HISTORY AND GEODYNAMICS OF THE LAKE BAIKAL RIFT IN THE CONTEXT OF THE EASTERN SIBERIA RIFT SYSTEM : A REVIEW

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The Eastern Siberian system* of Cenozoic rift faults and depressions, extending for nearly 1 800 km, is associated with a large domal uplift which frames the craton area of the Siberian platform in the south and southeast. The central segment of this system, in which the largest and oldest depression of Lake Baikal is located, runs immediately along the margin of the Siberian craton in the zone where it links with the Sayan-Baikal mobile belt. This depression makes up 1/3 of the total rift zone. The Baikal rift has been expanding from the central segment towards the northeast and west. A maximum thickness of sediments (7 500-8 000 m) has been recorded in the Baikal basin, decreasing to 500-1 000 m at the limits of the rift system. Rifting was accompanied by basaltic magmatism of fairly uniform petrochemical composition, dominated by alkaline olivine basalts. Magmatic conduit centers and volcanic fields are located quite independently of the rift faults and basins except for in the Tunka rift valley. Rifting in Eastern Siberia is an independent geodynamic phenomenon which is thought to have no direct relation to the collision of the Hindustan subcontinent with Eurasia. The Baikal rifting is mainly driven by a local source of energy, resulting from asthenospheric upwelling, heating and gravitational instability of the lithosphere.

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CONTENTS

* Editor's comment : in view of the size of the Siberian Craton, strictly this should be the South Eastern Rift System.

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INTRODUCTION

Systematic geological, geophysical and geodynamic studies of the Baikal rift have been conducted for nearly 30 years as part of international research programmes : "Upper mantle project" (initiated in the 60s), "Geodynamic project"(70s) and "Lithosphere programme" (80-90s). In the 70s studies focused on the geology, deep structure and seismicity of the northeastern flank of the rift zone, that is the area from the extreme northern point of Lake Baikal north east to the Olekma river, to meet the requirements of the construction of the Baikal-Amur railway line and industrial development of the area. Currently the study of the Lake Baikal basin is a priority, the lake (Fig. 1-4) being the world's largest fresh water body, which contains 23 000 km^3 or 1/5 of the world's fresh water reserves. Lake Baikal, having an average width of 40-50 km (maximum of 70 km) and extending for 636 km, is 1 637 m deep, *i.e.* its bottom is situated 1 181 m below sea level (Fig. 5). Numerous heat flow measurements have been run in the lake basin, as well as 3 000 km of single and multi-channel seismic profiling. Piston core sampling of bottom sediments along with observation of the morphology and structure of the lake bottom and its slope (using submersibles, "Pisces") have been conducted. These studies have provided us with more exact data of the inner structure and geodynamics of the Baikal depression, which is the center of the Baikal rift zone.

Through 1991-1992 the deep structure of the rift zone and its adjacent areas was scanned by teleseismic tomography. A temporary network of teleseismic stations was deployed along a 1 500 km NW-SE profile, across the lake and in an array around the lake. This study has provided a rich collection of data which is now being processed and interpreted. In March 1993 drilling of a borehole from the ice cover was performed, about 6 km from the western coast opposite the Buguldeika river mouth where the lake is 355 m deep (Fig. 6). The borehole penetrated 100 m of lake sediments (Holocene-Middle(?) Pleistocene), which are being thoroughly examined in researching the character of local and global climatic changes in this part of Asia.

From 1989 onwards scientists from the USA, Belgium, France, Japan and Germany joined together in geological and geophysical investigations in the Baikal region and this study became an area of wide international cooperation. New data on the structure and evolution of the rift zone were obtained as a result of this cooperation. They are partially under consideration in this paper, which is a so-called "prologue" to the series of articles on the basement structure and composition, the character of sedimentation in rift basins, volcanism, active tectonics, heat flow, deep structure and geodynamics of the Baikal rift, to be published in the following issues of the bulletin.

1. — STRUCTURAL SETTING AND THE BASEMENT OF THE RIFT ZONE

The Baikal rift developed over a compositionally and structurally heterogeneous basement which had been exposed to a polycyclic pattern of tectonic movements, magmatism and metamorphism during the Precambrian and Phanerozoic. Geological and geodynamic evolution of the region was conditioned by the interaction of the two contrasting parts of the lithosphere in Inner Asia, the Precambrian Siberian craton and the Sayan-Baikal mobile fold belt, Caledonian events having been most crucial for structural development of the latter. Petrophysical heterogeneity of the basement is defined by the fact that its structural fabric includes elements of diverse composition and age, having been subjected to transformation and remobilization in the course of a number of tectonothermal cycles of the Early and Late Proterozoic and Early Paleozoic.

1.1. THE INFLUENCE OF STRUCTURAL HETEROGENEITY OF THE BASEMENT

The general structural setting and the pattern of the rift zone evolution are controlled by its association with the junction zone of the above mentioned major structural units of Eastern Siberia (Fig. 6). The central segment of the zone, represented by the Baikal basin, the largest and oldest within the system, is located immediately paralleling the craton margin. This depression extends for about 680 km (which makes up 1/3 of the total extent of the rift zone). Westward and northeastward from the Baikal basin limits, rift faults and valleys deviate from the craton edge towards the Sayan-Baikal mobile belt either inheriting or crossing the structural pattern of the basement. It is only in the extreme northeast that the rift zone comes close to the craton again, cutting it in the area of the Aldan shield, where it finally meets up with the Chara and Tokko basins.

In the far southwestern area, that of Mongolia, a uniform rift "stem", uniting the South Baikal depression and the Tunka valley, branches into three basins : Busingol, Darkhat and Khubsugul, with the sublatitudinal rift structure orientation abruptly changing to submeridional. A natural constraint for the rift faults' and valleys' southward development is likely to be the largest Bolnai strike-slip fault, rejuvenated by an immense Tannuol earthquake (M=8,2) in 1905 to form a sinistral wrench fault for 307 km of its strike with 10 m horizontal displacement. At any rate, typical rift faults and valleys are not found south of the Bolnai strike-slip fault. Therefore, the Baikal rift zone is of an entirely intracontinental type and has no obvious links with oceanic rift structures, though favourable conditions for its development eastward along the system of the ancient Stanovik and Dzhugdzhur fault systems do exist. This point is to be discussed later.

In a wide sense the basement within the Baikal rift is a zone of multi-stage collision of the Siberian craton with the Sayan-Baikal mobile belt (BELITCHENKO & BOOS, 1990). It integrates the remnants of folded structures of the Early Paleozoic and Proterozoic affected by igneous rocks of different composition and age (Fig. 7). Granitoid magmatism is most voluminously represented within the area, its rock mass occupying nearly half of the rift zone area. The largest (area of tens of thousand km^2) and thickest (up to 20-22 km) among them are Paleozoic granitoid bodies in the northeastern part of the rift zone, the area between Lake Baikal and the Aldan shield.

Within this structurally complicated fold system, relatively rigid and stable massifs or "microcontinents" (Fig. 6), their structure readily reminiscent of a two-stage structure of the Siberian platform (basement + sedimentary cover), are dis-

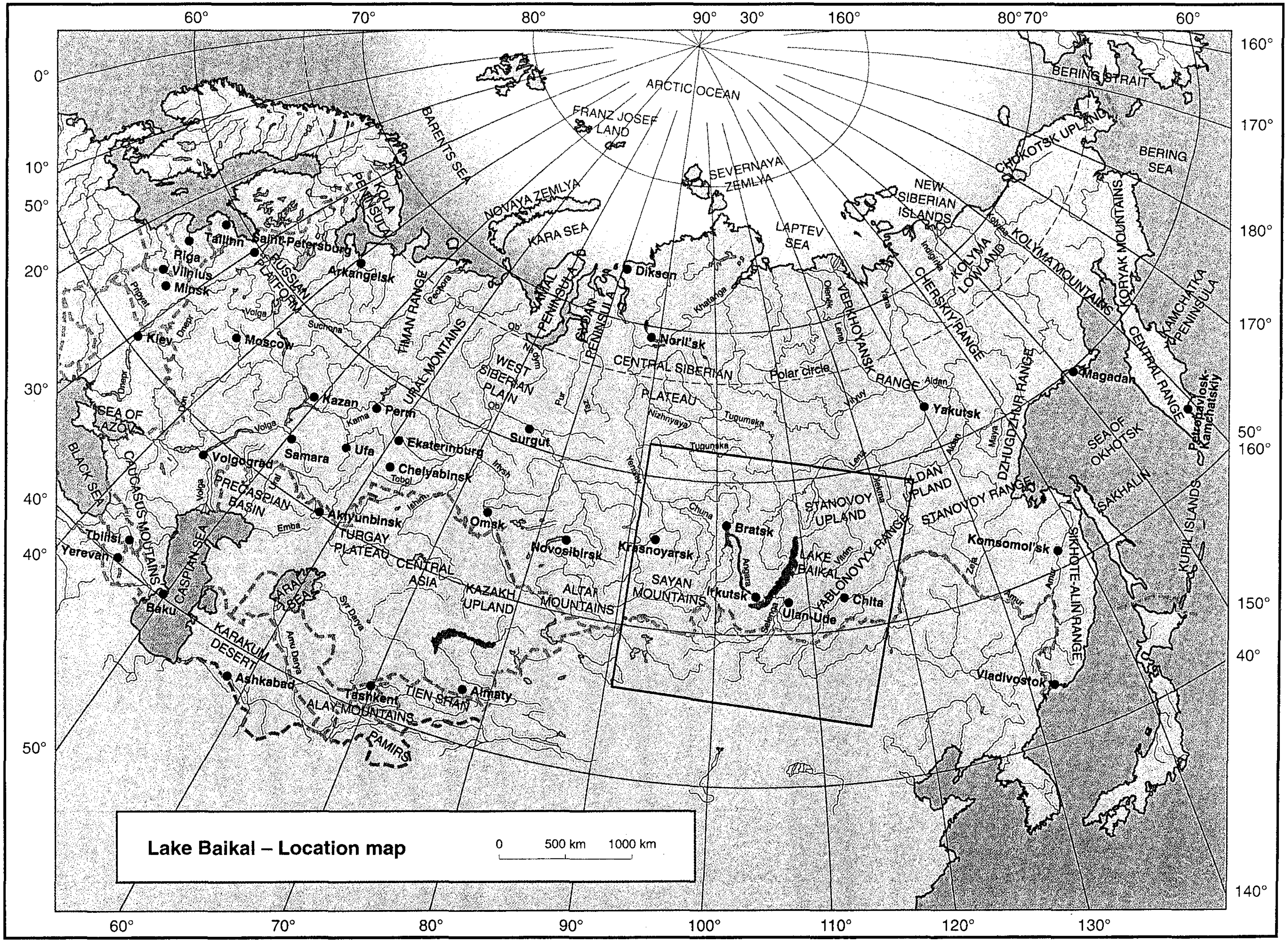

FIGURE 1 The location of Lake Baikal (the detail shows the limits of Fig. 2).

