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Joint orientations from Paleozoic sedimentary rocks in the Kyzyl Kum region, Uzbekistan, Central Asia

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Abstract. Over 18,000 joint orientations were measured from a spectrum of lithologies of various ages at natural exposures in the Central Kyzyl Kum region. For each exposure, we plotted joint orientation diagrams and identified local joint systems. Orientations of these systems were established from both (i) density maxima of poles to joints on stereograms and (ii) cluster analysis. Tilt-corrected data from coeval strata integrated over all the measurement localities were used to identify regional joint directions and their relative development. In Paleozoic sedimentary rocks these directions are, overall, close to fault and fold trends in structures related to pre-Paleozoic, Caledonian, and Hercynian evolutionary stages. However, regional joint systems display certain changes in their direction and development depending on rock age. In Cretaceous deposits, regional joint directions are chiefly inherited from those in Paleozoic strata. Our study of time-dependent changes in regional jointing characteristics proves that, as the region kept developing, the primary jointing became overprinted by additional random joints and tectonic joint systems. Our previous attempt to reconstruct paleostresses in the study region from joints in sedimentary rocks yielded results closely similar to fold trend data.

Introduction

Rock jointing, one crucial characteristic of upper crustal layers, is nearly ubiquitous in rocks of various origins and ages. Joints are not chaotic, but always show a regular quasi-periodic or roughly parallel arrangement. The rock jointing phenomenon has long been a challenge to researchers. A record of studies on rock jointing in North America and Western Europe spanning over 100 years is presented in, e.g., the overviews [*Hancock,* 1985; *Pollard and Aydin,* 1988]. These overviews, however, do not mention the weighty contribution to this issue from Russian workers. Their results are reflected in, e.g., synoptic sections of [*Chernyshev,* 1983; *Grachev and Mukhamediev,* 2000; *Permyakov,* 1949; etc.].

Students of jointing focus primarily on the number and orientation of joint systems, as well as their genesis and possible links with stresses operating in the earth's crust. To date, no generally accepted approach to these issues has been developed. The state of the art in identifying joint sets, mainly in cratonic areas, is presented in, e.g., [*Grachev and Mukhamediev,* 2000].

The key role played by rock jointing in certain processes addressed by solid earth sciences necessitates the search for various measures for its quantification. Over the recent decades, measures have been introduced to describe deformation properties, strength, damage, and permeability of fractured rocks. Various forms of second and fourth rank tensors constructed on vectors of single poles to joint planes were proposed in [*Cowin,* 1985; *Kawamoto et al.,* 1988; *Lee et al.,* 1995; *Oda,* 1986; *Salganik,* 1973; *Swoboda et al.,* 1998; etc.]. The respective tensors were termed "jointing tensor," "structural tensor," "permeability tensor," "damage tensor," etc.

We address two aspects of joint orientation studies in the Central Kyzyl Kum region:

- Identification of joint systems and analysis of their changes through space and over time.

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- Study of evolution of regional (including tensor) characteristics of joint patterns depending on rock age.

The Kyzyl Kum Plateau with its eolian relief lies in the extreme northwest of Central Asia, in Uzbekistan, between the lower reaches of the Amu-Darya and Syr-Darya Rivers (Figure 1). The plateaus interior is surmounted by the Central Kyzyl Kum Mtns. North and northeast of these, vast sands of the Kyzyl Kum Desert spread. In the west, across the Amu-Darya R. valley, which continues in a NW direction, the Kara Kum Desert lies. Southeast of the Central Kyzyl Kum Mtns., the system of Nuratau and Aktau Ranges and ZirabulakZiaetdin Mtns. stands out in the present-day relief.

In the end of the 20th century, south of the Central Kyzyl Kum Mtns. several strong earthquakes took place over a comparatively short period. The first, M = 7.0 quake, was recorded on April 8, 1976. Subsequent shocks occurred on May 17, 1976, with M = 7.3, on June 4, 1978, with M = 6.2, and on March 19, 1984, with M = 7.2 [*Graizer,* 1986]. Almost immediately thereafter, the Institute of Physics of the Earth of the USSR Academy of Sciences organized seismologic expeditions to establish macroseismic aftereffects of the quakes. These interdisciplinary studies included joint measurements. In the frames of this exercise, T. P. Belousov and A. L. Teremetsky measured over 18,000 joints in various lithologies of different ages. This paper presents results of processing and interpretation of their data.

1. Geologic framework and tectonic history of the Central Kyzyl Kum region

The Central Kyzyl Kum region is located within the Syr-Darya segment of the Turan plate, part of the Misian–ScythianTuran post-Paleozoic craton [*Khain,* 1977; etc.]. The study area is bounded in the east by the transverse West Tien Shan fault [*Rezvoi,* 1962] and in the north and northeast, by the west flank of the northern Nurata fault, separating it from the Syr-Darya basin. In the west-southwest, the uplifts are controlled by the west flank of the Kuldzhuktau–Aktau fault, and further south, by the Bukhara fault, separating the Central Kyzyl Kum from the Amu-Darya basin.

Within the Central Kyzyl Kum uplifts, two groups of structural features are recognized, (i) the Kuldzhuktau–Tamdytau system of uplifts comprising the Kuldzhuktau, Auminzatau, Aristanatau, and Tamdytau Mtns. in the south (Figure 2) and (ii) the Bukantau uplift, separated from the above features by the Dzhamankum and Mynbulak basins, in the north.

Basement of the study region was formed under the impact of two stages of Paleozoic orogeny. Caledonian tectonic movements in the first half of the Paleozoic (Cambrian to Early Devonian) affected the Riphean craton, resulting in NNW trending folded edifices. Hercynian orogenic movements (Middle Devonian to Permian) shaped structural features trending WNW and roughly E–W [*Geology...,* 1972; *Ibragimov et al.,* 1973]. The Hercynian stage of tectonic history over most part of the Turan plate terminated, and in the end of the Permian to the beginning of the Triassic the study area entered a cratonic phase [*Petrushevsky,* 1955; etc.].

In the second half of the Triassic to Jurassic, the Central Kyzyl Kum region represented a marine basin with individual insular uplifts on the site of the present-day mountains. In the Late Jurassic, general subsidence in the region became somewhat stronger, with terrigenous deposits giving way to lagoon and marine sediments [*Geology...,* 1972; *Ibragimov et al.,* 1973].

In the Early and Middle Paleogene to the first half of the Neogene, crustal subsidence in the Central Kyzyl Kum region began slowing down. The first signs of neotectonic reactivation, accompanied by invigoration of uplifting, became manifest in the Miocene to Pliocene [*Chediya,* 1971, 1972, 1986; *Shultz,* 1948, 1955, 1962; etc.]. In the terminal Pliocene to initial Pleistocene, a decline in tectonic movements took place [*Geology...,* 1972; *Krestnikov et al.,* 1979; *Yuriev,* 1967], which terminated in the beginning of the Middle Pleistocene. It was not until ca. 300 ka that the study region became once again the site of vigorous uplifting [*Krestnikov et al.,* 1979, 1980].

Arches of certain neotectonic uplifts in the Central Kyzyl Kum region display sporadic metamorphic basement outcrops represented by crystalline schist, gneiss, quartzite, and sandstone intercalated by dolomite and limestone. Their inferred age is Late Proterozoic [*Geology...,* 1972; *Ibragimov et al.,* 1973; *Khain,* 1977]. Paleozoic deposits are more widespread, their stratigraphic succession falling into Caledonian and Hercynian structural stages, comprised of several substages each (Figure 2).

The Caledonian structural stage is subdivided into the Cambrian–Lower Silurian and Upper Silurian–Lower Devonian structural substages [*Geology...,* 1972; *Ibragimov et al.,* 1973].

The lower part of the section of the Cambrian–Lower Silurian structural substage has not been established firmly, and it is only represented by sporadic outcrops in the vicinity of the Auminzatau and Tamdytau Mtns., composed of shale, limestone, and dolomite. Ordovician deposits were encountered in the Bukantau, Tamdytau, Aristanatau, and Kuldzhuktau Mtns. These are represented by shales with intercalations and lenses of chert, limestone, marble, gravelstone, sandstone, siltstone, a shale–sand member, and mafic extrusives and volcanics. The Upper Ordovician–Lower Silurian sections are divided into two types, terrigenous–carbonate and chert–carbonaceous shale [*Akhmedzhanov,* 1970]. In the Kuldzhuktau Mtns., terrigenous–carbonate deposits (gray sandy limestone intercalated by siltstone and shale, dolomite, and dolomitized limestone) are widespread. In the Tamdytau Mtns., the Lower Silurian is represented by brown fine-grained sandstone, siltstone, and clayey and carbonaceous clayey mudstone and siliceous, carbonaceous, and clayey sericite shales. In places, the upper part of the structural substage displays alternating layers of gravelstone, sandstone, and siltstone. This type of section is characteristic of the northern Tamdytau Mtns.

Terrigenous and carbonate deposits of the Upper Silurian–Lower Devonian structural substage are exposed in the Kuldzhuktau, Aristanatau, and northern Tamdytau Mtns.

Figure 1. Location map of the study area (shaded box) in the Central Kyzyl Kum region, central Uzbekistan.

Lower stratigraphic horizons are represented by gravestone, sandstone, and siltstone with sporadic thin intercalations and lenses of limestone. Further upsection, a member of limestone and dolomite intercalated by sandstone and shale occurs.

The Hercynian structural stage in the Central Kyzyl Kum comprises the Middle–Upper Devonian, Carboniferous, and Lower Permian structural substages. The Middle–Upper Devonian substage is represented by a carbonate formation composed of dolomite, dolomitic and marble-like limestone, schist, and, less frequently, gneiss and anhydrite. The base is made up of redbed sandstone and conglomerate. The Carboniferous structural substage in the Bukantau and northern Tamdytau Mtns. is composed of massive limestone intercalated by siliceous limestone and molasse deposits, pierced by Upper Carboniferous granite and granodiorite massifs; porphyritic diabase members are encountered. In the Tamdytau and Kuldzhuktau Mtns., the Middle–Upper Carboniferous strata are comprised of carbonate and terrigenous deposits, classified as flysch. These rocks are pierced by granite-granodiorite bodies of Upper Paleozoic age.

Rocks of the Lower Permian structural substage in the Central Kyzyl Kum region occur sporadically. These are dominated by molasse, granite, and granodiorite. The Upper PermianLower Triassic substage within the study region is lacking [*Ibragimov et al.,* 1973; *Khain,* 1977].

Mesozoic and Cenozoic rocks in the Central Kyzyl Kum region are mainly exposed along the periphery of uplifts. These are represented by Cretaceous, Paleogene, and Neogene deposits (conglomerate, sandstone, clay, dolomite, limestone).

2. Methods used while studying rock jointing

This section discusses methods prerequisite while handling the issues of interpretation of rock jointing in the Central Kyzyl Kum region, posed in Introduction.

