Russian Geology
and Geophysics
Vol. 36, No. 10, pp. 100-112, 1995

Geologiya
i Geofizika
UDC 551.243(571.151)

EVIDENCE FOR ACTIVE TECTONICS IN LAKE TELETSKOE (*Gorny Altai*)

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Support for a tectonic origin of the Lake Teletskoe Depression comes from several observations on basin architecture, satellite lineament analysis, morphotectonics and microtectonics. They confirm that the N-S segment of Lake Teletskoe is an extensional tectonic depression, which is located between two transgressive fault zones with opposite directions of Quaternary movements: the NE-trending sinistral West Sayan fault and the NW-trending dextral Shapshal fault. Extension in the Teletskoe basin is assumed to result from the eastward lateral offset of the West Sayan block bordering the basin at its eastern side with respect to the western block. Extensional structures better expressed in the southern part of the basin suggest its higher extension rate as compared with the northern one. This implies a counterclockwise rotation of the West Sayan block, in addition to its eastward movement.
Active tectonics, basin, strike-slip fault, normal fault, stress tensor

INTRODUCTION

The Gorny Altai region in southern Siberia corresponds to the western part of the Altai-Sayan fold belt, formed in the stage of Paleozoic accretion-collisional tectonics. It is a complex surelevated zone, where thrusts and high-angle reverse faults are present, as well as normal faults (Fig. 1). A general strike-slip stress regime in Altai is inferred from fault geometry and earthquake focal mechanisms [1–3]. This is consistent with the general stress trajectories of Eurasia, deduced from the World Stress Map [4].

Several authors [5–7] believe that southern Siberia is composed of microplates which are delimited by large fault zones which are still active at present. V. G. Trifonov [8] and N. V. Lukina [6] have studied in detail neotectonic structures (Late Pleistocene-Holocene) of southern Siberia and Mongolia, which are evidence of the presence of complex active fault zones, delimiting the mosaic of microplates that constitutes southern Siberia and Mongolia. The neotectonic structure is partly controlled by Cenozoic reactivation of major fault zones which often correspond to the Paleozoic suture lines and major strike-slip faults [9]. These were reactivated several times, as indicated by the frequent occurrence of Cambrian peridotite-serpentinite ophiolite fragments and Middle-Late Devonian, Late Carboniferous and Jurassic sedimentary lenses along them.

A system of Cenozoic depressions and sedimentary basins developed in this context was dominated by the activity of large wrench and thrust fault zones. The Kurai and Chuya Depressions developed at a high angle to the direction of horizontal principal compression (NNE-SSW in this area), probably as pull-apart basins during the Tertiary, and as ramp-type basins in the Quaternary [10]. Tectonic activity intensified in the Late Pleistocene, probably as the result of a modification in the stress regime. Lake Teletskoe developed only during this late stage and thus is a very young structure, related directly to the neotectonic activity (defined as the recent and still active geodynamic regime). The central part of the lake is a long (50 km), narrow (4–5 km) and deep depression, filled by 250–320 m water. Using the altitude of the summits of the adjacent

ISSN 1068-7971

RUSSIAN GEOLOGY AND GEOPHYSICS

(Geologiya i Geofizika)

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Vol. 36, 1995

Allerton Press, Inc. / New York

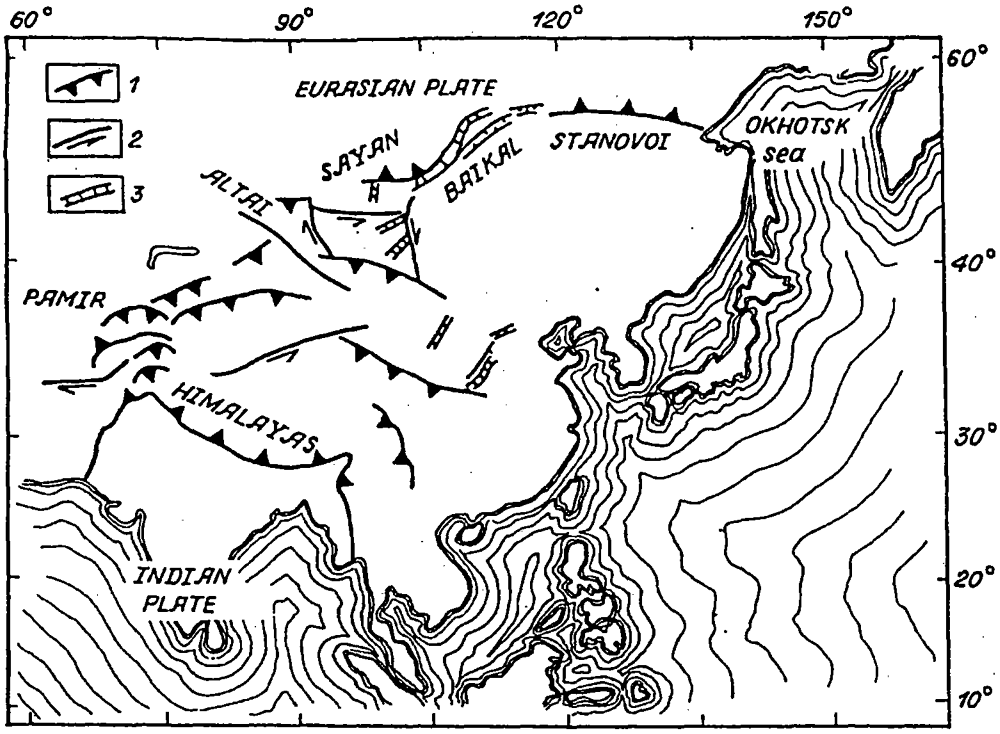

Fig. 1. Tectonic setting of Altai region in Central Asia.
1 **— overthrusts,** ***2*** **— strike-slip faults,** ***3*** **— rifts.**

mountains (2,500 m to the south and 1,500 m to the north) as pre-Cenozoic reference and taking into account the altitude of the water level (434 m), the water depth (325 m) and the sediment thickness (more than 100 m), we can estimate the total vertical displacement at between 2,800 and 1,800 m.