Figure 2

The region of Lake Baikal.

tinguished. All the indications suggest that microcontinents are the remnants of the primary destruction and disintegration of protocontinental Earth's crust in Eastern Siberia of Late Archean or Early Proterozoic age, this being the factor responsible for the general outline of the Siberian craton. It is worth noting, that in the northeast the rift zone dissects the Muya "microcontinent" across its boundaries and internal structural fabric, whereas the rift faults and valleys in the west, within the area of Northern Mongolia, conform somewhat to the fault boundaries of the Tuva-Mongolia "microcontinent".

Therefore, first order macroheterogeneity of the lithosphere (craton-mobile belt) is responsible for the location of the Baikal rift. At the same time, rifting features of the north-eastern flank show an independence from the ancient basement structure, dissecting it crosswise in the zone of the Muya "microcontinent", within the fold belt area, even invading the western flank of the Archean Aldan shield. This semi-independence of the Baikal rift from the basement structure results from a local mismatch between the general orientation of lithospheric extention, which controlled the development of the Baikal rift in the Cenozoic, and the orientation of some structural elements in the Sayan-Baikal fold belt in addition to a boundary of the Siberian craton in the Aldan shield area.

2. — GEOMORPHOLOGY AND NEOTECTONIC STRUCTURE

The Baikal system of rift faults and depressions occupies the so-called Sayan-Baikal domal uplift (maximum height 3 000-3 500 m above sea level) which is hypsometrically the

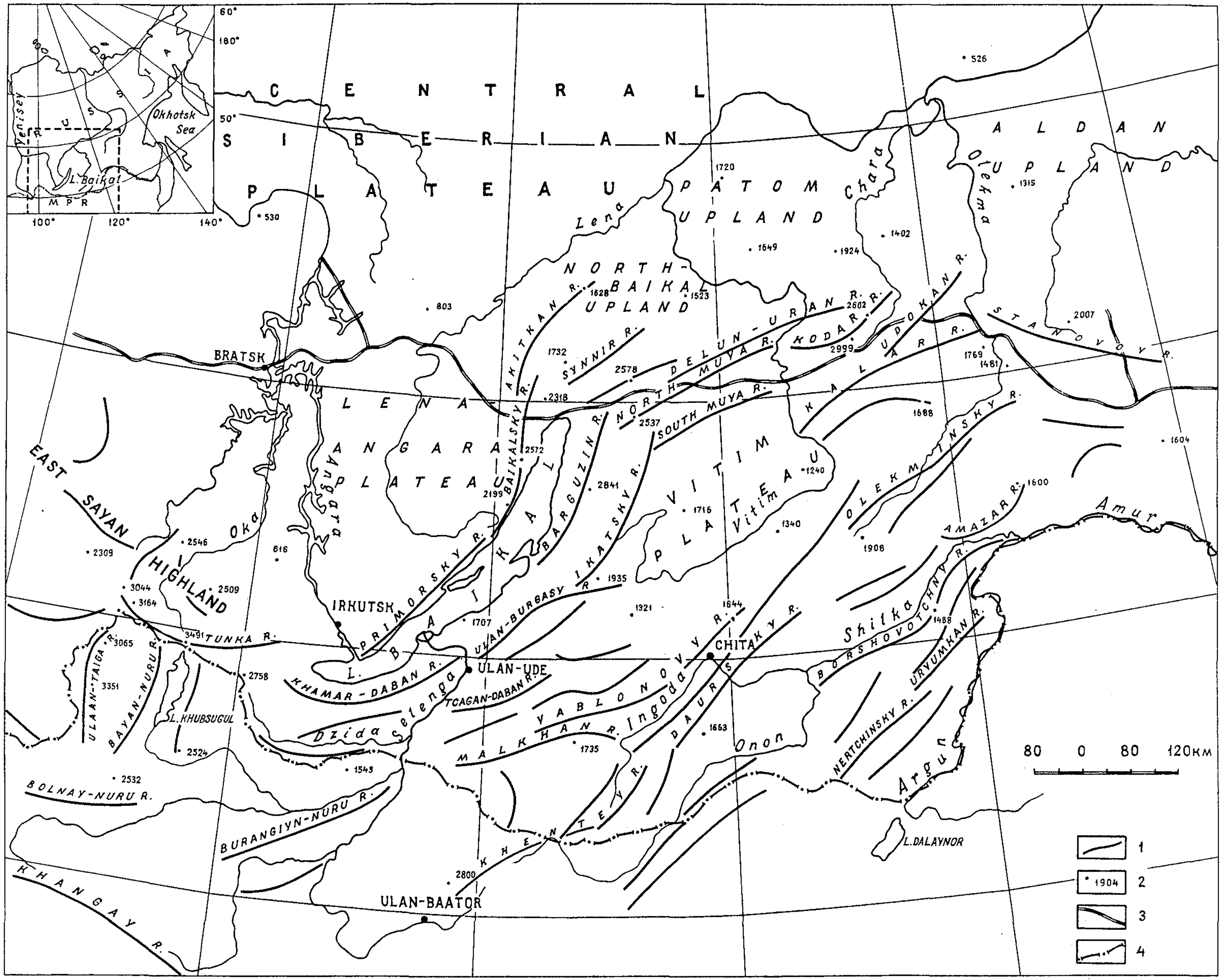

FIGURE 3
The major topographic features of East Siberia
1 – Trend of major ridges; 2 – Spot heights; 3 – Trans-Siberian railway; 4 – Border between Russia and Mongolia.

FIGURE 4

Sunrise on Lake Baikal. The area of Small Sea on the western coast of the lake.

highest part of the Eastern Siberian mountain belt. A 1 500 m contour line of the Cretaceous-Paleogene erosion surface delineates this uplift (Fig. 4), its Cenozoic amplitude attaining 1 500-2 000 m in places, above the initial position of the erosion surface in the Late Cretaceous-Early Paleogene. The domal uplift is a set of mountain ranges and high plateaux, framing rift valleys filled with continental sediments of the Paleogene, Neogene and Quaternary. It consists of two culminations separated by a hypsometric saddle in South Baikal, the Selenga river delta being confined by it. The Selenga is the major tributary of Lake Baikal, providing over 50 % of its water inflow. The above fact is obviously indicative of the primary nature of the Selenga saddle. It originated due to the low rate of vertical movements as compared to the rift zone flanks, uplifted to the height of 3 000-3 500 m (western culmination) or up to 2 600-3 000 m (northeastern culmination).

2.1. DISTRIBUTION AND MORPHOLOGY OF RIFT DEPRESSIONS

The geometry of the domal uplift and the location of rift structures appear to correlate. The only rift depression of South Baikal, which is also the deepest and oldest one, is situated in the saddle, whereas outside the Selenga saddle rift structures are widely scattered. This distribution pattern of the rift faults and valleys within the domal uplift structure is indicative of some causal relationship between them.

The Eastern Siberian Rift System consists of 13 large, self-contained, more or less parallel basins (Fig. 6), separated from each other laterally by long, high ridges and low transverse or diagonal links. The Lake Baikal basin, the largest one in the system, consists of the two "en-echelon" arranged depressions of South and North Baikal, extending for 450 and 390 km respectively. They are separated by a diagonally striking subaqueous Academician ridge, which is the northeastern continuation of the Olkhon island block (Fig. 5).

The South basin itself is divided into two segments by a bottom uplift within the Selenga delta and Buguldeika river traverse, where the lake depth diminishes to 350-400 m, contrasting with the nearby parts to the southwest (1 416 m) and northeast (1 637 m). Unlike the Olkhon-Academician rift link, the Selenga-Buguldeika link (SBL) is formed mainly by terrigenic deposition from both rivers on the opposite sides of the South Baikal depression (Fig. 5). The main role in the formation of this link surely belongs to the sediments of the Selena river, the basin of which embraces more than 70 % of the whole Baikal catchment-area. At any rate, the Selenga delta is the largest one to be formed in a continental environment. The SBL is dissected by faults of mainly NE-SW orientation, along which single blocks were uplifted so that morphology and structure of this link are determined by a combination of very rapid sedimentation by the Selenga river and, beneath these sediments, by episodic translocation of single blocks of crystalline basement that form the so-called tectonic "nuclei" of local uplifts. Here the effects of underwater gravitational sedimentary sliding take place due to considerable gradients of underwater relief, great thickness of weakly consolidated sediments and high tectonic activity. Thus, in its morphology, structure and origin, the Selenga-Buguldeika link contrasts with the main diagonal Olkhon-Academician ridge link, dividing the South Baikal basin into two almost equal parts (Fig. 5). It is more logical then to consider the South Baikal basin as a single structural unit, partitioned in its middle segment by a sedimentary-tectogenic link with a very thick (4 000-5 000 m) sedimentary cover, under which there are basement faults of different orientations, including those presently active, proved by the strong earthquakes of the last and present centuries (SOLONENKO & TRESKOV, 1960).

The other eleven rift basins range from 70 to 190 km in length and from 25 to 40 km in width. In addition to 13 large flexural basins there is a number of narrow, near-fault depressions which may give rise to large rift basins in the future (SOLONENKO, 1978).

The thickness of sedimentary fill in most of the rift basins ranges from 1 500 to 2 500 m. A maximum thickness of 7 500-8 000 m has been recorded recently in the South Baikal basin from multichannel seismic studies (HUTCHINSON *et al.*, 1992). Oil and gas prospecting drilling during the 50s in the Selenga delta penetrated 3 100 m of sediments and was stopped as soon as it reached those of Eocene or Early Oligocene age, but it did not touch the crystalline basement. Therefore, we have all the grounds to assume that Paleocene or even Upper Cretaceous sediments are to be expected in the lowest portion of the sedimentary fill. So, the initial stage of the evolution of the Baikal rift dates back to at least as early as the Paleocene, *i.e.* 60-65 My, rather than 30-35 My, as it has been stated before by many authors.

