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Fault systems in multiply deformed regions of Eurasia

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We have studied the orogenic fragile deformation of the upper Earth's crust of several areas of the Eurasian continent, where deformations have occurred many times – in the Tian Shan and Altai-Sayan regions of the Central Asian Paleozoic Fold Belt and in the Baltic region in the Fennoscandian Shield (East European Platform). Our processing of data on the trends of more than 4000 faults allows us to identify fault systems and relationships among these fault systems. Changes in the intensity and kinematics of the activity of fault systems in different epochs of deformation of regions are revealed. In the Tien Shan and Altai-Sayan regions, fault movements occurred during Early Paleozoic, Late Paleozoic and Late Cenozoic orogenies. No new fault systems appeared in the Late Cenozoic deformation in the Tien Shan, where only movement along Paleozoic faults that were suitably oriented occurred. In the Altai-Sayan region, we identify the Late Paleozoic associations of fault systems that activated in the recent epoch and the association of fault systems created in the Late Cenozoic. The Fennoscandian Shield shows different fault kinematics in four Early Proterozoic deformational periods. Our method of analysis of associations of fault systems contributes to a systematization of data on multi-stage deformation in the upper crust of these regions.

Keywords: tectonic faults, active faults, Tien Shan, Altai-Sayan, Fennoscandian Shield.

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1 Introduction

Intensively deformed rock complexes exposed on vast territories of continents have undergone several or many epochs and stages of deformation. Determining the time of occurrence of orogenic faults, the periods of their activity and changes in the direction of movement along the faults are tasks, the solution of which expands the knowledge of the geological history of regions. This article attempts to solve such problems for fault systems in strata that deformed in the Phanerozoic in the Central Asian Fold Belt and in the Proterozoic in the basement of the East European Platform (Figure 1).

The border between the upper and lower crust of the modern continent is at a depth of 10–15 km or more. It corresponds to the seismic discontinuity (F, K1) which serves as a partition defining the structural disharmony between the upper and lower crust. In many areas, the boundary between the upper and lower crust marked by a layer or series of bodies characterized by a reduced speed of seismic waves. Probably, it is a fluid-saturated porous cataclasite or mylonite [*Bagmanova et al.*, 2014; *Ivanov*, 1990, 1994; *Karakin et al.*, 2003; *Krasnopevtseva*, 1978; *Nikolaevsky and Sharov*, 1985; *Pavlenkova*, 2004]. The upper Earth's crust in different tectonic conditions has the properties of elastic-plastic or elastic-viscous rheological body. It can be brittle destruction – the emergence of fragile dislocations. The lower Earth's crust probably has properties close to those of the viscous-plastic body. In it, a fragile deformation does not occur or occurs in short-term local anomalies. Seismological data, seismic and magnetic-telluric sensing show that long faults studied on the Earth's surface penetrate the lower crust and the upper mantle. Extrapolation to the depth of the physical parameters of faults studied on the Earth's surface is possible within the

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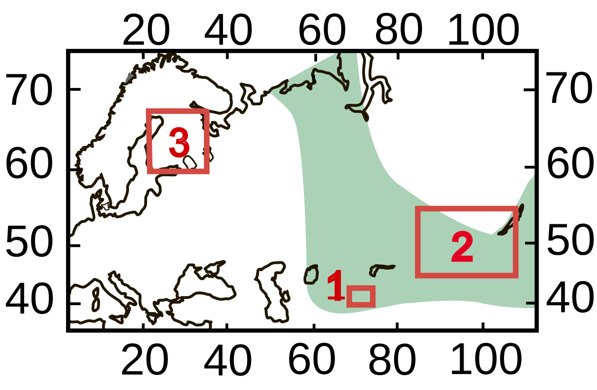

Figure 1: The investigated regions: Tien Shan (1), Altai-Sayan (2), Baltic (3). The Paleozoic Central Asian fold belt is colored.

upper crust. In the viscous-plastic environment of the lower crust and mantle, they should have a different expression than in the upper crust.

The study of active faults and hypocenters of intra crust earthquakes in southern Siberia showed that the depth of fault penetration into the Earth's crust is close to the length of fault lines on the daily surface (Figure 2). The article uses data on more than 4000 faults, the lines of which on the Earth's surface are more than six kilometers long. These faults penetrate into a significant part or cross the upper crust of the Earth.