N. V. Lukina [6, 9] explains its formation by a tectonic process, as a giant tension gash parallel to the local direction of horizontal principal compression. Lake Teletskoe is located at the western boundary of the Tuva plate (West Sayan block), which is delimited at its northern part by the West Sayan fault and at its southern side by the Shapshal and Khantai fault zone. According to Lukina [6], the NE-striking West Sayan fault is presently a sinistral strike-slip fault with a reverse component. The WNW-striking Shapshal fault is a reverse fault with a dextral strike-slip component. The Teletskoe Depression connects these two fault zones, and is considered to represent a local extensional structure, originating from the eastward movement of the West Sayan block along two strike-slip zones with opposite directions of movement. The depression itself is located approximately at the Teletsk-Bashkaus zone of compression [11].

This paper provides preliminary evidence for active extensional tectonics along the Teletskoe Depression, based on the interpretation of satellite images, morphological studies of the lake shoulders, field evidence, and interpretation of the morphological structures of the lake basin itself.

EVIDENCE FOR ACTIVE TECTONICS

Evidence for a tectonic origin of the Teletskoe Depression is provided by several observations on basin architecture, satellite lineament analysis, morphotectonics and microtectonics.

Basin architecture. Only the N-S trending part of Lake Teletskoe will be considered in this discussion, as it developed in an elongated, narrow and deep basin. The lake bottom morphology was investigated by a detailed bathymetric survey. The narrow, elongated basin has a curved configuration with its northern part almost N-S trending and the larger southern part, NNW-oriented. The aerial steep walls of the basin are rectilinear only along the southwestern segment. In the northern half and also along the entire eastern side, the flanks of the lake consist of curved segments, variable in size, with their concave side oriented basinward.

The bathymetric map clearly evidences a small subbasin in the northern half, where the greater depths have been recorded (Fig. 2). It is separated from the southern subbasin by a transverse zone of surelevation, 30 to 40 m high. The southern subbasin has primarily an absolutely flat floor at a depth of 300 m. Southward, the depth gradually decreases. The southern subbasin becomes narrow where the basin curves southeastward. All over its length the basin is limited by steep walls with a sharp break in slope between the flat floor and the flanks. Although these steep basin flanks characterize the entire basin, minor differences exist between the different segments. The small northern subbasin has a horseshoe shape, although deeper than the southern subbasin, which has a typical trapezoidal shape. Concerning the shape of the basin itself, the northern subbasin typically shows an asymmetric shape, with the western flank less inclined than the eastern one. The northern part of the southern subbasin on the contrary exhibits an asymmetry, although not always well expressed, where the eastern flank is less steep than the western one. The southern part has an absolutely symmetric shape.

Two types of morphological expression of recent faulting within the basin have been established:

– although usually regular, the subwater slope sometimes exhibits steps which could be related to longitudinal normal faults, affecting the slope itself. It is obvious that these steps are more frequent along the western slope all over the basin;

– a particular feature of the lake floor is present in the southern part of the basin. Whereas the lake floor is absolutely flat over most parts of the basin, its southern part appears to be inclined westward, with a step almost in the middle part. It is suggested that this feature corresponds to a fault affecting the southern part of the basin and trending almost along the axis of the basin.

Satellite lineaments. The Russian MIR satellite image (mosaic) and a SPOT satellite image have been investigated for the general lineament pattern of the basement upon which Lake Teletskoe developed. The MIR image displays particularly well a constant lineament pattern in the basement north of the lake (Fig. 3). The pattern is composed of three sets, trending N20°E, N60°E and N75°W and extending along the West Sayan fault zone. Its southern limit is not sharp, and N20°E and N75°W oriented lineaments sporadically occur south of the West Sayan fault. South of the lake, an almost unique N60°E trending lineament outlines the southern limit of Lake Teletskoe. The lineament pattern in the central region is less distinct on the MIR image.

The SPOT image was processed for structural analysis of the boundaries of the N-S trending part of Lake Teletskoe (Fig. 4). This image shows a very constant NNW set of rectilinear structures near and parallel to the SW boundary of the lake. On the opposite SE flank, the linear structures are still roughly NNW-oriented, but they display a marked curved shape. The linear pattern on both flanks of the northern basin part is much more lobate and more or less follows the shoreline. A small-scale linear fabric is prominent all over the eastern flank and is intersected by other linear structures. The large-scale curved shoreline of the lake is locally affected by small angular breaks, controlled by this intersecting lineament fabric. In the northern half of the depression, the basement does not bear the large lineament features which are so obvious in the southern part. In the SE flank, a prominent N- to NNW-trending, steeply dipping shear zone was identified in the field.

A more detailed lineament analysis based on directional filtering processing of the image is presented by E. Sintubin et al. [11]. They present a series of NE-trending lineaments in the northern part of the Teletskoe region, parallel to the West Sayan fault zone. They conclude from their analysis that there is a limited coincidence of lineament patterns with basement structures, except in the southeastern part of the region. Therefore, these lineaments should be mostly of brittle origin. However, they do not necessarily directly reflect recent tectonic activity, since brittle tectonics probably also occurred in the Late Paleozoic–Mesozoic period.

Morphology. Three main surfaces expressing characteristic relief forms are distinguished in the morphological structure of the Teletskoe region [12]. The first one ranges between 2,000 and 2,500 m, and is interpreted as remnants of an ancient peneplanation surface disrupted by faults. The second one, between 900 and 1,900 m, is also affected by faults. The lower level corresponds to terraces along the lake border at less than 600 m. The recognition of these surfaces disrupted by faults suggests tectonic movements in the blocks adjacent to the depression. Maximum vertical amplitudes of recent displacements occur between the lower and middle relief levels, where they are more than 700 m. Amplitudes of relative displacement between other levels are usually from 100 to 500 m.

The upper surface is characterized by a glacial morphology as the result of the Late Pleistocene glaciation of Gorny Altai. According to the morphology of the glacial valleys, their glaciers did not reach altitudes less than 1,200–1,400 m, and the valleys have a typical V-shape below this level. Only the Chulyshman valley glacier with its large catchment area succeeded in reaching the lake. The possibility that glacial processes had some influence on the morphology of the Teletskoe Depression during the first stages of its development cannot be excluded, but there is no evidence for the origin of the lake as a result of glacial processes [13].

