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Landform Analysis, Vol. 2: 81–92 (1999)

The north-eastern boundary of the Baikal rift zone

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Abstract: The Baikal rift zone is defined on its NE side by the Olyekma-Amur system of NW/SE-striking transverse lineaments. Transverse faults also separate the north-eastern part of the rift zone into the Chara and Tokko sections. The former shows a typical range of neotectonic forms which include (from NW to SE): the inclined horsts of the Kodar ridge; an axial system of grabens and interbasin faults and a marginal dome. The Tokko section is located within a sector of the Olyekma-Amur system of lineaments. Here, the neotectonic forms are smaller and a degradation of the NW flank of the rift zone has taken place. A large marginal step defines the south-eastern flank. It is considered that these structural modifications relate to changes in the anomalous mantle protrusion near the north-eastern boundary of the rift zone.

Key words: rift, Baikal rift zone, tectonic relief

Introduction

The problem of the extension and closure of the Baikal rift zone has been controversial for many years. Commonly, owing to the general lack of detail concerning the relationships of the different structural elements present in the rift zone, the various interpretations which have been proposed have all been inconclusive. This paper defines the boundary of the rift zone and describes the structural transformations in the regions of closure; we have selected the north-easternmost link in the rift zone, the Chara-Olyekma link, as the field model for our reinvestigation of this problem (Fig.1).

The tectonic relief of the NE part of the rift zone

A study of topographic maps, together with geological and geophysical surveys, permits the elucidation of recent tectonics in this region (Fig. 2). The tectonic relief reflects the form of the neotectonic structures; the patterns of neotectonic forms reflect the spatial relationships of the rift zone elements and also those in adjacent areas. Also, for a full structural analysis of the rift zone, it is necessary to erect a model of the tectonic relief (a summit-incidence surface); the mountain uplifts, with their complex and variable relief patterns, extend alongside the rift valleys which are the main elements of the rift zone structure.

In the Olyekma and Nyukzha valleys, the topography of tectonic relief clearly reflects the north-eastern limit of the rift zone (Figs. 1 and 2). Here lies the sharp change between the complex tectonic relief of the rift zone and the plains which are marginal to the Siberian Platform. In the NE, the rift zone is bounded by NW-striking transverse faults which are part of the extensive Olyekma-Amur lineament zone (Grishkyan *et al.*, 1977; Ufimtsev, 1984). In the Chara-Olyekma region, these can be either transverse faults, as in the Olyekma and Nyukzka valleys, or more complex combinations of tectonic relief forms (Fig. 3). As shown by the pronounced southward displacement of the eastern part of the Kalar gabbro-anorthosite massif (Zorin *et al.*, 1988), cumulative dextral displacements along these, reactivated many times during the Cainozoic, may be as much as 15 km. The westernmost components of this system are the faults which bound the Chara Basin to the NE and which also dissect the Tokko Basin. We refer to these as the Khani-Sulumat and Evonokit-Tokko transverse faults, respectively (Fig. 3). Close to their intersection, the structure of the rift zone is much transformed.

The tectonic relief provides a straightforward answer to the discussed question: does the rift zone continue to the E towards the limits of the Stanovoy Ridge.

or not? Because the Stanovoy Ridge is a large domal uplift, which has a well-defined periclinal form E of the mouth of the River Nyukzha (Ufimtsev, 1984) (Fig. 4), we believe not. The rift zone and the Stanovoy domal uplift have no structural links and the spatial links are ill-defined (Fig. 2). Further, the Baikal rift zone and the Stanovoy domal uplift relate to different mountain belts on opposite sides of the Olyekma-Amur lineament zone, a feature which is well reflected in the form of the tectonic relief (Figs. 1 and 2).

This model of tectonic relief enables us to estimate the importance of the recent structure of the rift zone which, as expressed by scarps and valley grabens, comprises faults of very variable strike. The influence of the transverse faults of north-western and submeridional strike increases with proximity to the Siberian platform; this reflects particular structural features in the basement. The faults become increasingly important close to the limits of the rift zone.

Close to the eastern boundary of the Chara Basin, the Baikal rift zone maintains a similar pattern of subzones across the strike i.e. consecutively from NW to SE: tilted horsts and asymmetric block uplifts (the Kodar Ridge); an axial subzone of basins, separated by interbasinal uplifts with large conjugate marginal steps; and a domal curve of the south-eastern flank (the Udokan and Kalar Ridges) (Ufimtsev, 1986) (Fig. 5). Along the strike, the rift zone is divided by transverse faults into sections which have analogous structures, although, near to the north-eastern boundary of the rift zone, the general sequence of these subzones is not so obvious. The marginal, Tokko, section of the rift zone differs structurally and morphologically from that of Chara (Fig. 2). When the structures of the Chara and Tokko sections of the rift zone are compared, the nature of the transformations on the eastern closure of the Baikal rift zone is very evident.

The axial subzone of the rift zone

The central part of the rift zone includes a system of Baikal-type basins which are separated by interbasin uplifts which have large marginal steps in their flanks. The Muya and Chara Basins are major structures, whereas the Tokko and Charuoda Basins, located near the eastern boundary of the rift zone, are appreciably smaller (Solonenko *et al.*, 1975; Khilko & Nikolaev, 1975). In most respects, the Chara Basin is a typical Baikalian basin. Its north-western flank is a steep fault scarp which is more than 1,500 m high (Fig. 6), whereas the southern flank is arcuate. Geophysical data indicate that the basement has subsided more than 2,000 m (Zorin & Khilko, 1969). Miocene and later sediments of thickness greater than 1,200 m are present in this basin, suggesting that, in the north-eastern part of the rift zone, some basins began to form in the Oligo-Miocene period. However, there can be no doubt that there has been persistent rejuvenation of their margins since then. The structural-morphological peculiarities of the basins of the Chara section, and the nature and age of their sedimentary fills reflect the fundamentally symmetrical properties of the recent structure of the rift zone (Ufimtsev, 1986).

The floor of the Chara Basin is flat and featureless; only in its southern part is the monotony broken by a belt of narrow uplifts of modest height and with outcrops of the basement. However, narrow transverse uplifts located along the NW-striking faults are also present in the floor of the basin. On the basis of geophysical data, such uplifts or steps separate two independent synclines (Zorin & Khilko, 1969). The Muya Basin is more complex; narrow interbasin uplifts of modest height fragment the larger basin into several smaller basins (Solonenko *et al.*, 1985). It also has a steep fault scarp along its southern flank (Fig. 7).