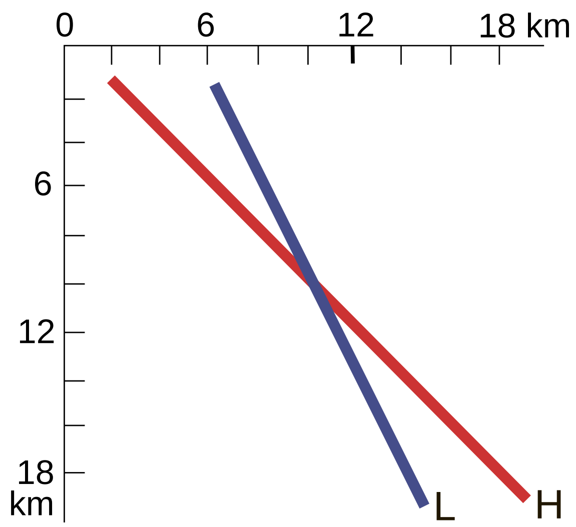

Figure 2: The ratio of the length of the lines of active faults (L, 1258 faults used) on the Earth's surface of the Baikal region of Southern Siberia and the depth of earthquake hypocenters (H, 2146 hypocenters used) in this region, which show the depth of fault activity, according to [*Sherman*, 1977], with changes.

2 Method

Complex of fault systems in four directions appear in a deformable body subjected to directional compression (scheme A, Figure 3). Two fault systems of reversed faults and thrusts formed at an angle of 90° to the direction of the compressive stress, and two fault systems of normal faults and grabens formed along this direction. These two fault systems form an orthogonal Normal and Reversed faults association. A Strike-slip faults association formed with two strike-slip fault systems. The strike-slip fault association is also orthogonal in an isotropic solid body. The angle between fault systems belonging to the normal-reversed and strike-slip fault systems associations is 45° in an isotropic hard body. The value of this angle can probably decrease to 30° in the Earth's crust and fragile deformation in the upper Earth's crust occurs according to scheme B (see Figure 3). The angles between the strikes of regional-scale fault systems that formed in the regional stress field are more than 30. If such fault systems identified in the region, and the angle between the strikes of which is less than 30°, then it is likely that they were formed in different stress fields – in different deformation epochs. In regions where orogenic deformations occurred in two or more epochs, old faults can activated in a new stress field. If the compression direction of the region changes by 30° or more, the kinematics of the activated old faults should change.

In the folded zones, which are composed of overthrust sheets, the allochthon reach 10–15 km of thickness and occupy most of the upper crust. At the stage of overthrusting, the upper crust of such

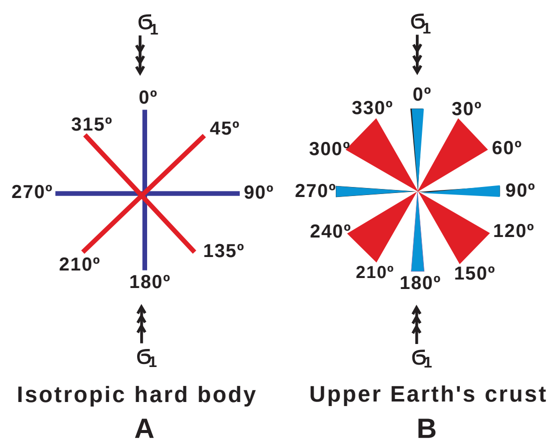

Figure 3: The intervals at which Normal and Reverse fault sytems association (blue fields and lines) and Strike-slip fault systems association (red fields and lines) can arise and function under compression of an object; σ_1 – the direction of compression

regions laminated by tectonic surfaces at the base of the overthrust sheets. These tectonic surfaces initially have a gentle slope. The formation of most overthrusts precedes the orogeny [*Burtman*, 2015]. Further, at the stage of folding, the allochthon and autochthon crumple into folds. At the same time, the tectonic soles of overthrusts acquire a different dip angle – up to vertical and overturned bedding. The physical conditions of movement and the kinematics of the overthrusts are specific. The above-mentioned scheme of fragile deformation is not applicable to the tectonic soles of the overthrust sheets. The above-mentioned relation between the length of the fault line and the depth of its activity does not apply to the tectonic soles of the overthrusts too. When studying the orogenic and post orogenic deformation of the overthrust-fold region, it is necessary to separate the tectonic soles of the overthrusts from the faults that arose during orogenesis and after orogenesis. The diagrams presented in this article show the strike of all types of faults, except for tectonic soles of the overthrusts and gentle thrusts.

The article proposes a method for determining changes in the kinematics and activity of fault systems in different epochs of orogenic deformation of a multiply deformed region, based on the results of statistical processing of data on faults that contain geological maps of this region. The picture of plicative deformations, their relationship with the accumulation of sediments, and data on the geodynamics of the region make it possible to determine the number of deformation epochs, and the orientation of the axes of stress fields in these epochs. Analysis of fault direction diagrams shows fault systems that have a wide regional distribution in the region. Comparison of the directions of regional compression at different epochs of deformation with the diagram of the directions of the faults of the region allows separate the fault systems that were active in different epochs and had different kinematics of this activity.