Several major trends of recent fault systems are reflected by the relief structure of the Lake Teletskoe region (Fig. 5). According to the specific relief morphology and recent tectonic patterns, this region can be subdivided into 6 parts:

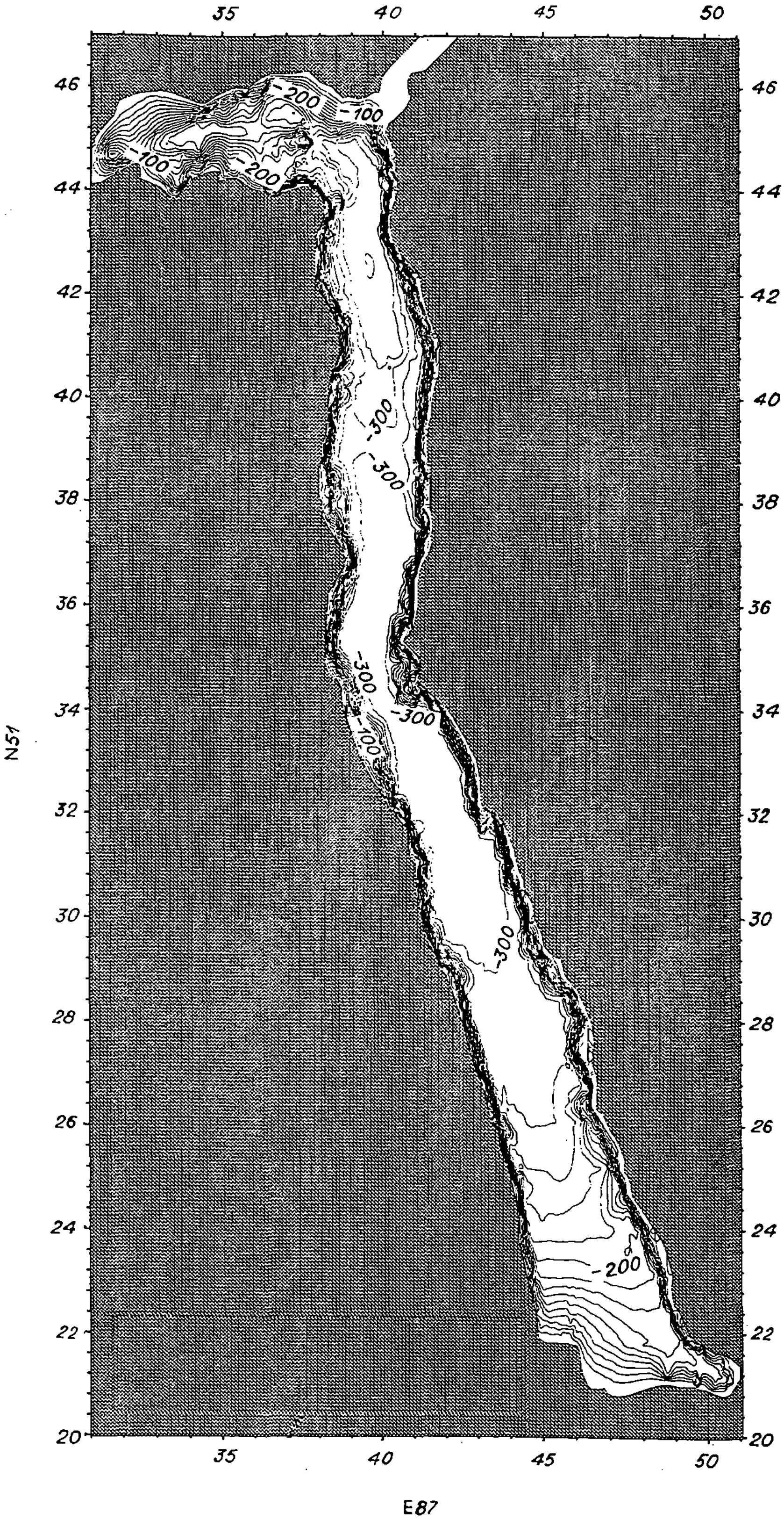

Fig. 2. Bathymetry of the N-S trending segment of Lake Teletskoe.

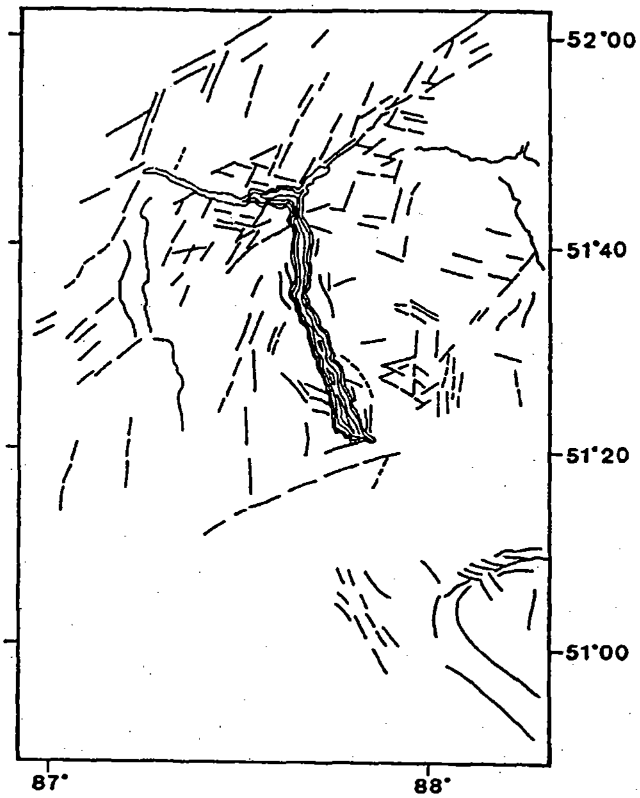

Fig. 3. Lineament pattern interpreted from the MIR satellite image.

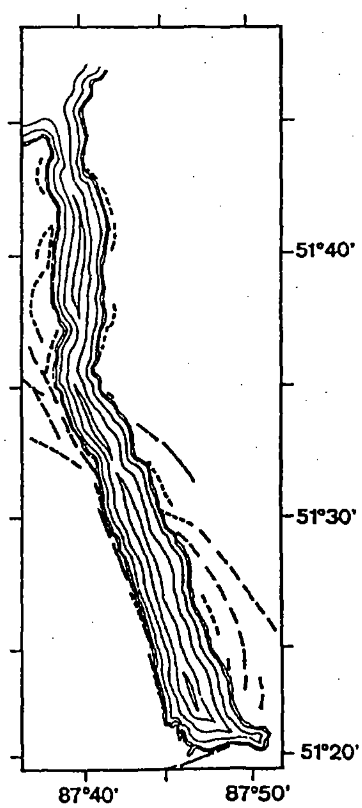

Fig. 4. Lineament pattern interpreted from the SPOT satellite image.

