does). The above timing would be actually twice smaller given that slip occurs at depths of 5–7 km (stress at greater depths is more stable) and the slickensides are exhumed afterwards. The processes for the time span we obtained can only create prerequisites for large strain. Notable crust shortening and 15–30% thickening in the orogen would require additional 30–50 Myr. Thus, three or four stress events hardly can fit into a span of 100 Myr, i.e., the duration of deformation obtained with very high strain rates about those at present (Trifonov et al., 2012) is at the limit of the estimates by Saintot and Angelier (2002).

Note that changes in the stress regime and direction of maximum compression in the NW Caucasus have been related to two or three events responsible for the formation of certain fracture sets (Rastsvetaev et al., 1999, 2010; Marinin, 2003, 2013; Marinin and Rastsvetaev, 2008; Marinin and Sim, 2015; Marinin and Tveritinova, 2016).

Paleostress interpretation: a case study of the Baikal rift. Similar paleostress data were reported by Delvaux et al. (1995, 1997) for the Baikal rift system, with main stress regimes recorded in the position of principal compression and extension axes. Compression was predominant in the Paleozoic and Mesozoic periods prior to rifting, and the latter was associated with extension events (protorift, active rift, and modern rifting). Note that those events were punctuated by more or less strong local stress states of strike slip when both compression and extension were quasi-horizontal.

The direction of principal compression in the Baikal region changed from NW to W–E (a difference about 45°)