2.1. Statistical analysis of joint measurement data

At each station in the Central Kyzyl Kum region, strike-and-dip measurements were taken on 100 joints. Measurements were taken exceptionally at natural exposures. The initial phase in field data processing is graphical visualization of joint planes on stereograms. This study makes use of the Wulff equal-angle stereographic projection. For the sake of definiteness, we assumed an upper-hemisphere orientation for normal vectors to joint planes.

Provided a representative enough set of N orientations of joints $\mathbf{n}_i$ has been established, their distribution is visualized by an array of points on a stereogram. An exemplary visualization of orientations of 100 poles to joints, measured from a limestone bed in the vicinity of the Auminzatau Mtns., Central Kyzyl Kum region, is given in Figure 3a. Hereinafter, crosses denote layer-normal vectors (poles to bedding).

Field measurements of orientations N, referring to an individual exposure or part thereof, are a random sample of the continuous orientation function $f(\mathbf{n})$, which defines density of the probability with which the pole to a joint plane

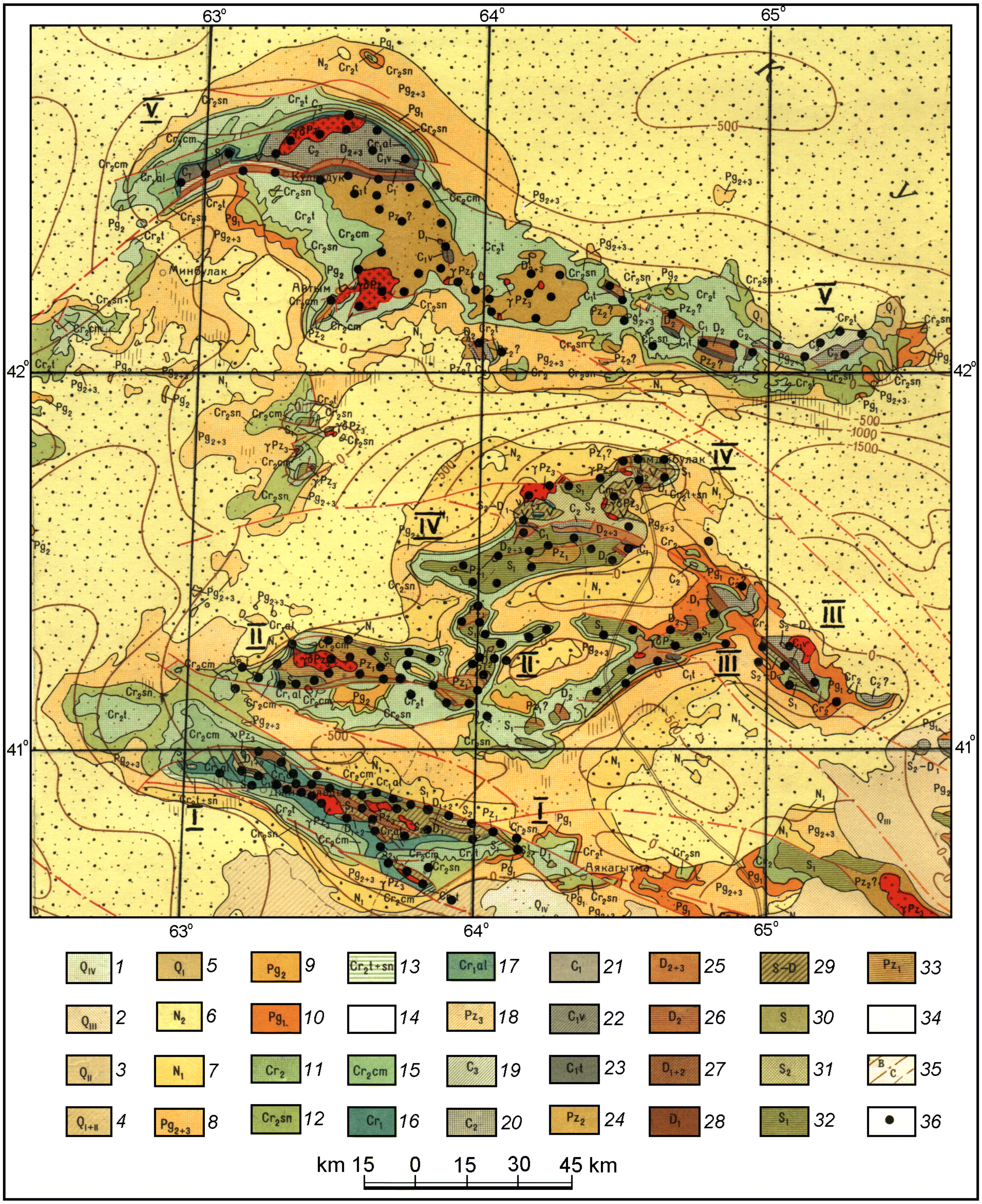

Figure 2. Location of joint measurement stations against geological framework of the Central Kyzyl Kum region [*Geologic...*, 1964].

Neotectonic uplifts: I = Kuldzhuktau, II = Auminzatau, III = Aristanatau, IV = Tamdytau, and V = Bukantau.

1–5 – Quaternary deposits: 1 – Holocene, 2 – Upper Quaternary, 3 – Middle Quaternary, 4 – Lower to Middle Quaternary, 5 – Lower Quaternary; 6 – Pliocene; 7 – Miocene; 8 – Eocene and Oligocene; 9 – Eocene; 10 – Paleocene; 11 – Upper Cretaceous; 12 – Senonian Superstage, Upper Cretaceous;

falls within the small solid angle $d\omega$ around the direction $\mathbf{n}$:

$$\frac{dN}{N} = \frac{1}{4\pi} f(\mathbf{n})\ d\omega,\ \ \mathbf{n} = \{\alpha, \beta\},\ \ d\omega = \sin\alpha d\alpha d\beta\ , \qquad (1)$$

where α and β are the polar and azimuthal angles of the spherical coordinate system. The function $f(\mathbf{n})$ describes jointing in the exposure under study and is termed "local joint orientation distribution."

The function $f(\mathbf{n})$ is normalized in such a manner that

$$\int_0^{\pi}\int_0^{2\pi} f(\alpha,\beta)\sin\alpha d\alpha d\beta = 4\pi\ . \qquad (2)$$

This natural normalization implies that, with a chaotic (equiprobabilistic) joint distribution, $f(\mathbf{n}) \equiv \mathbf{1}$. Such a description of pole densities is used widely in material science [*Bunge,* 1982] and structural geology [*Wenck,* 1993].

In order to reconstruct continuous distributions of joint orientations (pole densities), field measurement data are put to a smoothing transform. Assessing the pole density $f(\mathbf{n},\varepsilon)$ consists in juxtaposing fuzzy spikes from measured joint orientations:

$$f(\mathbf{n},\varepsilon) = \frac{4\pi}{N}\sum_{i=1}^{N} f^G(\mathbf{n},\mathbf{n}_i,\varepsilon)\ , \qquad (3)$$

where $f^G(\mathbf{n},\mathbf{n}_i,\varepsilon)$ is the spherical Gaussian distribution with a distance ε, whose center coincides with the pole $\mathbf{n}_i$ of the ith joint. In (3), summation is carried out over all the joint orientations measured. The dispersion parameter ε must be so chosen that individual spikes from measured orientations overlap, but, at the same time, essential characteristics of the distribution remain undistorted.

Summation of spikes from individual poles yields the smoothened function $f(\mathbf{n},\varepsilon)$, which approximates well the true pole density $f(\mathbf{n})$. Expression (3) can also be viewed as a realization of a two-dimensional numerical filter for discrete data with an isotropic Gaussian averaging window.

The spherical analog of the two-dimensional Gaussian distribution is not expressed through elementary functions, and its distribution law is written as follows [*Savelova and Bukharova,* 1996]:

$$f^G(\mathbf{n},\mathbf{n}_i,\varepsilon) = \sum_{l=0(2)}^{\infty}(2l{+}1)\exp\left\{-1(l{+}1)\varepsilon^2\right\}P_\lambda(\cos\tau)\ , \qquad (4)$$

where $P_\lambda(\cos\tau)$ is Legendre polynomials, τ is angular distance of the vector $\mathbf{n}$ from the distribution center $\mathbf{n}_i$, and $\cos\tau = \mathbf{n}\cdot\mathbf{n}_i$. The parameter ε defines the radius $f(\mathbf{n})$ of the Gaussian spike at its mid-height, in radians. In the case under study, based on 100 joint measurements, we chose the value $\theta = 14°$ (a spherical segment with an angle this large is ≈1/100 of the area of the sphere).

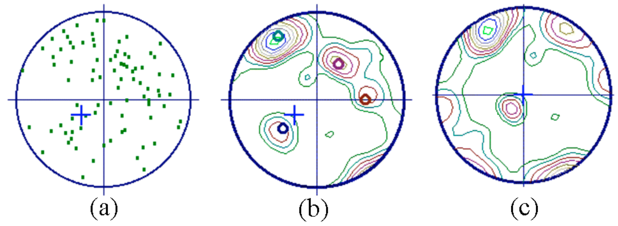

Figure 3. Joint orientation distributions from Silurian (S_1) bedded limestones at St. 84, dipping at 35° with an azimuth of 235°.
a – joint poles; b – continuous pole distribution and attitude of joint systems identified; c – pole density distribution, tilt corrected. Cross denotes pole to bedding, and circles, centers of clusters identified.

After calculating the pole density $f(\mathbf{n},\varepsilon)$ on a regular grid over the entire spherical projection area, pole density contours are constructed in order to obtain a graphical visualization of the joint orientation distribution. With a continuous function, drawing contours is a simple task. A quantitative pole pattern corresponding to the pole array in Figure 3a is given in Figure 3b. In all the pole patterns presented, level lines were spaced at 0.5 density level units of the chaotic distribution.

Not infrequently, the character of jointing can be grasped at a first glance at pole densities. However, in order to rule out subjective bias, automatic identification of statistically significant maxima ("joint sets") in the empirical pattern of pole distribution density is indispensable [*Grachev and Morozov,* 1993; *Grachev and Mukhamediev,* 2000]. First, all the local density maxima are identified. Some maxima correspond to real joint sets, while others emerge as artifacts of the statistical nature of measurements.

A criterion for detecting statistically insignificant maxima was found through a numerical experiment. We constructed 1600 sets of 100 vectors each, distributed randomly over the sphere. For this case, the true pole density is known ($f(\mathbf{n}) \equiv \mathbf{1}$). All the sets were processed as real joint orientation distributions, yielding local pole density maxima. These were treated as artifacts, which enabled us to plot the probability of detecting a false maximum as a function of the significance level (Figure 4). As a result, spikes with density

13 – Turonian Stage and Senonian Superstage, Upper Cretaceous; 14 – Turonian Stage, Upper Cretaceous; 15 – Cenomanian Stage, Upper Cretaceous; 16 – Lower Cretaceous; 17 – Albian Stage, Lower Cretaceous; 18 – Upper Paleozoic; 19 – Upper Carboniferous; 20 – Middle Carboniferous; 21 – Lower Carboniferous; 22 – Visean Stage, Lower Carboniferous; 23 – Tournaisian Stage, Lower Carboniferous; 24 – Middle Paleozoic; 25 – Middle and Upper Devonian; 26 – Middle Devonian; 27 – Lower and Middle Devonian; 28 – Lower Devonian; 29 – Silurian–Devonian; 30 – Silurian undivided; 31 – Upper Silurian; 32 – Lower Silurian; 33 – Lower Paleozoic; 34 – faults; 35 – depth to basement; 36 – joint measurement station.

