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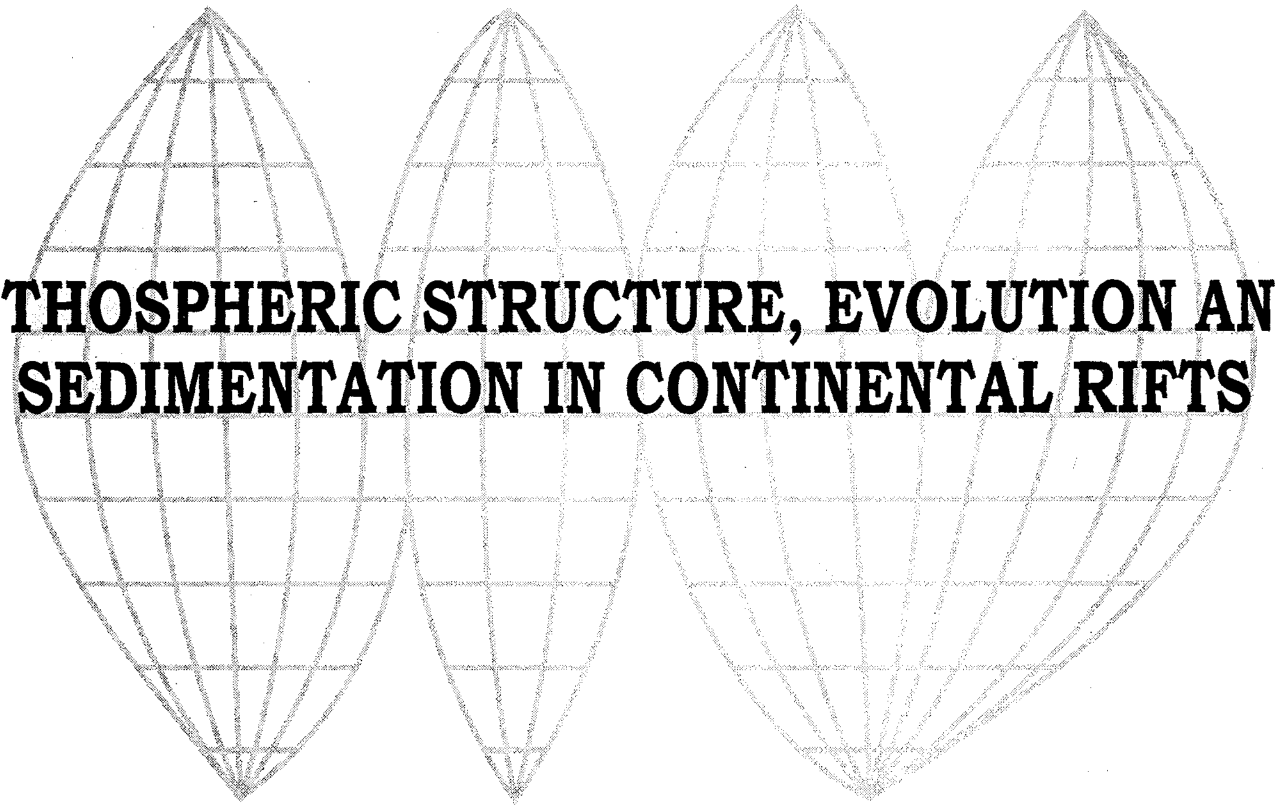

LITHOSPHERIC STRUCTURE, EVOLUTION AND SEDIMENTATION IN CONTINENTAL RIFTS

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Geodynamics of Baikal Rifting: new developments and perspectives

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Abstract

This paper reviews the recent developments in the understanding of the mechanism of rifting in the Baikal Rift Zone. It presents some of the main features of the Baikal rift studied in recent years, concerning the Paleozoic pre-rift history, the Mesozoic detachment-style extension and the Cenozoic rifting along the south-eastern margin of the Siberian Craton, in Central Asia. The Baikal rift zone was studied by a wide variety of approaches, including tectonics, sedimentation, volcanism, stress field and fault kinematics evolution in time and space from the Early Paleozoic to the Present-day, apatite fission track thermochronology, geophysical investigations, seismotectonics, geodesy and kinematic and finite element modelling. A new view of the rifting geodynamics is presented, as a result of a long-lived process occurring along a crustal-scale weakness zone at the margin of the Siberian Craton, and as a function of the intraplate context. Differences between Mesozoic detachment-style extension and Cenozoic rifting are highlighted. The main directions for future research are identified, in relation to the gaps in the present knowledge.