The Muya-Chara interbasin uplift has a complex structure, which is well reflected in the form of the tectonic relief (Fig. 2). This includes high (up to 2,000 m) and extensive longitudinal horsts (Fig. 8), steps and

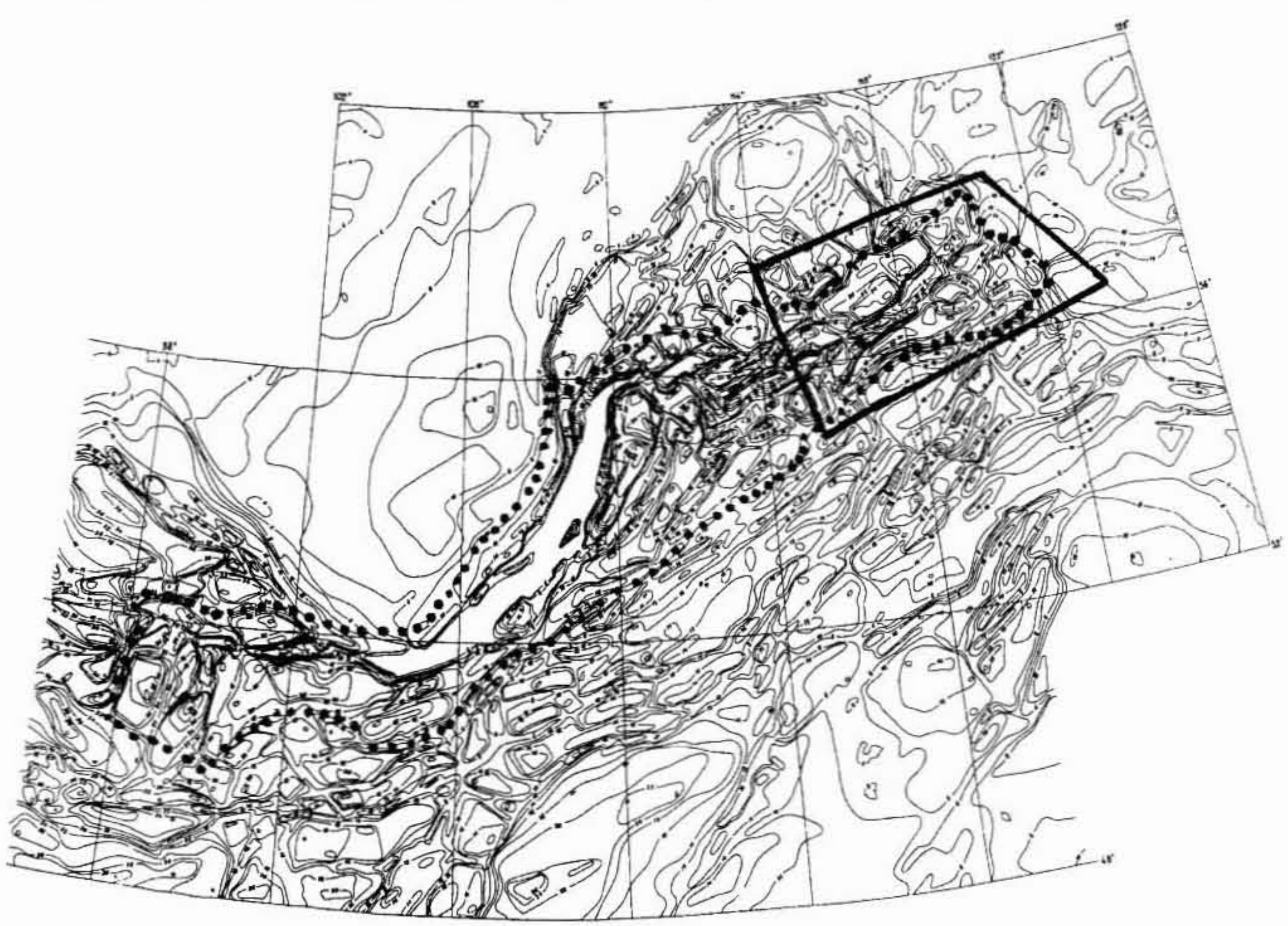

Fig. 1. The tectonic relief of southern East Siberia and North Mongolia. The boundary of the Baikal rift zone is shown by a dotted line and the entire line shows the boundary of the Chara-Tokko region. Contours are drawn at 200 m intervals and are marked in hundreds of metres.