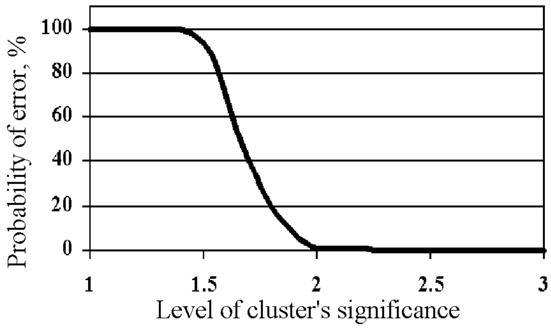

Figure 4. Probability of spurious identification of pole density maxima versus significance level (for 100 joints).

maxima not exceeding 1.5 are found to be false with a 94% probability. Spikes with density maxima greater than 2.0 are true with a 98% probability. The probability that a spike with a height between 1.5 and 2.0 is true is established from the curve shown in Figure 4. The procedure of applying the significance criterion is illustrated in Figure 5. Note that the criterion in point is valid with sets of 100 joint orientations. This criterion is easy to generalize for interpreting sets with other numbers of measurements N. The resultant graphical representation of the criterion will be a series of curves analogous to the one in Figure 4 and corresponding to different parameters N.

An example of joint analysis is depicted in Figure 3b, showing four joint sets identified from an exposure of Lower Silurian limestone in the Central Kyzyl Kum region. Three of these are bedding orthogonal.

A wealth of mathematical methods for the automatic classification of data into homogeneous groups of objects (clusters, taxa) have been elaborated [*Aivazian et al.,* 1989]. Certain cluster algorithms were used for processing joint measurements in order to isolate joint sets [*Hammah and Curran,* 1998; *Mahtab and Yegulalp,* 1982; *Shanley and Mahtab,* 1976]. In this study, while identifying joint sets, alongside the pole density analysis we employed an efficient sequential k-means algorithm, in which the number of clusters is not preset, but is constrained using iterative procedure [*Aivazian et al.,* 1989]. The analysis establishes the number of clusters and identifies to which cluster the points belong. The cluster's position on the projection sphere defines the center of gravity of its constituent points. In this manner, information is reduced: a vast number of field measurements are reduced to a description of coordinates and relative weights of a few clusters.

In this work, we employed two independent methods to identify joint sets:

1. Based on pole density maxima.

2. Based on centers of gravity of clusters. For most distributions, these two approaches yield similar results (see Section 3). This is illustrated in Figure 3b, in which centers of the clusters identified virtually coincide with pole density maxima.

In order to detect statistically insignificant maxima and clusters, we used the criterion for pole density significance in the center of a cluster (Figures 4, 5). In the context of the first approach, we assumed that a maximum of the function $f(\mathbf{n}, \varepsilon)$ smaller than 1.5 does not correspond to any joint set. If a maximum of the function $f(\mathbf{n}, \varepsilon)$ lies between 1.5 and 2.0, it corresponds with a certain probability to a set. Likewise, while using the second approach, joints forming a cluster with a density maximum smaller than 1.5 were classed as random. A cluster with a density maximum between 1.5 and 2.0 is spurious with a rather definite probability. Note that the issue of whether a joint set with its pole density maximum between 1.5 and 2.0 is real or not cannot be resolved by analyzing a single local joint distribution. Reality of such a set must be confirmed by its presence across a certain population of measurement stations in the framework of a massive joint measurement exercise covering many exposures.

Critical importance is attached to correcting joint distributions for the folding-induced tilt of bedding planes. An example of such tilt correction, in which the pole to bedding is brought to the projection center, is shown in Figure 3c.

2.2. Regional tensor characteristics of jointing

We put forward a tensor technique [*Belousov et al.,* 1994, 1996] for representing joint measurement data from a certain population of stations in a particular region or from coeval rocks in that region. For local joint orientation distributions, we introduce a symmetrical second rank tensor $\mathbf{J}$ with eigenvalues of $J_1, J_2, J_3 (J_1 \geq J_2 \geq J_3)$. The tensor $\mathbf{J}$ is represented by a sum of dyads composed of single joint-normal vectors, and it is normalized to the first invariant. It is defined positively for any orientation distribution, except the so-called "needle" distribution, where all the joints in the population in question are parallel to each other.

The tensor $\mathbf{J}$ is characterized by five independent scalar values, for which we may insert the invariants S (intensity of the deviator $\mathbf{J}$), ω_J (an angle of the form $0 \leq \omega_J \leq$

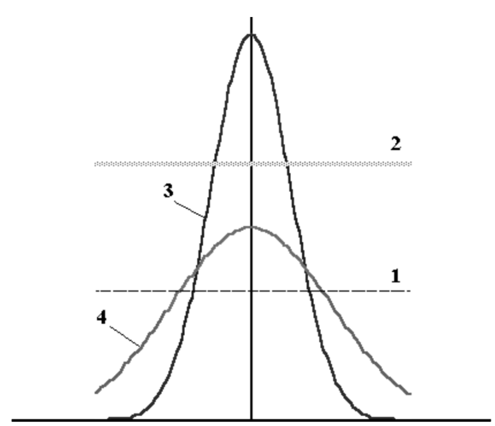

Figure 5. Scheme showing identification of statistically significant joint systems.
1 – chaotic pole density level, 2 – significance level, 3 – statistically significant joint system, 4 – statistically insignificant joint system.

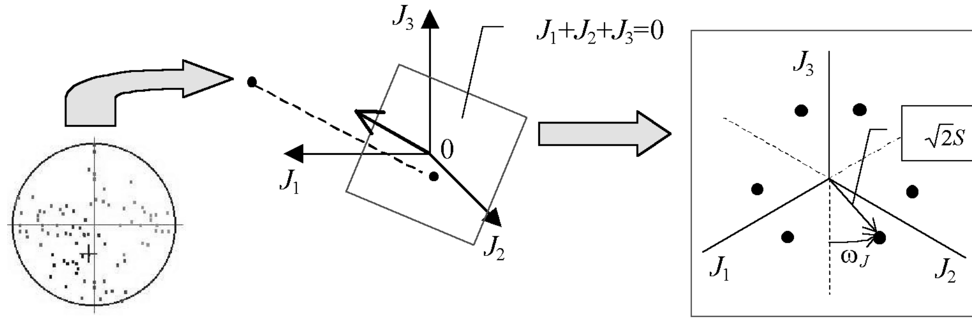

Figure 6. Diagram showing the invariants S and ω_J of the inertia tensor **J** for joint orientation distribution in the deviatoric plane $J_1 + J_2 + J_3 = 0$.

$\frac{\pi}{3}$), and three Eulerian angles designating the trihedron of principal axes of the tensor **J** in space. Hence, 100 joint measurements from an exposure become represented by five numbers. The tensor **J** reflects both the inner geometry of the orientation distribution, invariants S and ω_J being determined by the mutual position and relative strengths of pole distribution maxima on a stereogram, and its external geometry, the three Eulerian angles being determined by the joint set orientations relative to the spatial reference frame.

Let us resort to a graphical visualization of invariants of the tensor **J**, in which the point J_1, J_2, and J_3 in a three-dimensional space with homonymous mutually orthogonal axes is projected orthogonally onto the deviatoric plane $J_1 + J_2 + J_3 = 0$ (Figure 6). The deviatoric plane passes through the origin of coordinates and is equally inclined to the J_1, J_2, and J_3 axes. To obtain a symmetrical pattern, the projected point is reflected relative to the projections of the J_1, J_2, and J_3 axes and their negative continuations, ultimately to be transformed into six points in the deviatoric plane (Figure 6). The invariants $\sqrt{2}S$ and ω_J make up a natural polar coordinate system in this plane: $\sqrt{2}S$ is the distance in the plane from the projection of the point J_1, J_2, and J_3 to the origin of coordinates $J_1 = J_2 = J_3 = 0$ and the angle ω_J is the polar angle, counted from the negative continuation of the J_1, J_2, and J_3 axes.

The tensor **J**, because of its degeneration, is of little use while studying an individual joint orientation distribution. Its role increases considerably while analyzing regional jointing characteristics based on an entire population of local distributions. A population of points S, ω_J in a deviatoric plane, corresponding to **J** tensors for different stations in the study region (or, e.g., coeval rocks from across the region), creates a characteristic individual "portrait" of the inner geometry of tectonic jointing, inherent in this particular region. The value $\sqrt{2}S$ decreases as the local joint distribution under study approximates the chaotic (equiprobabilistic) one. For this reason, the greater the number of variously oriented (and inclined to bedding) random joints and tectonic joint sets that overpint, as the rocks keep evolving, the two primary conjugate joint systems (orthogonal to bedding), the closer to the origin of coordinates $J_1 = J_2 = J_3 = 0$ points visualizing such a joint distribution in the "portrait" become.

The angle of the form ω_J reflects other properties of the local joint distribution. With $J_1 = J_2 > J_3$ (which holds true, in particular, for "needle" distributions), $\omega_J = 0$, and data points in the deviatoric plane lie on negative continuations of the projections of the J_1, J_2, and J_3 axes. Conversely, with $J_1 > J_2 = J_3, \omega_J = \pi/3$, and data points lie on the projections proper of the J_1, J_2, and J_3 axes. Let the corresponding joint distributions be termed "disc" distributions. "Disc" distributions are exemplified, in particular, by distributions with three roughly bedding-orthogonal joint sets (in the case of roughly equal strengths of density maxima and angles between them on a stereogram) and by distributions with two almost orthogonal joint sets with roughly equal numbers of joints. In distributions with $\omega_J = \pi/6$, which can tentatively be termed "transitional," $J_1 - J_2 = J_2 - J_3$.

As the ratio of joint numbers in the two mutually orthogonal sets changes from 1 to 0, distributions change first from "disc" to "transitional" ($\omega_J = \pi/6$) and then to "needle" types. With general-type distributions, in which several joint sets are identified, positions of data points in the integrated "portrait" already depend on a greater number of parameters (ratios of joint numbers in the sets and angles between the sets).

It is worth noting that no rotations of local joint orientation distributions bear on positions of data points in the deviatoric plane, and, hence, such rotations do not affect the integrated "portrait" of the region.

Figure 7 shows integrated joint "portraits" of deposits of various ages from our study areas in the Central Kyzyl Kum region. These results are discussed in Section 4.