2.2. FAULTS

The rift basins are confined on one or both sides by fault scarps of 1 500-2 000 m above their base. A transverse profile of the majority of the depressions is asymmetric due to their northern and northwestern ("near-platform") slopes being higher and steeper than the opposite ones. The crystalline basement, covered by sediments, is dissected by small faults. As a whole, the morphologic and structural asymmetry of the depressions is confined by the fact that their northern and northwestern sides are formed by master

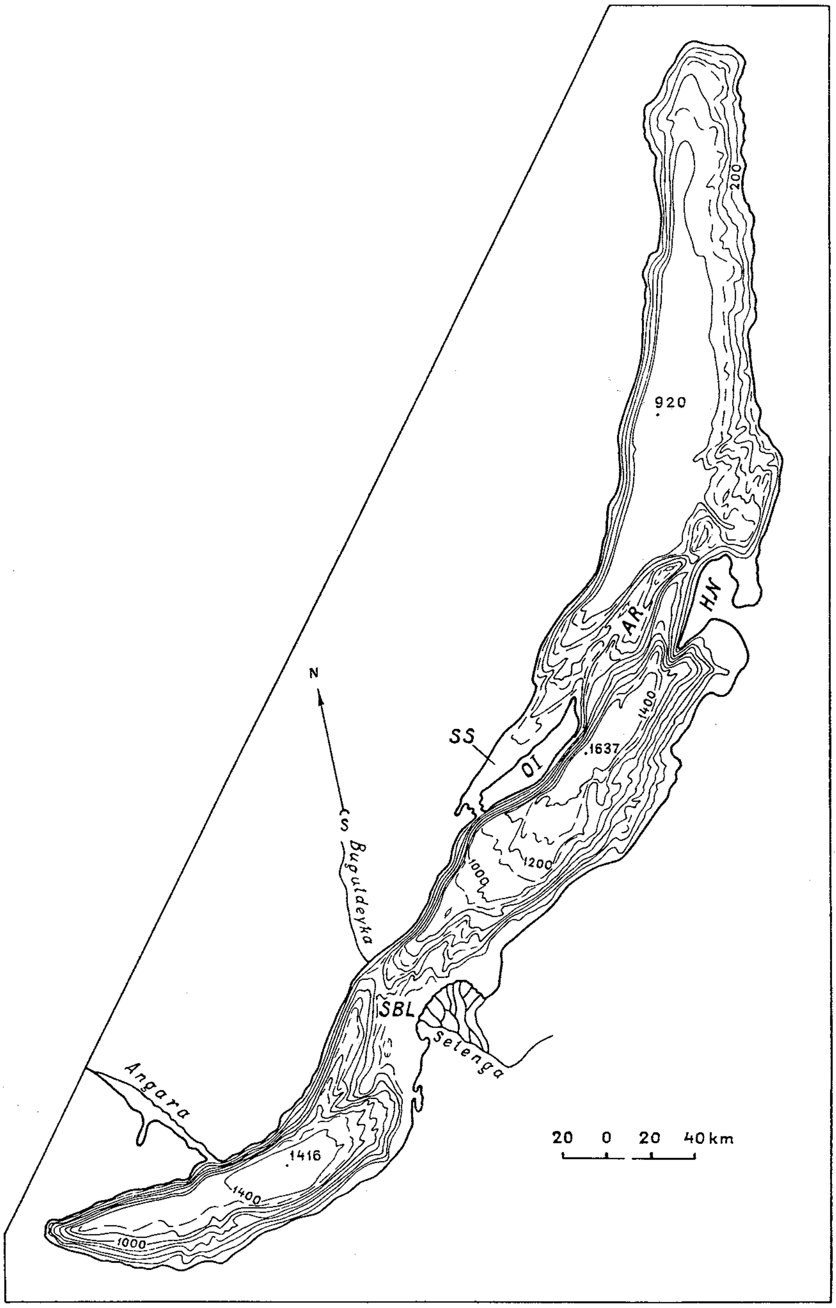

FIGURE 5
Lake Baikal bathymetry. Depth contour interval is 200 m; additional isobaths (dashed line) are at 100 m. AR – Academician ridge, HN – Holy Nose peninsula, OI – Olkhon Island, SBL – Selenga-Buguldeika link, SS – Small Sea.

faults, whereas the gentle southwestern ones are smooth bends of the basement with occasional normal faults. The clue to this asymmetry should be looked for by moving away from the Trans-Baikal plate, from the Siberian craton towards the south-southeast, and also by examining fault rejuvenation in the zone of Caledonian collision.

Faults of various strike and age (from Precambrian to Cenozoic) play a major role in the rift zone and reveal the critical importance that brittle deformation of the upper crust has in rifting (SHERMAN, 1992). Strictly speaking, the Baikal rift zone may be viewed as a complex intraplate boundary of initial lithospheric spreading in Eastern Siberia (SHERMAN, 1978). It is difficult to anticipate how far the process will develop in the future and whether it will cause a complete substitution of the ancient continental lithosphere by a new one, as is the case with the Red Sea rift, or whether the rifting will cease under continental conditions.

With the lithospheric vector remaining unchanged, further rift development along the strike seems to be complicated at both ends of the rift zone : it thrusts into the thick litho-

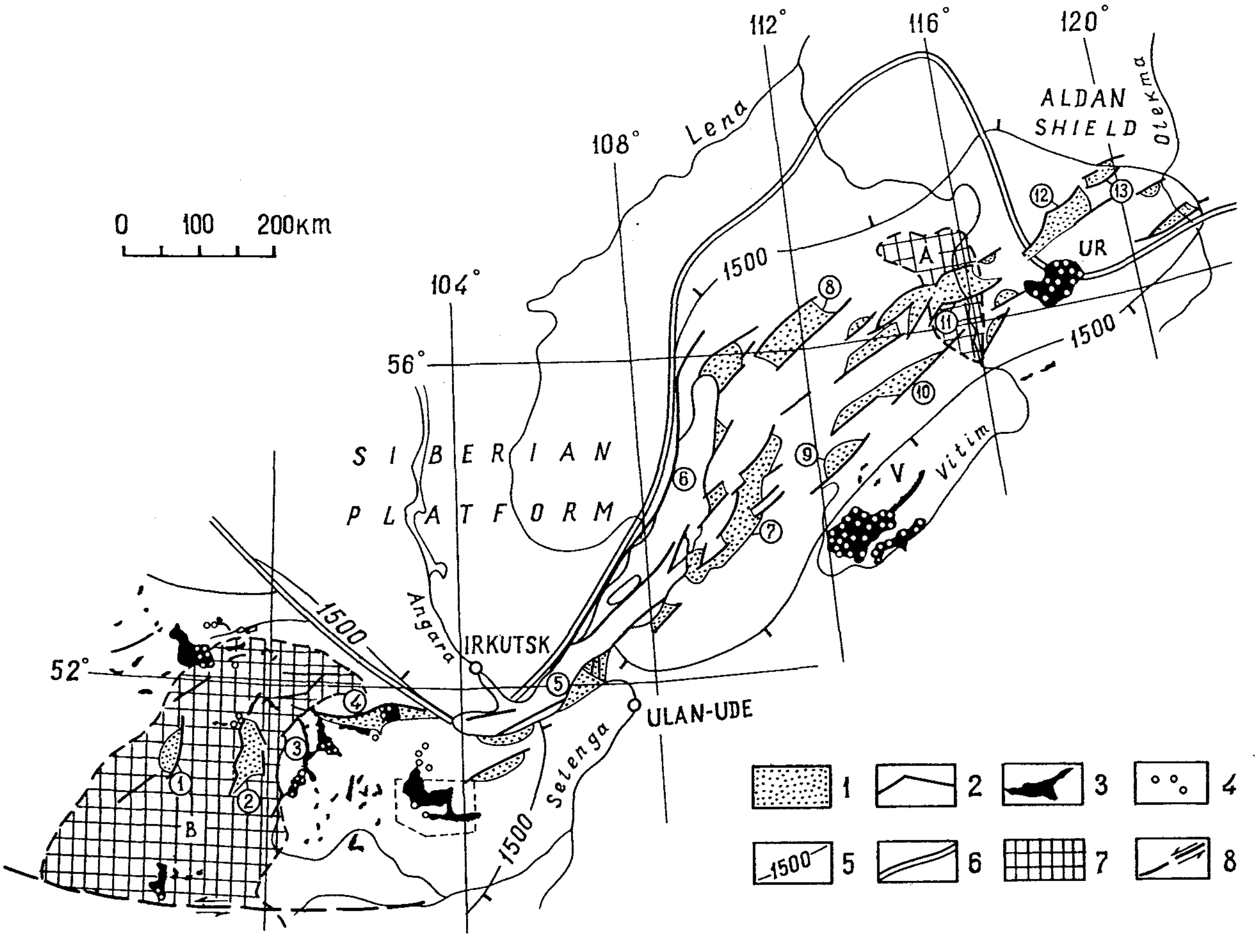

FIGURE 6

The general structural and geomorphic setting of the Baikal rift.
1) sedimentary infill; 2) major faults; 3) volcanic fields; 4) volcanic cones; 5) 1 500 m contour line of Cretaceous-Paleogene erosion surface; 6) rim of the Siberian platform; 7) microcontinents : A) Muya, B) Tuva-Mongolian; 8) Bolnai strike-slip fault.
Numbered circles – rift basins : 1) Busingol; 2) Darkhat; 3) Khubsugul; 4) Tunka; 5) South Baikal; 6) North Baikal; 7) Barguzin; 8) Upper Angara; 9) Tsipa; 10) Baunt; 11) Muya; 12) Chara; 13) Tokko.

sphere of the Aldan Shield in the northeast, whereas in the west its way is blocked by the sublatitudinal features of the Khangai massif in Mongolia. Anyway, the problem of the transformation of the Baikal rift into an oceanic one is still open to speculation and hypotheses.