3 Tien Shan region

The Central Asian Paleozoic fold belt occupies a significant part of the Eurasian continent (see Figure 1). This belt is located between the East European, Tarim, North Chinese and Siberian ancient platforms. The deformations occurred in the fold belt in the Paleozoic and in the Late Cenozoic. We have studied fault systems in the Tien Shan and Altai-Sayan high mountain regions of this belt. The Tien Shan region consists of the Southern, Middle and Northern Provinces (Figure 4) in which the Paleozoic deformations were different.

The intense deformations had been taking place in early Paleozoic Caledonian time in the Northern Province and in the late Paleozoic Variscian time in the Southern and Middle provinces. In the Early Carboniferous, the territory of the Southern

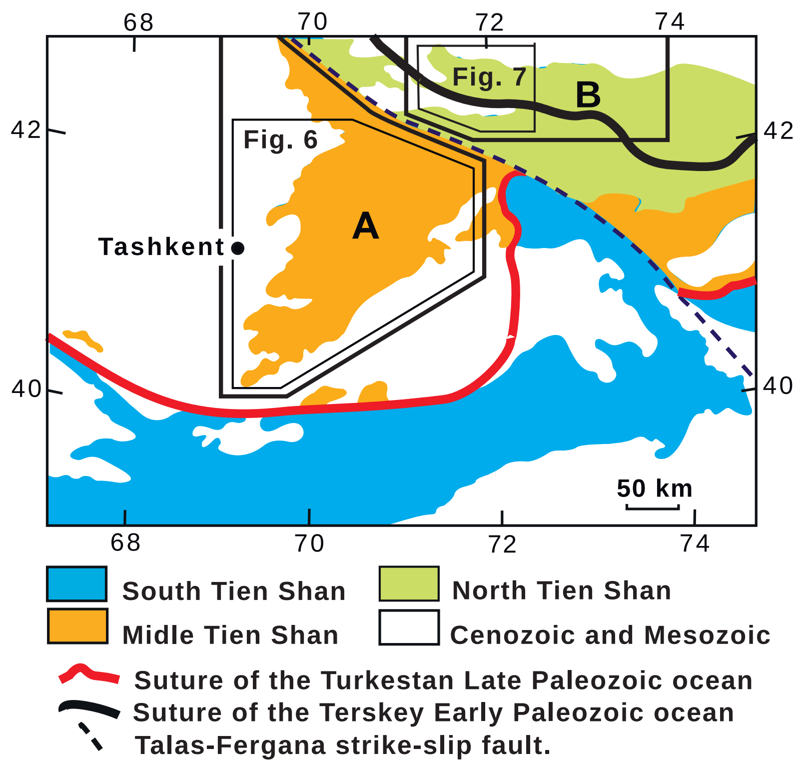

Figure 4: Paleozoic provinces of the Tien Shan.

Tien Shan was the outlying part of the Tarim continent. The Middle Tien Shan was part of the Kazakhstan continent. The Turkestan oceanic basin was located between these sialic blocks. Intense deformations of the Tien Shan were associated with the collision of the Tarim and Kazakhstan microcontinents. The Turkestan Ocean closed in the Late Carboniferous Kasimovian age [*Alexeiev et al.*, 2019; *Burtman*, 2015]. The suture of the Turkestan Ocean separates the tectonic zones of the Southern and Central Tien Shan.

Several stages have been distinguished in the history of the Late Paleozoic deformations of the Tien Shan [*Burtman*, 2008]. At the early stage, in the Late Carboniferous and in the Early Permian, numerous overthrusts formed at the edge of the Tarim microcontinent. After that, overthrusts and autochthon crumpled into synform and antiform folds during orogenesis. At the same time, the overthrust plates acquired different inclination and strike along the folded belt. During the last stage, in the Late Permian time, disjunctive deformations prevailed. All overthrusts are located in the Southern Tien Shan. This contributed to the selection of the Chatkal region of the Middle Tien Shan (A, see Figure 4) for the study of fault directions in the Late Paleozoic orogenic epoch. The Tien Shan subjected to next orogeny in the Late Cenozoic.