3. Results of the rock jointing study from the Central Kyzyl Kum region

3.1. Field measurement data

We measured joint orientations in rocks that make up the Central Kyzyl Kum uplift at 181 stations, 161 of which are located on sedimentary rocks. Figure 2 shows location of stations against a geological map of the study region at a

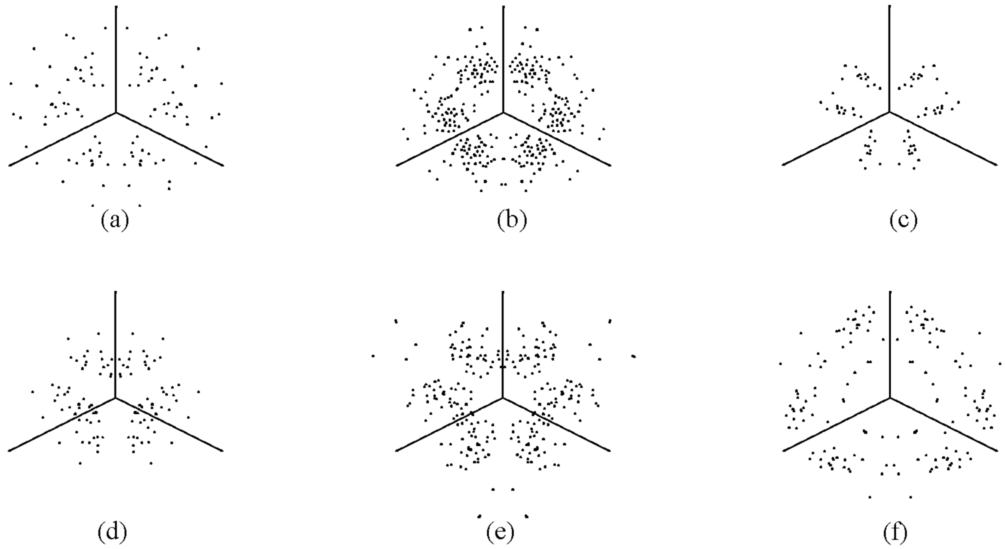

Figure 7. Integral joint distribution "portraits" in the Central Kyzyl Kum region from rocks of various ages: a – Early Paleozoic (Pz_1), 17 sts.; b – Silurian (S), 49 sts.; c – Late Silurian to Early Devonian (S_2–D_1), 12 sts.; d – Devonian (D), 17 sts.; e – Carboniferous (C), 40 sts.; f – Cretaceous–Paleogene (K–Pg), 25 sts.

1:1 500,000 scale [*Geologic...*, 1964].

Within the study area, joint measurement coverage is most detailed over sedimentary rocks of Paleozoic age, which were studied at 135 exposures. Specific age intervals were covered as follows:

- Lower Paleozoic (undivided, Pz_1), 17 stations.
- Silurian (S), 49 stations: Lower, 35 sts., Upper, 7 sts., and undivided, 7 sts.
- Upper Silurian to Lower Devonian (S_2–D_1), 12 sts.
- Devonian (D), 17 sts.: Lower to Middle, 10 sts.; Middle, 4 sts.; Upper, 1 st.; and Middle to Upper, 2 sts.
- Carboniferous (C), 40 sts.: Lower, 7 sts.; Middle, 29 sts.; and Upper, 4 sts.

At 13 stations, Late Paleozoic granites (11 sts.) and diabases (2 sts.) were studied. A separate group is comprised of Paleozoic quartzites, which were studied at 7 stations: 2 Silurian, 4 Middle Carboniferous, and 1 Upper Paleozoic.

Because Mesozoic and Cenozoic rocks in the Central Kyzyl Kum region are poorly exposed and, in most cases, represented by clayey lithologies, our joint measurements on these rocks were limited to 26 exposures, including chiefly Cretaceous sediments (23 sts.), 8 from the Lower and 15 from the Upper Cretaceous. Cenozoic deposits were covered by measurements at 3 stations only, including 2 in the Paleogene (Pg) and 1 in the Pliocene–Early Pleistocene (Ng_2^3–Q_1) rocks.

Lithologies that received the most dense coverage are limestones (66 sts.) and shales (63 sts.). Less detailed measurements were taken from sandstones (19 sts.), conglomerates (11 sts.), granites (11 sts.), quartzites (7 sts.), and other rocks (4 sts.).

Our field studies encompass, from south to north, the neotectonic uplifts of the Kuldzhuktau (41 sts.), Auminzatau (38 sts.), Aristanatau (20 sts.), Tamdytau (24 sts.), and Bukantau Ranges (58 sts.) (Figure 2).

3.2. Analyzing results of field observations

3.2.1. The format of data presentation. Within neotectonic uplifts of the Central Kyzyl Kum region, Paleozoic deposits are most widespread (Figure 2). The rocks are considerably deformed, tilts of sedimentary strata over the entire population of stations ranging from 20° to 70°, dominant values being 50°–70° (hereinafter, see Figure 8).

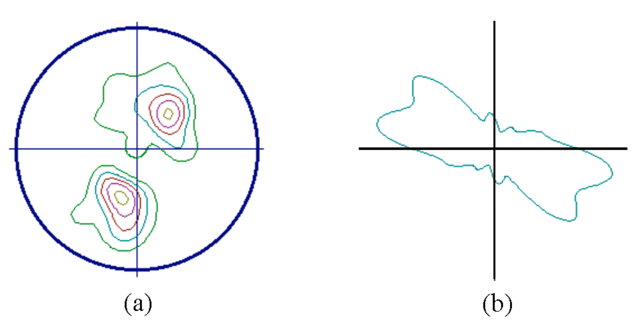

Figure 8. Dip angle densities for sedimentary strata from exposures under study (a) and a rose diagram of reconstructed hinge line directions for an imaginary averaged fold (b).

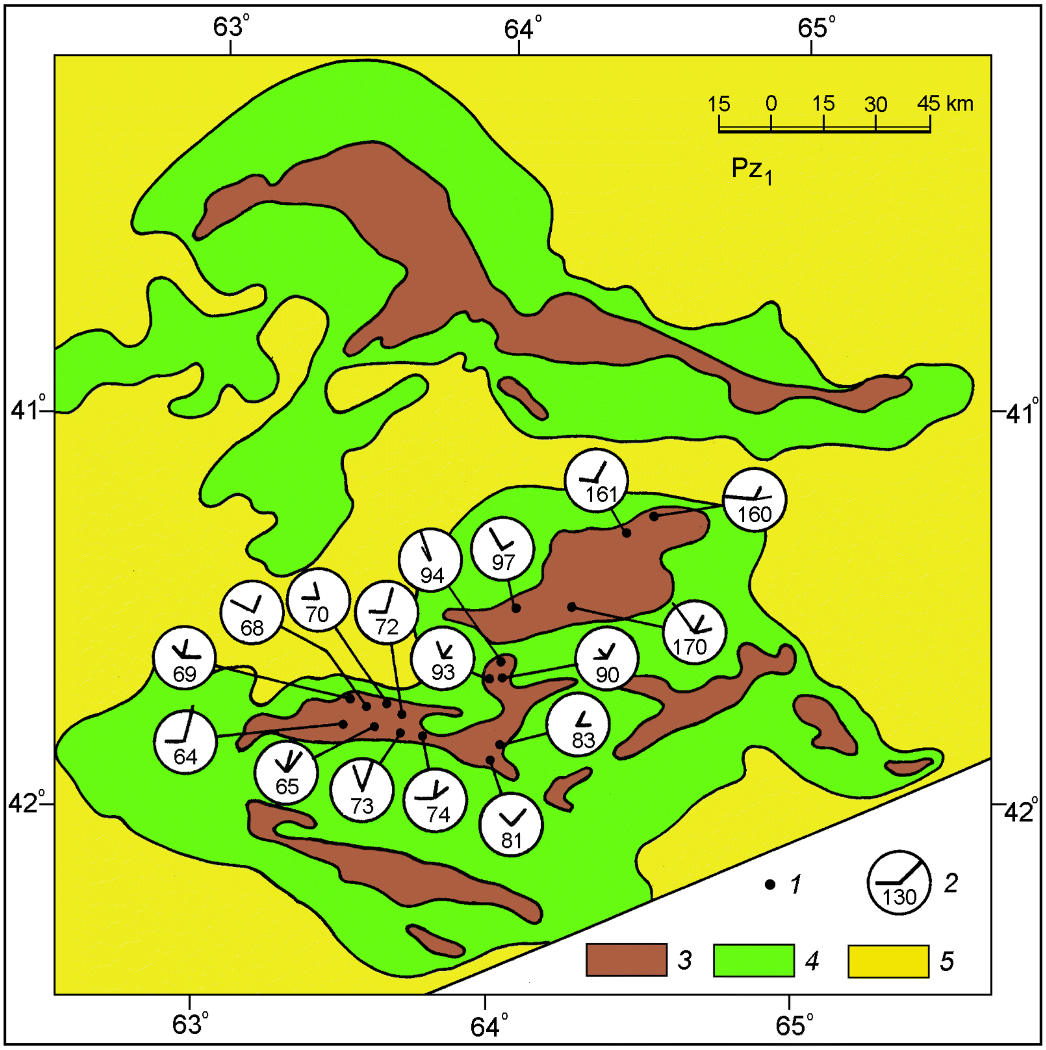

Figure 9. Scheme showing strikes of local joint systems in tilt-corrected Lower Paleozoic strata from the Central Kyzyl Kum region.
1 – joint measurement station; 2 – strike of a joint system in northerly quarters and station number (bar length proportionate to joint density in the system); rock ages: 3 – Paleozoic, 4 – Cretaceous to Paleogene, and 5 – Neogene to Quaternary.

Note that joint sets identified from sedimentary rocks are presented for local tilt-corrected joint orientation distributions.

In this paper, stereograms of local joint orientation distributions from all the exposures studied are given in Appendix[1], and results of identification of joint systems are presented in pertinent schemes (Figures 9–14). The schemes depict strikes of joint systems, as identified from maxima of the density function $f(\mathbf{n}), \varepsilon)$ on stereograms. Strikes of those systems whose pole density maximum on stereograms is $\leq 10^{\circ}$ apart from the bedding pole (see Sts. 31, 32, 37, 43, 44, etc.) are not depicted on the schemes. With angular distances like this, even small errors in strike-and-dip measurements will result in large errors while defining joint system strikes. In certain cases, systems with observable similarity in terms of strike differ considerably in their dip azimuth and/or angle.