3. — VOLCANISM

Volcanic activity has accompanied practically the entire evolution of the Baikal rift zone, though it has had a fairly limited volume and specific relations with structural development (Fig. 6 and 7). Basaltic lavas and those petrochemically close to them form three independent groups of volcanic fields in the areas of : 1) East Sayan, Khamar Daban, North Mongolia; 2) Vitim plateau; 3) Udokan ridge. The first group, being the largest, involves numerous large and small volcanic sheets of highland plateaux, intensively modified by erosion, as well as small cinder cones of the East Sayan highland, Tunka basin and Khamar Daban ridge. This western group of volcanic fields coincides with the western culmination of the Sayan-Baikal uplift and contains over half the total volume of young volcanics, roughly equal to 6 000 km^3. On the Vitim plateau and Udokan ridge, volcanic fields are more compact covering the area of about one thousand square kilometers. The Vitim volcanic plateau (about 3 500 km^2), however, is located beyond the domal uplift, near its southeastern end. The volcanic field of the Udokan ridge is situated some 25-30 km south of the Chara rift valley and occupies the top part of the ridge, providing plateau-like morphology of its surface throughout its area of about 1 500 km^2. On both the Vitim and Udokan plateaux there is a considerable number of central-type volcanic structures : slaggy cones, explosion craters and lava domes. Most of these centers are aligned with a NE-SW trend, indicating their relationship with a fissure-type magma supply.

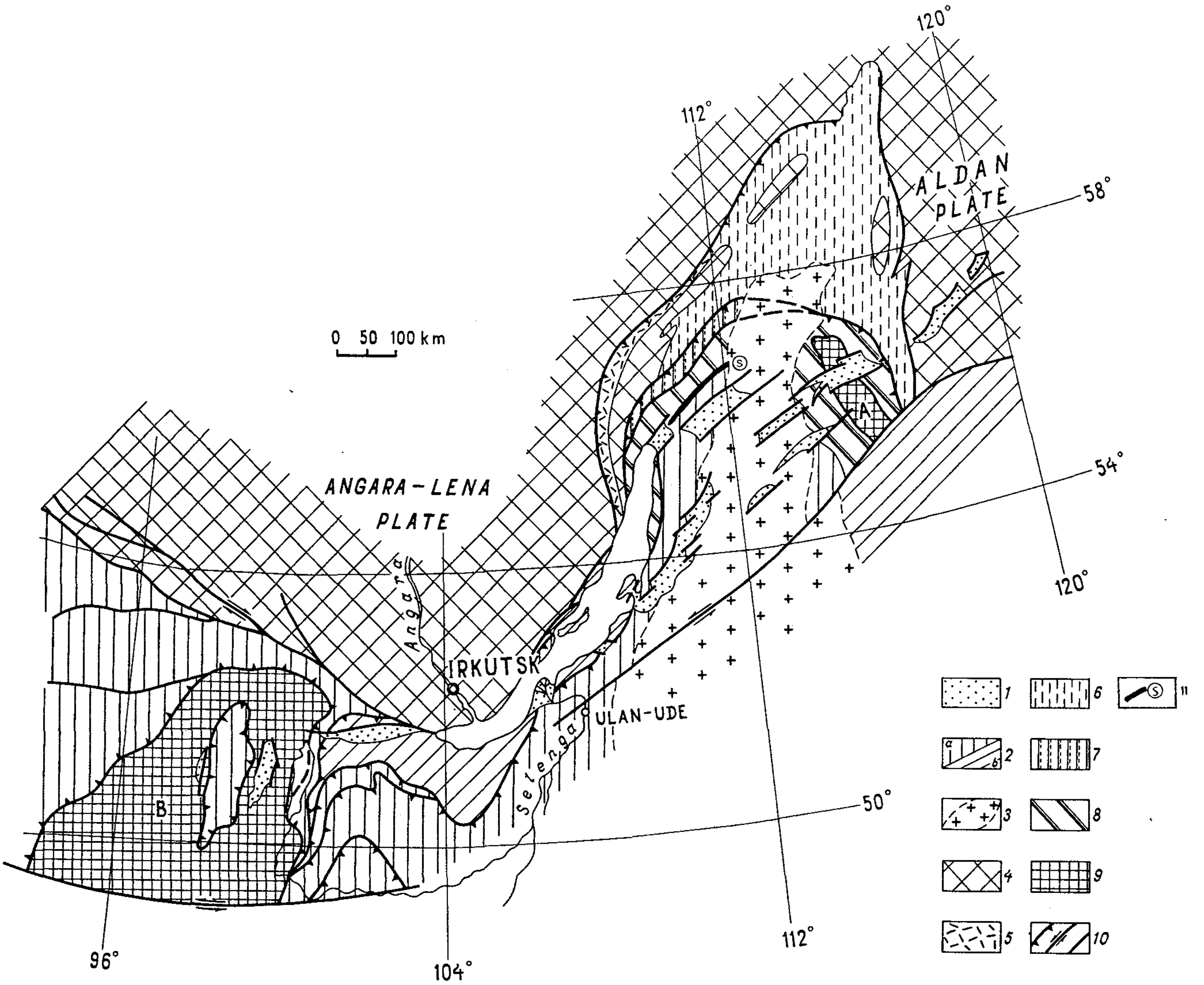

FIGURE 7

Main tectonic features of the Baikal rift basement (compiled by BELITCHENKO, 1990).
1) Cenozoic sedimentary infill of rift basins; 2) Caledonian collision belt : a) Late Precambrian – Early Paleozoic complexes of oceanic and transition evolution stages, b) complexes of Precambrian belt basement; 3) conventional outline of the Barguzin – Vitim Early Paleozoic granotoid batholith; 4) Siberian platform; 5) Early Proterozoic Akitkan volcanic belt of active continental margin; 6) Late Proterozoic Patom marine marginal trough; 7) Late Proterozoic sedimentary-volcanogenic continental slope deposits (the Olokhit zone); 8) Muya ophiolite belt (Proterozoic); 9) microcontinents : A) Muya, B) Tuva-Mongolian; 10) overthrusts, major shear zones and other faults; 11) Stanovik fault system (possible site of NE prolongation of the Lake Baikal rift basin).

3.1. SPECIFIC FEATURES OF VOLCANICITY AND TECTONISM-MAGMATISM CONTRADICTION

Among classical Cenozoic continental rifts (Rio Grande, East Africa, Central Europe) the Baikal rift is of minor importance in terms of volume of volcanism. To stress the point, we may compare it to the eastern branch of the East African rift system, equal to the Baikal rift in terms of extension and width and comprising both the Kenyan and Ethiopian rifts, where the total volume of volcanics is close to 500 000 km^3 (BAKER *et al.*, 1972). In this case the major magmatism site is within the rift valleys proper as well as on the adjacent shoulders. The volume of volcanics within the Eastern Siberian Rift System is nearly two orders less and they are distributed independently of rift valleys and major faults. Volcanic fields are only located in rift valleys (Tunka, Khubsugul) or in their vicinity in the western part of the rift zone.

Typical in this respect is the Tunka basin (Fig. 8), where drilling penetrated 2 100 m of sediments and intersected 40 basaltic bodies, with a total thickness of about 400 m, which constitute 1/5 of the entire drilled sequence (Fig. 9). It is of interest that intraformational basaltic flows (or sills) are only concentrated in the most downwarped eastern part of the basin, and do not occur throughout the rest of it. This fact is explained by maximum extention and crustal cracking at the bottom of the basin in the zone of the most significant

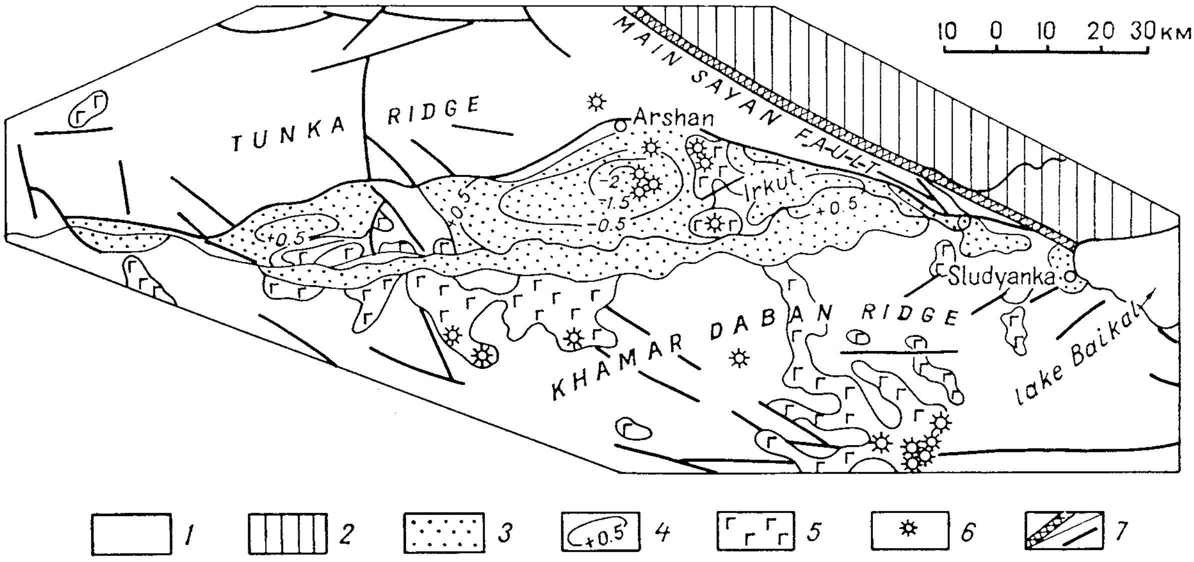

FIGURE 8
The Tunka basin structure.
1) crystalline basement; 2) marginal uplifted zone of the Archean basement of the Siberian platform; 3) Neogene-Quaternary deposits; 4) contour line of the basement (km); 5) Oligocene-Neogene-Quaternary volcanics (mainly basalts); 6) volcanic cones; 7) Main Sayan strike-slip fault (south-western edge of the Siberian craton) and major Cenozoic faults.