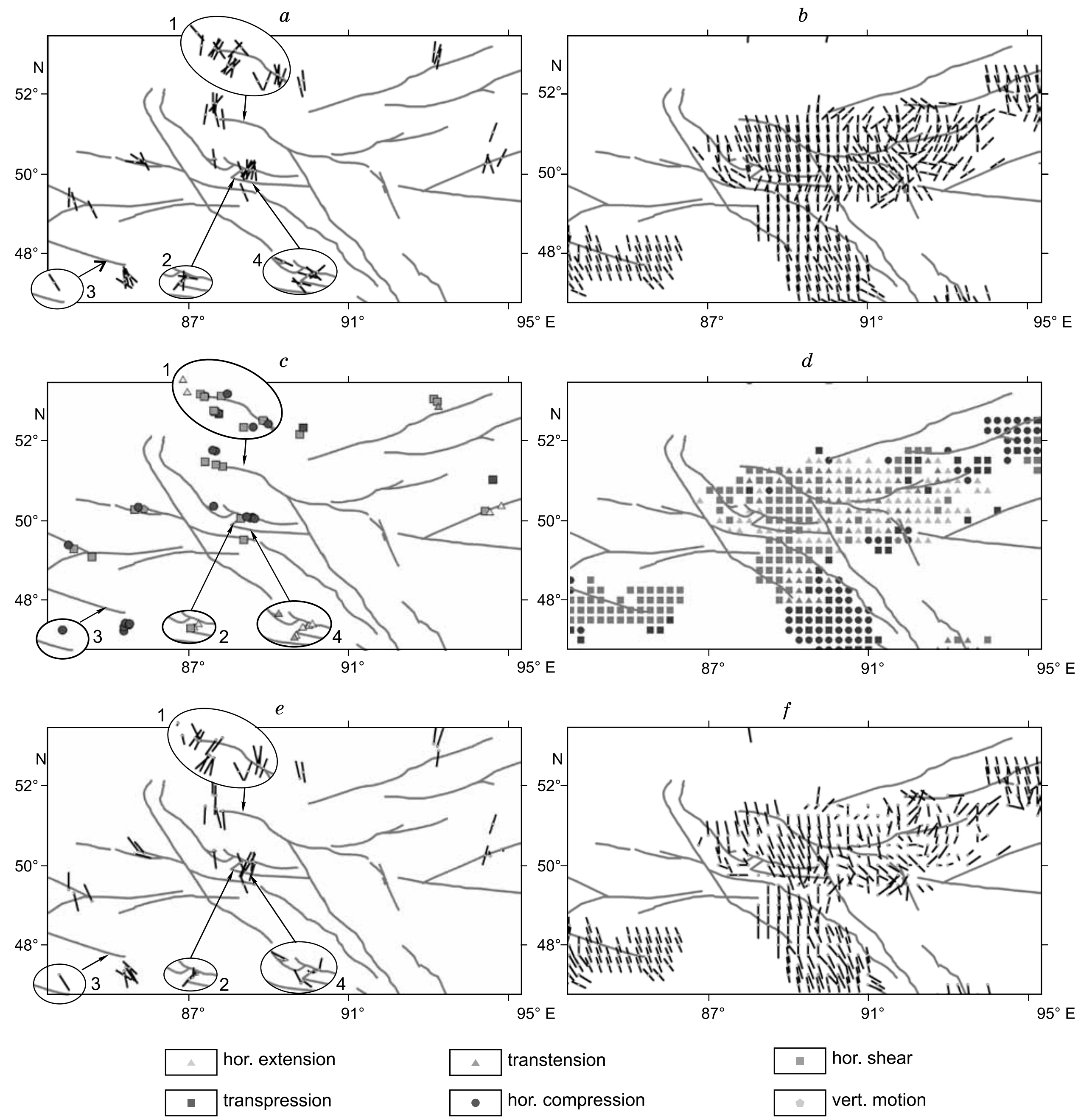

Fig. 6. Stress pattern in the Altai mountain area, according to fault slip (*a*, *c*, *e*) and earthquake mechanism (*b*, *d*, *f*) data ((Delvaux et al., 2013) and (Rebetsky et al., 2012, 2013), respectively). *a*, *b*, Maximum compression; *c*, *d*, stress regimes; *e*, *f*, maximum stress directions. *a*, *c*, *d*, Main pattern for Late Pliocene–Early Pleistocene; insets 1, 2, 3: Middle Pleistocene–Holocene; inset 4: Eocene–Miocene.

during Paleozoic stages 1 and 2 recorded in stress states along most of the northern Baikal side (Fig. 4*b* and *c* from (Delvaux et al., 1995)). The available data for Paleozoic stage 1, with inferred N–S and NE compression, are restricted to the areas of Ol'khon Island and its surroundings. The data on the Mesozoic and protorift stages with N–NE horizontal compression (Delvaux et al., 1995, 1997) refer, respectively, to the northwestern flank and central part of the rift system. The data on stress states for different stages of the region history are unevenly distributed, and the difference in stress directions reaches 45°–60°. Data for all four compression stages are available for a single site of the northern rift shoulder (Ol'kon area).

The setting of NW extension during the active rifting stage (Delvaux et al., 1997) was identified only in outcrops from the northern and southern Baikal sides and along faults in the Barguzin Range. Evidence of NE maximum compression during the same event is known from two sites in Transbaikalia which show stress directions similar to those in the Mesozoic. Delvaux et al. (1997) provide no explanation for the lack of stable extension in Transbaikalia at the time of rift origin and evolution. Neither there are slickenside data for that area which would allow determination of stress corresponding to Paleozoic compression.

Thus, Delvaux et al. (1995, 1997) likewise applied the approach of differentiating stress states with proximal directions of principal compression and extension according to tectonic settings, as one can see in their table of regional stress tensors.

Parfeevets and San'kov (2006) applied a similar approach to reconstruct paleostress regimes in the southwestern extension of the Baikal rift system in the Hövsgöl and Tunka basins, and obtained similar results. They distinguished three deformation events: early W–E extension, early W–NW compression, and late strike slip (NE maximum compression).

This result of Parfeevets and San'kov (2006) is in line with the combination of compression and extension in the northern and southern sides of Lake Baikal reported by Delvaux et al. (1995, 1997). Note that the sites of structural measurements mostly occur at the boundaries between rift basins and their flanking mountains, for obvious reasons of accessibility and exposure. Structures of different genesis may form in these transitional zones, with paleostress signatures, as a result of lateral displacement of the basin-range boundary. Below we consider processes in these zones that may be responsible for periodic stress change (see Discussion).

The reconstructed local paleostresses for the Baikal rift are generally consistent with its stress regime at the current evolution stage. Horizontal extension is common to all crust zones exposed to subsidence while zones of uplift evolve under quasi-horizontal maximum compression. The transitional zones, where the sense of vertical movements changes between subsidence and uplift, may store record of both horizontal compression and extension regimes.

Another point is to see whether the orientation of principal stresses (and geodynamic regime) should be necessarily quasi-permanent over the region during each stage. Note that stress heterogeneity (and respective stress direction change) is due not only to heterogeneity in crust properties but also to the specificity of deformation which may be more complex than simple lateral compression or extension (Myagkov and Rebetsky, 2016).

Paleostress interpretation: a case study of the Altai. In a later publication, Delvaux et al. (2013) distinguished three stress events for the Altai area: Eocene–Oligocene, Late Pliocene–Early Pleistocene, and Middle Pleistocene–Holocene (Fig. 6*a*, *c*). The Eocene–Oligocene stress pattern is heterogeneous in the eastern Chuya basin, where the crust experiences horizontal extension while maximum horizontal compression axis trends W–NW. Stresses in two other events correspond to transpression at N–S (Late Pliocene–Early Pleistocene) and N–NE (Middle Pleistocene-Holocene) maximum compression. For each regime, the axes of compression may be up to 90° different within the same outcrops.

Thus, Delvaux et al. (2013) no longer strictly adheres to the principle of stable principal stress trends and geodynamic regimes in distinguishing stress events.

Comparison of paleostresses reported by Delvaux et al. (2013) with modern stress patterns inferred from seismological data (Rebetsky et al., 2012, 2013) shows that the paleostresses at different sites are either similar or slightly different from the modern setting (Fig. 6*b*, *d*).

If Delvaux et al. (2013) distinguished the stress events proceeding from mineralogical criteria, the fragment of the orogen they studied has not change much in its stress state since the Oligocene (i.e., for about 30 Myr).