3.2.2. Identifying regional joint directions: Terms used. This study addresses rock jointing at two spatial scales, local and regional. The local level corresponds to an individual rock exposure, and regional, to the entire population of exposures distributed across a certain area. Accordingly, joint systems identified from an individual exposure are termed local systems by us, and those traceable over the

[1]See online version of the paper, *http://rjes.agu.org/v03/tje01065/appendix.htm*

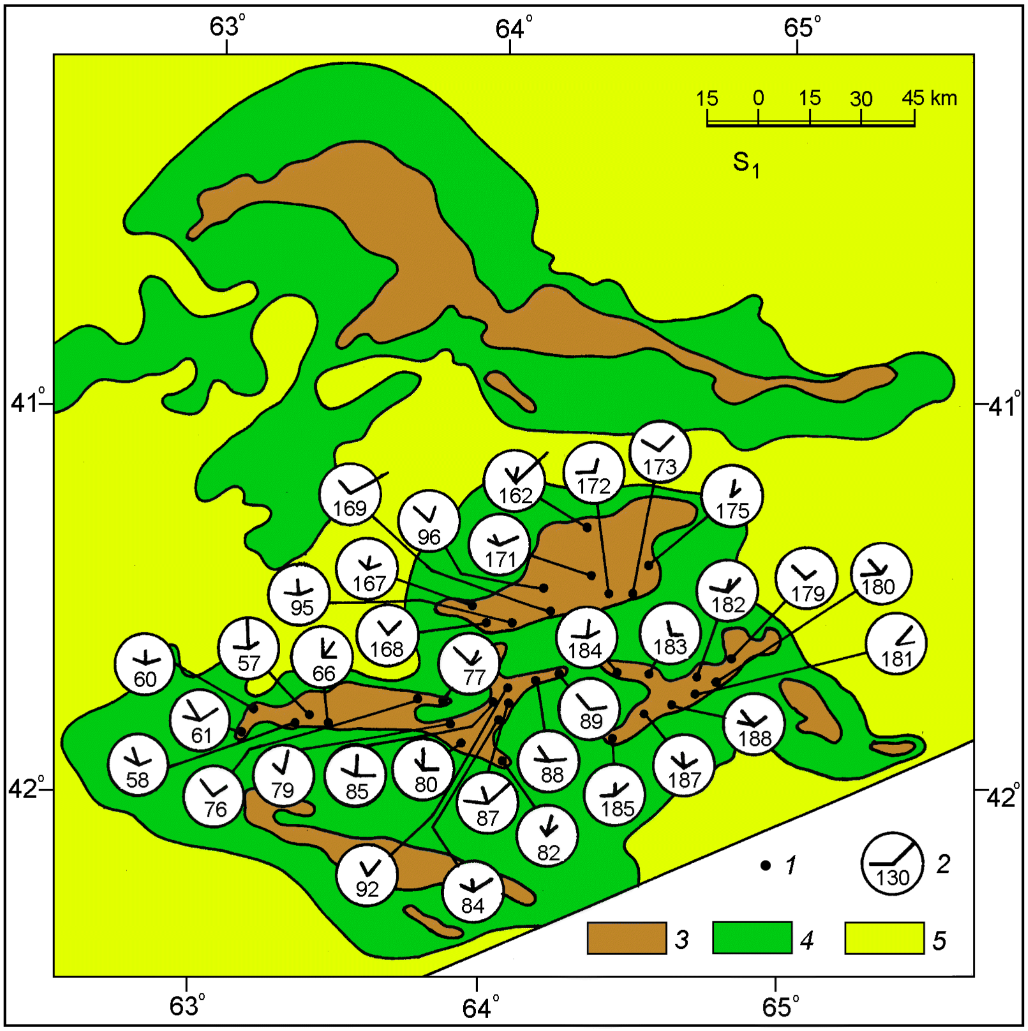

Figure 10. Scheme showing strikes of local joint systems in tilt-corrected Lower Silurian strata from the Central Kyzyl Kum region. Symbols as in Figure 9.

entire population of exposures of coeval rocks are termed regional systems.

While analyzing rock joints in the Central Kyzyl Kum region, we tackled successively two problems:

1. Identifying local joint systems in each exposure under study.

2. Identifying regional joint directions (regional joint systems) based on orientations of local joint systems.

Local joint systems referred to in Section 3.2. are identified by analyzing pole density maxima (Method 1, discussed in Section 2.1.).

Solving the second problem was, in practice, reduced to plotting directions of all the local joint systems identified from a given population of stations on a rose diagram and to establishing the regional directions, into which local systems are grouped. In so doing, a regional joint system traceable through more than a half of the entire population of stations under study was tentatively tagged by us as consistent. Regional joint directions were classified as inconsistent if the local systems of matching orientations were identified at less than one-half, but more one-third of the exposures. In the remaining cases, we viewed the regional joint system to be non-existent in reality.

For the sake of brevity, while describing the results of our study of regional joint orientations, we use the following gradations of development of local and regional systems. Note that these gradations are based on the criterion for pole density maxima significance, obtained in Section 2.1. (Figures 4, 5). With a pole density maximum on a stereogram greater than 2.0, the system is said to be well-developed. The same term can be extended to a regional system, provided it is chiefly identified based on well-developed local systems. Things become more complicated when a pole density maximum on a stereogram lies between 1.5 and 2.0. According to the criterion used, the issue of whether or not this maximum corresponds to a local joint system cannot, strictly

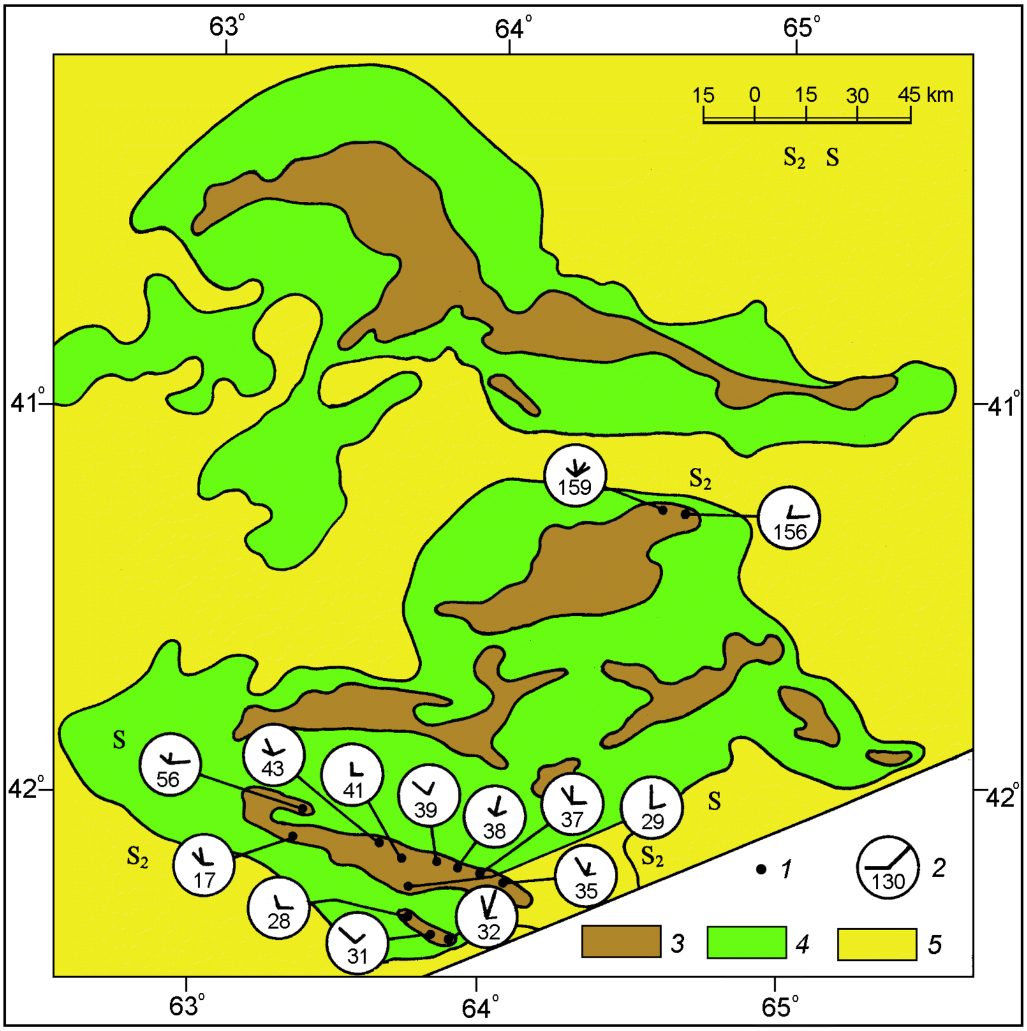

Figure 11. Scheme showing strikes of local joint systems in tilt-corrected Upper Silurian and undivided Silurian strata from the Central Kyzyl Kum region. Symbols as in Figure 9.

speaking, be solved unambiguously. However, provided the corresponding direction is consistently traceable through the majority of coeval rock exposures, it would stand to reason that the regional system of this direction exists in reality. In this study, such a regional system is termed a "sparsely developed" system. While specifying the strike of a regional joint system, we usually give in parentheses the range of pole density maxima corresponding to local systems that comprise this direction.

Regional joint systems matching in strike fold and fault structures of pre-Paleozoic, Caledonian, and Hercynian evolutionary stages are referred to as principal systems here.

3.2.3. Rock jointing in the Caledonian structural stage. We studied joint orientations in sedimentary rocks of the Caledonian structural stage in the Central Kyzyl Kum region at 88 stations.

The lower portion of the Cambrian–Lower Silurian substage is composed of undivided Lower Paleozoic sedimentary deposits, chiefly represented by shale and limestone. Shales received a more detailed coverage, at 14 stations out of the total of 17.

Local joint orientation distributions in the Lower Paleozoic rocks are characterized (Figure 9) by either two (7 sts.) or three (10 sts.) joint systems. Regional joint directions trend NNE (0°–30°), W–E (265°–280°), and NW (310°–320°). The most consistent among these is the NNE direction, which persists through nearly all the stations (Figure 9). This joint system is also characterized by considerable pole density maxima on stereograms ranging from 1.5 to 4.5, most frequently equaling 2.0–3.5. Assumedly, this trend is inherent to structural features of the most ancient, pre-Paleozoic, origin [*Ibragimov et al.,* 1973]. A roughly E–W to WNW joint strike, displayed by fold and fault structures formed during the Hercynian evolutionary stage of the Kyzyl Kum region, is almost equally consistent. This joint system, however, is less well developed in the Lower Paleozoic rocks, showing pole density maxima of 1.5–2.5. The NW-trending