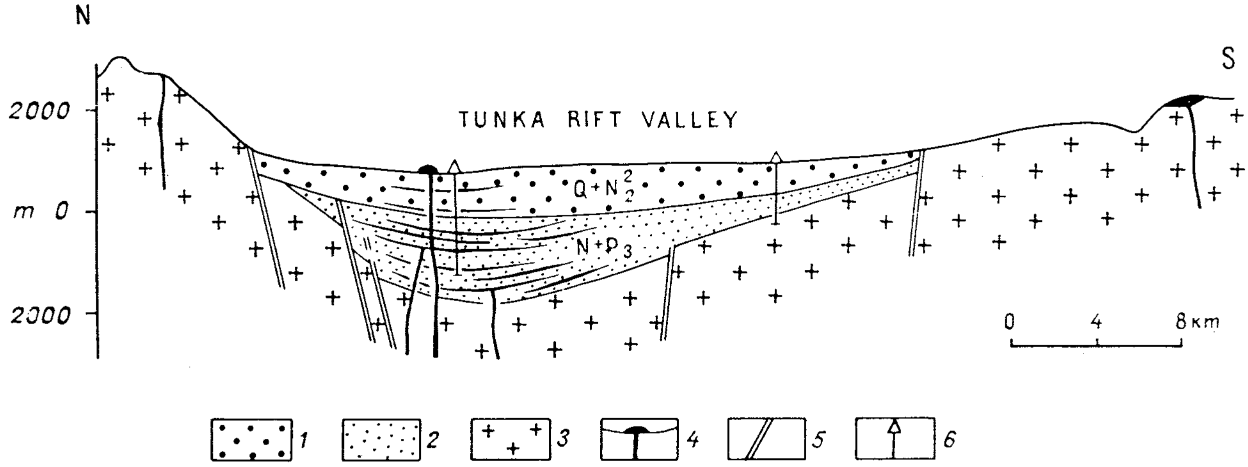

FIGURE 9
Cross-section of the Tunka basin.
1) Pliocene-Quaternary; 2) Oligocene-Miocene-Lower Pliocene; 3) Precambrian basement; 4) basalts; 5) faults; 6) borehole.

bend, which greatly contributed to basaltic magma penetration. Less voluminous magma flows and cinder cones from the more recent eruptions (Upper Pleistocene-Early Holocene) are also situated above this very zone (Fig. 10).

In all the main areas the most voluminous volcanics (Oligocene-Miocene) form fairly thick sequences (up to 500-600 m) consisting of dozens of separate lava flows with occasional lenses of lacustrine and fluvial sediments and minor tuffogenic material. Lava sheets conserve contrasting topography dissected by ancient river valleys which were 400-500 m deep, which suggests the existence of low-amplitude uplifts at the site of rift shoulders prior to volcanic eruptions. The Pliocene-Pleistocene flows are present in all three provinces, their distribution being significantly dependent on recent topography. Basaltic flows filled river valleys, moving along them for tens of kilometers (Fig. 11).

Large stratovolcanoes appear to be lacking within the Baikal rift area. The main pattern of magma transit was by fissure eruptions. In principle, the presence of shield volcanoes might be expected, though the latest evidence clearly suggests the dominance of fissure eruptions through the entire portion of rifting geological history which has been studied. It is only at the Udokan plateau that a few trachyte craterless cupolas of 300 m high and 1,5 km in diameter (RASSKAZOV, 1985) are found.

It is still unexplained why there are no young volcanics in the Baikal basin. The lithosphere beneath this depression

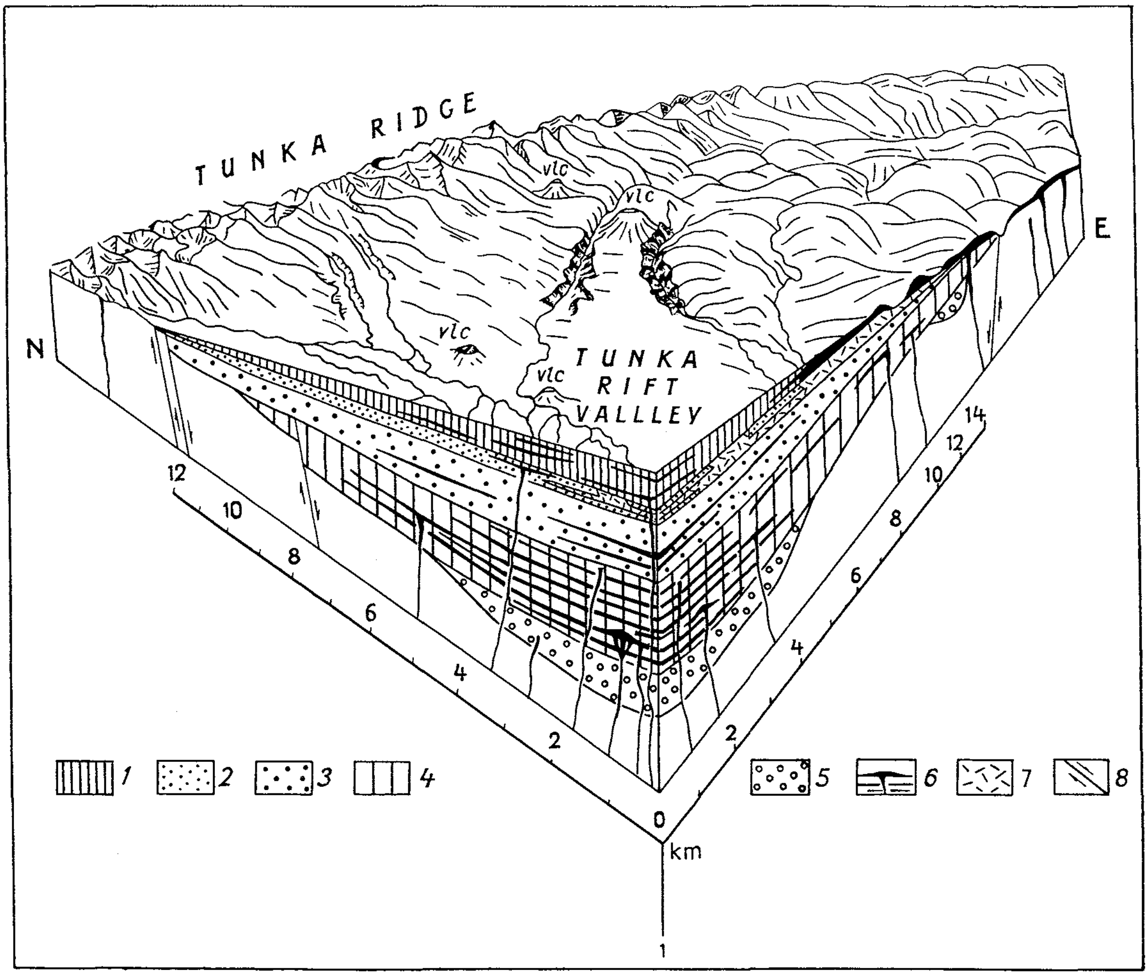

FIGURE 10

Block-diagram of the Tunka rift valley (north eastern quarter).
1) Pleistocene-Holocene; 2) Upper Pliocene-Lower Pleistocene; 3) Upper Pliocene; 4) Oligocene-Miocene-Lower Pliocene; 5) Sedimentary and volcanic rocks (Upper Cretaceous-Lower Paleogene ?) at the base of rift valley infill; 6) basaltic sheets and fissure vents; 7) pyroclastics; 8) faults.

is very extensive and ruptured (at least in the upper crust) by numerous faults. The asthenospheric layer here is the closest to the Earth's crust base (ZORIN *et al.*, 1989). Nevertheless, Cenozoic volcanics have not been found either in the Selenga delta boreholes or in the mountains surrounding the lake. Dikes of basic rocks which cut the shoreline Precambrian crystalline basement in places have been dated by the K/Ar method to be several hundred million years old and obviously are not associated with Cenozoic rifting. It was once believed that small dikes of biotite augitite from the Ushkany islands, situated at the crest of the subwater Academician ridge near Holy Nose peninsula are of Cenozoic age (Fig. 5). K/Ar dating estimated their absolute age to be 52 My (YESKIN *et al.*, 1978), which suggested extremely early rifting magmatism, as is the case with the Upper Rhine graben shoulders (LOGATCHEV, 1984). Later K/Ar dates of these rocks, however, were in the range of 139-144 My (BAGDASARYAN *et al.*, 1983). Thus the situation became pretty unresolved.

The occurrence of magmatism in the Lake Baikal rift basin is still questionable. The general situation, with the extention and thinning of the Earth's crust and maximum upwelling of an asthenospheric diapir should have provided voluminous volcanism, primarily in the form of fissure eruptions. Basaltic sheets are likely to intercalate with submarine sediments which are as thick as 7 500-8 000 m (South Baikal) and 4 000 m (North Baikal), but this may only be established with some certainty when deep drilling has penetrated the entire thickness of the sedimentary fill. However, calculations and modelling of gravitational and heat fields of the rift zone suggest (ZORIN, 1971; ZORIN & OSOKINA, 1984) the possible presence of dikes of mantle material in the lowest part of the crust, beneath the Lake Baikal rift basin. It is still a challenging mystery why this material has not forced its way to the surface in the form of fissure eruptions of basaltic lava.

3.2. PETROCHEMISTRY AND DIFFERENTIATION

Volcanic rocks of the Eastern Siberia Rift System have a rather uniform petrochemical composition. They are dominantly alkaline olivine basalts, trachybasalts and basa-

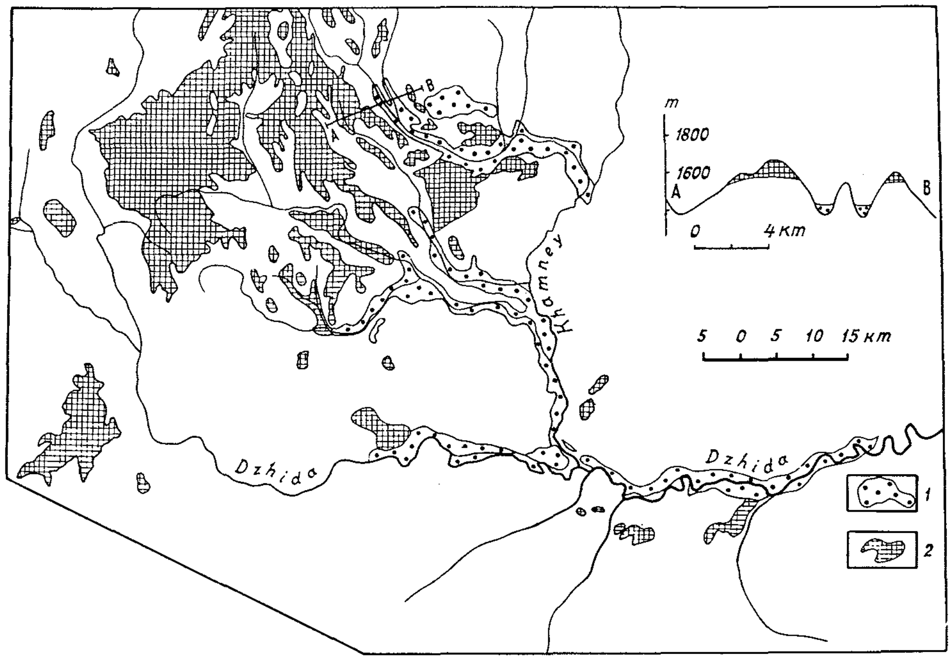

FIGURE 11

The distribution of basalts of different ages in recent topography (the Dzhida river basin, southern slope of the Khamar-Daban ridge; the area is framed by a dashed line in the left part of Fig. 4).
1) "valley" basalts (Upper Pliocene-Quaternary); 2) "watershed" basalts (Oligocene-Miocene), AB) cross-section illustrating the geomorphic position of the two basalt generations.