3.1 Middle Tien Shan

Diagram I (Figure 5) shows the strike of 439 faults in the Chatkal region of the Middle Tien Shan. Chatkal district (A, see Figure 4 and 6) cover the territory of ranges (Kuraminsk, Chatkal, Pskem, Ugam, Karzhantau and Talas) and intermountain valleys. Geographical coordinates of this territory: 40°–43°N. and 69°–72°E. The source of data on faults is from the map [*Klishevich*, 1989]. Diagram I shows two orthogonal associations of fault systems (I-1 and I-2, see Figure 5). Each association consists of two fault systems – two rays directed at an angle of about 90° to each other. Association I-1 includes rays 0°/180° and 90°/270°, association I-2 contains rays 40°/220° and 120°/300° (hereinafter, the modern geographic coordinate system is used). The Tien Shan Late Paleozoic fold system had a sub latitudinal strike. The direction of the compressive stress during its formation was close to the meridian direction. Under such conditions, association I-1 was Normal and Reverse faults association and association I-2 was Strike-slip faults association.

3.2 Northern Tien Shan

Four or more epochs of orogeny were in the Northern Tien Shan (B, see Figure 4). The territory of the Northern Tien Shan belonged to Kokshetau-Issyk-Kul and Syrdarya sialic blocks in the Early Paleozoic. They separated by the Terskey oceanic basin. The Terskey Ocean was closed in the Middle Ordovician after the subduction of the oceanic crust. The collision of these blocks was accompanied by orogenic deformations. The distribution of the Late Devonian molasse in the Northern Tien Shan testifies to orogenic processes in that time. Then, the Northern and Middle Tien Shan covered by orogenesis in the Permian time and in the late Cenozoic.

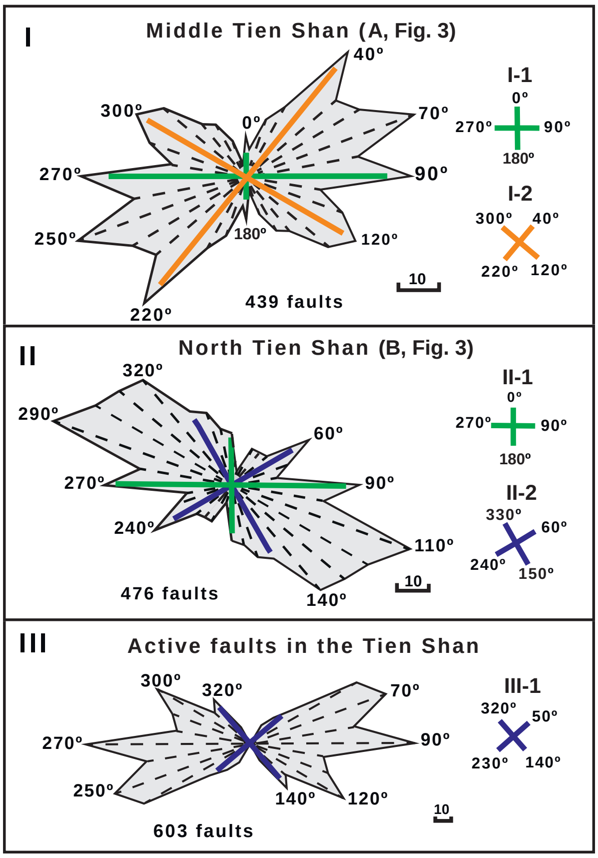

Figure 5: Diagrams of fault directions in the Tien Shan region (polar projections, interval – 10°) with fault system assemblages I-1, I-2, II-1, II-2 and III-1.

Diagram II (see Figure 5) shows the strike of 476 faults in the western region of the Northern Tien Shan (B, see Figure 4 and 7). The area is located on the territory of the Kyrgyz and Talas ridges. The geographical coordinates of this territory is 42°–43°N and 71°–74°E. The data sources on the faults are from [*Burtman et al.*, 1961; *Kiselev and Korolev*, 1964]. Diagram II has two rays (60°/240° and 90°/270°) and a broad band dominated by NW/SE faults. This diagram shows associations of fault systems II-1 and II-2, oriented at an angle of 30° to one another. Association II-1 is identical to the Late Paleozoic Normal and Reverse

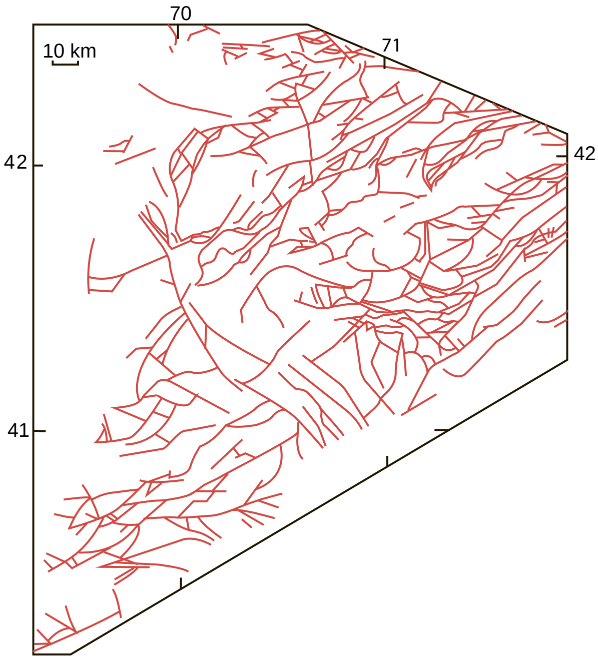

Figure 6: Fault network in the Chatkalregion of the Middle Tien Shan (see Figure 4).

