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MORPHOSTRUCTURE OF THE KODAR-UDOKAN SECTION OF THE BAIKAL RIFT ZONE

ABSTRACT. The morphostructure of the region is a natural result of active geodynamics in the eastern Stanovoe Upland. Extreme seismic conditions become apparent in rare devastating earthquakes (up to 10–11 in the Mercally scale), as well as in frequent slight ones. Seismic events affect topography and produce seismic deformations of different scale and morphology. Areal disturbances (like the New Namarakit Lake in the South-Muya Mountains origin) and, more often, local deformations (like destructions of the Kodar ridge rocky saddles or clamms [gorges] opening) are evident. Using morphotectonic analysis methods the morphostructural scheme of the Kodar-Udocan section of the Baikal rift zone (perhaps pull-apart basin) is done. In our model piedmont and mountain territories are divided in five level groups of blocks. Neotectonic movements' amplitude is estimated at 5000 m.

KEY WORDS: Chara basin, morphotectonics, active tectonics, block analysis, seismoalpine topography, seismic deformations.

INTRODUCTION

The Baikal rift zone is the most seismically active continental region in Russia (Fig. 1) [New seismic map..., 1996]. Dozens of $M_W \geqslant 4$ and hundreds of $M_W < 4$ earthquakes happen here every year [Earthquakes..., 2007; Earthquakes..., 2009]. Such tense seismic conditions reflect in impressive morphostructures in the Kodar-Udokan segment – one of the most active parts of the rift. The Kodar-Udocan section of the Baikal rift zone (perhaps, pull-apart basin [Explanatory dictionary..., 2002]) is located on its eastern flank. As is well known, in the Pleistocene and the Holocene, the Baikal rift zone was subjected to magmatogene activity [Active tectonics..., 1966]. The section includes the Chara (or Upper-Chara) basin, the Kodar and the Udokan ridges on its sides, and the interbasin tectonic sowneck between the Chara and the western Muya basins. We can consider the Kodar-Udokan section to be the outermost eastern pronounced rift segment. The issue of the eastern rift closing remains an open problem. Thirty kilometers easterly is the feebly marked Tokko basin; it gives us no reason to search for the rift closing in the Chara basin. In this paper, we concentrate on the tectonic aspect of the morphostructure evolution and are putting aside many issues concerning the morphological expression of the Quaternary volcanism in region.

GEODYNAMICS

The formation of the Baikal rift zone became possible because of the existence of the border between the thick (more than 50 km), cold, and strong pre-rift lithosphere of the craton and the fold belt lithosphere of not more than 35 km in thickness [Petit, Burov, Tiberi, 2008]. Rift development on the Siberian craton boundary is believed to be impossible without the mantle plume influence and an appropriate field of strain. The plume presence evidence is shown by a number