nites. Volcanic sequences which vary in chemical composition, from alkaline olivine basalts and basanites to olivine tholeiites, are only found in rare cases (Tunka basin, East Sayan highland) (RASSKAZOV, 1993). The main reason for the insignificant degree of magmatic differentiation is the probable long-term existence of melting sources at the same depth within the upper mantle and the ease of melt transfer through fissures to the surface. The volcanic rocks from the easternmost Udokan plateau are, however, markedly differentiated, ranging from mildly alkaline (alkaline olivine basalts and basanites) to trachyte, mugearite and benmoreite, the latter occurring from the latest eruptions (Pliocene-Pleistocene-Holocene). They generally form small extrusive cupolas 300 m high, or explosive craters on the surface of the Precambrian basement and basaltic plateau. The last eruptions of trachyte pumice took place here about 2 100 years ago (RASSKAZOV, 1985). This is the latest volcanic event within the Eastern Siberian Rift System.

The Cenozoic magmatism is much less differentiated than that of the East Africa, Central Europe, Western USA and Rio Grande rifts. Acid differentiates of the rhyolite type and other silicic varieties, as well as highly alkaline and strongly undersaturated volcanics with carbonatites which are well represented in the East African rifts and Upper Rhine graben are entirely lacking. Intermediate types (trachyte, mugearite, benmoreite) are apparently of minor importance and are mainly related to the final stages of volcanic activity and occur as isolated domes, explosive craters and lava flows. They make up about 5-7 % of the total volume of volcanics.

3.3. DEEP-ORIGIN INCLUSIONS AND PARENTAL MELTS

Volcanic rocks of all three provinces contain lherzolite and pyroxenite nodules as well as megacrysts of pyroxene, garnet, anorthoclase, ilmenite, phlogopite and amphibole. Among the lherzolite nodules, spinel, garnet-spinel and garnet-bearing nodules and some containing water-bearing paragasite and phlogopite are found (ASHEPKOV *et al.*, 1988; MELEKHOVETSKY *et al.*, 1986). Some of these inclusions are apparently from the area of initial upper mantle melting with the temperature and pressure being 1 000-1 200 °C and 20-30 kbar. Others are attributed to deep seated cognate cumulates, having crystallized under less deep conditions, with temperatures ranging from 900 to 1 000 °C and pressure being 15-20 kbar. The study of nodular composition indicates that the upper mantle of the Baikal region consists of spinel and garnet lherzolites with pyroxenite lenses. The mineral and chemical composition of the nodules, together with physicochemical modelling, suggest that the parental melt could have formed by partial melting (5-10%) of spinel and garnet lherzolite at a depth of 80-100 km. Melt fractionation and partial crystallization of primary melts at the beginning of their ascent could result in the formation of large cumulate inclusions of pyroxene, anorthoclase, kaersutite, titanophlogopite, garnet, spinel and titanomagnetite.

The distribution of volcanic rocks across the Baikal region shows the indepedence of volcanicity from rift-forming in the lithosphere. Structural development and magmatism are thus equivalent manifestations of the deep rift forming process. The areas of lithospheric maximum extension here could not easily be penetrated by magmatic melts. On the contrary, volcanic fields avoid these places and are located beyond them. Thus, in the case of the Lake Baikal rift zone, the relationship between extensional deformation of the upper lithosphere and magmatism is paragenetic, rather than direct. Only in three regions of the asthenosphere upwelling beneath the rift zone complex have favourable conditions for basaltic magma melting and its transit towards the surface appeared and lasted for a long time (15-35 My). The true meaning of these specific conditions is still open to speculation. This is one of the peculiarities and mysteries of continental rifting in Eastern Siberia and the focus of future studies. It is probable that the mantle melting chambers of the three mentioned provinces correspond to some deep zones of extension and decompression which have not become manifest in surface geological structures.

4. — ON THE TWO-STAGE EVOLUTION OF RIFTING

4.1. COMPOSITIONAL DIFFERENCES WITHIN VERTICAL SEQUENCE OF SEDIMENTARY FILL

It has been long noticed (LOGATCHEV, 1958; FLORENSOV, 1960) that the sedimentary infill of rift basins can be subdivided into upper and lower parts, differing in lithological and facial composition and corresponding to two evolutionary stages. The lower part of the section comprises Paleocene (?), Eocene, Ologicene, Miocene and, probably, Lower Pliocene sediments composed of sandstone, siltstone, argillite and clay, with rare beds of brown coal (tens of meters thick in places), diatomite and marl. These deposits are generally found close to the periphery of the depressions. The major characteristic of the lower unit is the abundance of fine-grained sediments intercalating with layers of coal, diatomite and diatomiaceous clay. Lenses of coarse-grained sediments (conglomerates, gravels) are extremely rare and are associated with the sites where long-established rivers run into basins. The lower sequence is a fairly diverse mixture of lacustrine, paludal and fluvial sediments, accumulated under subtropical (Paleocene-Eocene) to moderately warm (Oligocene, Miocene) climatic conditions. The presence of brown coal and diatomite layers and shell concentrations of fresh water mollusks suggests a high biological productivity and accumulation in the basins.

Since fine-grained sediments of the lower strata dominate both in the central part of the basin and near the bordering mountains, the sedimentary basins of Eocene-Oligocene-Miocene may be assumed to be wider than those of Middle Pliocene-Pleistocene (or topographic expression of the flanks was minimal). Erosional dissection and topographic contrasts on the rift shoulders were less significant than those of the later stage. Plateau-like uplifts around rift valleys were dissected by rivers to a depth of 400-500 m, as indicated by morphology of the surface, buried beneath Oligocene-Miocene basalts in Khamar-Daban, East Sayan and the Udokan highlands (LOGATCHEV *et al.*, 1974).

All the above-mentioned structural and compositional features of the lower sequence suggest a rather moderate rate of tectonic movements during 40-50 My, with subsidence of the rift valleys proceeding much faster than the uplift of their shoulders, which rose to the height of no more than 500-700 m above the basins. The thickness of the lower sequence in major basins ranges from 1 500 to 2 000 m (probably attaining 5 000 m in the South Baikal basin).

The upper sequence, consisting of Pliocene, Pleistocene and Holocene sediments, differs from the lower one by the prevalence of coarse-grained sediments and their facies corresponding to present topography. At the margins of the depressions, the upper sequence comprises localised sandy-gravel, pebble and boulder deposits, conglomerates and fanglomerates of fluvial, fluvio-glacial and gravitational origin. Immediately at the foot of the relief there are moraines deposited by Pleistocene glaciers which moved from the mountains towards the depressions and even into the water at the northern extremity of Lake Baikal. In the inner part of the Lake Baikal basin the upper sequence is more fine-grained. Sands, silts and gravels of fluvial, lacustrine and paludal origin prevail here and they intercalate with each other. Clastic material is characterized by a low degree of roundness. At the marginal parts of the depressions the upper sequence overlies the lower one with well expressed angular unconformity above which the sediments are abruptly more coarse-grained. All this indicates increased tectonic vertical movements during Middle Pliocene, 3-4 My ago. At that time the outlines and boundaries of the rift valleys reached their present form and contrasts in elevations between depressions and neighbouring uplifts sharply increased. The latter in some cases acquired the features of Alpine-like relief (the Tunka, Barguzin, Baikal and Kodar ridges) having an altitude of 2 500-3 000 m. Crustal movements are still taking place at present as recorded by repeated levelling surveys and seismic activity. The seismicity of the Lake Baikal rift is higher than that of all other continental rifts (LIPMAN *et al.*, 1989). The upper unit sediments are as thick as 1 000-1 200 m, the sedimentation rate during the later stage being 5-10 times higher than that of the Eocene-Oligocene-Miocene stage. A sharp increase in the rate of tectonic movement took place in the Middle Pliocene.

As for volcanism, the major part of the 6 000 km^3 of Cenozoic lavas was erupted during the Oligocene and Miocene. The absolute age of the basalts ranges mainly between 32-8 My (RASSKAZOV, 1993). The areas of volcanic eruptions reduced considerably in Pliocene-Pleistocene. At that time insignificant fissure eruptions took place and small cinder cones were formed. Lava flows of Pliocene-Quaternary age generally followed the present topography and filled river valleys (Fig. 11).

The Baikal rift two-stage development should be considered only as a general direction of the evolution of continental rifting. The changes in velocity and sense of tectonic movements, in climate and in relief, which are inevitably reflected in the composition and structure of both stages of sedimentary filling, surely occurred within each of the two main stages, but these second-order changes are to be revealed in the future. The multi-channel seismic profiling data, obtained by researchers from the Institute of Oceanology RAS in 1989 and processed together with specialists from the Branch of Atlantic Marine Geology USGS in Woods Hole (ZONNENSHAIN *et al.*, 1992; HUTCHINSON *et al.*, 1992), are, in this respect, rather promising. Line N8, 100 km long, obliquely crossing Lake Baikal at the North and South basins' en-echelon junction through the underwater Academician