TYPICAL SPATIAL HETEROGENEITY OF CRUSTAL STRESS AND STRAIN

The possibility for the formation of heterogeneous crustal stress and strain is discussed below with reference to theoretical tectonophysical studies, as well as to data of GPS, underground mining, and field structural measurements for current stress estimates. The main focus is on local stress changes that correspond to different geodynamic regimes at the same stress mechanism.

Theoretical tectonophysics. Locally heterogeneous stress patterns were considered in a theoretical study by Osokina (2008) for a regional state corresponding to a strike slip regime. The heterogeneity arises near the end of a vertical shear (Fig. 7) and is controlled by relative magnitudes of horizontal principal stresses and the lithostatic vertical stress. Different types of stress may coexist within a small area and principal stresses along the same trajectory may switch between extension and compression across the shear.

Another example of theoretically investigated lateral stress variations (Goncharov, 1988) concerns an advective flow in a layer driven by density instability (Turcotte and Schubert, 1985) which produces near-surface zones of horizontal extension above the upwelling flow part and horizontal compression above downwelling, while the layer remains invariable in length and width. In the case of a flow deep in the crust, near-surface stress may differ from that deeper in the layer. Thus, theoretical calculations show that local stresses may vary from extension to compression at the same mechanism of external loading.

GPS data. GPS data can provide information on lateral crust deformation. Data processing begins with estimating three lateral strain components that act upon the crust surface and then proceeds to the directions and magnitudes of principal lateral strain. The principal strain axes in Central Asia often trend along maximum horizontal shortening and elongation, i.e., strike-slip is the predominant deformation regime in the region (San'kov et al., 2011). In a few cases, intermediate principal strain is observed in the lateral direction, and the total lateral strain may be positive or negative, corresponding to elongation or shortening, respectively.

The results of San'kov et al. (2011) presented as triangles of elongation or shortening (Fig. 8) show that zones of local extension (basins) and compression (uplifts) may coexist within the same geological structures of the Central Asian orogen. The quality of stress determination from GPS data in this case depends strongly on the network size and on the fact whether the triangles fall within structures of the same geodynamic regime.

Rock mechanics. Natural stress measurements in outcrops for mining applications are performed *in-situ*, within the upper 1–3 km of the crust, to characterize unloading and hydraulic fracture of boreholes (Peive and Kropotkin, 1973). These measurements show that geodynamic stress regimes correlate with directions of vertical movements.

Horizontal compression along σ_x and σ_y ($\sigma_{x,\,y}$) is mainly about 75% smaller than vertical compression (Fig. 9) in basins and in zones of slow subsidence (Markov, 1977). On the other hand, horizontal compression is commonly about 60% larger than vertical one in basement rocks exhumed as a result of uplift (Markov, 1980; Kozyrev et al., 1996). Furthermore, horizontal compression in orogenic areas and shields is greater than in sediments of cratonic areas at the same depths.

Markov (1985) cited examples of the Khibiny and Lovozero mountains in the Kola Peninsula as regimes of horizontal compression in zones of past and present uplift and related rapid denudation. Following Voight and Pierre (1974), Markov (1985) attributed high horizontal compression to residual stress associated with elastic stress release caused by denudation; residual stress was analyzed theoretically in our recent study (Rebetsky et al., 2011, 2017b). Horizontal compression in orebodies in the Khibiny Mountains coexists with horizontal extension in the host rocks (Zhirov et al., 2016). Thus, field data confirm that horizontal compression and extension can coexist within a single structure.

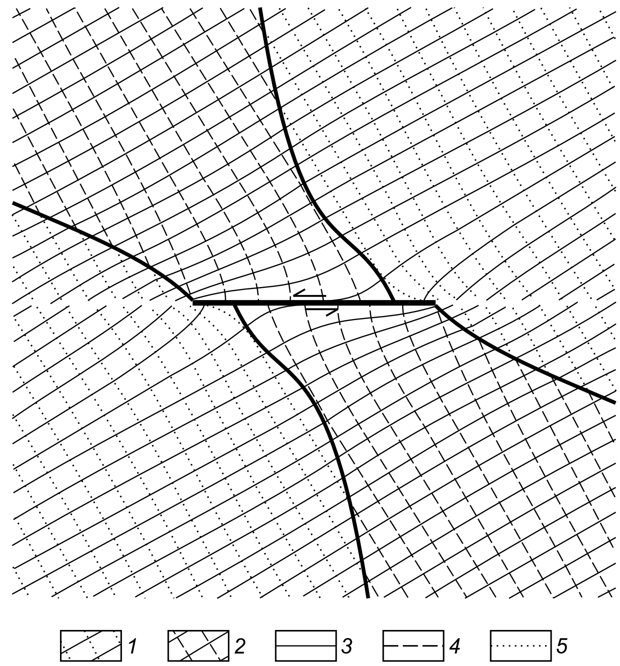

Fig. 7. Trajectories of principal stresses and domains of different stress regimes near a left-lateral strike slip (plan view), after (Osokina, 2008). *1*, horizontal shear; *2*, horizontal compression; *3*–*5*, trajectories of principal stress axes: maximum compression (*3*), intermediate stress (*4*), maximum extension (*5*).