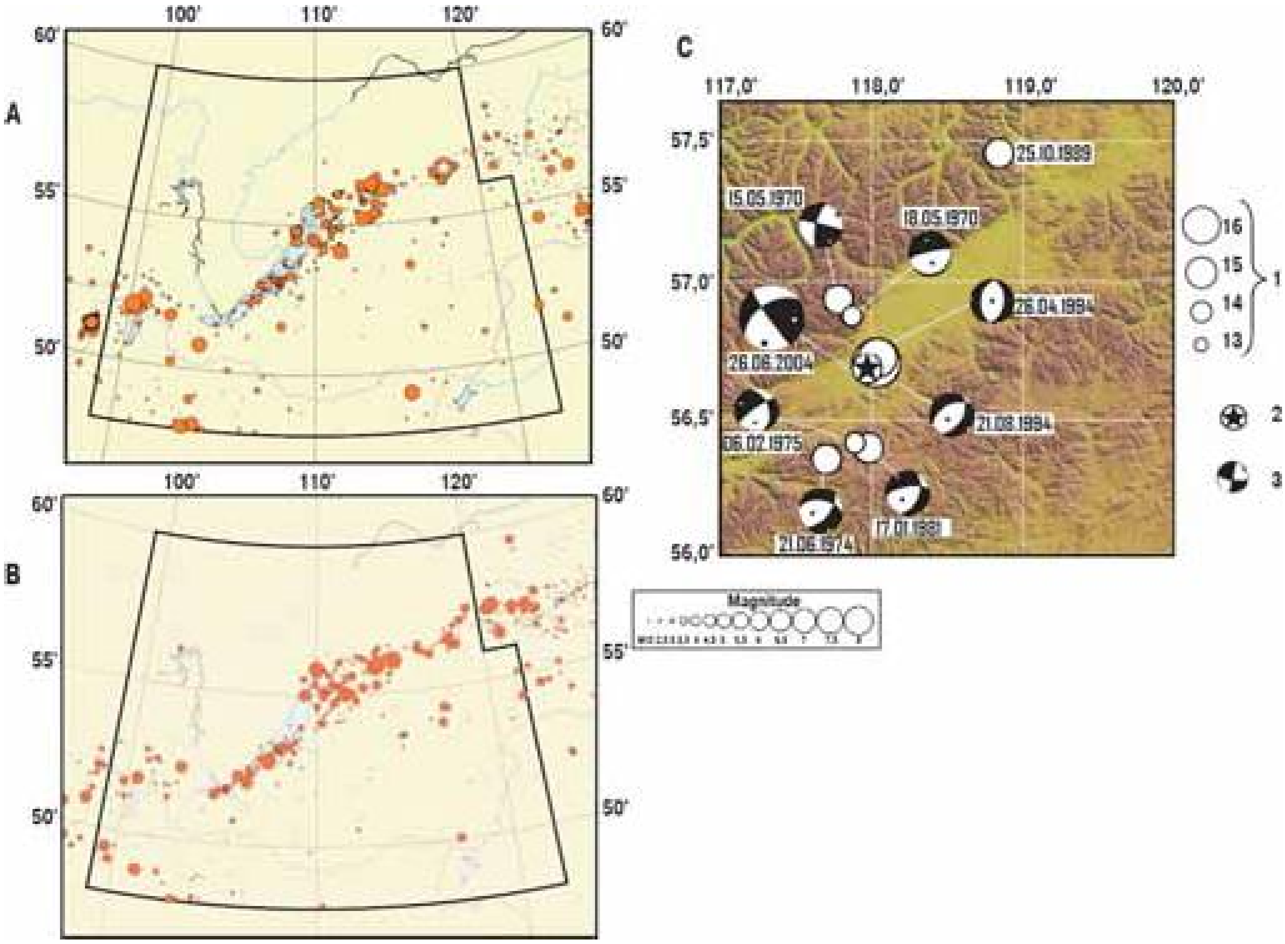

Fig. 1. Seismicity of the Baikal rift zone:

A – in 2004 [Earthquakes..., 2007; B – in 2007 [Earthquakes..., 2009] (earthquakes not lower than 33 km; the strongest in the year is marked by the star); C – epicenters of strong earthquakes in the Chara basin and adjacent ranges in 1960–2004 (1 – earthquake epicenter with date; 2 – the epicenter of the earthquake on 28 June 2004; 3 – focal mechanism in the lower hemisphere [Goljova et al., 2010])

of authors [Ufimcev, 2002; Logachev, 2003; Zorin, Turutanov, 2005 and others].

The asthenospheric upwelling zone traces along the rift axis under some basins of the north-east, including the Chara basin. Presumably, the upward plume part is located here, which provides for the Kodar-Udokan culmination of the Sayan-Baikal arc rise in the Stanovoe upland. Stress along the rift axis extends to its north-eastern flank. The Chara basin was forming under pulling stress created by a slipping constituent (, while its mountain border is a part of an arch formed during warming pahse. The Muya-Chara interbasin tectonic sowneck is a product of the inverse-compensational isostatic uplift [Ufimcev, 2002]. The seismic environment is the product of the regional geodynamic processes. Tectonic movements (including the latest period) control the basalt magmatism activity.

Active geodynamics manifests in rare devastating (reaching 10–11 points n the Mercalli scale), as well as in frequent small earthquakes (see Fig. 1). Seismic events in the Kodar-Udokan region (the strongest – Muyskoe in 1957 with M_W=7,8, Nukzhinskoe in 1958 with M_W = 6,5, Kodarskoe in 1970 with M_W = 5,6, Charskoe-I in 1994 with M_W = 5,8, Charskoe-II in 1994 with M_W = 6,3, and some weaker ones) create a number of seismic deformations throughout the rift zone section. The Charskoe-III earthquake is the latest, typical for the region, and one of the strongest. It happened on June 28, 2004, and had a 5,1 point magnitude. Its focal mechanism demonstrates reverse strike-slip and strike-slip offsets in the north-western and north-eastern directions with fault planes. That corresponds to the local stress field [Giljova et al., 2010].

Fig 2. View of the Medvezhy pass from the Medvezhy stream valley. Dotted lines show the block-divider zone; arrows show pressure directions. Photo by E. Tokareva

The Medvezhy pass (H = 2200 m), a saddle between the Medvezhy stream and the Lednikovaya river valleys in the Kodar ridge, is one of the examples of the resent seismic deformations (Fig. 2). It is difficult to trace the block-divider in this area on a topographical map; the saddle has a U-shaped lengthwise profile with 30° slopes, while the adjacent slopes are notably steeper. Strongly brecciated biotite granites were found on the saddle; these rocks are the evidence of "dry" dislocation metamorphism in the tectonic displacement zone. It shows that the block-divider extends into this area. The topography around the saddle was altered after the 2008 earthquakes. The pass was fractured; the slope of the Ledinkovaya valley became steeper and harder for tourists. Such deformations confirm the presence of a relatively high-ranked block divider in the compressed and strained state.