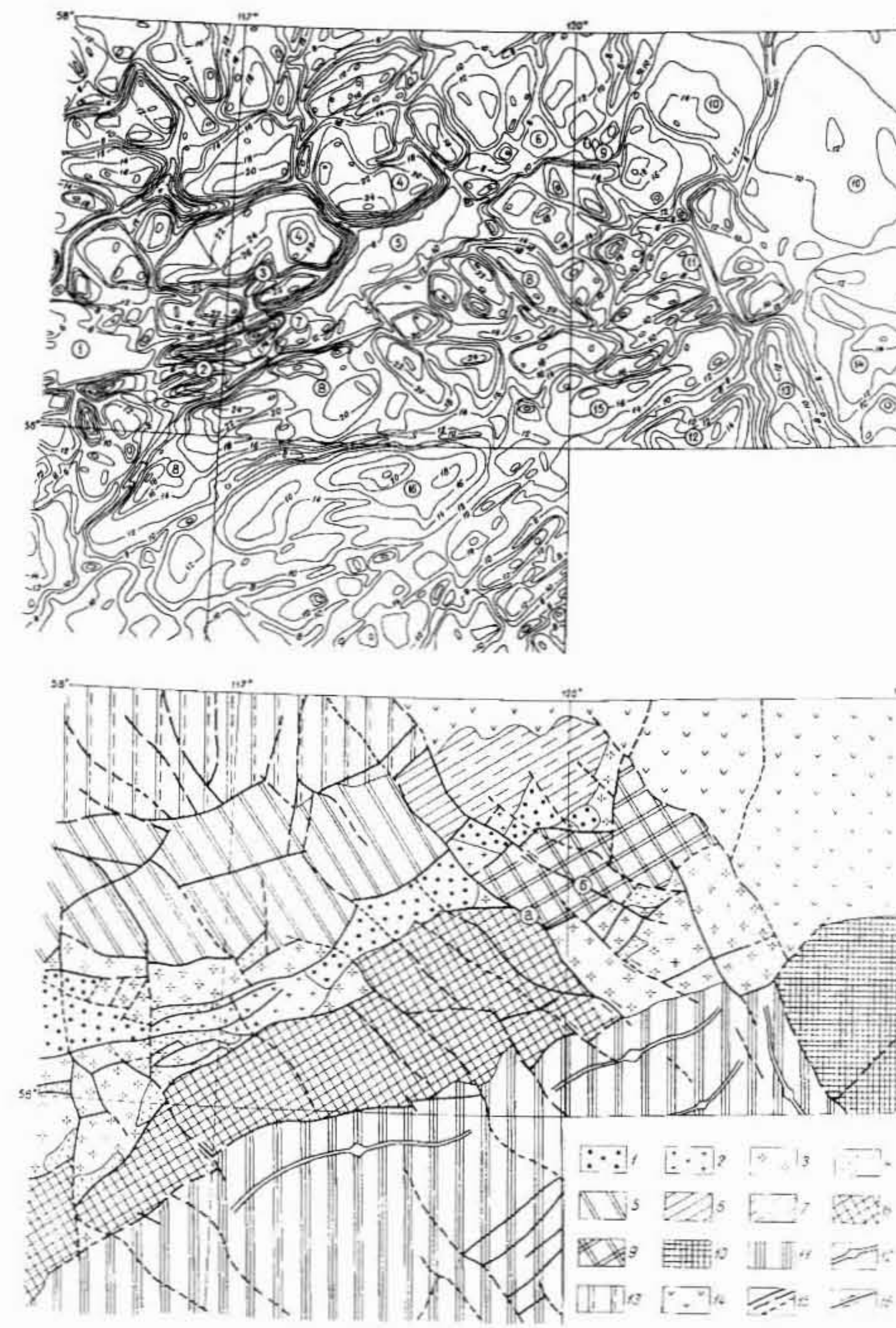

Fig. 2. Tectonic relief (above) and neotectonic forms of the north-eastern part of the Baikal rift zone (below):
1–4 – axial subzone, including large basins (1), interbasin uplifts (2), marginal steps (3) and small basin (4); 5–7 – the north-western flank of the rift zone, including inclined horsts with "normal" inclination (5), longitudinal inclination (6) and places of degradation of rift shoulder (7); 8–9 – marginal dome also with indications of block disintegration (9); 10 – large domal uplift; 11–12 – zone of linear warping including separate domes; 13–14 – marginal part of platform including zone of gentle folds (13) and gentle inclination of tectonic relief (14); 15–16 – faults, also with the horizontal displacements (16). Contours are drawn at 200 m intervals and marked in hundreds of metres. Numbers and letters in circles mean: the Muya Basin (1), the Konda (2) and Upper Sulban (3) small basins, the Kodar uplift (4), the Chara (5) and Tokko (6) Basins, the Muya-Chara interbasin uplift (7), the Kalar-Udokan dome (8), the Charuoda Basin (9), marginal part of the Siberian Platform (10), the near-Olyekma marginal step (11), the South-Dyryndian uplift (12); the Chelbaus (13), Stanovoi (14), North-Dyrynda (15) and Yankan (16) uplifts; the Khani-Sulumat(a) and Chara-Evonokit (b) transversal faults.

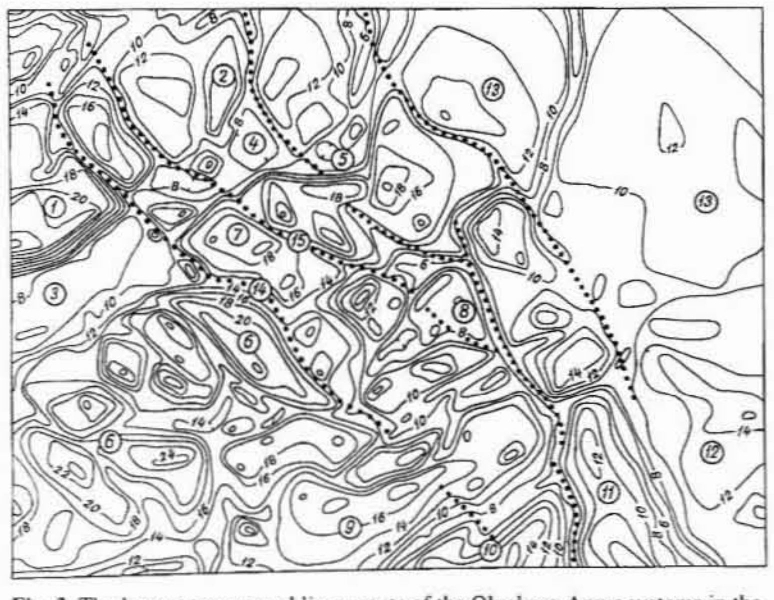

Fig. 3. The largest transversal lineaments of the Olyekma-Amur systems in the region of the NE termination of the Baikal rift zone and their reflection in tectonic relief. Contours are drawn at 200 m intervals.

discrete small basins and a morphology similar to that of wide river valleys (Fig. 9). Geophysical evidence indicates that, in the Sulban and Konda Basins, which open to the west in the side of the Muya rift valley, Cainozoic sediments may exceed 500 m thickness (Zorin *et al.*, 1980) which contrasts with the valley-like forms of these grabens. Along the strike, the latter are transformed into narrow subsidences, the floors of which are often occupied by glacial lakes (the Greater and Lesser Leprindo etc.). Perhaps, in these true tectonic depressions which join the Muya and Chara rift valleys, further deep subsidences which are partially filled with Cainozoic sediments will also be found.

The Chara-Muya interbasin uplift comprises a complex of blocks which are located on the flanks of the Chara and Muya basins (Fig. 2). These are large-scale tectonic steps with differential tectonic relief and with structures which are similar to the interbasin uplifts with which they are closely connected in space. Certainly, these steps, whether on the rift valley or the interbasin uplifts, are of the same type, the only significant difference between them being the relative position of these block complexes in the recent structure of the rift zone. The large steps marginal to the Muya-Chara interbasin uplift have a complex structure and consist of steps of variable height, elevated (up to 2,400 m) horsts and small basins. The Upper Sulban small basins are good examples of the latter. These are limited to the N by the Kodar uplift and a chain of high horsts and steps in the S (Fig. 10–II). Miocene sediments of basinal facies (diatomites) were reported here by Endrykhinsky *et al.* (1983); of course, this facies is incompatible with the alpine relief surrounding the Upper Sulban Basin at the present time. This evidence is important in two respects: firstly, it demonstrates that the large and the small basins on the north-eastern side of the rift zone are all contemporaneous, even where close to the intensive uplifts of the rift zone flanks. Secondly, the small basins have later been affected by inversional uplifts, so that they have been transformed into erosional valleys (as in the case of the Upper Sulban small basin). This style of development of the small basins is present along the whole rift zone and it undoubtedly reflects the symmetric properties of its overall structure (Ufimtsev, 1986). The marginal step blocks which surround the Upper Sulban Basin have been affected by recent uplifts of such intensity that, in terms of their elevation, they are very little different from the contiguous Kodar uplift (Fig. 10–I). The large marginal step in the southern part of the Muya Basin has a more complex structure (Fig. 2). This consists of a row of high horsts on the flanks of the basin; this includes the Shaman horst, which is oriented transversely (Fig. 7). This is located in a zone of submeridional mar-

Fig. 4. The Kodar uplift near valley of the Apsat river mouth, view from the south. In the center – outcrops of Jurassic continental sediments. Arrow shows the surface of displacement of large Apsat collapse-fault of seismogenic (?) origin.