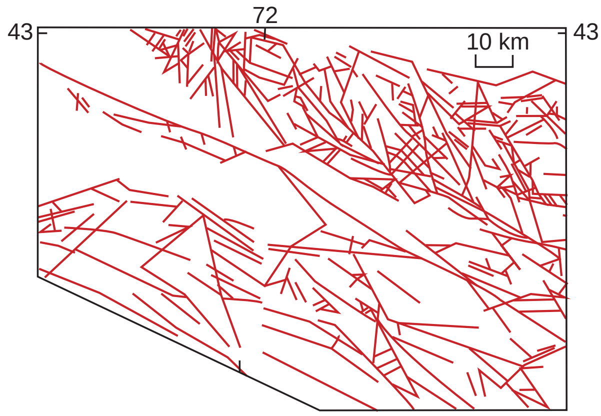

Figure 7: Fragment of a network of faults in the Northern Tien Shan (see Figure 4).

fault association I-1 of the Middle Tien Shan. Consequently, the position of association I-1 is consistent with the position of the regional stress field in the Late Paleozoic. This is evidence that the faults of association II-1 formed in the Caledonian Provinces during the Late Paleozoic orogeny, which covered the whole of the Tien Shan. The Strike-slip fault association could be association II-2.

The band of the NW/SE direction in diagram II contains data on 199 faults that have a strike in the interval 110°–140°/290°–320°. It is not possible to distinguish associations of fault systems involving faults of this band. The NW/SE direction has the suture of the Early Paleozoic Terskey Ocean in the area under consideration (see Figure 4). It suggests a connection between the NW/SE strike faults and the collision process that occurred in the Caledonids in the Ordovician.

3.3 Active faults in the Tien Shan

Many faults of the Paleozoic deformations were active in the Late Pliocene-Holocene. Diagram III (see Figure 5) shows the strike of 603 active faults located on the territory of all tectonic zones of the Tien Shan, in coordinates 35°–45°N and 65°–95°E. The data source is Map of active faults of the Eurasia [*Bachmanov et al.*, 2017]. Diagram III has four rays. The smallest of them indicates the existence of poorly developed association of fault systems, which have a strike of 140°/320° and 50°/230°. These strikes are close to the directions of fault systems in the Late Paleozoic association II-2. The three large rays of diagram III extend at 20°–30° towards one another. There are no faults associated with them in the chart field. Analogs of these rays of diagram III presented on the diagrams of Paleozoic faults. A ray with a strike of 90°/270° is on diagrams I and II, rays 120°/300° and 70°/250° – on diagram I, a ray of 140°/320° – on diagram II. These data indicate that, in most cases, new faults did not arise in the Late Cenozoic deformation, but displacements occurred along the Paleozoic faults.

The Late Cenozoic orogeny of the Tien Shan has been caused by the collision of the Hindustan continent with Eurasia [*Molnar and Tapponnier*, 1975]. The kinematics of active faults and GPS data indicate: the position of maximum stress was close to the meridional [*Burtman*, 2012]. Late Cenozoic orogeny occurs in the Tien Shan in a stress field, the orientation of which is similar to the orientation of the Late Paleozoic stress field. The small association of fault systems III-1 may be the result of reactivation of the Paleozoic association. There was no widespread reactivation of Paleozoic associations in the Late Cenozoic. At that time, the Late Paleozoic faults "came to life", probably in the local stress fields from earthquakes.