In many respects, seismic events form large and small seismic dislocations and define the appearance of the Kodar ridges and valleys topography. Probably, the highest level of the Kodar belongs to a unique, i.e., seismic-alpine, mountain type. We noticed the active seismic destruction of a number of complex high-altitude climbing passes. Such destruction is very impressive in the peaked watersheds of the Upper and Middle Sakukane rivers (passes Pioneer – Fig. 3, Balitisky, Of Three Gendarmes, and others). The extraordinary sharpness of the landforms distinguishes the seismic-alpine topography from the classic alpine topography of the Alps, the Big Caucuses, the Pamir, and the Tan-Shan formed during numerous phases of anastomosing glaciation. The typical features of the landscape denudation complexes include widely spread steep (up to pendant) slopes, anomalous number of carlings and "gendarmes" on the ridges, and profound fragmentation of saddles that frequently are saw-like. At the lower elevations, the seismic-alpine topography is controlled by continuity of the gravitational trains in the lowest parts of river valleys, rocky glaciers, and stepped lengthwise stream profiles.

Fig. 3. The easterly Pioneer pass view from the BAM peak (3072 m).
Fresh seismic deformations on the watershed of the Upper and Middle Sakukane.
Dotted lines show the block-divider zone; arrows show seismic cracks.
Photo by E. Chesnokova

MORPHOSTRUCTURE

The Chara basin is a concave tectonic macrorelief landform partly filled with sediments (Fig. 4). Its bottom presents a predominantly subaerial accumulative plane influenced by mainly exogenous agents in tectonic submerge conditions [Geology and seismicity..., 1984]. Accumulative landforms in the basin bottom have glacial, fluvial, and limnic genesis. In several locations, differential tectonic movements in the basin uplift the bedrock to the surface and form individual hills.

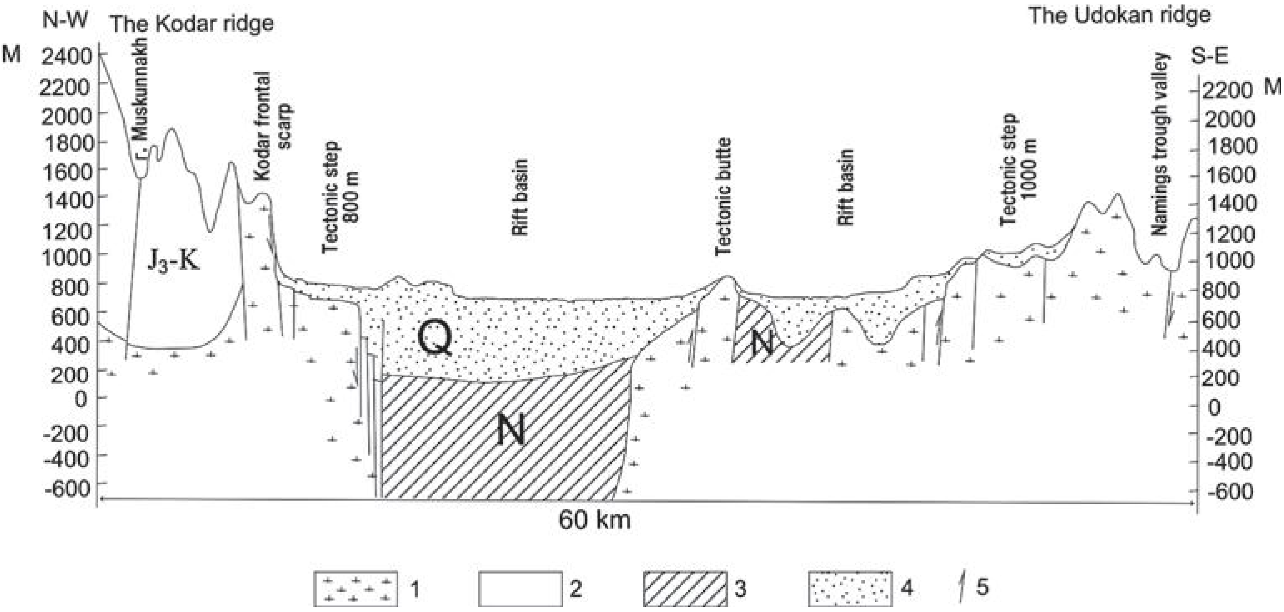

Fig. 4. Schematic geologic-geomorphic section across the Chara basin in the Apsat coalfield line [by Enikeev, 2009] with the authors' modification (position on Fig. 5).

1 – bedrock, 2 – mesozoic sedimentary deposits, including carboniferous, 3 – sandstones, conglomerates and boulder-pebble Neogene deposits, 4 – quaternary, mainly sandy fluvioglacial-alluvial and glacial deposits; 5 – fault kinematics

No boreholes reached the bedrocks in the central part of the rift (the deepest of them has 1180 m in face [Enikeev, 2009]); therefore, the maximal thickness of the sediments is unknown. Sedimentation of Lake Baikal is uncompensated; on the contrary, the Chara basin exhibits compensative warping. The large number of lakes in the north-eastern (downstream) part of the basin points to unsteady sedimentation. According to the foundation bedding depth assessed from geophysical data, the north-eastern part of the basin plunges faster than its south-western part.