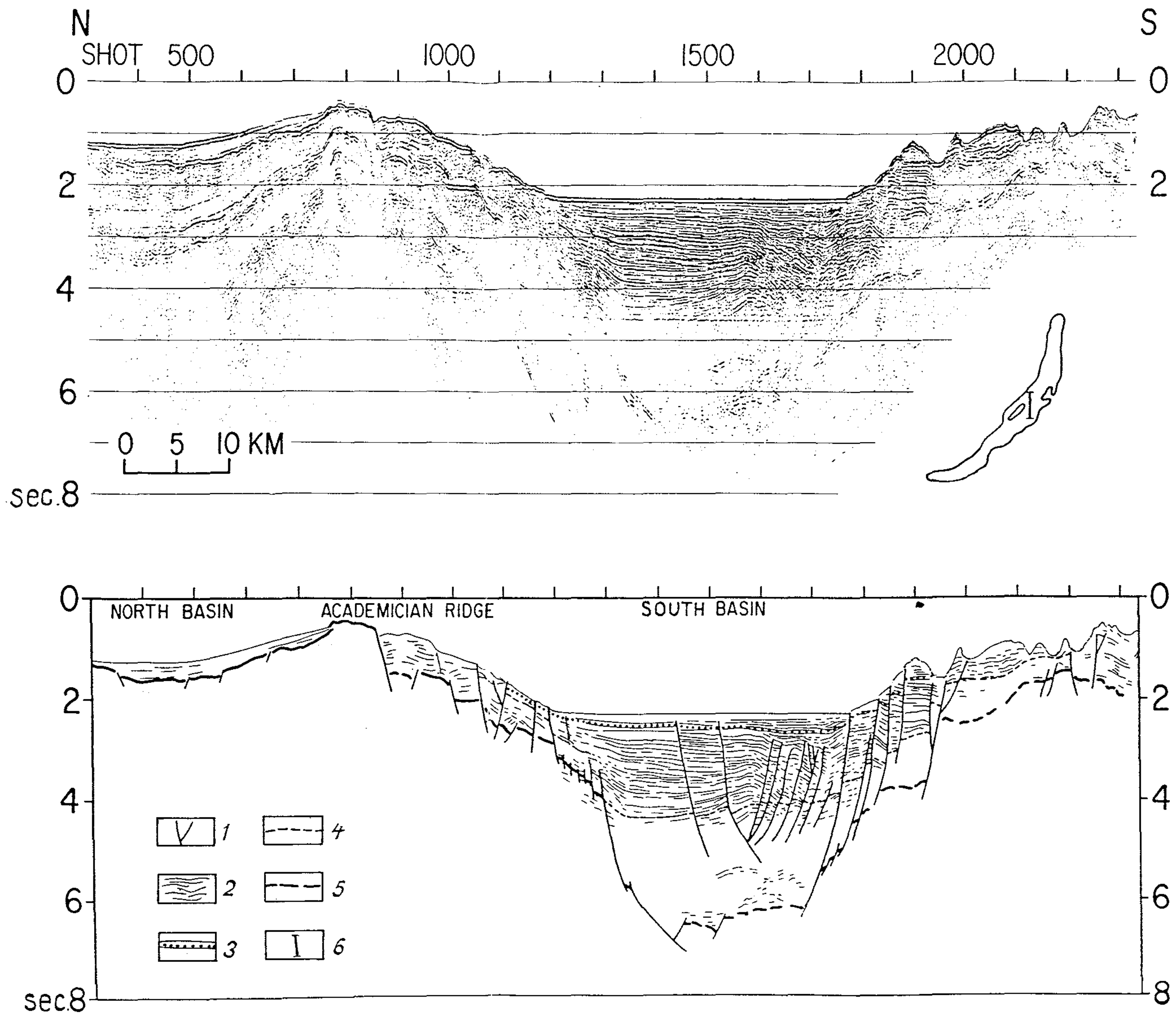

FIGURE 12
Multichannel seismic line N8 and its interpretation (by HUTCHINSON *et al.*, 1992).
1) faults; 2) reflectors; 3) base of Upper unit (Pleistocene + Holocene); 4) base of Middle unit (Middle + Upper Pliocene); 5) basement; 6) location of multichannel seismic line N8 in Lake Baikal contour (right part of this figure).

ridge, is one of the most informative profiles (Fig. 12). According to seismic data processing, three units are distinguished by this profile. The Lower unit lies on the Precambrian basement in the axial part of the basin and extends, becoming thinner, on to the flanks. Usually these sediments are acoustically transparent. The increase of thickness in a S-N direction outlines the primary structure of a half-graben. The maximum thickness of the Lower unit is about 2 000-3 000 m near the large normal fault, and between shot points 1 300-1 400 m (Fig. 12).

The Middle sedimentary unit is characterized by steady subparallel reflections and reaches a thickness of 1 000-2 000 m within the basin. Under the basin and on the slopes the Middle unit is dissected by a considerable number of low amplitude, steep, normal faults. According to the interpretation of A. Golmstock, L. Zonnenshain and D. Hutchinson, the Middle unit formation marks a significant change in sedimentation style, related to a major change in the sense of tectonic movements and environment.

The Upper unit is also characterized by extensive subparallel reflectors and is not usually affected by deformations within the flat bottom of the lake, but is displaced by active faults on the steep slopes of the basin. It is on average 300 m thick and slightly thickens in a N-S direction, on the eastern side of the basin, up to 500 m.

The direct age correlation of the three units shown on profile N8 is impossible because of the lack of reliable data.

Nevertheless, taking into account the contrast of acoustic features of the Lower and Middle units, as well as the indicators of angular unconformity occurring between them in some places, the authors (HUTCHINSON *et al.*, 1992) are inclined to think that the boundary between the Lower and Middle units corresponds to the turning-point of the Baikal basin evolution, which separated the two main stages of the rift zone's structural development. The Upper unit, judging by its insignificant thickness, as well as by its distribution, character and the insignificant effect of faulting on it, includes Pleistocene and Holocene sediments and most likely reflects the last strong impulse of the Sayan-Baikal dome tectonic uplift. This coincided with climatic cooling and rather considerable glaciation of the surrounding mountains, which is reflected on the character of lake sedimentation. Nevertheless, against the background of the complete Baikal rifting history, these late tectonic and other natural changes are taken to be an episode which took place within the second stage of development.

4.2. GEODYNAMICAL MEANING OF THE TWO-STAGE EVOLUTION

Thus, the composition and age of sedimentary infill of rift basins suggests a two-stage evolution of the Baikal rift zone. At an early stage, covering the time period of no less than 40-50 My, a "slow rifting" took place under a low extension rate of the lithosphere. Tectonic movements were moderate and the uplift of rift shoulders was insignificant. In the Middle Pliocene the rate of tectonic movements and lithospheric extension increased abruptly, giving rise to "fast rifting", which is still in progress today. It is at this stage that the subsidence of the Lake Baikal basin appeared to be at a maximum, and gradually it developed into the world's deepest fresh water body. The thickness of Pleistocene-Quaternary sediments in water-free basins outside the Baikal depression attains 1 000-2 000 m. The elevation of adjacent rift shoulders is of the same order or a little higher, *i.e.* the rates of depression subsidence and rift-shoulder rise became roughly equal.

Two-stage rifting is not specific to the Baikal rift, it is well illustrated in the case of the Upper Rhine graben (ILLIES, 1978), as well as in the Kenyan and Ethiopian rifts in East Africa, which have exceptionally voluminous volcanism. It is of interest that in rift zones such as the Kenya rift, which have intensive magmatism, the early stage volcanism showed a widely distributed pattern covering an extensive area of the domal uplift and only then, as the lithosphere spread along the rift channel, did it concentrate, mainly within the Gregory rift valley (LOGATCHEV, 1978).

It is probable that the majority of continental Cenozoic rifts developed in two stages, despite differences in scale of accompanying volcanism. The early and long lasting stage of slow rifting, occupying a great deal of the history of the rift zone, was followed, in the Pliocene, by a stage of increased deformation and fast brittle destruction of the Earth's crust which is, in fact, continuing at present. The Lake Baikal rift has been explained (LOGATCHEV & ZORIN, 1987) as being due to the dynamics of the asthenospheric uprise. The early stage ("slow rifting") is associated with a gradual and slow rise of the asthenospheric diapir, responsible for insignificant lithospheric extension and low amplitude (300-400 m) general uplift of the Sayan-Baikal dome and a slow, mainly plastic, downwarp of the Earth's crust beneath the rift basins.

The later stage ("fast rifting") started when the asthenospheric uprise drew nearer to the Earth's crust base and the asthenospheric substance spread southeastward from the margin of the "cold" slab of the Siberian craton. It resulted in a sharp increase in lithospheric extension, its rapid growth creating normal and strike-slip faults, increased subsidence of rift basins and considerable (1 500-2 000 m) uplift of rift shoulders. The sedimentation rate in the basins at the stage of "fast rifting" increased in comparison with the previous stage by 5-10 times. This value indicates a sharp contrast in the rate of tectonic movements and lithospheric deformation in the course of the two-stage Baikal rift evolution.

5. — DEEP STRUCTURE AND GEODYNAMICS

The velocity of P-waves at the Moho discontinuity is 7.7.-7.8 km/sec below the Baikal rift zone, as compared to 8.1.-8.2. km/sec below the Siberian platform and Transbaikalia (KRYLOV *et al.*, 1981). Anomalously low velocities in the mantle beneath the rift zone are also indicated by P-wave delays from distant earthquakes and explosions (ROGOZHINA & KOZHEVNIKOV, 1979). At the subvertical emergence of seismic rays from distant sources the delays are about 1 second, suggesting that the thickness of the layer producing the delay (the asthenosphere) is not less than 200 km. According to ZORIN *et al.* (1989), there is a maximum upwelling of the anomalous mantle surface beneath the axial zone of the Baikal rift, which dips gradually southeastward beneath the mountain systems of Transbaikalia and Northern Mongolia. On the contrary, it dips steeply towards the Siberian platform where the lithosphere increases up to 100-200 km (Fig. 13).

The teleseismic tomography of the mantle beneath the Baikal rift, carried out in 1991-1992 by a Russian-American team, has, in general confirmed the existence of an asthenospheric bulge in this region (oral communication by P. Davis and Yu. Zorin).

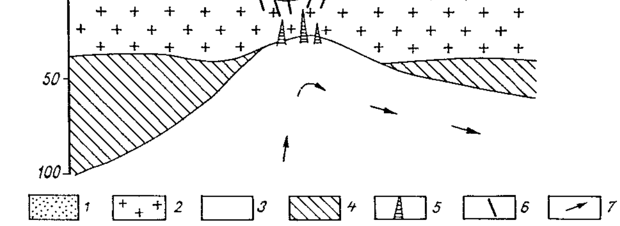

FIGURE 13

Simplified model of deep structure of the central segment of the Baikal rift system.
1) sediments; 2) crust; 3) asthenosphere; 4) normal upper mantle; 5) basic and ultrabasic intrusions; 6) faults; 7) tentative direction of asthenosphere material migration.