Key Words: *Baikal Rift Zone, Geodynamics, Stress field, Metamorphic Core Complexes, Siberia, Paleozoic, Mesozoic, Cenozoic*

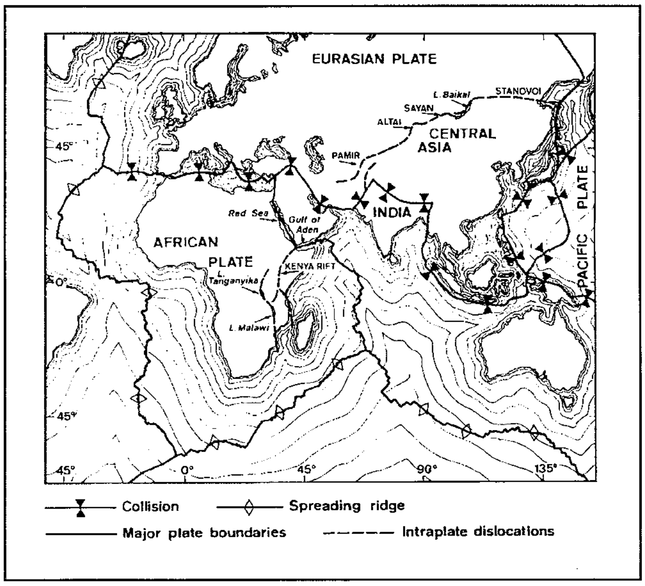

Figure 1: Plate tectonic context of the East African and Baikal Rift Systems.

Introduction

The presence of active intracontinental rift systems with uncompensated deep-water basins such Lakes Tanganyika and Malawi (Nyasa) in the East African Rift System, and Baikal in Central Asia, gives rise to several problems regarding the mechanism of basin formation in continental lithosphere, in relation to intraplate tectonics. In particular, one of the most important results of the ILP World Stress Map project (Richardson, 1992; Zoback, 1992; Zoback et al., 1993) is that most of the interior of continental lithospheric plates is actually under compressional stress. Africa is surrounded by mid-oceanic spreading ridges and a continental collision to the North, and Central-Asia is predominantly under compression, induced by the India-Eurasia collision and convergence (Fig. 1). In these conditions, how do such deep extensional rift basins develop? To address this fundamental question, it is necessary to investigate not only the rift basins themselves, but also their lithospheric structure and their general intraplate tectonic context.

The Baikal rift zone is part of the broad Central-Asian dislocation belt which extends from the Pamir to the Stanovoy area and includes also the Tian-Shan, Altai and Sayan massifs (Fig. 2, insert). This belt separates the Siberian Craton and the Kazakhstan plate, considered to be undeformable, from Central and East Asia. Cenozoic deformation in this belt is believed to be driven mainly by the collision and convergence of India with Asia (Cobbold and Davy, 1988; Tapponnier and Molnar, 1979; Burov et al., 1993). To the East, the subduction of the Pacific ocean under the eastern margin of Asia is interpreted generally as a free boundary, with many extensional basins (e.g. Molnar and Tapponnier, 1975).

Along this Central-Asian dislocation belt, a wide range of sedimentary basins developed (ramp-type, pull-apart, grabens and rifts), together with regional uplift and mountain building. Present-day deformation style and stress field is changing progressively from compressional in the Tian Shan Mountains, transpressional in Altai and West Sayan, transtensional in East Sayan and extensional in the Baikal Rift System. North eastwards, the stress regime remains extensional as far as the Stanovoy belt, where it becomes compressional.