Tectonophysical data on modern stress. In this section, we report natural stress patterns obtained by tectonophysical analysis. In addition to paleostress inversion, modern stress can be studied using earthquake focal mechanisms (Gephart and Forsyth, 1984; Yunga, 1990; Rebetsky, 2003). Both lines of research are based on brittle fault data. Earthquake source parameters have implications for present deep crustal stress. Tectonophysical stress patterns are considered below for the crust of orogenic areas.

As inferred from earthquake mechanisms (Rebetsky et al., 2012, 2013), the Altai–Sayan area evolves under compression and extension in the horizontal plane (Fig. 10). Maximum compression is most often quasi-horizontal in mountain ranges exposed to slope erosion (65% of the uplift area in the cited studies), while quasi-horizontal maximum extension acts in plateaus, where surface denudation is minor and extension or transtension are predominant regimes (Rebetsky and Alekseev, 2014), as well as in foredeeps and intermontane basins conjugated with uplifts. In these subsided areas, 75% of determinations correspond to quasi-horizontal maximum extension and a setting of transtension in the horizontal plane (Fig. 10). Large intermontane basins in growing orogeninc areas evolve under horizontal strike slip.

Features of seismicity are such that earthquake mechanism data from subsided areas are commonly fewer than those from uplifts (Zhalkovskii et al., 1995) and are averaged on a larger scale for reconstructions and interpolations in geodynamic mapping. Maximum extension may be also

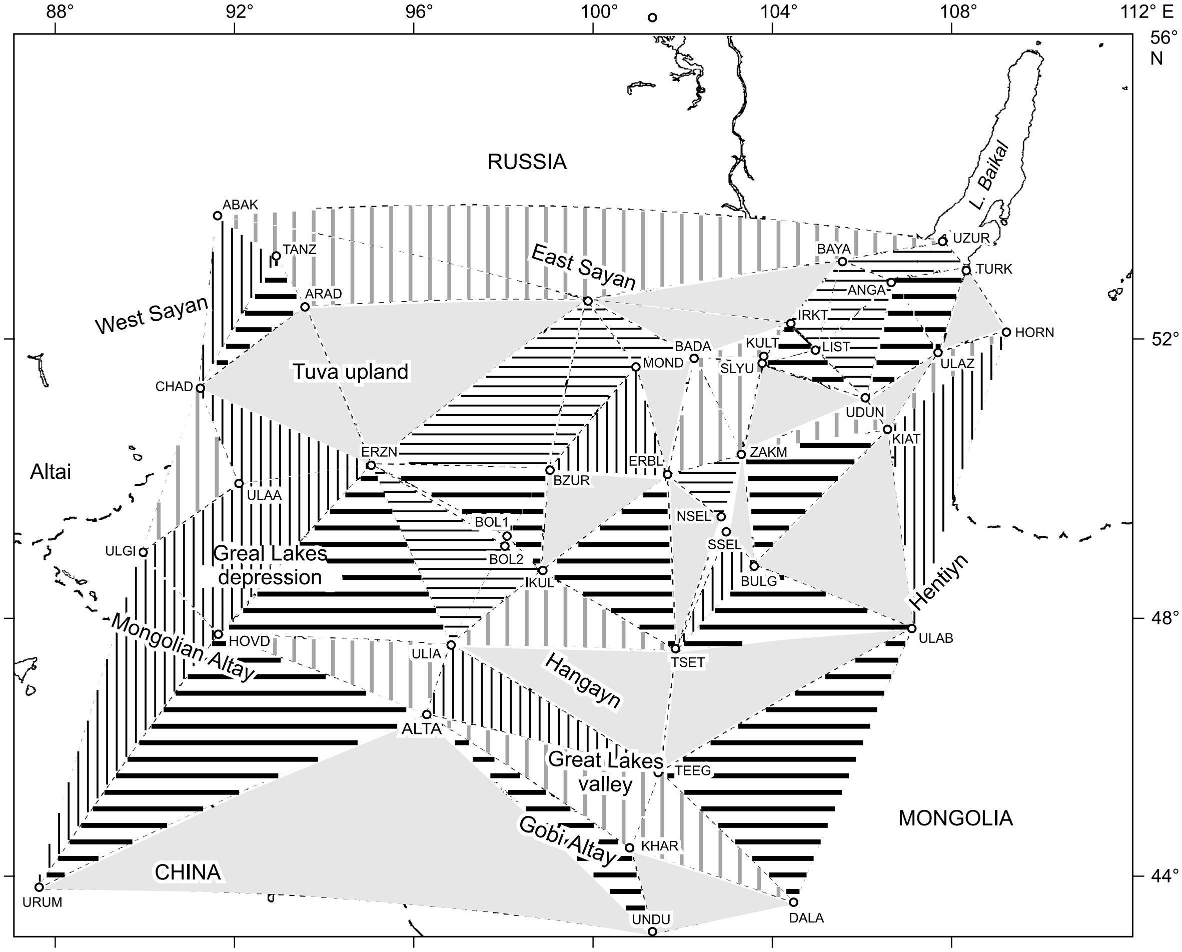

Fig. 8. Surface deformation in the Mongolian and Gobi Altay, Sayan, Hangayn, and Baikal, from GPS data. Modified after San'kov et al. (2011), with zones of lateral strain of different magnitudes and directions. Horizontal hatching: lateral extension; vertical hatching: lateral compression; light gray shade: minor change in lateral extent; denser hatching shows higher magnitude of lateral strain; circles mark permanent GPS stations.