When the asthenospheric material reached the Moho, its upward movement should have ceased because its density significantly exceeded that of the crust. Since then (3-4 My ago) there has been lateral migration of asthenospheric substance towards the south-southeast from the thick, cold lithosphere of the Siberian craton. This movement resulted in intense crustal extension which in turn caused considerable vertical movements along faults and deepening of the rift depressions. The probable southeastwards migration of asthenospheric material seems to be the major cause of the typical "Baikal" asymmetry of rift basins, expressed in high (1 500-2 000 m) fault scarps forming their northern and northwestern slopes, as compared with those to the south and southwest where the basin flanks are due to basement surface bending, with associated small amplitude faults. Another possible cause of the asymmetry of the Baikal rift depression may be the inheritance of Precambrian and Early Paleozoic overthrust zones, resulting from the collision of the Sayan-Baikal mobile belt and Siberian craton, by faults produced by Cenozoic riftogenesis. It is quite likely that both mechanisms, that of the detachment from the platform edge and the inheritance of ancient collision overthrust zones by younger faults, operate together. The abundance of volcanic fields, mainly south and southeast of the rift faults and depressions (except for the western part of the rift zone), is also indicative of the feasibility of the deep migration of asthenospheric material from the Siberian craton, which is presented in primitive form by the model (Fig. 13).

6. — DISCUSSION AND CONCLUSIONS

All the data available on the geology and deep seated structure of the Baikal area and its neighbouring regions suggest that the active Lake Baikal rift, hidden in the interior of Asia, has no direct connection with the world rift system and forms a separate area of Cenozoic tectonothermal activity. However, no one will deny that, if the present stress field pattern were to exist for an infinitely long period and lithospheric extension were to progress, in a million years the Baikal rift could propagate eastward along the longitudinal trending Stanovik and Dzhugdzhur fault system and eventually join the Okhotsk Sea in the Uda bay area. The rift propagation towards the south and southwest on the western termination is unlikely, due to a transverse (to the rift strike) orientation of lithospheric structural fabric throughout the area of Northern Mongolia. The association of the initial lithospheric extension with the suture zone between the Siberian craton and mobile belt suggests that the junction zone between parts of Eastern Siberia, which are contrasting in terms of their thermodynamic and rheologic properties, favours ductile and brittle deformation of the lithosphere. The highest values of absolute crystalline basement subsidence (up to 7 000-7 500 m in relation to other parts of the rift zone) and extension of the upper part of the Earth's crust (15 km) are specific to the South Baikal basin. At any rate, drilling to 3 100 m in the Selenga delta has reached sediments no older than the Eocene. The presence of Paleocene and probably Late Cretaceous sediments is expected within the undrilled part of the sedimentary section at depths of 4 000-6 000 m.

6.1. BILATERAL PROPAGATION OF RIFTING

The South Lake Baikal basin is thus probably the earliest part of the Eastern Siberia Rift System and is its historic core (Fig. 14). In the Oligocene and Miocene, rifting progressed in both directions from the South Baikal basin. The most extreme basins of the rift system (Northern Mongolia and the Olekma river catchment) originated no earlier than the Late Pliocene at the beginning of the "fast rifting" stage. The bilateral propagation of the Baikal rift could not be strictly synchronous and completely symmetrical in both directions due to structural anisotropy of the basement and differences in lithospheric rheology. This is the major probable cause of differences between the parts of the rift system located to the northeast and west of the central South Baikal segment. The northeastern part is more developed than the western one both in fault length and density, number and size of rift basins and the area exposed to rifting. It is obvious that the differences between both "wings" of the Baikal rift reflect more favourable conditions for its propagation northeastward resulting from an almost complete matching of the rift-forming tectonic stress with major structural heterogeneity of the Earth's crust, developing as far as the Aldan shield margin where the rifting decreases due to a sharp thickening of the lithosphere and transverse orientation of the basement structural fabric across the rift trend. The picture is considerably different at the western "subdued" rift flank : the number of rift basins here is much less (only 4, Fig. 6), with less fault density and extent and fairly sharp substitution of E-W orientation (Tunka valley) by a sub N-S one (Khubsugul, Darkhat, Busingol basins). The above suggests somewhat complicated conditions for lithospheric destruction by rifting resulting from possible changes of stress field, unfavourable orientation of crustal, structural heterogeneities and possibly the manifestation of some lithospheric microplate movements within the complicated tectonic structure of Northern Mongolia.

6.2. LOCAL OR EXTERNAL SOURCE OF TECTONOTHERMAL ACTIVITY ?

In terms of two-directional rift propagation from South Baikal, a general symmetry of its morphology with regard to the central segment, expressed by two culminations of domal uplift and "multiplication" of the rift basins within their boundaries, as well as asthenospheric upwelling towards the crustal base with a most probable migration of its heated material from the craton towards the south-southeast, the most acceptable theory seems to be the idea of the dominant role of a local source of energy and rifting driving mechanism. Taking into account the effects of the collision between the Indostan and Eurasia continents on Cenozoic geodynamic evolution of Inner Asia, as predicted by MOLNAR & TAPPONIER (1975), it is still difficult to realize that this mechanism appears to be the leading one for the origin and development of the Baikal rift. Its western terminus is located some 2 500 km from the Himalayan collision front and 1 600 km from the Tibet plateau's northern margin. The influence of the Indo-Eurasia collision on the splitting and spreading of the lithosphere in the area of the Baikal rift is unlikely to be the case, for the stress propagation in the lithosphere for a distance of 1 500-2 500 km is physically impossible. Yet, if that were the case, then, according to indenting experiments (DAVY *et al.*, 1990), the structural pat-

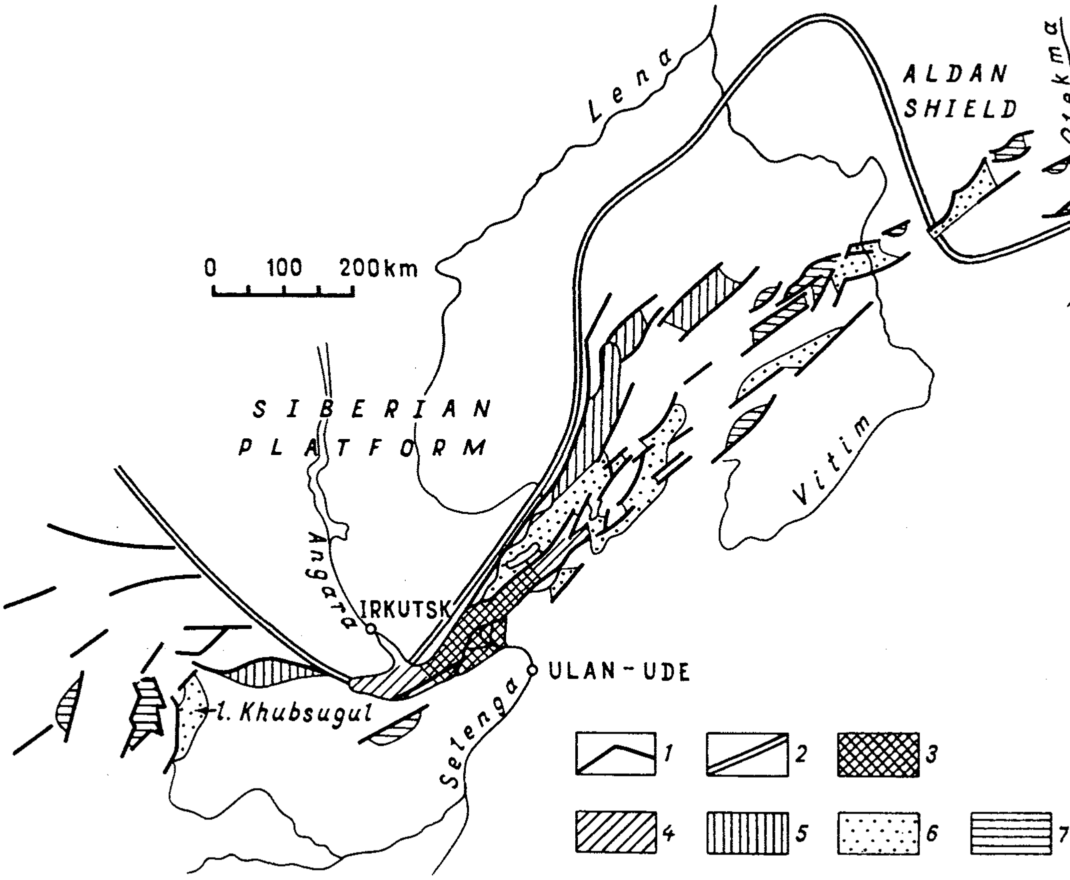

FIGURE 14

The beginning of basin formation in the Baikal rift system, indicating bilateral rifting propagation from the South Baikal basin. 1) major faults; 2) Siberian platform rim; 3) Upper Cretaceous (?)-Paleocene; 4) Paleocene-Eocene; 5) Oligocene-Early Miocene; 6) Miocene-Early Pliocene; 7) Middle-Late Pliocene-Quaternary.

tern of the fault system between the Himalayas and Baikal would have been totally different from that presently observed. At any rate, lithospheric extention and faulting should have begun at the northern margin of the Tibet highland and developed northeastward in the direction of Lake Baikal. The propagation of the Baikal rift in both directions from the central segment is, apparently, in conflict with this mechanism. Maybe the compressive strains, resulting from the Indo-Eurasia collision, to some extent reached the area of the Baikal rift but they rather hampered rifting at its western part and, probably, favoured it in the central and northeastern parts of the rift zone. The collisional hypothesis of the origin of the Lake Baikal Rift has not been clarified by the existence of its modification (ZONNENSHAIN & SAVOSTIN, 1981) assuming autonomous movements of small lithospheric plates as well as the action of a stress field from the Himalayan collision front.

Although the hypothesis that the Lake Baikal rift originated from the collision between the India and Asia plates obviously looks very attractive and has numerous advocates, it still requires special geodynamic studies to be conducted within a wide band between the Baikal rift and the Himalayas. In the future these studies could be undertaken by researchers involved with the "Baikal-Himalayas" project, part of International programmes of "Geological Correlation" or "Lithosphere". For the time being, the author believes that the driving force of intraplate rifting in Eastern Siberia was, and still is, an upwelling and lateral sperading of asthenospheric material, resulting in heat and gravitational instability of the lithosphere. This caused the appearance of arched uplift, rejuvenation of old and origination of new faults, considerable vertical and horizontal movements of crustal blocks, the formation of the dispersed set of rift basins and ranges, and also the volcanism, being discontinuous in time and space.

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