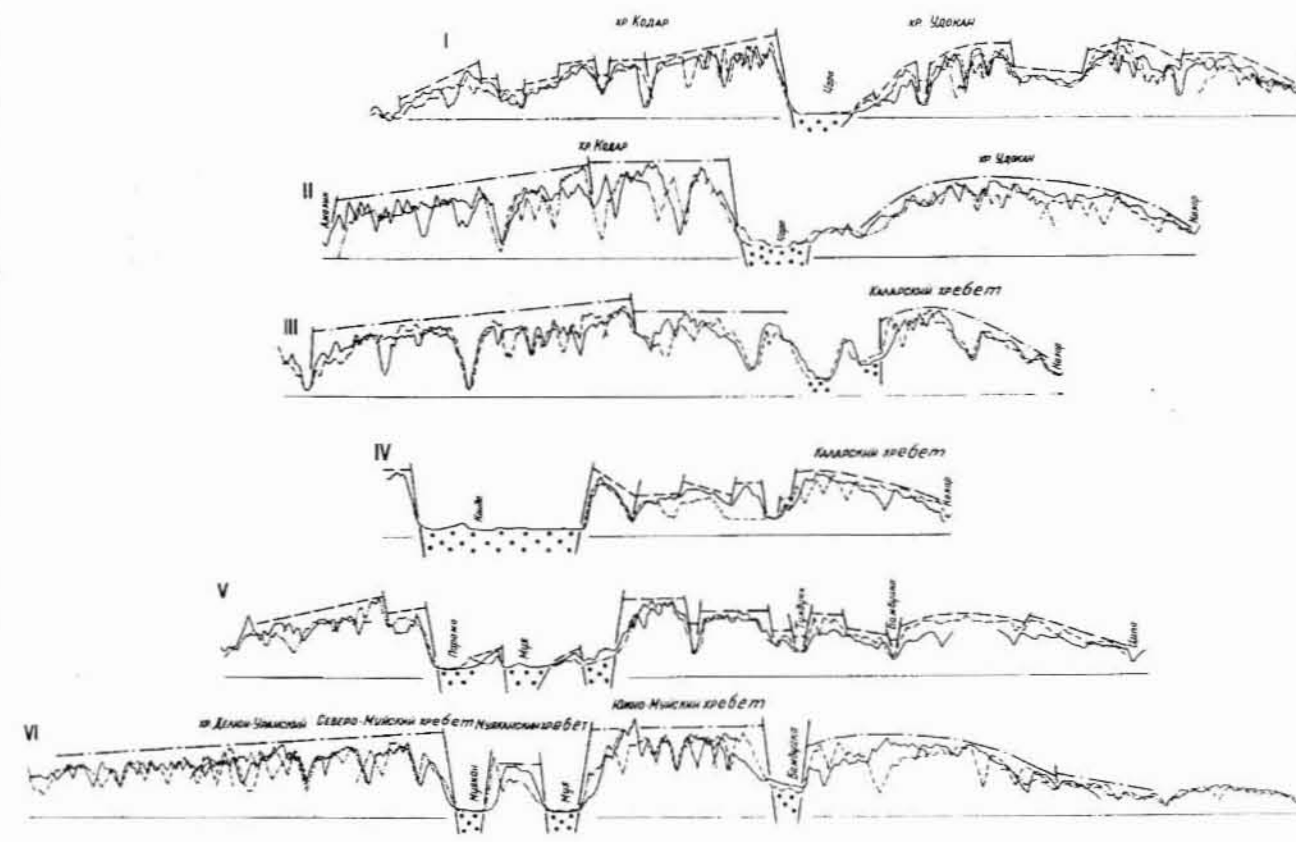

Fig. 5. Transversal profiles of the north-eastern part of the Baikal rift zone and their structural interpretation (thick lines). Vertical scale is 10 times the horizontal.

ginal faults of the Muya median massif. A complex system of steps of variable height and small basins which have been affected by recent subsidence are present south of here. These basins are analogues of those in the western part of the Muya-Chara interbasin uplift and they are probably directly linked.

The intermontane basins and interbasin uplifts which separate them are poorly known near to the north-eastern boundary of the rift zone. The Tokko Basin has been described only in morphological terms. Glacial and fluvioglacial relief forms are present in its floor. The basin is of limited size and is divided into two parts (Solonenko *et al.*, 1985; Solonenko *et al.*, 1975; Khilko & Nikolaev, 1975).

In terms of its dimensions and the complexity of its structure, the Muya-Chara interbasin uplift is more important than that between the Chara and the Tokko. However, the latter is a more important element in the overall rift structure. The diminished scale of the structural forms near to the north-eastern termination of the

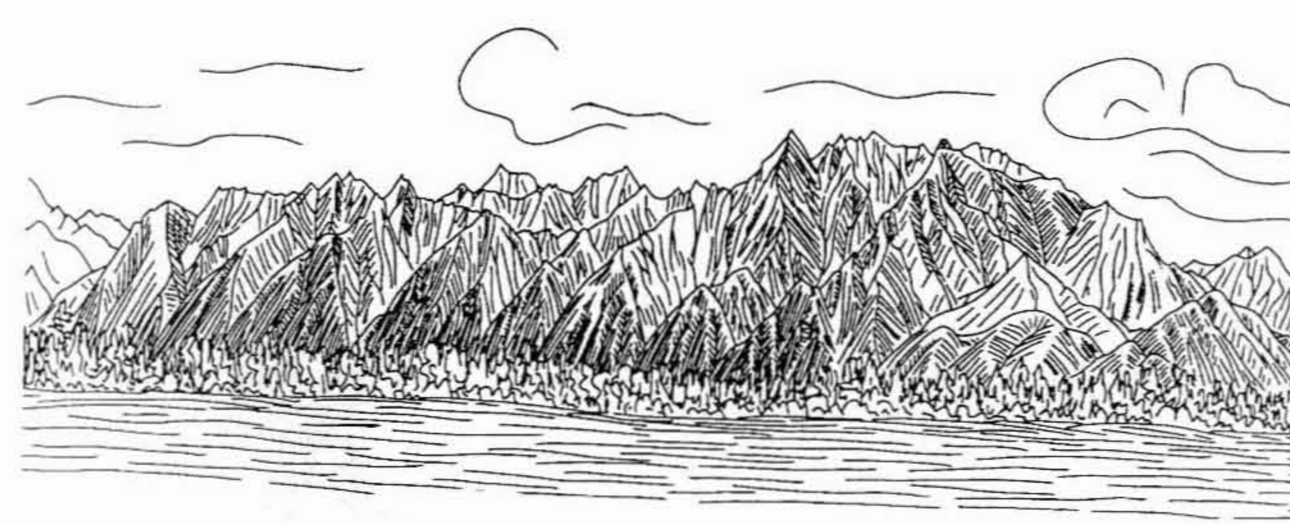

Fig. 6. Tectonic scarp on the northern flank of the Chara Basin between the valleys of Middle Sakukan and Apsat. View from the south-east.