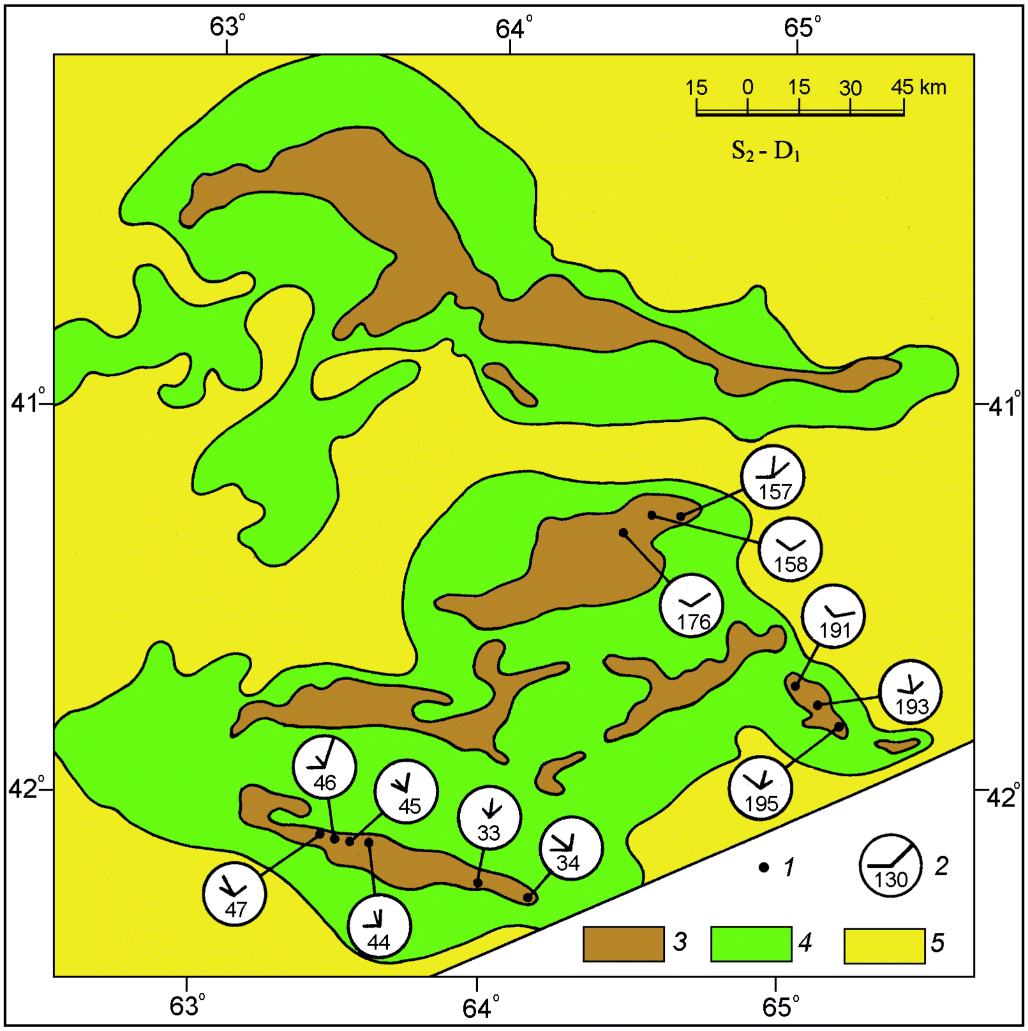

Figure 12. Scheme showing strikes of local joint systems in tilt-corrected Upper Silurian to Lower Devonian strata from the Central Kyzyl Kum region. Symbols as in Figure 9.

joint system is sparsely developed (1.5–2.0), but, apparently, it is a real regional system, since it is identified at 6 out of 17 stations. This direction is manifest by most structural features, faults inclusive, that formed in the study region during the Caledonian orogenic stage.

Among rocks comprising the Caledonian structural stage in the Central Kyzyl Kum region, sedimentary rocks of Silurian age are developed on virtually all the uplifts in the study area, except Bukantau. We studied their jointing at 49 stations. Among these deposits, the most detailed measurements were taken from Lower Silurian sedimentary rocks (35 sts.), composing the upper part of the Cambrian–Lower Silurian substage (Figure 10).

On the Auminzatau uplift (Figure 2), jointing in Lower Silurian deposits was studied rather exhaustively (16 sts.). These deposits are represented by shale (13 sts.) and limestone (3 sts.). At 13 stations shown in the scheme, three joint systems are identified, and only three stations yielded two systems each. The totality of stations yield four regional joint directions, N to NNE (0°–10°), NE (35°–50°), W–E (270°–280°), and NW (315°–320°). These data show that within the Auminzatau uplift, in the Early Silurian, in place of the Lower Paleozoic NNE trending joint system, two new systems, oriented N to NNE and NE, emerged. At the same time, joint systems oriented NW and roughly E–W persisted. The best developed systems of all are those directed NNE (with pole density maxima in the range 2.0–3.5), NE (2.0–3.5), and NW (1.5–3.0). Note that in the west of the Auminzatau uplift the N to NNE trending (pre-Paleozoic) joint system is better developed, while in the east, the NW trending (Caledonian) system is. The roughly EW to WNW direction, inherent in structures formed at the Hercynian stage of the Kyzyl Kum history, is sparsely (1.5–2.5) and inconsistently developed in the Lower Silurian rocks.

Lower Silurian sedimentary rocks are also exposed on the Aristanatau uplift in the southeastern Central Kyzyl Kum region (Figure 2). In most exposures, rocks of this age, represented by limestone (5 sts.) and shale (4 sts.), exhibit

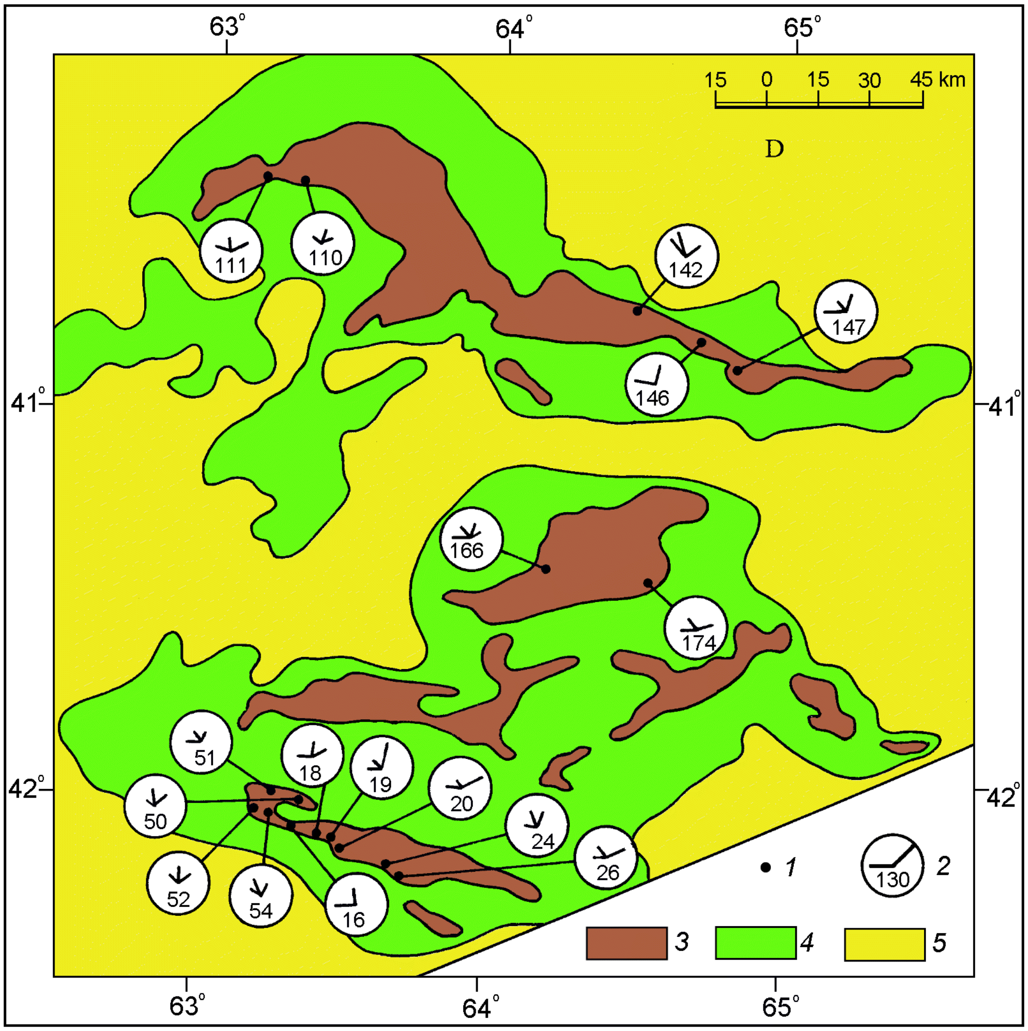

Figure 13. Scheme showing strikes of local joint systems in tilt-corrected Devonian strata from the Central Kyzyl Kum region. Symbols as in Figure 9.

three joint system (Figure 10). The entire population of stations yields joint systems oriented NNE (5°–15°), NE (40°–55°), W–E (270°–280°), and NW (310°–320°), i.e., in virtually the same manner as on the Auminzatau uplift. All the regional joint systems are consistent. Of these, best developed systems are those directed NNE (2.0–3.5) and NE (2.0–3.5), while those directed NW are developed somewhat less well (1.5–2.5). Joints directed roughly E–W to WNW in Lower Silurian rocks on the Aristanatau uplift are developed sparsely (1.5–2.0).

Within the Tamdytau uplift, located in the central part of the Central Kyzyl Kum region, north of the Auminzatau and Aristanatau uplifts (Figure 2), we measured jointing in the Lower Silurian sedimentary rocks at 10 stations. The rocks studied are represented by shale (6 sts.) and limestone (4 sts.). In most exposures, joint pattern in the Lower Silurian rocks displays three local joint systems, for which the entire population of stations yields NNE (10°–20°), NE (45°–60°), ENE to E (75°–90°), and NW (305°–315°) regional directions. All these regional systems are consistent. Maxima of the density function $f(\mathbf{n}, \varepsilon)$ on stereograms are expressed, from strongest to weakest, by the following values: NE (2.0–4.5), NW (1.5–3.0), ENE to E (1.5–2.5), and NNE (1.5–2.0).

As appears from the above data, on the Auminzatau, Aristanatau, and Tamdytau uplift, located in the southern and central parts of the Central Kyzyl Kum region, joint patterns in Lower Silurian rocks are strongly similar (Figure 10). On the other hand, in a northeasterly direction, strikes of the two regional NE-trending joint systems swing gradually to the south, from 0°–10° and 35°–50° (Auminzatau) through 10° and 40°–55° (Aristanatau) to 10°–20° and 45°–60° (Tamdytau). The NW-trending joint system also changes its trend, swinging south from 315°–325° on Auminzatau through 310°–320° on Aristanatau to 305°–315° on Tamdytau.