The Baikal rift zone developed along the suture zone between the Siberian Craton and the East Sayan-Transbaikal Caledonian fold belt (Fig. 2). The geometry of the southern margin of the Siberian carton had a profound influence on the tectonic evolution and setting of the Baikal and Sayan areas. It forms a characteristic south-pointing V

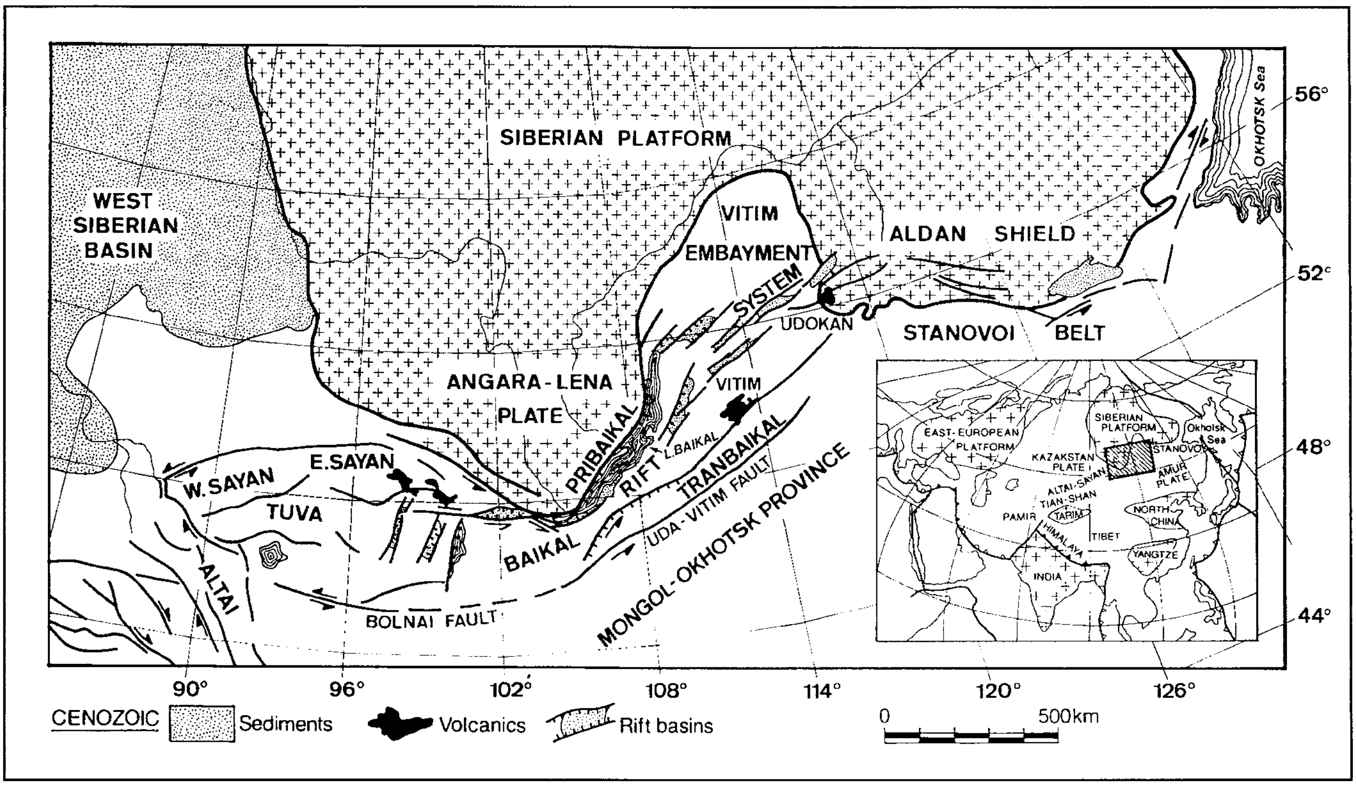

Figure 2: The Baikal Rift System and its intracontinental tectonic setting in Central Asia (after Delvaux et al., in press).