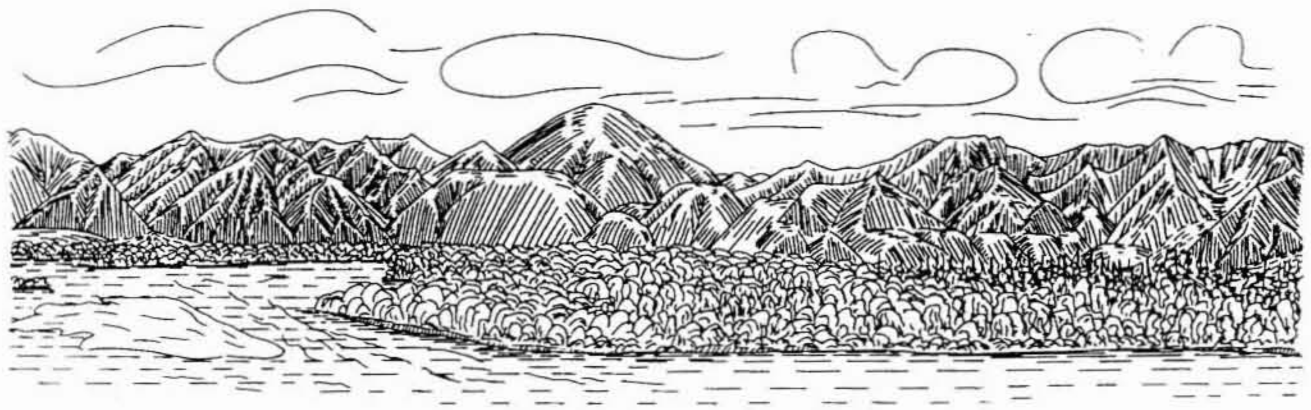

Fig. 7. The southern flank of the Muya Basin near the Vitim valley. In the center – Shaman Massif. View from the north.

Baikal rift zone belies the simplicity of the structure of the Chara-Tokko interbasin uplift and its structural importance (Fig. 2). And if the longitudinal NE-striking faults are the most important elements in the structure of the Muya-Chara interbasin uplift, the transverse Khani-Sulumat Fault is the most important element in the Chara-Tokko uplift.

The north-western flank of the rift zone

The north-western flank of the rift zone is formed from a system of large, inclined horsts which unite in the Kodar uplift (Figs. 2, 9 and 12). There is a pronounced inclination of the summit-incidence surface to the NW, i.e. away from the central part of the rift zone (Figs. 2 and 10). Morphologically, this flank of the rift zone is homogeneous, being cut only by graben-valleys. Jurassic continental coal-bearing sediments are present in the northern part of the Chara basin, close to the boundary of the Kodar uplift. During the Cainozoic rifting period, the Jurassic piedmont basin became dissected by the Kodar Fault, part of it being inverted by more than 2,000 m.

In that part of the Kodar uplift nearest to the transverse Khani-Sulumat Fault, a distortion of the summit-incidence surface occurs; this is not towards the NW, which is typical, but to the NE, along the strike of the rift zone (Fig. 11). Further to the E, between the Khani-Sulumat and Evonokit-Tokko transverse faults which intersect the northern side of the rift zone, an isolated horst is present; this is inclined to the NE (Figs. 2 and 3) and it bounds the Kodar uplift. Even further to the E, in the northern part of the Tokko and Charuoda basins, several steps and small horsts are present (Fig. 13). Thus, hereabouts, the north-western flank of the rift zone loses the shoulder counteruplift features which are present in the rift valleys (a large inclined horst). The same is also observed along the SW boundary of the rift zone (Ufimtsev, 1986). These structural transformations on the boundaries of the rift zone have considerably altered the symmetrical nature of its recent structural evolution.

The Kalar-Udokan Dome

The southern flank of the rift zone on the Vitim/Olyekma interfluve is formed from the Kalar-Udokan Dome (Figs. 2, 5 and 14). In the western part of the region (the Kalar Ridge), this uplift has a well-defined periclinal form, representing a half-dome, on which the crest is broken by a high tectonic scarp which has narrow intermediate steps (Figs. 14–V and 14–VI). The

Fig. 8. The horst within the limits of the interbasin uplift southwards the valley of the Sulban river. View from the NW.

morphology of the southern and northern flanks of the dome indicates that the domal curve is complicated by an antithetic fault which displaces along the axial part of this uplift. Eastwards from here, near the Chara Basin, the dome is wider but its core appears to have undergone pronounced subsidence. The latter produced the Kalar Basin, which has a limited fill of Cainozoic sediments. Owing to the presence of a Lower Palaeozoic component of its sedimentary fill, the basin must be of great antiquity. Analysis of the lateral profile of the dome in this region shows that its northern flank is narrow (Fig. 14–III), whereas the wide southern flank is formed from the Upper Kalar Basin, together with the horst which complements it on the northern side.

The Kalar-Udokan Dome is divided by NW-striking transverse faults into several sections, each of which has its own morphological characteristics (Fig. 14). Near the western pericline, the dome is dissected by a large sinistral strike-slip fault (Fig. 2), whereas dextrally-shifting faults predominate in its eastern part. These shifts have a north-westerly strike. On geomorphological evidence, most of the transverse faults penetrate the Chara Basin, while a few can be traced even further, as far as the boundary of the Kodar inclined uplift. This emphasises the great importance of the Kodar Fault in recent tectonics. The Kalar-Udokan Dome is cut off in the east by the Khani-Suimat Fault which underwent strike-slip movement in the most recent structural evolution of this region. Thus the dome is terminated by a well-defined pericline. However, the domal curve which is peculiar to the SE flank of the rift zone is still an influence eastwards from here, near the boundary of the Tokko section.

Eastwards from the Khani-Sulumat Fault, the domal curve is displaced to the N relative to the Kalar-Udokan Dome and is much narrower (Figs. 2, 14–I, and 14–II). By comparison with the region of the Udokan and Kalar Ridges, the tectonic relief of the domal curve here has resulted in block disintegration, although the essential character of curve deformation can still be detected on transverse profiles. On the left bank of the Olyekma, NW of its bend, the periclinal form of the marginal domal curve is still easily identified at the closure of the rift zone.

In contrast to the domes of the Selenga-Vitim zone, the domal curve of the SE flank of the rift zone is prominent, but is complicated by the transverse faults of north-westerly strike.

In the Tokko section, the south-eastern flank of the rift zone has other peculiarities consequent on the reduction of the marginal domal curve. South of the latter, near the termination of the rift zone near Olyekma, a large and complex marginal step is present. This is represented by a series of tectonic relief steps which have variable heights, horsts and small basins, one of which, at Imangra, is a rejuvenated Jurassic graben.