Tectonic block structures that correspond to the lithosphere units of different ranks form mainly under the influence of vertical movements'effects, even assuming noticeable horizontal movements. Topography is the most clear visual demonstration of tectonic blocks identified using geomorphic, geological, and geophysical data.

A small-scale schematic map of the terrain structures contours (Fig. 5) shows the specific morphostructural features of the region. The Chara basin is the visible space-forming depression in the centre of the map. To the north-east and south-west of it, we can see tectonic morphostructures with the same (lower than 1000 m) altitude. In the north-east, there is the Tokko basin; in the utmost south-western part, there is the Sulban and Kouanda basins. The latter ones are separated by the extremely north-eastern spurs of the South-Muya Mountains (above 2250 m); we can also name these structures the Muya-Chara interbasin tectonic sowneck.

The Chara and Tokko basins are separated by a lower tectonic sowneck, just few meters higher than 1500 m. From the north, the Chara basin is bounded by the Kodar ridge, whose peaks are often over 2750 m (the dominant, Peak BAM, is 3072 m high). The Kodar has massive structure; its most important tops are situated rather close. We can isolate individual large blocks. In the Kodar ridge, the Upper-Sulban basin is well seen through block-dividers. The Kodar is bounded from the north by tectonic depressions with the Senj (north-west) and the Malaya Tora (south-east) rivers and altitudes not exceeding 1000 m. The Udokan-Kalar area is located in the south-eastern part of the scheme. The pattern of the terrain structure contours shows that the Udokan and Kalar ridges are difficult to separate. At the same time, neither of them looks as a united mountain range. The topographical maximums concentrate in the central part of the Udokan; however, it does not look like a large united massif. In comparison with the Kodar, the Udokan is more "descrete". In the Udokan-Kalar area there is the Upper-Kalar basin situated at the same level as the Upper-Sulban basin. Also, we can see the depression with the Kalar river in the outermost south-eastern part of the map that can be traced through block dividers.

The pattern of the terrain structure contours depends, undauntedly, on the block division and allows us to estimate the amplitude of the Neogene-Quaternary movements. Thus, in the zone of the Kodar fault between the Apsat and Middle Sakukane, this amplitude reaches about 1700 m; in the south-eastern periphery of the Chara basin, the amplitude of mutual displacement of the outermost blocks of the Udocan (estimated with the series of downthrows) reaches 1000 m. In the through block-dividers zones in the Kodar and Udokan ridges, throws with several hundreds meters amplitude were repeatedly found during field research and on topographic maps and recorded with remote sensing data.

The Olekma-Vitim mountainous country is a morphostructure of the first order; in the study area, it includes four morphostructures of the second order: the Kodar, the Udokan, and the South-Muya ridges, and the Chara basin [Lopatin, 1972]. Their general characteristics are presented below.

The Chara basin is a 120 km long Baikal-type basin. It is a tectonic depression elongated in the north-eastern direction and bounded