quasi-horizontal in basins (Zaisan, Toja and central Tuva basins), but less often (25% of basin area).

The correlation between geomorphology and geodynamics shows up in tectonophysical reconstructions based on data from the KNET seismological network in the Northern Tien Shan (Rebetsky et al., 2012, 2016). Zones of horizontal

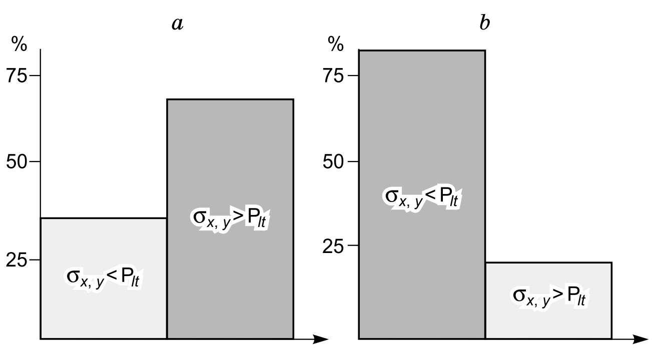

Fig. 9. Relative magnitudes of horizontal and vertical stresses (P_{lt}) for basement (*a*) and sediments (*b*), according to (Markov, 1985).

extension occur along the southern border of the Chu basin adjacent to the Kyrgyz Range. The Suusamyr, Kyzylei, and Kochkor intermontane basins evolve in settings of horizontal strike slip or transtension with quasi-horizontal principal deviatoric extension. The crust of ranges undergoes horizontal compression or transpression.

The combination of quasi-horizontal maximum compression in ranges and deviatoric extension in basins revealed by stress inversion for the Altai–Sayan and Tien Shan regions corresponds to a stage of active mountain growth. At this stage, denudation in uplifted zones and deposition in basins are compensated by ongoing uplift and subsidence, respectively.

Thus, the current stress and strain fields in intracontinental orogens can show lateral variations in azimuthal directions of principal stress axes and in the respective geodynamic regime. These areas often undergo changes from uplift to subsidence (periodic vertical crust movements according to Belousov (1954)). That is, the same volume of crust may experience alternated regimes of horizontal compression and extension.

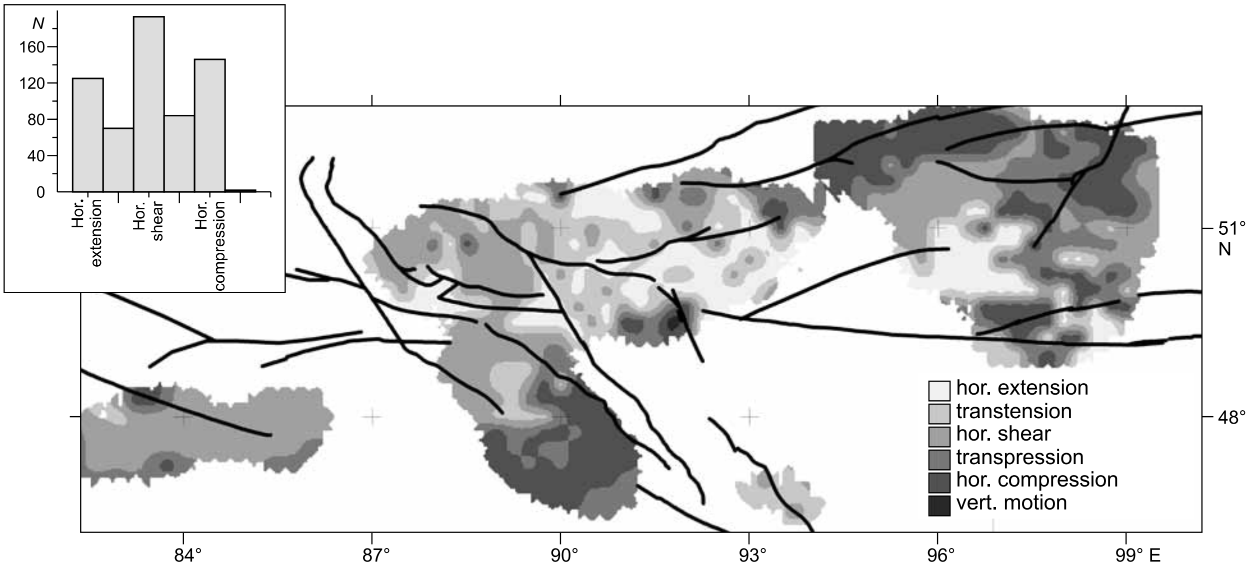

Fig. 10. Stress regime in the Altai–Sayan area (Rebetsky et al., 2013) and map of faults, after (Trifonov et al., 2002). Inset shows histograms of stress types.