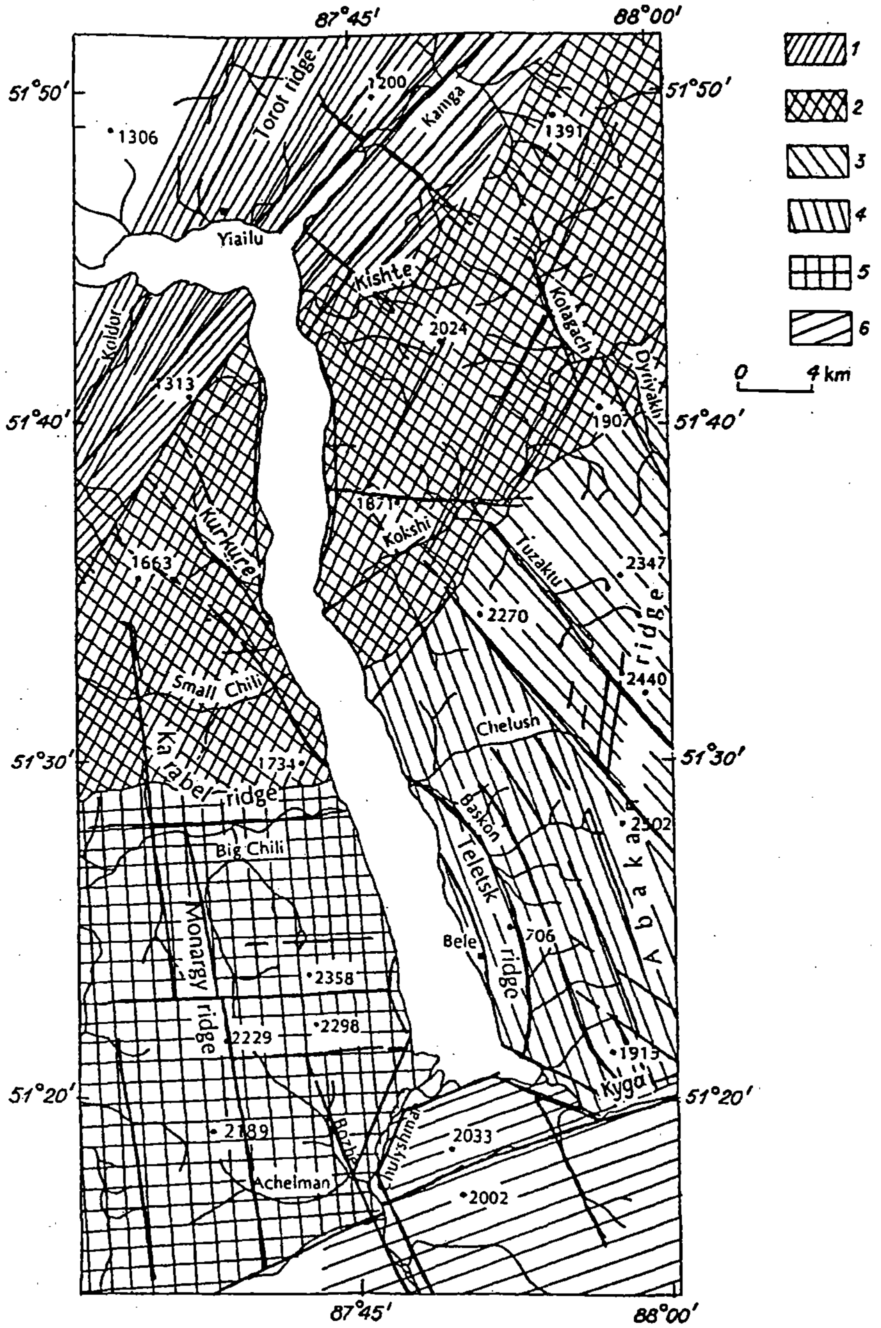

Fig. 5. Map of zoning of the Lake Teletskoe region according to the relief morphology and neotectonic pattern (compiled by I. S. Novikov, E. V. Deev and E. M. Vysotsky). For explanation see the text. Terrains within which various systems of faults are expressed: *1* — of the NE strike and younger, of the NW strike; *2* — of the NE and NW strike, complicatedly oriented; *3* — of the NW strike, *4* — of the NNW strike, *5* — of the submeridional and sublatitudinal strike; *6* — of the ENE strike.

— in the northern part of the investigated area, the interaction of the West Sayan fault zone with the Kuznetsk-Altai fault zone characterizes the modern relief structure and neotectonic features of this region. The most clear structure appears on both flanks of the NE-trending Kamga valley, which exhibit steps resulting from downfaulted blocks. This structure is intersected by relatively young NW-trending faults;

— a complicated structure of relief on both sides of the lake in the valleys of the Kurkure, Mal. Chili and Kokshi Rivers is evidently due to the interaction between NE-trending faults in the northern part and NW-trending fault zones which are better developed southward. Amplitude of relative displacement along these faults is estimated at 100–500 m.

The southern part of the Lake Teletskoe region has a different structure than the northern one, and both eastern and western flanks are also different.

— in the upper part of Abakan Ridge (the Tuzaktu and Chelyush area) a NW-trending fault system displays traces of modern tectonic activity not older than 10,000 years, affecting the Late Pleistocene deposits;

— closer to the lake, along the western slope of Abakan Ridge, a NNW-trending fault system is interpreted as the most important feature controlling the relief structure and neotectonic features. Near the lake, it corresponds to spoon-shaped faults of the Teletsky Ridge and Bele terrace. The origin of the Bele terrace is a tectonic step on the flanks of the Teletsky Ridge, on which Late Pleistocene sediments accumulated. It was later isolated from the rest of the depression by migration of normal faulting toward the center of the depression. Several other steps occur on the summit slope of the Abakan Ridge with amplitudes of 100 to 300 m;

— two major fault systems characterize the relief structure and neotectonic features of the western side of the lake from the Achelman River mouth in the south to Karabel Ridge in the north. The EW-trending system has a vertical amplitude of displacement of 100–200 m and the NS-trending faults have displacements of 100–300 m. The latter appear far to the west and the south;

— the southern termination of the lake is controlled by an ENE-trending fault system. One of the faults forms the southern border of the depression and has a limited extension. Another, 3–4 km south of the former, controls the location of the Kyga valley and seems to be a major feature controlling the block structure of this part of the depression. Between this fault and the lake, the Kyga valley appears as a graben, delimited by two NW trending faults systems.