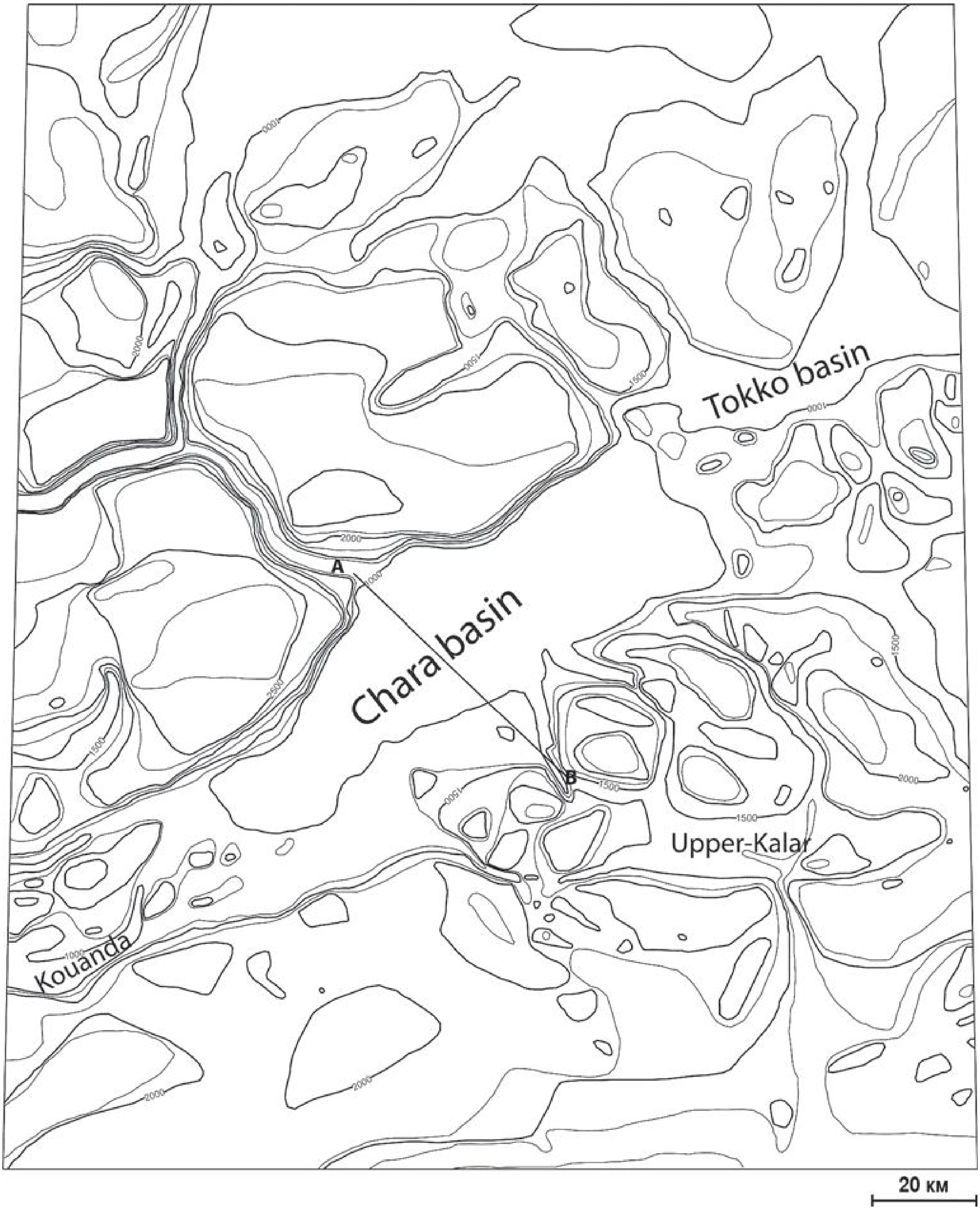

Fig. 5. Schematic map of the terrain structure contours (every 250 m). A–B – transect line (see Fig. 4)

by the Kodar and Udokan tectonic scarps flanks. The basin has an asymmetrical structure: the north-western (Kodar) side slope is much steeper, i.e., 35–60°; the mostly submerged foundation fragments are along this side. The bottom represents a predominantly subaerial accumulative plane as we have already mentioned above. However, the plane is squeezed between the mountain massifs and we can consider the direct structure/topography correlation. At the same time, in the bottom of the basin, there are bedrock protuberances that correlate with separated uplifted blocks and tectonic buttes. In the south-western part of basin, the South-Muya – Udokan junction, the inversionally uplifted tectonic step, is located. Probably, it was forming during the uplift-submerge process [Ufimcev, 2002]. Step altitudes are 1000–1200 m, which is visible both on the map (see Fig. 5) and in the transverse geologic-geomorphic section (see Fig. 4).

The Kodar ridge is a complicated blocky construction. The transverse section shows the asymmetric structure with flat northern and steep southern slopes. In the north-eastern part, the ridge smoothly connects with the Baikal-Patomskoe and Olekma-Chara uplands; in the south, it abuts the Chara basin with a tectonic escarp. The Kodar is a tilted horst in a form of an asymmetric range. It is divided into a number of large blocks that consist of smaller cells.

The Udokan ridge is a complicated arch-blocky asymmetric structure. In the south-west, the Udokan arch becomes the Kalar ridge half-arch. That is why the northern slope is steeper than the southern. The northern macroslope is complicated by a series of small intramountain basins and grabens and has a stepped form. The steps are separated by tectonic escarps of east-north-eastern direction. The mountainous steps of the Udokan gradually transition into the piedmont steps of the Chara basin. The axled Udokan area is formed by several separated blocks and determines the blocky structure of range.

The considered part of the *South-Muya Mountains* is the eastern closing of the horst rise. The north-western ridge slope is a high-amplitude fault escarpment with 25–50° steepness. The north-eastern part of the mountains is very complicated. The entire width of the Kouanda-Sulban watershed is fractured with a great number of young faults [Active tectonics..., 1966]. The Sulban graben separates the mountains from the Kodar in the north; the Kouanda graben detaches Udokan in the south.

METHODS

Block morphotectonics analysis was done for a large-scale (detailed) study of the upper lithosphere and a further detailed endogenous topography investigation. The fundamentals of the methods are discussed in literature [Simonov, 1972, and others]. We used the assumption that beneath almost all streams, there are large faults and fracture densification. The initial principals consider block-divider delineation using only river network analysis. However, ruptures may become apparent not only in drainage systems but in some geomorphic and landscape characteristics too. Presence of long straightened river valley sections, their 90° bends, river interceptions, and seismogenic landforms (seismic deformations) support theoretically delineated block dividers.