4 Altai-Sayan region

The considered territory of the Altai-Sayan region (2, see Figure 1) is located in the Southern Siberia in geographic coordinates 45°–55°N and 84°–104°E. The placement of the Early Paleozoic, Middle Paleozoic and other terrains was complicated (Figure 8). Orogenic dislocations occurred in the region in the Cambrian, Ordovician, Silurian, Devonian, Late Paleozoic and Late Cenozoic [*Buslov and Grave*, 2015; *Safonova et al.*, 2011]. Diagram IV (Figure 9) shows the directions of 1187 faults in this region. The data source is the Fault Map [*Sidorenko*, 1980]. Three associations of fault systems distinguished in diagram IV. Associ-

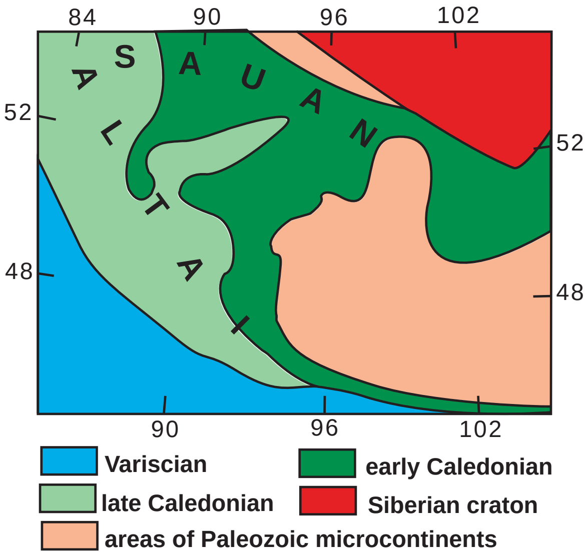

Figure 8: Paleozoic provinces of the Altai-Sayan region according to [*Safonova et al.*, 2011], with changes.

ation IV-1 includes fault systems of 60°/240° and 140°/320°. Association IV-2 formed by fault system of 90°/270° and faults of the meridian direction. Association IV-3 contains 20°/200° fault system and faults that strike 110°/290°. The angle between the strike faults of systems IV-2 and IV-3 is only 20°, which makes it likely that these fault systems will occur at different times, at different epochs or stages of deformation.

As the Tien Shan, the Altai-Sayan region subjected to the Late Cenozoic orogeny caused by the collision of the Hindustan continent with Eurasia [*Grave et al.*, 2007; *Molnar and Tapponnier*, 1975]. Diagram V (see Figure 9) shows the strike of 663 faults active in the Late Pleistocene – Holocene, which are located on the same area. The data source is Map of active faults of the [*Bachmanov et al.*, 2017]. Diagram V shows two orthogonal associations of fault systems. It is the V-1 association with the 70°/250° and 160°/340° rays, and the V-2 association with the 0°/180° and 90°/270° rays. These associations are oriented at an angle of 20° to one another. It indicates the formation of associations V-1 and V-2 at different times, in different epochs or at different stages of deformation. A significant number of faults have a strike of 110–140°/290–320°. A system of faults associated with faults of this direction about 90° is not possible to distinguish in the diagram V. For plotting diagram VI (see Figure 9), data of active faults in diagram V have been subtracted from the dataset on which diagram IV is based. As a result, diagram VI shows the directions of 524 faults along which there was no movement during the Late Cenozoic epoch. This diagram shows two orthogonal associations of fault systems: association VI-1, which is similar to association IV-1, and association VI-2, similar to association IV-3. There are no analogues of association IV-2 in diagram VI.

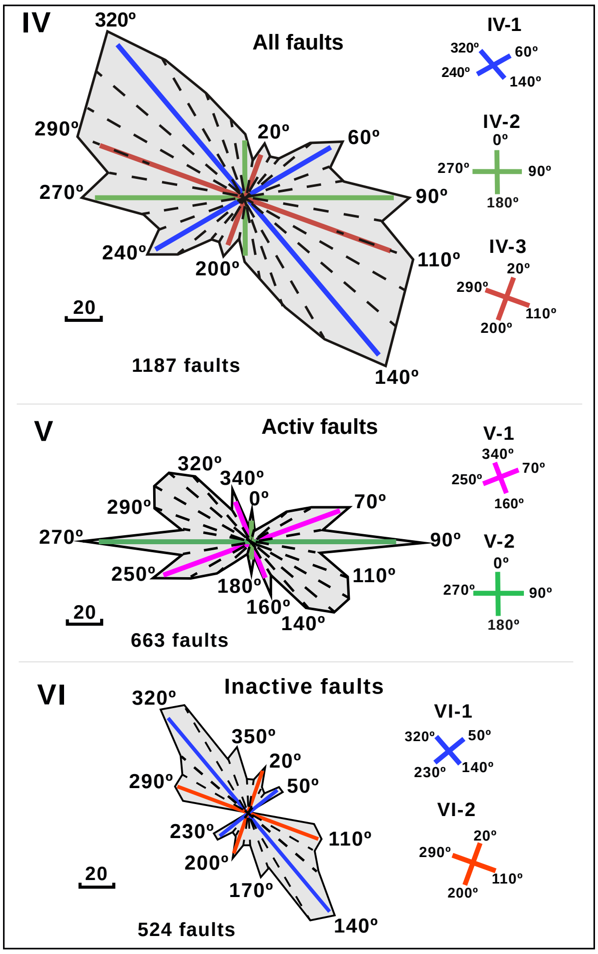

Figure 9: Diagrams of fault directions in the Altai-Sayan region (polar projections, interval – 10°) with fault system assemblages IV-1, IV-2, IV-3, V-1, V-2, VI-1 and VI-2.