The southern part of the lake is characterized by the fact that both sides are of different neotectonic structures, expressed in relief morphology (Fig. 6). Moreover, the fault-related lineaments cannot be traced from one side to the other. This suggests different tectonic accommodations along both sides of the lake. In the north, both sides of the lake consist of the same material. In the south, the western shore consists of non-foliated granitic rock, while the eastern shore consists of rocks of the compression zone.

Field structures. There are many pieces of evidence for active tectonics observed in places along Lake Teletskoe (Fig. 7). These are neotectonic fault scarps, morphological lineaments and minor faults and joints observed in the Late Pleistocene terraces. The latter were used for paleostress analysis, to compute four parameters of the reduced stress tensor, as defined by J. Angelier [14]: the principal stress axes $\sigma 1$ (maximum compression), $\sigma 2$ (intermediate compression) and $\sigma 3$ (minimum compression) and the ratio of principal stress differences $R = (\sigma 2 - \sigma 3)/(\sigma 1 - \sigma 3)$. Two additional parameters of the full stress tensor are ratio of extreme principal stress magnitudes ($\sigma 3/\sigma 1$) and lithostatic load, but these cannot be determined from fault data only. The first four parameters are determined using successively an improved version of the Right Dihedron method [15], and a rotational optimization method, using the TENSOR computer program developed by D. Delvaux [16]. The results are presented in Table 1.

The NS-trending segment of Lake Teletskoe is bordered by steep slopes with the typical morphology of a young fault scarp, characterized by the presence of triangular facet spurs, tectonic steps and paleoseismic dislocations. In the northern half of the NS segment, the eastern side of the lake is very characteristic. It has fresh triangular facets (Fig. 8, a), on top of which is a 20–30 m high step with denuded rock in the middle of the forest (Fig. 8, b). On the opposite side of the lake, a break in slope in the middle part of the western flank indicates the presence of a fault at Cape Ezhon (Fig. 8, c). Near Bele village, a well-preserved terrace of Late Pleistocene fluvio-lacustrine sediments outcrops along the eastern border of the lake. It has been attributed to the Middle Würm–Late Pleistocene interglacial period (30,050±435 yrs) [17], on the basis of radiocarbon dating of sapropel fragments. In the terrace sediments on the lake shore a few minor normal faults were observed to displace the sedimentary layers (Fig. 8, d), as well as a subvertical sand dike showing synsedimentary WNW extension (Fig. 8, e). The paleostress tensor obtained is poorly constructed because of the lack of microstructures. An extensional regime is, however, clearly indicated by the presence of both normal faults and sand dikes.

The southern extremity of the Teletskoe Depression terminates abruptly against a ENE-trending scarp, and is divided in two lateral branches, along the Kyga River to the southeast and along the Chulychman River to the southwest. A few kilometers southward, the Kyga River turns abruptly and is controlled by a marked ENE-trending lineament. From satellite image interpretation and field morphology, it appears that all these

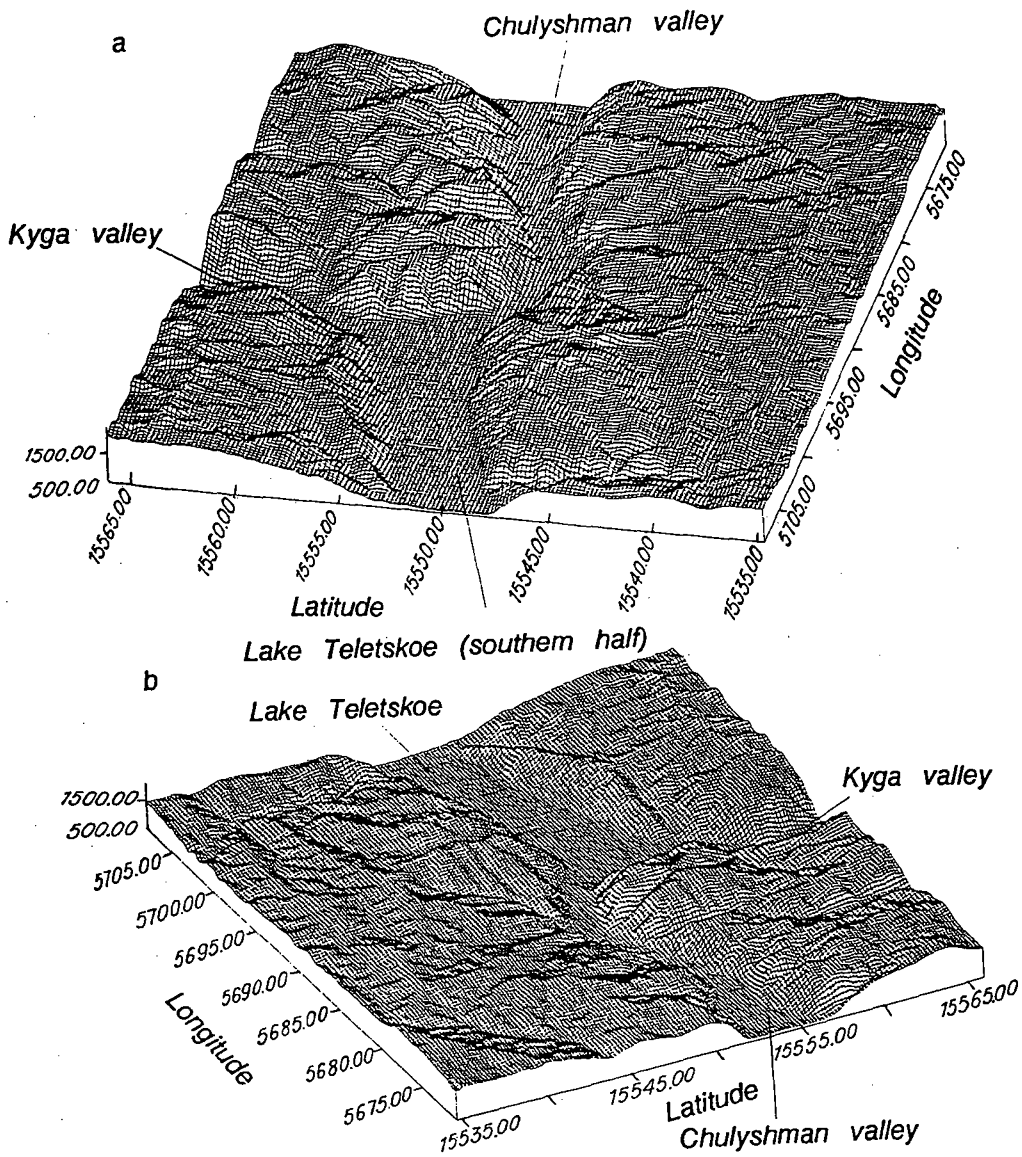

Fig. 6. 3D orthographic view of the southern part of the Lake Teletskoe region. Vertical scale 114%. a — view toward the south; b — view toward the NE. On the eastern side of the lake, the Teletsky Ridge and Bele terrace are isolated by spoon-like faults. The Kyga and Chulyshman valleys are seen respectively in the southeastern and southwestern extension of the Teletskoe Depression.