The most impressive example is the frontal Kodar escarp that separates the ridge block (Kodar) from the Chara basin [Grachev, 1972]. Block dividers were also delineated using suture and tectonic lines and saddles. Large block dividers in mountainous areas correspond to rivers of highest order in the Horton-Straller system; through block-dividers – to river headstreams and their contact across the lowest cols. For extreme block tops analysis, we used five categories: innermost, descended, mid-high, uplifted, and most uplifted. We talk only about relative submerge or uplift. The result of the mountainous land block analysis is the delineation of 46 blocks of the second order; they are: 1) innermost – lower than 1700 m; 2) descended – 1700–1950 m; 3) mid-high – 1950–2300 m; 4) uplifted – 2300–2700 m; 5) most uplifted – above 2700 m (Fig. 6).

BLOCK ANALYSIS

In the topography of the Chara basin, of the Udokan, and especially of the Kodar, the morhotectonic mosaic structure can be seen. Sometimes, it defines the major orography features, in particular, in the Kodar glacier upland [Kovalenko, 2011].

One block on the Kodar has the highest altitudinal difference compared to the others and belongs to the "innermost" category. This

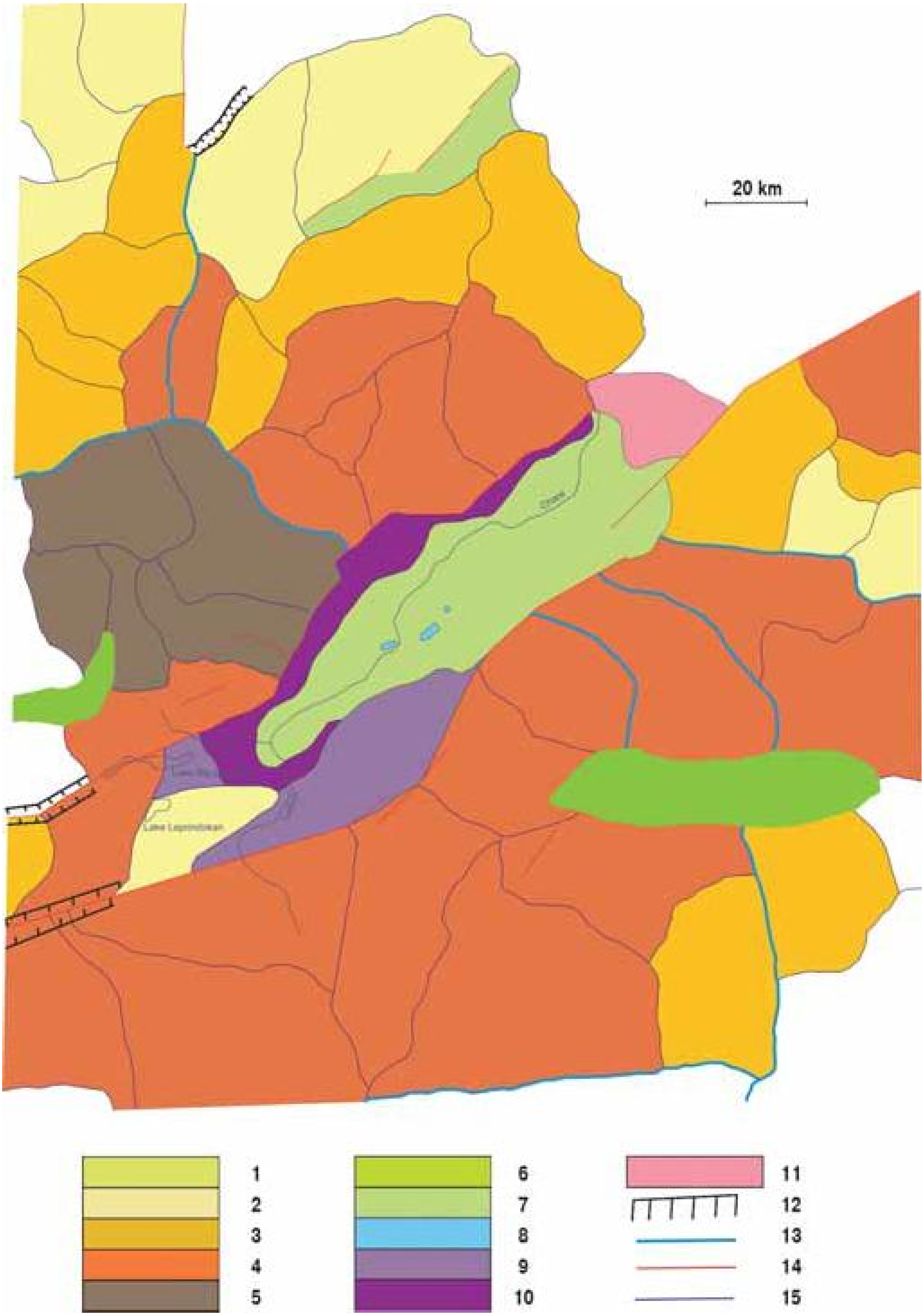

Fig. 6. Morphostructural elements scheme of the Kodar-Udokan segment of the Baikal rift zone. Block morphostructures motion tendencies:

1 – active submerge; 2 – temperate descend; 3 – comparative stabilization; 4 – temperate uplift; 5 – active uplift; rift basins bottoms: 6 – intramountain; 7 – intermountain; 8 – tectonic buttes; tectonic steps with altitude: 9 – near 1000–1200 m; 10 – near 800 m; 11 – small block fragmentation zone with denudation-tectonic topography; linear morphostructures (tectonic lines): 12 – frontal escarps of graben-like depressions, 13 – through the block-divider zone; 14 – large relief ruptures; 15 – ordinary block dividers block has a depression, where the Malaya Tora River flows through. The depression is evident on the schematic map of the terrain structure contours (see Fig. 5). According to its morphology, the block belongs to the eastern Kodar periphery; its maximal altitude is higher than that of the Chara basin step elevation (1000–1200 m). The block is disjointed from the ridge body by distinct lineament zones; that is why we can consider it a plunged fragment of the ridge instead of the initial basin level.

Blocks with altitude below the average can be found in all studied ridges. They have features of mountain structure peripheries in the north of the Kodar, the east of the Udokan, and the east of the South-Muya Mountain. The blocks of middle height are situated at some distance from ranges axes areas, near the Olekma-Chara upland. Such blocks make a transition between descended and uplifted blocks like in the north-west of the Kodar.

Uplifted blocks have features of the central parts of mountains, but there are several outstanding blocks. The majority of blocks and all the uplifted block groups have contact with negative structures. This is the case in the central parts of the Kodar and the Udokan, in the Chara basin contact zone, in the north of the Udokan near the Tokko basin, in the west of the Kodar near the Upper-Sulban basin, and in the southern and central part of the Udokan near the Upper-Kalar basin. The highest block of the South-Muya Mountains is compressed between the grabens of the Sulban and the Kouanda. This is true for the most uplifted blocks. They group around the highest block in the Stanovoe upland and are situated between the Upper-Sulban and the Chara basins. Exactly in such contact zones, both direct and indirect signs of endogenous activity become clearly apparent, especially in cases when blocks are divided by a prominent fault zone.

The whole morphostructural scheme allows us to recognize that the differentiation exists not only between the main structural elements but also inside them. In uplifted and submerged blocks, contact zones, fault zones, and through block-dividers junctions we expect a great amount of endogenous activity to manifest morphologically. The presence of differently uplifted block morphostructures is also a sign of such activity.

N.A. Logachev [2003] estimates the sediment volume in the Chara basin at 2700 km^3. The area that now provides solid sediments to the basin is about 6600 km^2 wide. The total volume of the river valleys that surround the basin is about 1050 km^2, considering that these valleys were filled before the last activation period and the rest of the sediment material was brought from higher mountain levels. If we distribute the superfluous volume equally over the mountain watershed, we find less than 250 m of denudation in quaternary erosional period.

The extreme top of the Kodar is 3072 m high and the foundation bedding depth is not less than –600 m; Yu.A. Zorin [2005] estimates it at –1600 m level. Therefore, we can evaluate the bedrock surface altitude amplitude in the north-east of the Baikal rift zone at just under 5000 m (3072 + 1600 + 250 = 4922 m).

During the 1961–2010 field research in the Sulban, the Upper and Middle Sakukan in the Kodar, and the Lower Ingamakit in the Udokan we have repeatedly found seismogravitational collapses and landslides, "indents" and gaped clefts in massifs, seismotectonic cracks, and other morphological consequences of seismic processes (Fig. 7, 8). Great relief deformations in the form of lengthwise seismotectonic cracks can be seen in contact zones of different breaks with the main Kodar fault. Large seismic topography and structures deformations in a vaster area are shown in "Active tectonics..." by V.P. Solonenko [1966] and his co-authors. Therefore, we can see topographic signs of broad endogenous activity.