Analyzing joint measurements from seven stations in undivided Silurian strata exposed on the Kuldzhuktau uplift

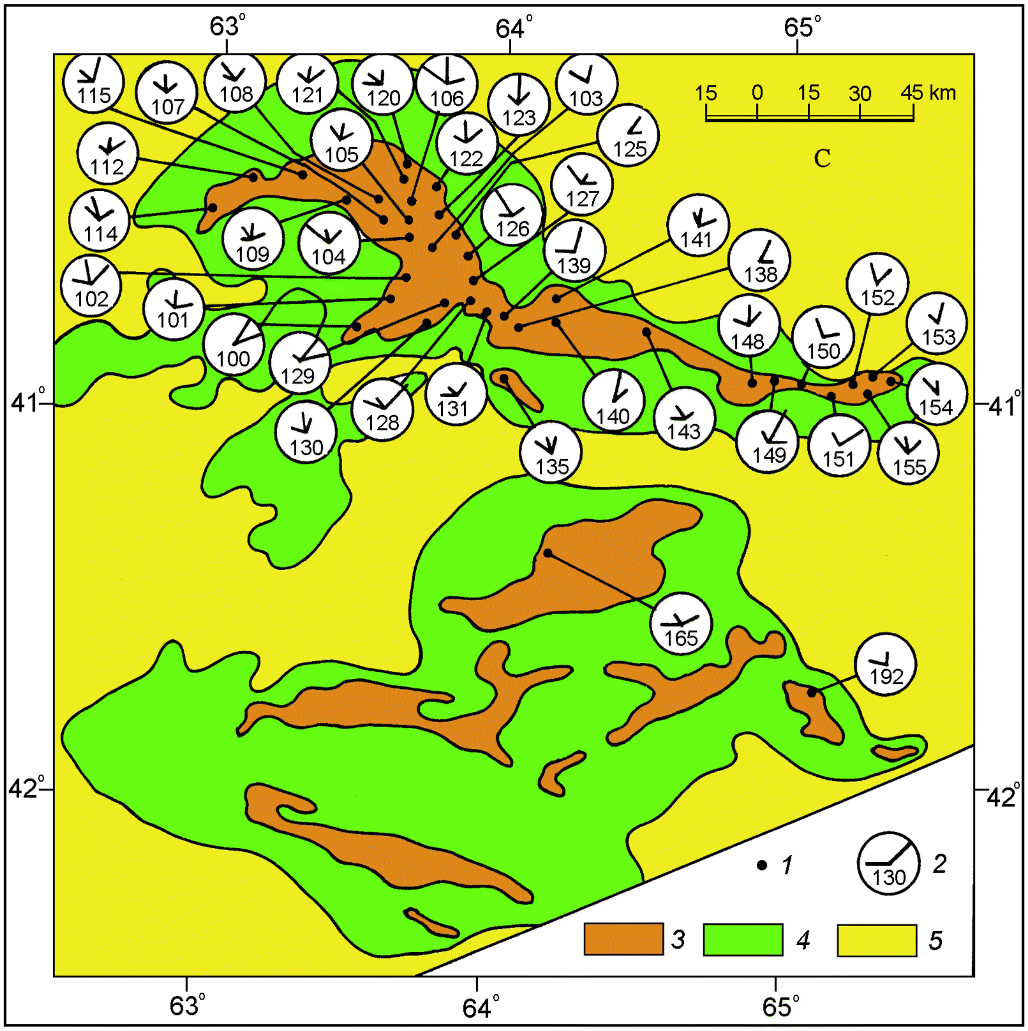

Figure 14. Scheme showing strikes of local joint systems in tilt-corrected Carboniferous strata from the Central Kyzyl Kum region. Symbols as in Figure 9.

yields a pattern roughly similar to the Lower Silurian sedimentary rocks (Figure 11). Regional joint systems are oriented NNE (5°–10°), ENE (80°–85°), and NW (315°–320°) and are manifest consistently. A NE (50°–55°) direction is also identified. However, it is sparsely developed (1.5–2.0) and inconsistent. The latter circumstance suggests that no real regional system directed NE exists.

The lower part of the Upper Silurian–Lower Devonian substage of the Caledonian structural stage in the Central Kyzyl Kum region is comprised of sedimentary rocks of Late Silurian age, chiefly represented, according to our observations, by limestone. Joint measurements from were taken these rocks at few stations on the Kuldzhuktau Mtns. (5 sts.) and Tamdytau Mtns. (2 sts.) (Figure 11). The whole population of stations yields regional joint systems oriented NNE (15°–20°), ENE (80°–85°), NW (305°–315°), and NNW to N (350°–355°). These systems, except the NNE one, are classed as consistent. The best developed of these are those directed NW (2.0–3.0), NNE (2.0–3.0), and NNW (2.0–2.5). The roughly E-W directed joint system is developed much more sparsely (1.5–2.5).

Undivided Upper Silurian to Lower Devonian sedimentary rocks, predominantly limestones, were covered by joint measurements at 12 stations located in the Kuldzhuktau (6 sts.), Aristanatau (3 sts.), and Tamdytau Mtns. (3 sts.) (Figure 12). At most stations, local joint orientation distributions are featured by three joint systems. The entire population of stations yields NNE (10°–20°), NE (45°–55°), W to WNW (265°–280°), and NW (300°–320°) directions for these systems. All the systems are consistent, the NW one being manifest at virtually all the stations. The NNE directed joint system has the largest pole density (2.0–3.5). The systems trending NW and NE are developed less well and nearly equally (1.5–3.0 and 1.5–2.5, respectively). Compared to the joint pattern in the Lower Silurian deposits, the joint system with a roughly EW to WNW trend is more consistent, but has weak pole density maxima of 1.5–2.0.

In the upper part of the Upper Silurian to Lower Devonian substage in the Central Kyzyl Kum region, joint measurements were taken from limestones of the undivided Lower to Middle Devonian sequence (D_{1-2}) at 10 stations on the Kuldzhuktau uplift (Figure 13, Sts. 16, 18–20, 24, 26, 50–52, 54). Local orientation distributions are characterized by three joint systems. Regional joint systems trend NNE (15°–25°), NE (50°–60°), W to WNW (270°–280°), and NW (310°–320°). The joint system with a Tien Shan trend (W to WNW) is most consistent, although its pole density maxima are not strong (1.5–2.0). In the Lower–Middle Devonian rocks, regional joint systems striking NNE (1.5–3.0) and NE (1.5–2.5) are developed much better.

3.2.4. Rock jointing in the Hercynian structural stage. Sedimentary rocks of the Hercynian structural stage were covered by joint measurements at 47 stations. Of this number, only seven stations covered limestones of the Middle to Upper Devonian structural substage on the Bukantau (5 sts.) and Tamdytau (2 sts.) uplifts (Figure 13, Sts. 110, 111, 142, 146, 147, 166, 174). The joint pattern from rocks of this age is virtually identical to that from the Lower to Middle Devonian deposits as established from the totality of stations. Regional joint systems identified from these seven stations trend NNE (15°–20°), NE (50°–60°), W to WNW (270°–280°), and NW (315°–320°). The most consistent joint system is that with the Tien Shan trend, and the least consistent, that with a NE trend.

Sedimentary deposits of the Carboniferous structural substage were covered by joint measurements at 40 stations (Figure 14). Of these, 38 are located on the Bukantau uplift, while the Tamdytau and Aristanatau uplifts are each covered by one station. Carboniferous rocks are represented by shale (20 sts.), limestone (10 sts.), sandstone (6 sts.), and conglomerate (4 sts.). In these rocks, joint pattern is somewhat different from that in the Devonian deposits. On stereograms, joint orientation distributions display, as before, three principal systems. Regional systems are oriented NNE (10°–20°), NE (40°–55°), W–E (260°–275°), and NW (300°–320°). Joint systems directed NE, W–E, and NW are consistent. Alongside the above systems, an additional sparsely developed (1.5–2.0) joint direction emerges trending NNW (340°–350°), which was identified by us in more ancient rocks only from the Upper Silurian deposits (NNW to N, 350°–355°). This direction is detected at few stations, and, according to the criterion advanced, it is not a joint system. Of the principal systems, the NE trending one is best developed (2.0–4.0). The joint systems with NNE, NW, and W–E directions in Carboniferous rocks are developed less well (1.5–2.5).

Sedimentary rocks of the Lower Permian structural stage in the Central Kyzyl Kum region are spread extremely scantily, and they were not covered by our study.

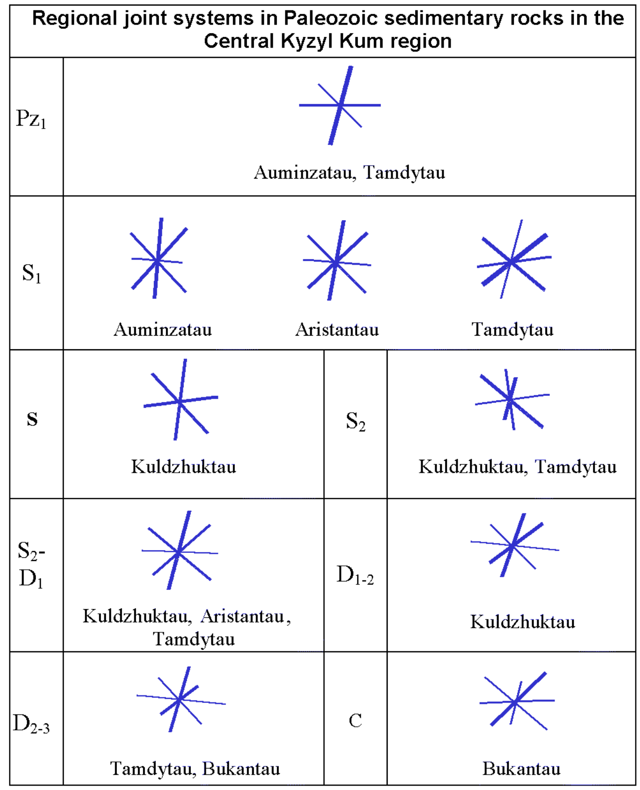

Figure 15. Strikes of regional joint systems in tilt-corrected sedimentary strata of various ages. Line thickness depicts qualitatively the degree of development of a system as a function of magnitude of density maxima of poles to joints. Line length depicts qualitatively the consistency of identification of a system, i.e., the proportion of stations at which local joint systems of a corresponding direction are identified.

4. Discussion

4.1. Directions of regional joint systems

1. A thorough analysis of joint measurements in Paleozoic sedimentary rocks from the Central Kyzyl Kum region (Figures 9–14, Appendix) has identified local and regional joint systems. The regional joint systems thus established are summarized in Figure 15.

- Based on local joint system orientations obtained from coeval rocks, regional joint directions (regional joint systems) were identified. In most cases, four regional systems are present, trending NE, NNE, NW, and roughly E–W. The last three regional joint directions (principal joint systems) are ubiquitous. These directions are close in trend to fault and fold structures of the pre-Paleozoic, Caledonian, and Hercynian evolutionary stages, respectively.
- The most consistent of the principal joint systems identified from Paleozoic rocks is the system of a NW

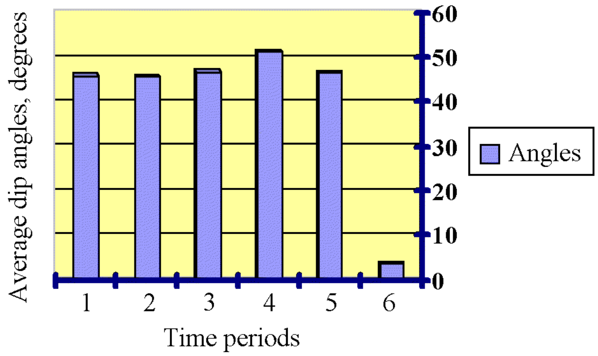

Figure 16. Average dip angles of sedimentary strata from exposures of various ages in the Central Kyzyl Kum region. 1 – Early Paleozoic (Pz_1), 2 – Silurian (S), 3 – Late Silurian to Early Devonian (S_2–D_1), 4 – Devonian (D), 5 – Carboniferous (C), 6 – Cretaceous to Paleogene (K–Pg).