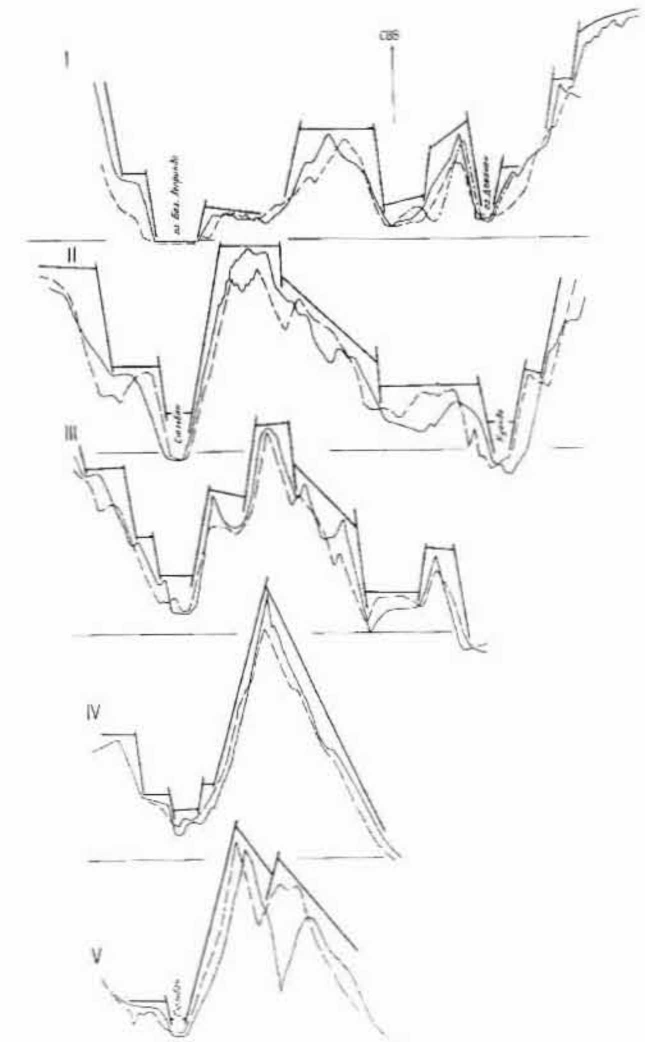

Fig. 9. Transversal profiles of the Muya-Chara interbasin uplift and their structural interpretation (thick lines). Vertical scale is 10 times the horizontal.

Structurally, this large step is analogous to the marginal steps on the flanks of the Muya Basin and the Muya-Chara interbasin uplift. However, its location on the termination of the rift zone has no counterpart elsewhere, except, perhaps, along the south-western margin of the Khubsugul section (Fig. 1); in terms of its structural/morphological relationships, the latter is poorly understood. This is another distinctive feature of the Tokko section of the rift zone.

The vicissitudes of geological structure in the region have undoubtedly influenced the formation and development of the large step near the R. Olyekma. Certainly, the smaller tectonic steps located southwards from the Khani valley are spatially connected with the northern part of the Kalar gabbro-anorthosite massif, which has the form of a subhorizontal plate (Zorin *et al.*, 1988). The lower tectonic relief elevations here appear to be related to the occurrence of this high density massif in the upper part of the Earth's crust.

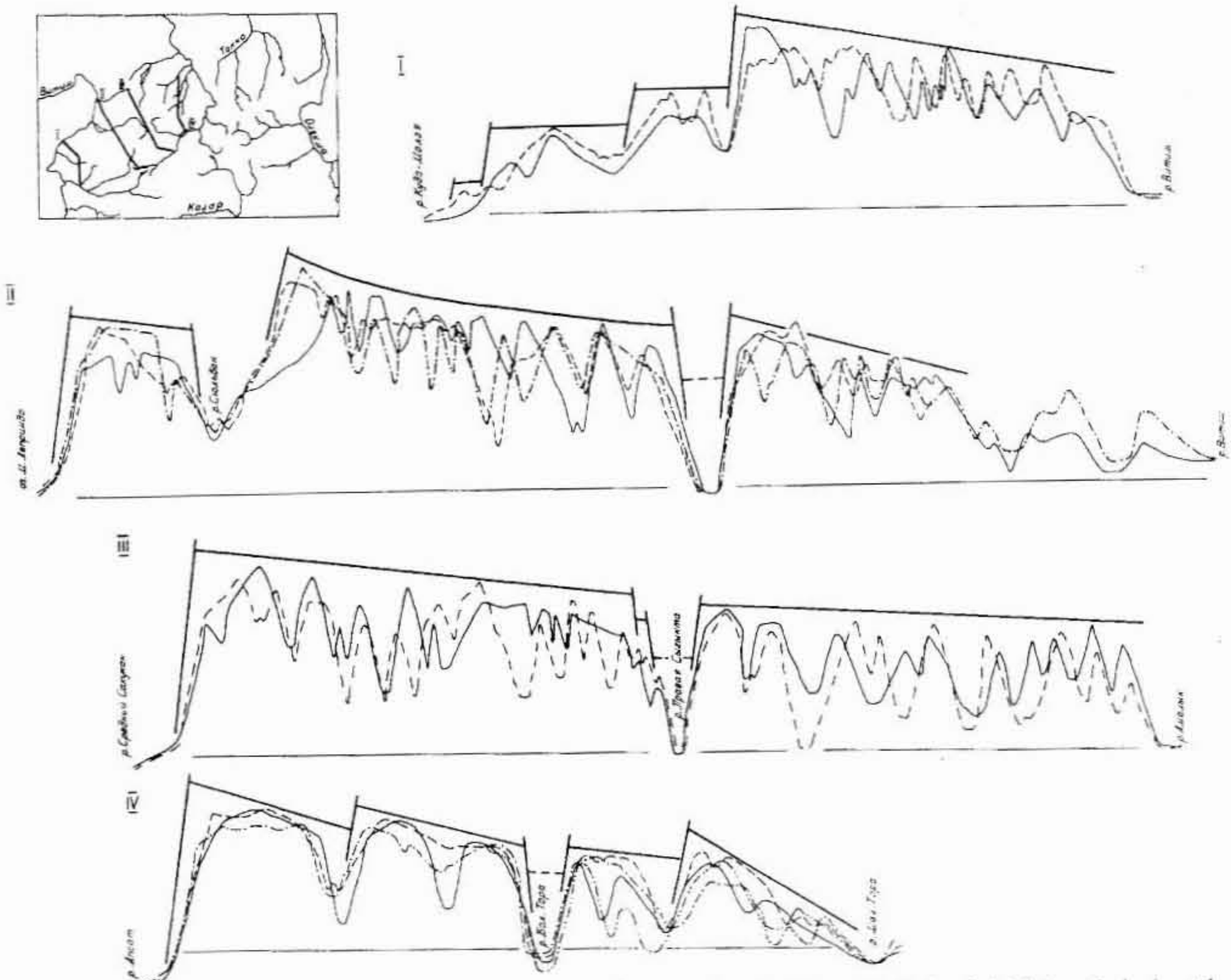

Fig. 10. Transversal profiles of the Kodar uplift and their structural interpretation (thick lines). Vertical scale is 10 times the horizontal.