structures are controlled by the activity of faults of different orientation. Near Chiri village, a series of three tectonic steps of EW orientation is caused by southward-dipping steeply-inclined faults with well-expressed normal movement. Each step is 5–10 m high, but no slip indicators were observed on them.

The northeastern branch of Lake Teletskoe developed in the narrow and elongated depression of the Kamga River. It lies at the southwestern extremity of the Major West Sayan Fault. Indications for active sinistral strike-slip faulting along this line are given by the typical morphology of rectilinear fault segments and oblique tension gashes, by the displacement of deltaic cones at the mouths of small rivers flowing into the bay, and by the presence of Quaternary fault breccia at Cape Airan (site AL05). In this site, 86 minor faults with slip line were measured in the fault breccia, and the stress tensors computed typically show horizontal NS principal

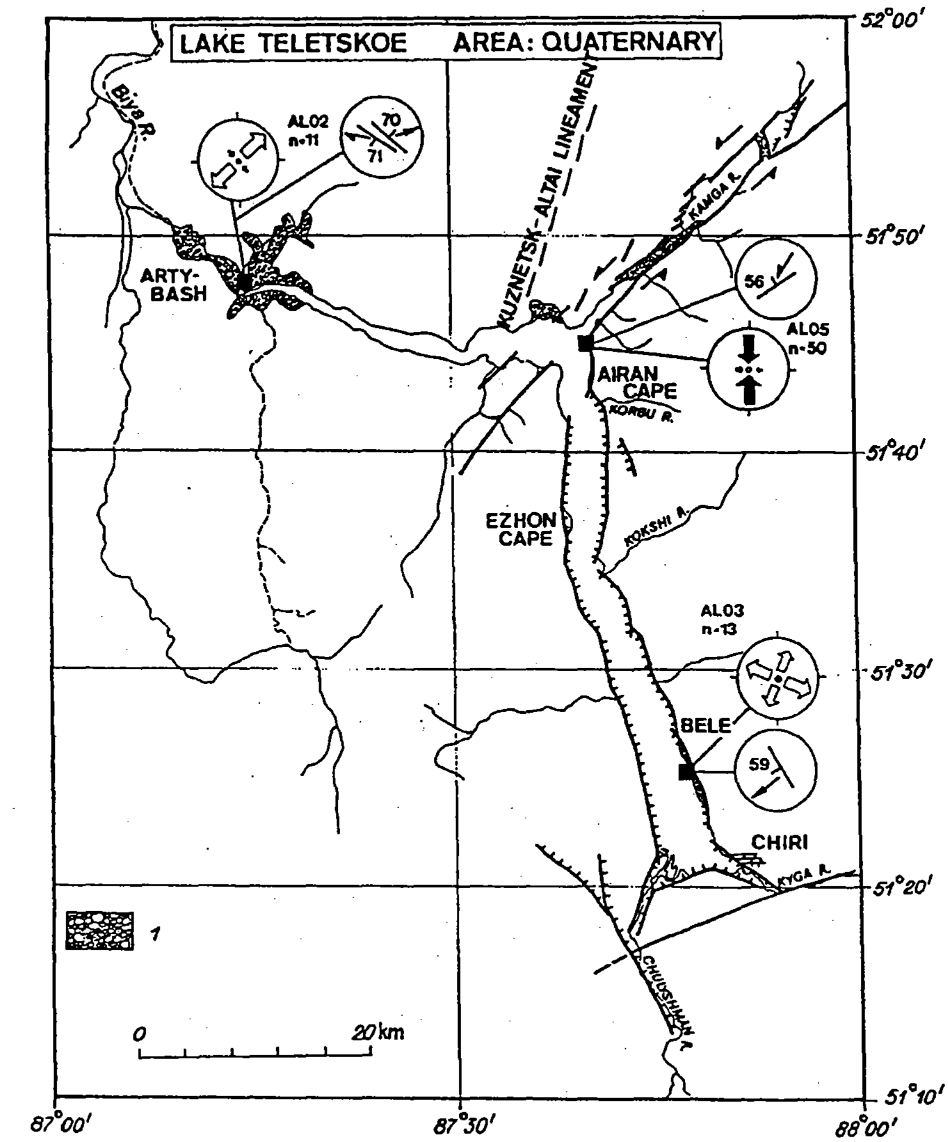

Fig. 7. Kinematics and paleostress reconstructions from microtectonic data.
1 **— Late Pleistocene deposits.**

compression. The main movement plane trends NE and dips 56° S with an oblique reverse-sinistral movement (Table 1).

For the northwestern branch of the lake, the tectonic control is less apparent. However, a system of well expressed conjugated minor faults and joints affects the Late Pleistocene deposits in a sand quarry near Arty-Bash village (site AL02). The slip lines could not be observed, despite evident normal displacement (Fig. 8, f and g). In the absence of slip indicators, pairs of conjugated faults can be combined to reconstruct the theoretical slip lines, assuming that they belong to simple conjugated sets (faults formed parallel to the intermediate stress axis at 30° from the principal compression stress axis). Using these data, an extensional type of stress tensor with a strike-slip component can be reconstructed (Table 1). The mean movement plane and slip lines computed provide evidence for an oblique extension with dextral strike-slip component along WNW-ESE-oriented normal faults.