(Caledonian) direction, whose strike azimuth ranges from 300°–320°. This system is, as a rule, well developed and manifest at a large number of stations. A somewhat broader azimuth range is displayed by the roughly E–W trending joint system of Hercynian (W to WNW) directions. The degree of development of this system is lower as well. Much broader strike variations are shown by the systems with NNE (pre-Paleozoic, anti–Tien Shan) and NE directions.

- Joint systems in Paleozoic sedimentary rocks in the Central Kyzyl Kum region show changes in their direction and degree of development depending on age. The joint pattern from Lower Paleozoic rocks exhibits regional joint systems striking N to NNE, NW, and W to WNW. The strongest pole density maxima are displayed by the NNE directed system, identified persistently at many stations. In Early Silurian time, this joint system split into two new ones, oriented NNE and NE, which are also traceable into younger Paleozoic rocks. The NW (Caledonian) joint trend is expressed consistently, albeit less well, as compared to the N to NNE trending system from Lower Paleozoic rocks. With rare exceptions (as, e.g., in S_1 rocks on the Tamdytau uplift), the above regularities in the degree of development of principal joint systems in Lower Paleozoic rocks persist to the end of the Caledonian evolutionary stage. Note that in nearly all the sedimentary rocks of Paleozoic age, the roughly E–W trending, Hercynian, joint system is developed sparsely, but it is identified consistently.

- Joint system orientations in Paleozoic rocks change not only with rock age, but also from place to place. This is demonstrated rather convincingly by new joint measurements from Silurian rocks, whose massive character enables the analysis of jointing to be performed for each particular local neotectonic uplift in the study region. Thus, on the Auminzatau, Aristanatau, and Tamdytau uplifts, located in the southern and central parts of the Central Kyzyl Kum region, joint patterns in Lower Silurian rocks change in a northeasterly direction. Trends of the NNE and NE regional joint system swing gradually to the south, from 0°–10° and 35°–50° on the Auminzatau through 10° and 40°–55° on the Aristanatau to 10°–20° and 45°–60° on the Tamdytau uplift. At the same time, the NW trending joint system also swings south, from 315°–320° on the Auminzatau through 310°–320° on the Aristanatau to 305°–315° on the Tamdytau uplift. This leads to corresponding spatial changes in angles between the joint systems.

2. For the sake of comparison, alongside joint orientations from Paleozoic strata, we studied joints from Cretaceous deposits (23 sts.) and from Upper Paleozoic granites (11 sts.) from the Central Kyzyl Kum region.

- Analyzing joint orientations in Cretaceous sedimentary rocks reveals consistent and nearly equally well developed regional joint systems trending NNE (10°–25°), NE (40°–50°), WNW (285°–295°), and NW (305°–310°). Hence, the joint pattern characterizing Paleozoic strata maintains its principal features into Cretaceous deposits as well. As for the joint pattern in Cenozoic deposits, covered by as few as three stations, it can only be inferred to have three joint systems, directed NE (40°–50°), W–E (270°–275°), and NW (315°–325°).

- The joint pattern in granites exhibits six regional joint directions, ranging in azimuth from 10°–80° and 290°–340°. Consistent regional systems are those oriented WNW (290°–305°) and NNE (10°–20°).

4.2. Integrated characteristics of joint patterns and paleostress

Techniques used to construct integral tensor characteristics of regional joint distributions (Section 2.2.) yield a sort of individual "portrait" of the inner geometry of jointing, inherent in each particular study region, and enable one to trace its evolution over time. Analyzing the evolution of individual "portraits" for certain seismoactive regions reveals rather systematic regularities [*Belousov et al.,* 1996, 1997]. In particular, data points from more ancient rocks on an individual regional "portrait" plot, on average, closer to the origin of coordinates than those from younger rocks. This is due to the fact that, albeit the individual regional "portrait" does not depend on rotations of local joint distributions, folding processes nonetheless bear on it indirectly. The more strongly deformed ancient rocks contain a larger number of random joints and tectonic joint systems overprinting the primary joints.

The above regularity in the evolution of the integral "portrait" holds true for our study of joint patterns in the rocks from the Central Kyzyl Kum region (Figure 7). Although the average $\sqrt{2}S$ value increases rather sharply in passing to the Cretaceous–Paleogene evolutionary stage (Figure 7f), no perceptible change in the average distance of data points from the origin of coordinates over the Paleozoic period took place. This might be due to the fact that during the Paleozoic the intensity of rock deformation (as expressed in the average dip angle of strata) experienced no considerable variations (Figure 16). On the other hand, the Paleozoic rocks are deformed much stronger than the Cretaceous–Paleogene ones.

In the light of the above, it is of interest to establish quantitative relations between percentages of random joints and fold deformation intensity. Results of the cluster analysis performed show that percentages of random joints averaged over all the exposures of Paleozoic strata from Central Kyzyl Kum are 29.8% for Pz_1, 31.4% for S, 30.0% for S_2–D_1, 36.4% for D, and 29.9% for C. Note for comparison that a respective value for the Carboniferous limestones from the Moscow syneclise equals 29.8% [*Grachev and Mukhamediev,* 2000]. Dependency of random joint percentages in Paleozoic rocks of the Central Kyzyl Kum region on the average dip angle of strata is illustrated in Figure 17. The plot indicates that percentage of random joints increases with intensity of fold deformations.

To summarize our discussion of the evolution of regional tensor characteristics of jointing, note that integrated "portraits" of joint orientation in Devonian and Carboniferous rocks of the Central Kyzyl Kum region very seldom display data points with small angles of the form ω_J (Figure 7d, e).

In principle, results obtained in this work enable us to reconstruct orientations of principal paleostress axes during sequential evolutionary stages of the Central Kyzyl Kum region. We proposed a model calling for rheological (localization) instability in rocks resulting in plastic deformations localized in narrow regularly spaced layers as a formative mechanism for joint systems during sediment diagenesis in active regions [*Belousov and Mukhamediev,* 1990]. This model permits the geometry of two conjugate primary joint systems to be related to paleostresses at work during sediment lithification [*Belousov and Mukhamediev,* 1990; *Belousov et al.,* 1997].[2]

Earlier, we performed a tentative reconstruction of paleostresses in the study region [*Belousov et al.,* 1997]. The reconstruction procedure was complicated by the fact that in Paleozoic strata in the Central Kyzyl Kum region the two primary conjugate joint systems are overprinted by additional systems of tectonic genesis. For this reason, in paleoreconstructions using the model of plastic deformations localized in a lithifying sediment layer, not all the local joint orientation distributions measured were acceptable, but only those in which primary joint systems could be identified reliably enough. In the latter case, the bisector of the acute angle between these two systems in tilt-corrected strata corresponds to the maximum horizontal compressional paleostress axis $S_{H,\max}$. It was shown that, despite changes in local joint system orientations (and, consequently, in angles between them) in coeval rocks, bisectors of acute system angles maintain relatively consistent directions in space.

Our paleoreconstructions show that in Paleozoic time the axis $S_{H,\max}$ was oriented in the NE quarter. More specifically, in the Lower Paleozoic it pointed, supposedly, ENE, and by the end of the Paleozoic it assumed an NNE orientation. Results of this study are supported by data on the regional direction $S_{H,\max}$, as identified from fold structure trends. Indeed, the Caledonian orogeny, which terminated in the mid-Paleozoic, shows dominant NNW trends [*Geology...,* 1972; *Ibragimov et al.,* 1973], which implies a ENE orientation for $D_{H,\max}$. Structural features of the Hercynian orogeny strike WNW, which is apparently due to $S_{H,\max}$ being directed NNE.

In Cretaceous time, the maximum compressional stress axis, as restored from rock jointing, likely acquired a NW orientation [*Belousov et al.,* 1997]. This, however, bore no essential impact on the strike of fold structures formed in Hercynian time. This is evidenced, in particular, by Figure 8b, showing a rose diagram of strikes of horizontal hinge lines of imaginary folds constructed from the analysis of dip azimuths and angles of strata at joint measurement stations.

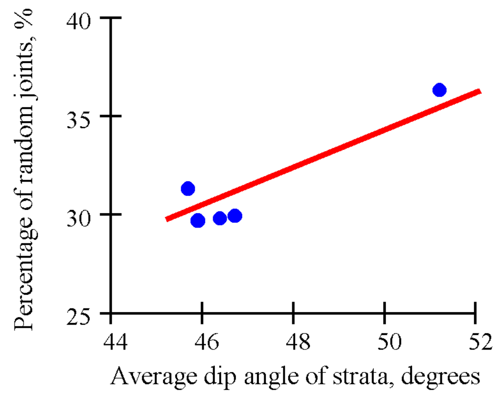

Figure 17. Percentage of random joints versus average dip angle from Paleozoic sedimentary strata from the Central Kyzyl Kum region.

Conclusions

Our results were obtained from the analysis of joint measurements from 181 natural exposures in the Central Kyzyl Kum region. Dip-and-strike measurements on joints were taken from a spectrum of lithologies of various geneses and ages. While analyzing and interpreting our experimental data, we focused most exhaustively on Paleozoic sedimentary rocks. For each particular exposure, joint orientation distributions were constructed and local joint systems identified. On the basis of orientations of these local systems, regional joint directions were established.

It is worth noting that joint systems were identified in the absence of data concerning deformations of stratigraphic levels. This caused a loss of information on structural positioning of joint systems generated by fold deformations, and, consequently, complicated discrimination of these tectonic systems from primary regional joint directions. At the

[2] Some patterns of old fracture systems allow reconstructing recent strain directions [*Grachev and Mukhamediev,* 2000].

same time, we identified local joint system directions using two methods, (i) from density maxima of poles to joints on stereograms and (ii) based on the cluster analysis. Both methods yielded closely similar values, which enhances the reliability of these results.

Generally, regional joint directions, as identified from the totality of exposures of sedimentary rocks of each particular age level under study, are close to strikes of fault and fold structures of the pre-Paleozoic, Caledonian, and Hercynian evolutionary stages. At the same time, directions of regional joint systems change somewhat both across the region and depending on rock age. An example of across-region changes is provided by the NNE, NE, and NW trending systems in Lower Silurian sedimentary rocks swinging gradually to the south as one moves from southwest to northeast. An example of regional directions changing over time is furnished by how the NNE trending regional system observable in the Lower Paleozoic rocks splits into two new systems oriented N to NNE and NE in younger Paleozoic rocks. The degree of development of regional joint directions undergoes changes as well.

The joint pattern inherent in Paleozoic strata maintains its principal features into the Cretaceous deposits. A comparative study of jointing in sedimentary and igneous rocks reveals a certain lithologic dependency of joint patterns.

The study of evolution of regional tensor characteristics of jointing provides evidence that, in particular, in the Central Kyzyl Kum region, just as in some other active regions, primary jointing became overprinted, as the region kept evolving, by additional random joints and tectonic joint systems. This is further supported by our finding that percentage of random joints increases with intensity of fold deformations.

Our tentative reconstruction of paleostresses in the study region from joints in sedimentary rocks using the localization instability model fits well the data on the regional direction of compression, as established by analyzing fold trends in Caledonian and Hercynian orogenic structures.

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