The results of tectonophysical analysis of stress in large intermontane basins are supported by optical distance data (laser interferometry) showing that the Tajik basin is expanding though being exposed to horizontal compression according to plate tectonic considerations (Guseva et al., 1993). This inference is also consistent with seismological evidence of quasi-horizontal elongation axes of seismotectonic strain in large zones near the basin axis (Lukk et al., 2008). N–S and total lateral elongation at 10^{-6}–10^{-7}yr^{-1} was also recorded by silicon strain gauges at stations of the Alma-Ata test ground located in the foothills of the Zaili Alatau Range (Tikhomirov et al., 2001). Repeated leveling indicates stable subsidence in the Chu, Issyk Kul, and Fergana basins (Abdrakhmatov and Tsurkov, 1991).

DISCUSSION

The reported results show that a large scope of mechanisms responsible for lateral and vertical lithospheric deformation cause changes in principal stress directions as well as in the geodynamic stress type. These changes were predicted theoretically by tectonophysical analysis and revealed by field structural measurements. The current stage of geodynamic evolution is not an exception, as several local states of horizontal compression, extension and shear may coexist within some areas. Data on stress features impose rigorous constraints on the choice of possible external effects and can be used as a criterion to check rock mechanic models for specific geological structures.

Paleostress and local structures. Mikhail Gzovsky (1959, 1963) who was at the origin of field structural studies in Russia placed emphasis on appropriate characterization of mechanisms producing local structures. Namely, he focused on folds resulting from axial and lateral compression in the Baijansai uplift, especially on conjugate fracture pairs in the limbs, arches, periclinal parts, and cores of anticlinal folds, to look into their genesis. He used data on small structures, such as cleavage, boudinage, shear joints, etc., for reconstructing paleostress that acted at the time of deformation in the Late Paleozoic. As a result, he (Gzovsky, 1959, 1963) revealed nearly vertical maximum compression (σ_3) and quasi-horizontal minimum compression (σ_1) in the largest (few kilometers wide) anticlinal folds of the Baijansai uplift (Fig. 11), with the σ_1 axis trajectories parallel to fold limbs. This tendency was recorded in typical conjugate reverse shears observed in the limbs of anticlines and grabens in the arch part of the uplift.

Structural data on synclinal folds mainly represented their limbs that border anticlinal folds. Gzovsky (1963) hypothesized a quasi-horizontal orientation of maximum compression in the middle of synclinal folds proceeding from low-angle dips of the stress axes toward the cores of the anticlines. See Fig. 11, where the trajectories of these axes warp up smoothly while the axes of maximum deviatoric extension fan out from the core of the synclinal fold; the intermediate principal stress σ_2 trends along the hinges of both anticlinal and synclinal folds.

The largest (first-order) folds within the Baijansai uplift show signatures of lateral compression. As Gzovsky (1959, 1963) showed, folds of different sizes (first- and second-order major structures and third-, fourth-order and smaller subsidiary ones) provide information on different scales of stress in mountains. The stress states that acted during the formation of subsidiary folds correspond to mechanisms of both axial and lateral compression.

Thus, Gzovsky correlated paleostresses to local and subregional structures rather than to regional-scale effects.

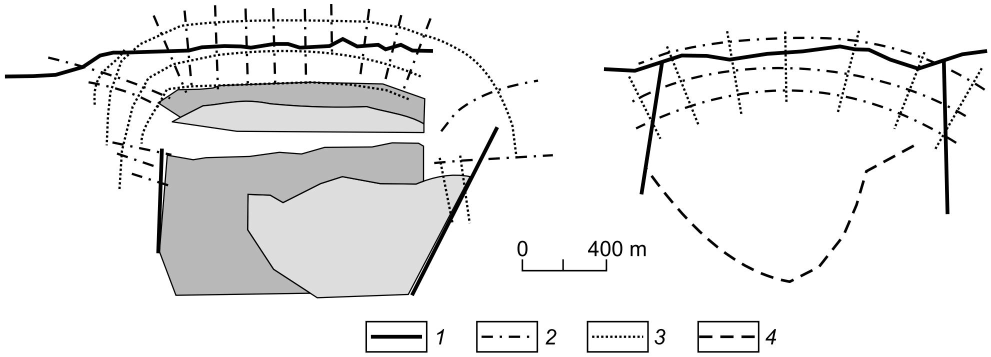

Fig. 11. Trajectories of principal paleostresses obtained by Gzovsky (1963) for the Manchabyr anticline (*a*) and Aksuran syncline (*b*) within the Baijansai uplift. *1*, faults; *2*, trajectories of algebraically minimum principal stress σ_3; *3*, trajectories of algebraically maximum principal stress σ_1; *4*, bottom of Aksuran syncline, simplified after (Gzovsky, 1963).