DISCUSSION

Lake Teletskoe is described by N. V. Lukina [5] as a young graben formed by a lateral offset of the West

Table 1

Paleostress Tensors in the Lake Teletskoe Region

Tensor parameters

Observation point	Region, outcrop	n(nT)	%/nT	σ1	σ2	σ3	R	α	Type/quality of tensor	
AL02	Arty-Bash, sand quarry	18(20)	95	83/198	03/317	06/048	0.73	9.4	Shear extension	A
AL03	Cape Nizh. Kamelik, terrace	13(13)	100	87/087	03/202	06/292	0.10	0.8	Semi-radial extension	C
AL05	Cape Airan, tect. breccia	50(86)	58	09/357	29/092	59/250	0.58	11.1	Pure compression	AA
		20(86)	35	23/199	15/103	62/343	0.61	12.7	Pure compression	B
Total: 4 tensors		101		02/179	69/274	21/088	0.94			

Slip planes

Observation point	Characteristics	n (quality)	Princ. mov. plane	Aux. mov. plane
AL02	Terrace, Lower Pleistocene	18(A)	11 × 70/042 67/071ND	6 × 71/214 47/282 ND
AL03	Terrace, Upper Pleistocene	13(C)	6 × 59/238 57/228 ND	6 × 79/300 (extension fractures)
AL05	Tect. breccia, Quaternary	50(AA)	21 × 58/146 36/209 IS	20 × 60/028 44/332 ID
AL05	Tect. breccia, Quaternary	20(B)	10 × 70/209 68/236 IS	6 × 88/330 66/245 NS

Note. *n* — number of data used; *nT* — total number of undifferentiated data in database; %/*nT* — percentage of data used for computation; σ1–3 — principal stress directions in format dip/azimuth; *R* : shape ratio of stress ellipsoid (σ2 – σ3)/(σ1 – σ3); α — mean deviation angle between observed and computed slip directions; tensor quality: AA — very good, A — good, B — medium, C — poor; tensor type: function of inclination of stress axes and *R* ratio; princ. mov. plane — principal movement plane with slip line and slip sense; aux. mov. plane — auxiliary movement plane with slip line and slip sense (number of faults, dip/dip direction of plane, plunge/azimuth of slip line).

Sayan block relative to Gorny Altai, owing to conjugated strike-slip movements along the western segments of the NE-trending West Sayan fault and the NW-trending Shapshal fault, under regional N-S to NNE-SSW compression. In this model, the opening of the Teletskoe graben is the result of rigid block interaction between two major strike-slip faults moving in opposite directions (Fig. 9). Preliminary heat flow measurements in the lake were made by A. Duchkov et al. [18], but their results are ambiguous and give no support for the riftogenic hypothesis on the origin of the Teletskoe Depression.

Our results are generally consistent with this hypothesis, and they can contribute to this model. Evidence of normal faulting is present in the lake basin, as well as along its border and on both shoulders of the lake basin. These are:

– the steep slopes of the subwater basin, which themselves present steps indicative of normal faults within the slope itself;

– the longitudinal faults which border the lake and which are particularly well expressed along the southwestern rectilinear shore;

– the lobated structures which are most evident in the southeastern part on land, and less evident in the northern half of the basin. Nevertheless, the curved shape of the lake border in the north and in the southeast implies listric faults, responsible for this kind of basin structure;

– the morphological evidence of block faulting on the shoulders of the lake;

– particularly in the south, the inferred longitudinal active fault in the middle of the lake, and the block configuration which characterizes this part of the basin.