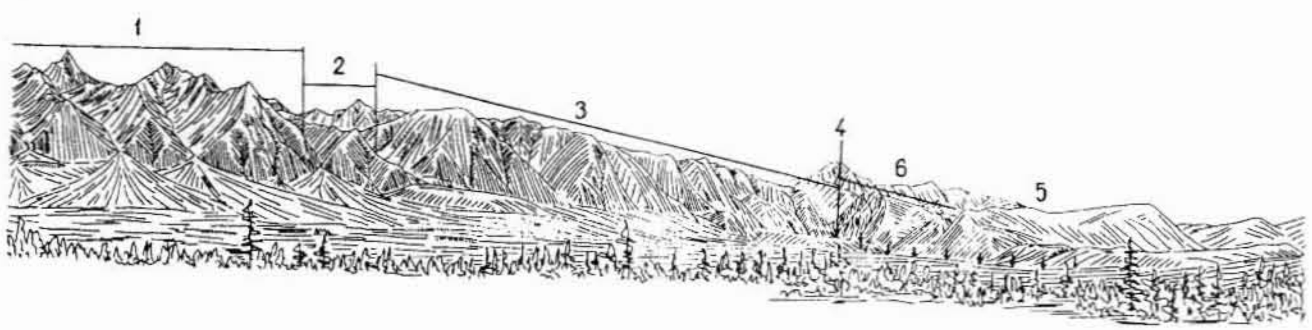

Fig. 11. The north-eastern part of the Chara Basin, view from the south. Arrows show the Khani-Sulumat transversal fault (4): 1 – the Kodar uplift with normal inclination of tectonic relief (from an observer); 2 – transversal valley-graben; 3 & 6 – horsts with inclination along the strike of the rift zone; 5 – a part of the Chara-Tokko interbasin uplift.

Discussion

As well as the common relationships of structural elements which formed this zone within the Tokko section, a sharp change of morphology and spatial relations of neotectonic forms is also apparent at the limits of rifting in the Chara-Olyekma link of the Baikal rift zone. The succession of neotectonic forms within the rift zone typically consists of (in succession from NW to SE): inclined horsts, which are separated from rift valleys and interbasin uplifts by steep fault scarps; axial systems of rift valleys and interbasinal uplifts with large marginal steps, which are locally virgate, and divided by block uplifts; domal uplifts along the south-eastern flank. This regular interchange across the strike of these rift-zone elements is linked paragenetically to the morphology of the protrusion of anomalous mantle (Krylov & Krylova, 1982).

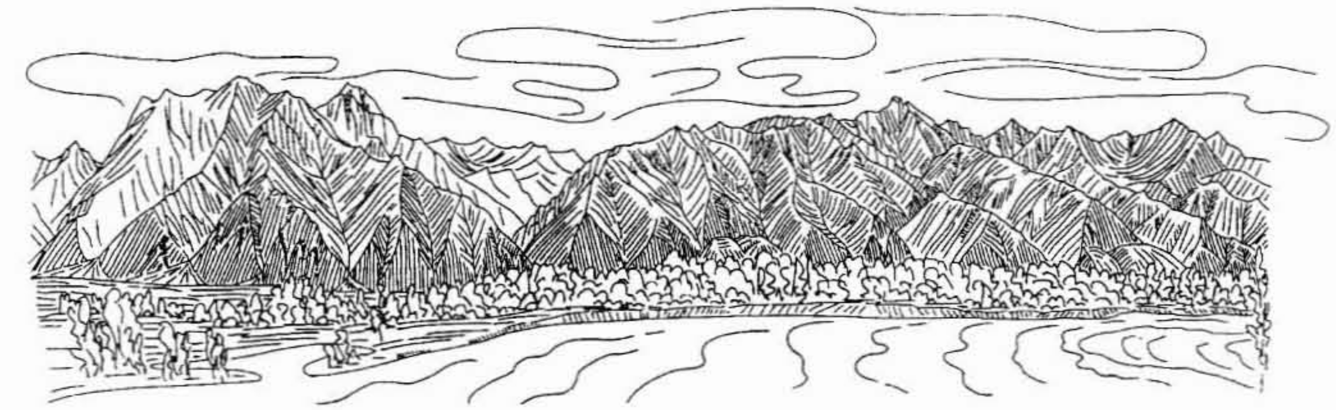

Fig. 12. The northern flank of the Chara Basin and the Kodar uplift eastwards the valley of the Apsat river. View from the SW.

The form of the anomalous mantle protrusion, which is typical of the Baikal rift zone, is traceable from seismic data to the NE, at least as far as the Nyukzha and Olyekma valleys (Parfenov *et al.*, 1985) and, as the structure of the rift zone is similar, the protrusion of anomalous mantle does not appear to change significantly up to the end of the Chara section. Certainly, it extends as far as the transverse faults of the Amur-Olyekma system. The deep-seated character of these fractures is emphasized by the clear expression of the fault system in the relief of the north-eastern part of the rift zone (Fig. 15).

There are important transformations in the structure of the rift zone in the Tokko section. The main features of these are: a general reduction in the scale of the neotectonic forms; the occurrence of a large marginal step on the south-eastern flank; a structural degradation of the north-western flank (Figs. 2, 10 and 13). This latter feature is undoubtedly the most important with respect to possible interpretations of the deep structure of the north-eastern closure of the rift zone. The inclined horsts of the north-western flank of the rift zone are commonly located above a subvertical boundary of the anomalous mantle protrusion (Ufimtsev, 1986) and they have developed under the influence of two conjugate processes: they function as inclined shoulder-counteruplifts of rift valleys (Milanovski, 1976). The tectonic distortion of these blocks has increased because of anisotropic warming of the lithosphere near the subvertical boundary of the mantle pro-