Paleostress and vertical movements. Rebetsky (2008) and Rebetsky et al. (2017b) revisited the idea that residual stress can be responsible for high horizontal compression which was first suggested by Voight (Voight and Pierre, 1974). Residual stress is associated with exhumation of rocks subjected to irreversible pseudo-ductile strain at large depths. The deformation results from vertical gravity compaction of laterally constrained rocks rather than from horizontal compression. The residual stress is basically compressive but can produce elongation when it relieves partially near the surface: the rocks look like swelling and pushing apart the host frame. The unloading is never complete, and near-surface rocks always experience large horizontal compression (hundreds of bar) while vertical compressive stress is minor.

The rocks under residual stress crop out on slopes of uplifts (areas of rapid erosion) where most of outcrops in orogens are located. Thus, partial relief of residual horizontal compression due to the presence of previous fractures can produce slickensides with reverse or strike-slip geometry (depending on the altitude of stress measurements in mountains). According to the available experience, principal stress directions are commonly variable at sites where outcrops lack distinct geological structure at the local level. This may be evidence of residual stress effect on the inferred stress states, while settings of horizontal compression or strike slip are statistically representative.

Data averaging scale. According to theoretical tectonophysical considerations (Osokina, 1987) and data of geology and seismology, stress patterns are hierarchic, i.e., averaging at different scales may lead to different directions and types of principal stresses. In seismology, the effect of scale shows up as different slip geometries inferred from earthquake mechanisms in orogens (Altai–Sayan, Tien Shan, Pamirs, and other mountain systems). Present stress fields reconstructed from the mechanisms of earthquakes of different magnitudes in these areas will have different parameters. When selecting data on joints from an outcrop, a geologist not often can be sure about the sizes of fractures that represent specific slips: whether they are tens of centimeters or hundreds of meters long. Correspondingly, two quite different stress states can be inferred for the same outcrop.

The problem was solved in tectonodynamic analysis by a special method suggested by Nikolaev (1992) for fractures and lineaments of different sizes detected in aerial and satellite imagery. Nikolaev distinguished three main scale ranks of stress fields that involve, successively, upper crust, crust as a whole, and lithosphere as a whole, which may lead to stress fields of three hierarchies that would differ in the area extent and depth of averaging (Fig. 12).

Local heterogeneity of stress fields. Local tectonics (folds, faults, intrusions, etc.) can produce spatial heterogeneity of stress on a scale of few to tens of kilometers. Local stress fields may be part of a larger stress field with its own principal stress directions, as for example in solutions by Osokina (1987) obtained for a heterogeneous stress field near a fault (Fig. 7). Measurements in different walls of the fault, in its end or middle parts, in outcrops of a limited accessibility, may yield quite different directions of principal stresses.

Sim (1996) suggested an algorithm called "common stress field" search, for processing paleostress data of this kind. In this method, data on principal compression and extension directions are plotted in a unit hemisphere; the stress

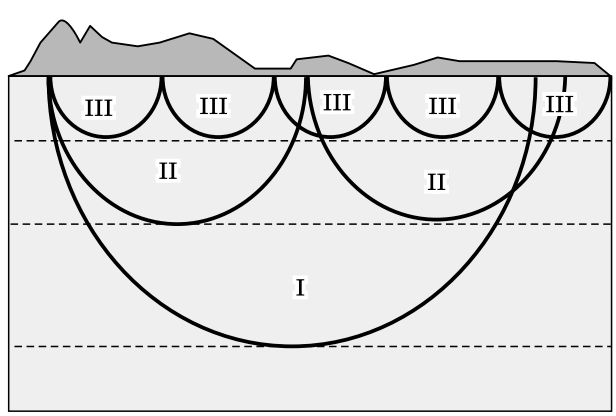

Fig. 12. Stress systems of different ranks (I–III) that cover different lithospheric depths, after Nikolaev (1992).

pattern is interpreted as a single heterogeneous local stress field if all projections of the axes fit the respective quadrants drawn from the sphere center, with a 90° vertex angle and mutually orthogonal axes (Fig. 13). Thus one can see whether locally changing principal stress directions record different stress events or a stress field spatially heterogeneous at the local level.

CONCLUSIONS

The current stress states inferred from tectonophysical studies correspond to different geodynamic regimes in large intermontane basins (especially, rift basins) and the flanking mountains. This inference is consistent with geological data from the northern border of the Tunka rift basin (Ruzhich et al., 1972) and the areas of Lake Hövsgöl (Ruzhich and Khilko, 1985) and Chara basin (Ruzhich, 1978), as well as with seismological data on earthquake mechanisms from the Tunka and Hövsgöl rifts (Melnikova et al., 2001). According to the latter data, the mechanisms of about ten events correspond either to dip-slip or to oblique slip with a nearly vertical *P* axis and a nearly horizontal *T* axis, respectively. Earthquakes along the basin borders have both reverse slip, strike-slip and dip-slip mechanisms or their combinations, and sources with reverse slip and normal slip can be closely spaced (within 5–10 km). Proceeding from these results, (Ruzhich et al., 1972; Ruzhuch, 1978) hypothesized that horizontal extension in basins can coexist with horizontal compression in the flanking mountains, which agrees with our results (Rebetsky, 2015).