Comparison of diagrams IV, V and VI (see Figure 9) leads to the following conclusions. Associations IV-2 and V-2 are similar in direction and in the number of faults in their rays. This indicates the origin of faults in associations IV-2 and V-2 in the Neotectonic epoch. The band of active faults in SE / NW directions in diagram V contains activated Paleozoic faults of associations VI-1 and VI-2. Comparison of the 140°/320° ray lengths of associations IV-1 and VI-1 shows that about 40 percent of Paleozoic faults of such direction activated by Late Cenozoic earthquakes. In contrast to the Tien Shan, there was no coincidence of the directions of compressive stress in the Late Paleozoic and Late Cenozoic in the Altai-Sayan region.

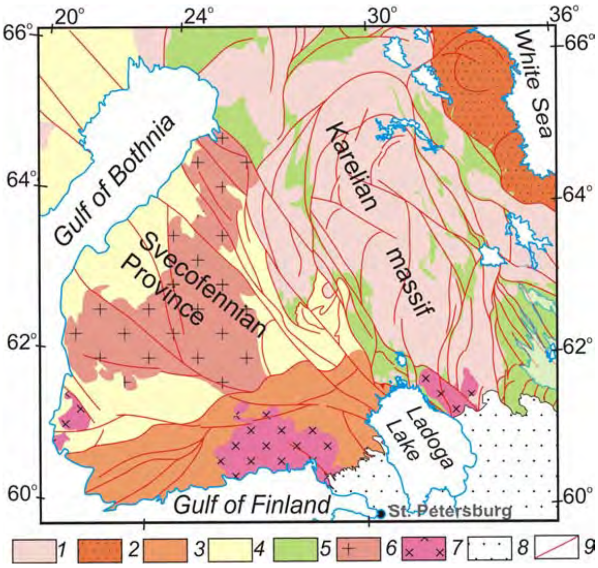

Figure 10: Archean and Proterozoic provinces of the Baltic region according to [*Kolodyazhnyi*, 2006; *Mints*, 2018; *Morozov*, 2010; *Sidorenko*, 1980]. 1–2 – Achaean complexes (1 – Karelian massif, 2 – Lapland-Belomorian belt); 3–6 – Paleoproterozoic complexes (3 – South Finland belt, 4 – Svecofennian province, 5 – Karelian province, 6 – Central Finland granite massif); 7 – Early Riphean granite Rapakivi; 8 – Ediacaran-Phanerozoic cover of the East European plate; 9 – main faults.

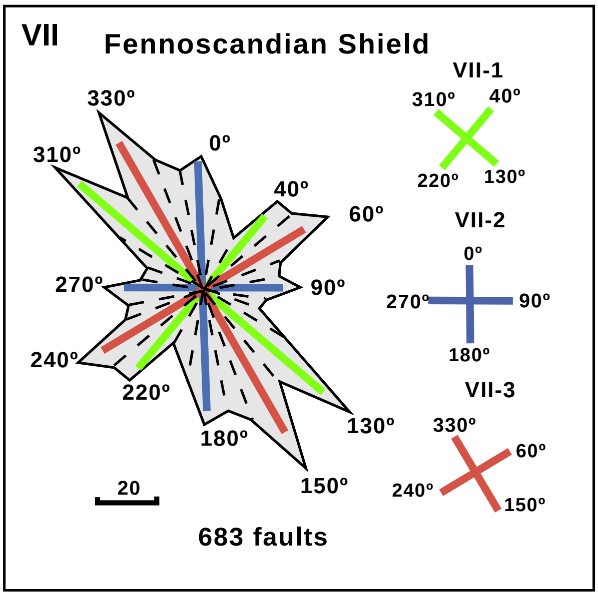

Figure 11: Diagram of fault directions in the Baltic region (polar projection, interval – 10°) with fault system assemblages VII-1, VII-2 and VII-3.