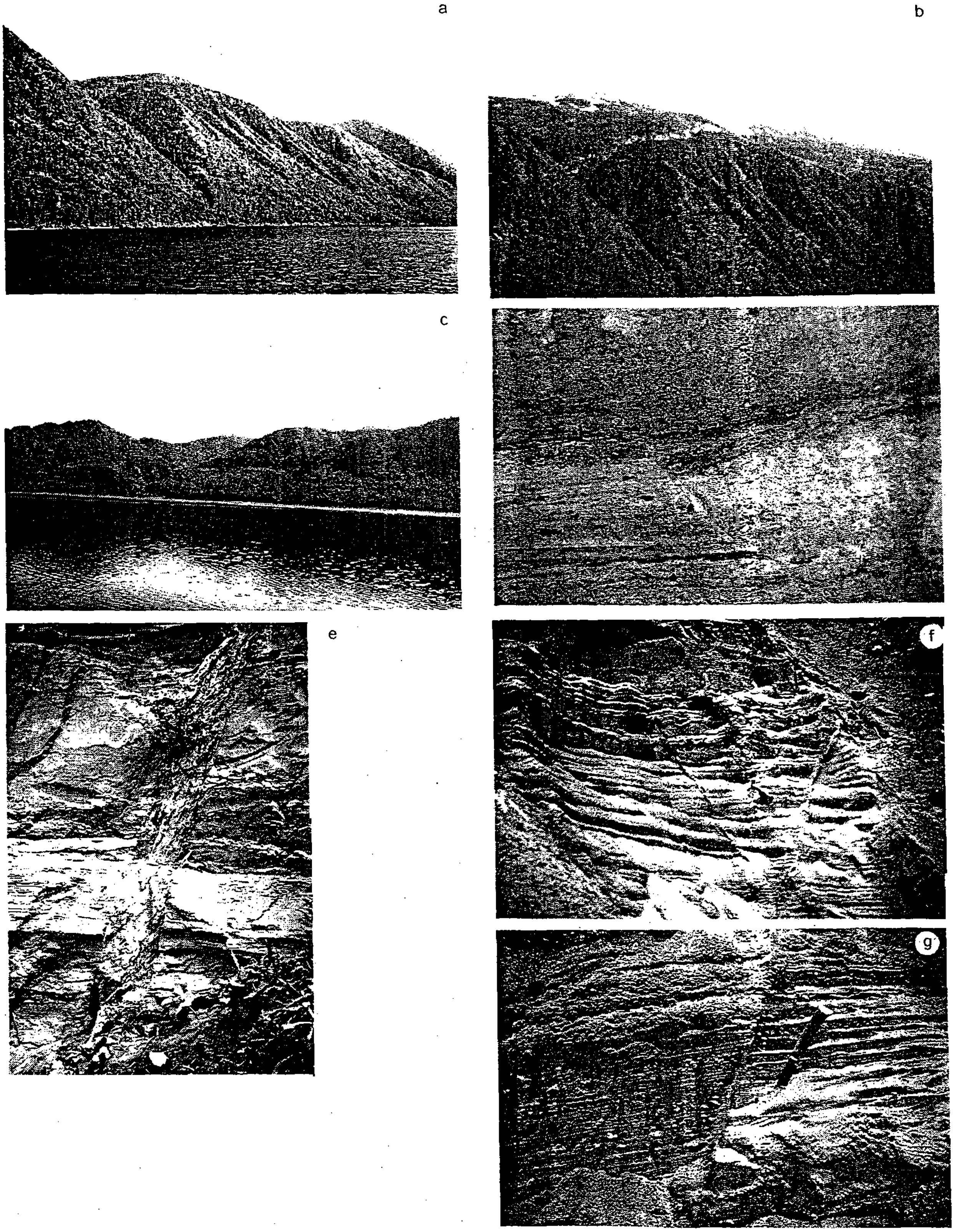

Fig. 8. Outcrop photographs. a — Triangular facets along the eastern scarp bordering the northern half of the lake; b — neotectonic step on top of the scarp displayed in photo a; c — break in slope at the foot of the western fault scarp at Cape Ezhon; d — minor fault affecting Late Pleistocene sediments of the Bele terrace; e — synsedimentary sand dike in the Bele terrace; f — conjugated minor fault in the Late Pleistocene terrace at Arty-Bash; g — small fault with apparent normal offset in the Late Pleistocene terrace at Arty-Bash.

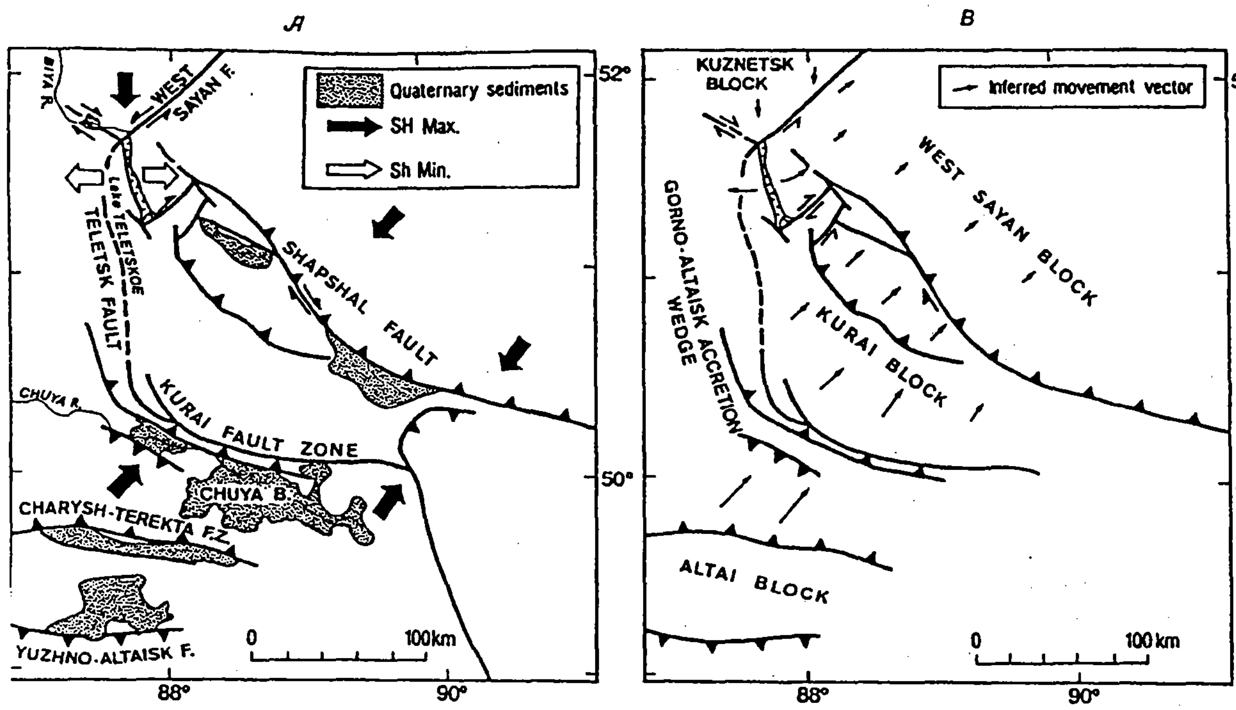

Fig. 9. Dynamic sketch for the opening of the Teletskoe depression. ***A*** **— Kinematics of fault movements and regional directions of horizontal principal stress based on this work and [10],** ***B*** **— inferred relative block movement.**

Although these extensional structures occur all along the NS trending basin, they are much better expressed in its southern part. Another obvious feature is the difference in character between the northern and southern parts of the basin. They are distinguished by the shape of the basin, but also by the presence in the northern part of lobated faults at both sides of the basin, and in the southern part, by rectilinear faults along the western side [13] and lobated structures at the eastern side.

The above structural features confirm that the N-S segment of Lake Teletskoe is an extensional tectonic depression, located between two transpressive fault zones with Quaternary movement in the opposite direction: the NE-striking West Sayan fault and the NW-trending Shapshal fault. The sinistral character of the West Sayan fault was confirmed by direct observations, and the dextral character of the Shapshal fault is assumed from the block faulting configuration at the southern end of the basin.

Opening of the Teletskoe Depression is consequently assumed to result from the lateral offset to the east of the block which borders the basin at its eastern side, relative to the western block. Moreover, as the recent extensional structures are more strongly expressed in the southern part of the basin, it is assumed that the rate of extension is higher in the southern part, compared to the northern one. This suggests a counterclockwise rotation of the block east of Lake Teletskoe, in addition to its eastward movement.

The observations of minor faults in the sand quarry in Arty-Bash suggest that the northwestern segment of the lake is also partly controlled by en echelon normal faulting which defines a NW-trending tension zone. The Kuznetsk block, north of the lake, thus appears as a southward-pointing wedge between the West Sayan fault and the NW tension zone. In the general compression context, this wedge should move southward to accommodate the opening of the Teletskoe Depression. The idea that this block rotated was formulated for the first time by N. L. Dobretsov in the report on the 1994 field work [19].

Thus, the Lake Teletskoe basin represents a local extensional basin, resulting from the differential movement of stable blocks in the general compressional context affecting the Central Asian continent.

ACKNOWLEDGMENTS

This work was completed in the framework of a governmental agreement between the Siberian Division of the Russian Academy of Sciences and the federal scientific institutes of Belgium. We specially thank

Academician N. L. Dobretsov and Dr. V. D. Ermikov who coordinated this project and organized the field work. Critical review was by M. Sintubin and M. Buslov.

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