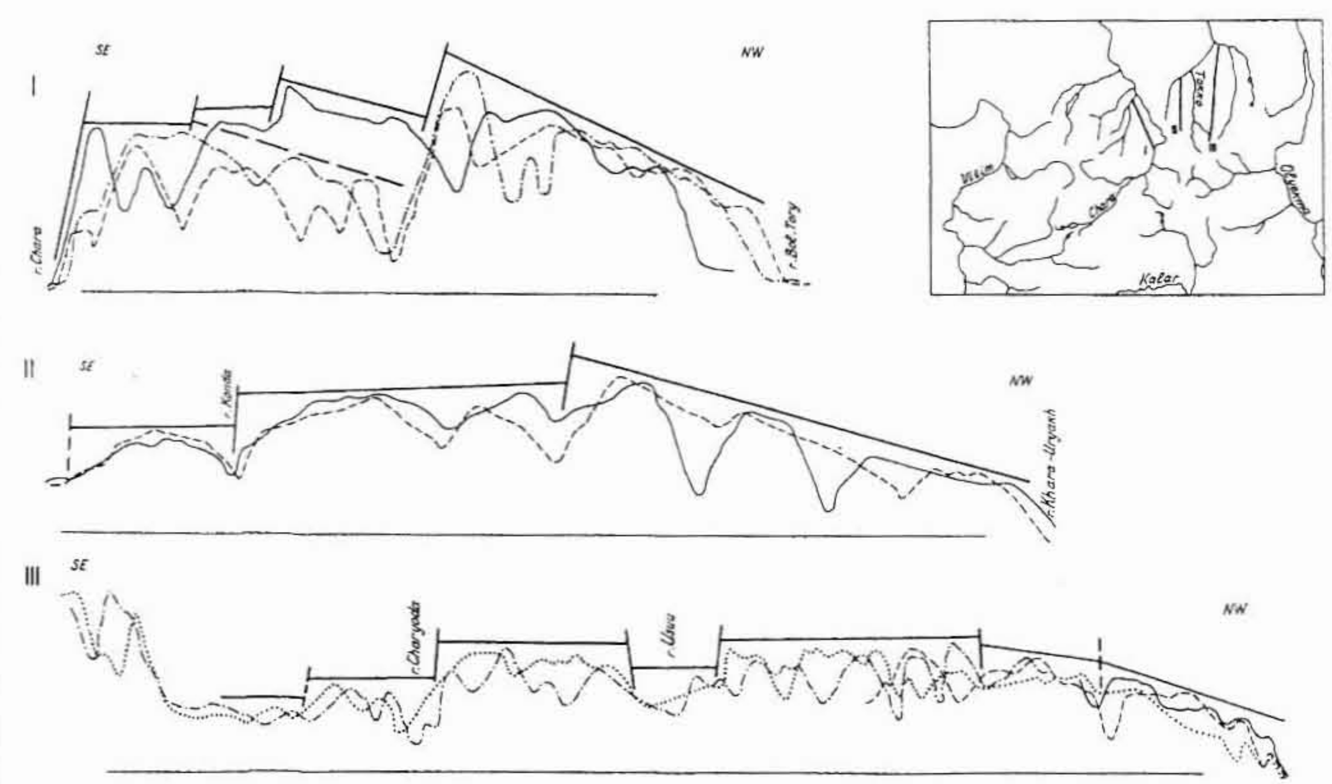

Fig. 13. Transversal profiles of the north-western flank of the rift zone near its termination and their structural interpretation (thick lines). Vertical scale is 10 times the horizontal.

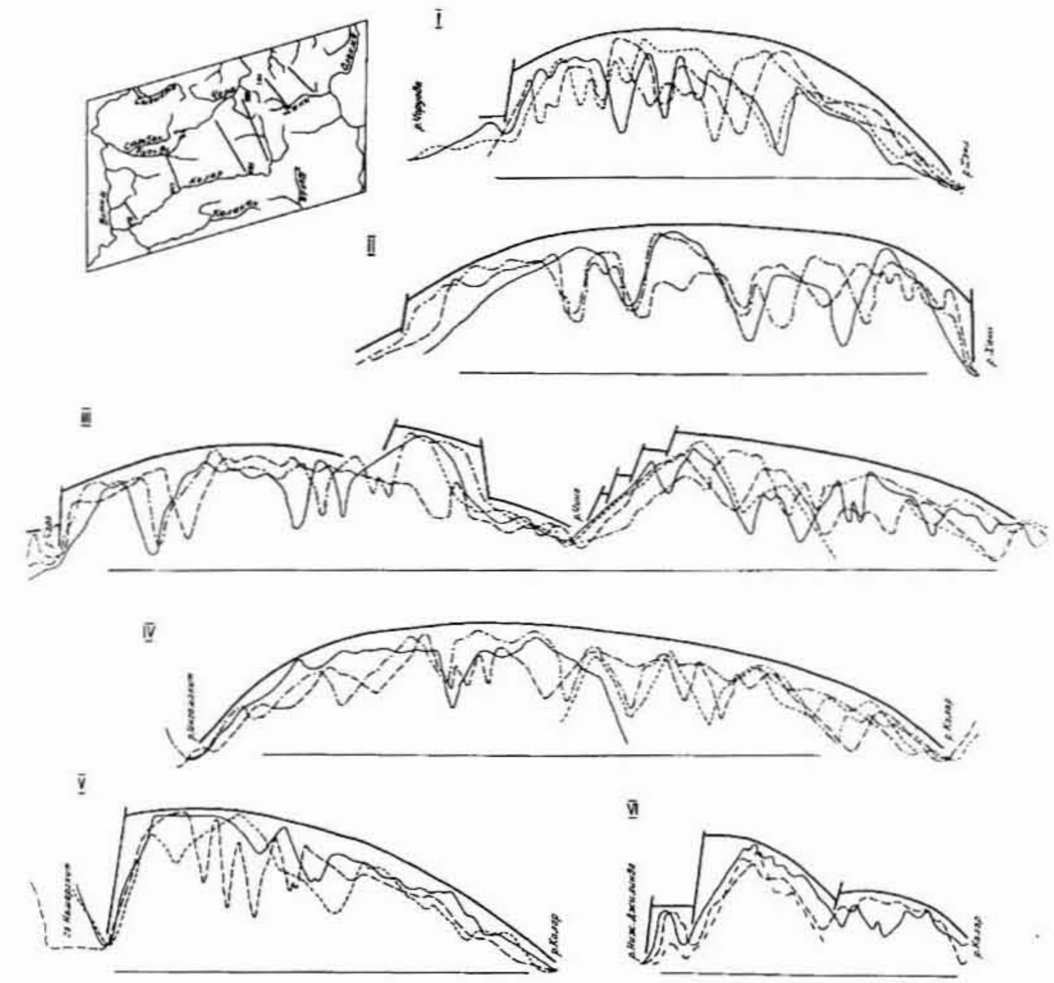

Fig. 14. Transversal profiles of the Kalar-Udokan dome and their structural interpretation (thick lines). Vertical scale is 10 times the horizontal.

trusion (Ushakov & Galushkin, 1977). As far as is known, this last factor played no part in delimiting the

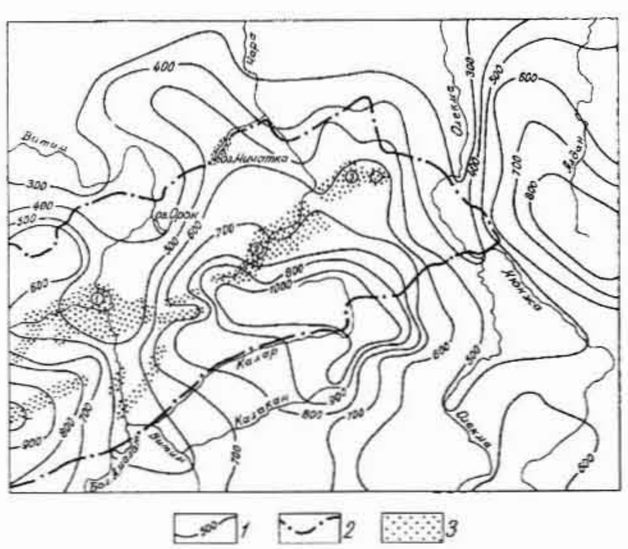

Fig. 15. Socle surface of the north-eastern termination of the Baikal rift zone, building according to the heights of thalweg of valleys of main rivers. Contours are drawn at 100 m intervals: 1 – contours of socle surface are drawn at 100 m intervals; 2 – boundary of rift zone; 3 – basins; 4 – position of the Olyekma- Amur system of transversal fault.

Tokko section of the rift zone. Therefore, we conclude that the lithosphere was colder here than in other parts of the Baikal rift zone.

This study was carried out with the financial support of the Russian fund for fundamental research (96-05-64773).

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