5 Baltic region

The Baltic region is located in the southern part of the Fennoscadian Shield – the exposed Precambrian basement of the East European Platform (3, Figure 1). The region (Figure 10) covers Southern Finland and southwestern Karelia in geographic coordinates 60°–65°N and 21°–36°E. The region is composed of Late Archean and Early Proterozoic rocks of the Fennoscadian Shield and Edicarian rocks of the cover of the East European Platform. In the Early Proterozoic, the Fennoscandian Shield experienced deformations caused by collision and accretionary processes. Paleotectonic reconstructions [*Kärki and Laajoki*, 1995; *Kärki et al.*, 1993; *Kolodyazhnyi*, 2006; *Mints*, 2018; *Morozov*, 2010; *Nironen*, 1997] allow to suggest changes in the Paleoproterozoic regional stress field in the upper crust of the Baltic region, which lead to a change in the kinematics of displacements along faults. Diagram VII shows the directions of 683 faults in the Baltic region (Figure 11). The source of data is the fault map [*Sidorenko*, 1980]. The diagram shows three orthogonal (and near-orthogonal) associations of fault systems. Association VII-1 contains rays 40°/220° and 130°/310°, association VII-2 – rays 0°/180° and 90°/270°, and association VII-3 has rays 60°/240° and 150°/330°.

Several stages of deformations distinguished in the Baltic region, and the regional stress field was different in that stages [*Burtman and Kolodyazhny*, 2020]. At stage D1 (~2.2–1.9 Ga), the direction of regional compression was NW/SE, at stage D2 (~1.9 Ga) – it was NE/SW, at stage D3 (~1.89–1.80 Ga) – sub latitude, at stage D4 (~1.80–1.78 Ga) – sub meridian. NW/SE direction of regional compressive stress at stage D1 should the activity of faults in associations VII-1 and VII-2. Association VII-1 was Normal and Reverse fault association and VII-2 was Strike-slip fault association. At NE/SW direction of compressive stress at stage D2, the activity of faults of associations VII-2 and VII-3 is likely. Association VII-2 was Strike-slip association, and VII-3 was Normal and Reverse fault association. At stages D3 and D4, faults of associations VII-2 and VII-1 or VII-2 and VII-3 were active. The kinematics of faults at stages D3 and D4 were also different (Figure 12).

6 Conclusions

Statistical processing of data on the directions of faults in regions of different types and ages made it possible to distinguish fault systems in them, their orthogonal associations, and to determine the time of activity of these associations.

1. Faults of probably Early Paleozoic age and two associations of fault systems of Late Paleozoic age are common in the Northern Tien Shan. In the Middle Tien Shan, there are two associations of fault systems formed during the Late

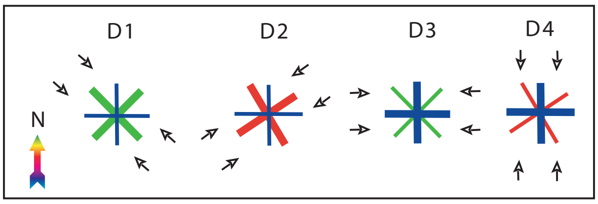

Figure 12: Diagrams of Early Proterozoic activity of fault systems in the Baltic region. D1 – D4 – stages of the Early Proterozoic deformations. Colored lines indicate the type of activity of ensembles of fault systems (see Figure 11): wide colored line – Normal-Reverse type of activity, narrow colored line – Strike-slip type of activity. Black arrows show the direction of lateral regional compressive stress.

Paleozoic orogeny. The entire territory of the Tien Shan was covered by orogenic deformation in the Late Cenozoic. No new fault systems appeared in the course of Late Cenozoic deformation, the movements along the Paleozoic faults with suitable directions occurred.

2. There are two Late Paleozoic associations of fault systems in the Altai-Sayan region. As in the Tien Shan, a part of the Paleozoic faults was active in the Late Cenozoic. Unlike the Tien Shan, a new fault system association created in the Altai-Sayan region in the Late Cenozoic. The Tien Shan and Altai-Sayan regions are areas of high seismicity. The data obtained on the time of formation and activity of fault systems in regions of high seismicity will help in selecting sites for construction of engineering structures.

3. In the Fennoscandian Shield, there was an activity of associations of fault systems in four Early Proterozoic deformation epochs. The kinematics of the faults in these associations was different in different epochs.

4. Study of fault system associations showed that a significant number of faults were active in two or more eras of deformation. The direction of movement along the fault is determined by the stress field acting in the epoch of deformations. It does not depend on the kinematics of this fault in previous epochs of deformation. Analysis of the associations of fault systems allows separate the fault systems that were active in different epochs of deformation of the region. The proposed method of interpreting diagrams, showing associations of fault systems, contributes to the systematization of multi-stage disjunctive deformations in the upper crust of tectonic region. The proposed method of interpreting diagrams showing associations of fault systems contributes to the systematization of multi-stage fragile deformations in the upper crust of regions.

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