shape projection (the Angara-Lena plate). The baikal rift basins are located along the south-eastern margin of this plate, while the East Sayan mountains develop along its south-western margin. The boundary between these two provinces is sharp, marked by the Main Sayan fault system. The basin formation mechanisms are also very different from one side to the other. Deep uncompensated basins formed in the Baikal rift, while small N-S trending grabens form in the Sayan mountains. Wrench fault basins are dominant in the Altai, and compressional basins in the Tian-Shan. Style of deformation, seismicity and stress field suggest that a continuum of deformation exists in Central Asia, from the India-Asia collision zone to the Altai-Sayan-Baikal-Stanovoy belt.

The presence of a large asthenospheric diapir under the central part of the Baikal rift zone and its adjacent region is suggested by the results of gravity inversions (Logatchev and Zorin, 1992 and Logatchev, 1993). An asymmetric upwarp of the lithosphere-asthenosphere boundary beneath the central part of the Baikal rift zone is suggested by the results of teleseismic investigation by Gao et al. (1994a) and the same experiment also revealed a seismic anisotropy indicating a horizontal, NW-SE flow in the upper mantle, at right angles to the rift trend (Gao et al., 1994b). In north-western Mongolia, the Khubsugul and Hangai areas seem also to be underlain by a hot upper mantle (Zorin et al., 1990; Baljinnyam et al., 1993; Windley and Allen, 1993). However, it appears that the average heat flow in the Baikal Rift Zone is relatively low (57 ± 14 mW m^{-2} outside lake Baikal with a background of 50 mW m^{-2} in Lake Baikal Lysak, 1984; 1995), as compared to the Kenya Rift (105 ± 50 mW m^{-2}: Keller et al., 1991), that the crust is relatively thick (40-45 km), and that crustal thinning it not a general feature (Diament and Kogan, 1990; Petit et Déverchère, 1995). In the northern part of the rift, crustal thinning may even be absent (Burov et al., 1994) and the lithospheric strength is higher than expected (Déverchère et al., 1993). Therefore, the Baikal Rift do not match the "typical" rifting model, unlike for example, the Kenya Rift. The deep structure of the Baikal Rift and surrounding regions thus remains a major question, of crucial importance for understanding the geodynamics of rifting. The uniqueness of the Baikal Rift Zone is that it is the world's intracontinental rift zone which is situated the furthest from the nearest plate boundary (2500 km). In spite of this, continental deformation occurred in the Cenozoic in response to both far-field sources of intraplate stresses and to direct upper mantle influences (Dobretsov et al., 1996).

The main objectives of our work in Siberia and Central Asia since 1991 are the investigation of tectonic and kinematic processes in the Baikal Rift System, the formation of sedimentary basins in a general compressional intraplate setting and the interplay between plate-scale and local stress field fluctuation. A comparison of tectonic evolution, structure and stress field, both in time and space, may yield new ideas and new questions, e.g. on the lithospheric effects of plate-scale far-field stress on rift initiation, on the relative importance of pre-existing basement structures in controlling the rift geometry, on the interplay between stress field evolution and basin-bounding fault kinematics, and on the effects of stress field fluctuation on mountain building and basin formation processes.

In order to contribute to the understanding of the rifting mechanism, this investigation concentrated on two major questions: Why true rifting in Baikal occurred only in the Late Cenozoic although brittle conditions were established since the early Paleozoic and when a strong extensional event had already occurred in the Mesozoic ? Why did rifting develop only along the south-eastern margin of the Angara-Lena plate, and is isolated from the world system of continental rifts and oceanic spreading ridges?