The basin-range boundary can be displaced, either in a directed or in an oscillative way (Belousov, 1976), which mixes up signatures of different stress states within a single outcrop. Therefore, the structures of different slip geometries coexisting along basin-range boundaries cannot be used for division of regional stress events.

Furthermore, the number of successive events distinguished by grouping of reconstructed paleostresses according to proximity of principal directions is limited by the time required for evolution changes. Namely, each dramatic stress change as a prerequisite for a new postcritical state and buildup of high irreversible strain (faulting) requires at least 50 Myr of stable uniform loading.

On the other hand, tectonophysical reconstructions of crustal stresses in active orogens show heterogeneous patterns (Rebetsky et al., 2012, 2013; Rebetsky, 2015) with intricate combinations of quasi-horizontal maximum compression in growing uplifts and maximum deviatoric extension in basins with ongoing sedimentation. Stress heterogeneity is also predicted by theoretical modeling (Goncharov, 1988; Osokina, 2008).

At the time being, it is difficult to suggest unified recommendations for the interpretation of reconstructed paleostresses in different tectonic settings: orogens, rifts, passive and active margins, etc. Each case may be particular. In

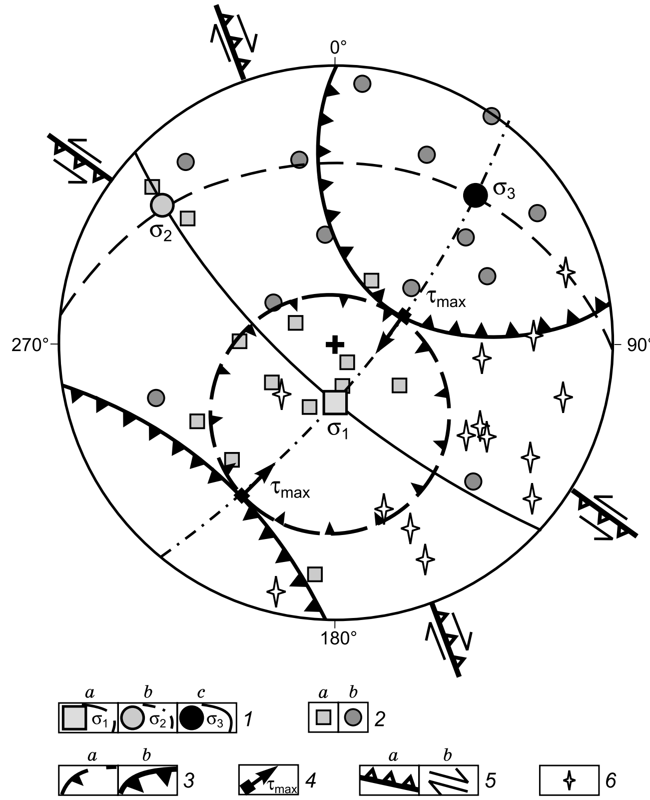

Fig. 13. Stereoplot of local stress states by L. Sim (Rebetsky et al., 2017a). Wulff net, upper hemisphere. *1–3* are regional (*1*, *3*) and local (*2*) stress states: extension (*a*), intermediate stress (*b*), and compression (*c*) for stress state 1; extension (*a*) and compression (*b*) for stress state 2; extension (*a*) and compression (*b*) quadrants for stress state 3; *4*, poles of maximum tangential stress planes; *5*, geometry of slip along planes of maximum shear stress: reverse slip and strike slip; *6*, fold hinges.

some cases, it may be reasonable to present results from each local crust volume separately or to distinguish local stress states within this volume, with reference to the present stress pattern (Delvaux et al., 2013; Soumaya et al., 2015). Heterogeneity of present stress fields (Fig. 6) means that no distinct events of different stress regimes can be distinguished at the site.

It is important to apply the approach by L. Sim of common stress field search in analysis of regional stress patterns. According to this approach, local deviations in stress directions are caused by spatial stress heterogeneity or by scale inconsistency of slip indicators used for inversion in the case when local stress axes fit into the compression and extension quadrants.

The approach used by Gzovsky early in the history of tectonophysical stress inversion studies appears to be the most suitable. It allows tracing stress changes associated with the evolution of specific structures (e.g., large folds). Stress states in large basins and ranges have been found out to correlate with one another and to be often bipolar, which is meaningful for paleostress interpretation.

Anyway, the current practice of simplified interpretations in terms of compression or extension based on plate tectonics contradicts the evidence of heterogeneity in the current stress fields. The respective simplified reconstructions hardy would be reliable.

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