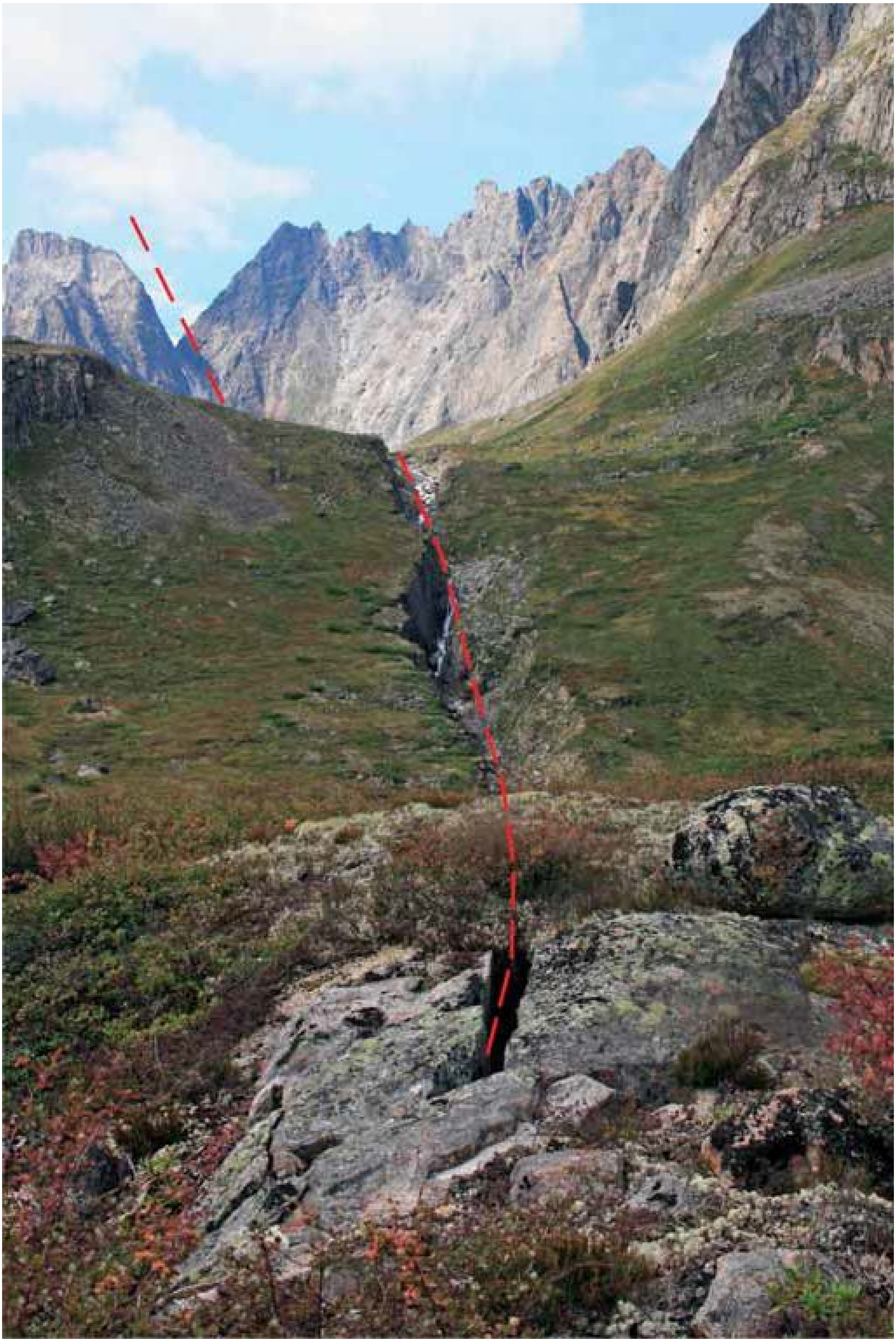

Fig. 7. 15-m deep seismotectonic narrow with the Uglovoy stream in the central part of the Kodar ridge. Dotted line shows the trace of the weakened zone.
Photo by S. Maznev

Fig. 8. The rocky canyon of the Uschelisty downstream in the Udokan ridge. Dotted lines show slopes of tectonic genesis in the canyon. Photo by S. Maznev

Presence of intramountain basins and differently uplifted morphostructures determines local denudation and accumulation areas. Naturally, mountainous lands remain a province of prevailing pulling down. Mainly, products of bedrock weathering transport by streams and rivers (historically – by glaciers) with through block-dividers. Such dividers are, per se, large tectonically weakened zones and crack frequency zones enlarged with glaciers and rivers. Such zones join through the low cols, and their tectonic genesis can be suggested. On the saddles of this kind, in tectonic gorges among river valleys in different phases of anastomosing glaciation, transaction-type glaciers were forming. As a consequence, presence of lakes and wetlands on pass saddles of through block dividers is typical.

The altitudes of block dividers are different on the sides of the rift axis. The pass saddles in the Kodar have elevetation of 900–1100 m; in the Udokan, it is 1200–1500 m. Such difference can be explained in the following way: in the Kodar, they are the result of the initial ridge division, but in the Udokan, they are the product of arch splitting and disintegration. In the Kodar, the largest block dividers split macroblocks with different tectonic movement rates, whereas in the Udokan, such lines occur due to stretch strain realization.

CONCLUSION

Active geodynamics in the Kodar-Udokan segment of the Baikal rift zone is naturally reflected in the morphostructures of the region. Fault slips take place regularly in seismic dislocations and new seismic deformations occur. Fresh fault escarpments, tearing off walls of collapses, and talus are current activity indicators in the region. In spite of the evident Pleistocene-Holocene volcanism weakening in the Udokan, we cannot speak about the seismotectonical activity decrease in the region. We can also see a widely spread topography reaction to stretch strain and to pressure stress in the south-eastern Kodar. ■

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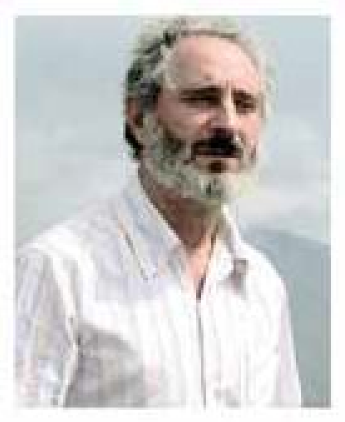

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