To answer these questions, it is necessary to investigate the geodynamic process in the Baikal Rift Zone since the beginning of the amalgamation of microcontinents around the Siberian Craton, in the Early Paleozoic. As a first step, Melnikov et al. (1994); Delvaux et al. (1995c) reconstructed the stress field evolution during the pre-rift period, and examined the tectonic setting for the different stages of evolution. Sklyarov et al. (1994a; 1994b), Ermikov (1994), Delvaux et al. (1995c) and Van der Beeck et al. (in press) paid special attention to the Mesozoic tectonic evolution related to the convergence and closure of the Mongol-Okhotsk ocean between China and Siberia, and the related extensional tectonics, uplift and denudation, and Cretaceous inversion. For the Cenozoic, the history of rifting, fault kinematics and stress field have been reconstructed by Delvaux et al. (in press). For the Late Tertiary and Quaternary, special attention was paid to the timing of tectonic activation and geodynamic changes, not only in the Baikal Rift Zone, but also in adjacent regions of Central Asia, including the Sayan, Altai and Tian-Shan massifs (Delvaux et al., 1995b, 1995d). Investigation of the present-day stress and strain field spatial variations, from the Baikal Rift Zone to adjacent regions, brings new insights in the rifting mechanism (Petit et al., 1996). Since 1994, GPS geodesy coupled by finite element modelling (Lesne, 1996; Déverchère et al., this issue) have been undertaken, to quantify the present-day deformation.

In this paper, we will review the main progress in the geodynamics of the Baikal Rift Zone, discuss some of the major remaining problems and often guidelines for future investigations.

Paleozoic Collisional Evolution

After the final closure of the Paleo-Asian ocean at the southern margin of the Siberian platform, the marginal suture with the Sayan-Baikal Caledonian belt was repeatedly and preferentially reactivated during the subsequent Phanerozoic history. The progressive closure of the Paleo-Asian and Mongol-Okhotsk oceans generated successive continental collisions, which were recorded in the Baikal area by brittle-ductile and brittle deformations.

Since the Early Paleozoic, the Mongol-Okhotsk oceanic plate was subducting under the south-eastern margin of the Siberian Craton. In the Late Ordovician-Silurian, collision of a continental mass with the Siberian plate caused crustal thickening, intense granite magmatism and metamorphism in the Transbaikal area (Angara-Vitim Batholith). West of the present-day Lake Baikal, the Pribaikal fold-and-thrust belt developed along the margin of the Siberian plate, with decollement of the Upper Riphean and Lower Paleozoic cover from the basement of the Siberian Craton (Litvinovskii et al., 1994; Melnikov et al., 1994; Delvaux et al., 1995c). The major phase of granite emplacement occurred in the Late Ordovician - Silurian, during the collision stage. Post-collisional granitic magmatism continued during the Mid-Devonian - Late Carboniferous, but with reduced volumes (Neymark et al., 1993; Litvinovskii et al., 1994). Paleostress investigation along the western margin of Lake Baikal (Delvaux, 1995c) makes it possible to define the following succession of compressional stages: (1) Late Cambrian-Early Ordovician N-S compression, (2) Late Silurian-Early Devonian NW-SE compression and (3) Late Carboniferous-Early Permian E-W compression. This tectonic history is responsible for the major structures of the basement. Most of the controlling structures for the Baikal rifting were formed during this period.

Mesozoic Highly Extensional Tectonics and Inversion

The Mesozoic was characterised by the continuation of oceanic evolution in the eastern part of the Mongol-Okhotsk ocean and its final closure in the Late Jurassic-Early Cretaceous, due to the lithospheric collision of the Mongol-China block with Siberia. In Altai, only limited tectonic movements occurred during this period, but important deformations related to the closure of the Mongol-Okhotsk ocean affected the Transbaikal area, southeast of Lake Baikal.

Mesozoic volcano-sedimentary grabens and metamorphic core complexes in Transbaikal

In the Transbaikal region, a system of Mesozoic volcano-sedimentary continental grabens stretches for more than 1300 km in a NE-trend, in South Siberia and North Mongolia, up to the Stanovoy belt (Fig. 3). It is about 600 km wide in its central part and is composed of chains of individual depressions 15-20 km wide and 50-150 km long, separated by 45-50 km wide horsts (Ermikov, 1994; Delvaux et al., 1995c).

The depressions started to form in the Middle Triassic. Acid volcanism is dominant in the Late Triassic - Early Jurassic. In Early-Middle Jurassic, trachybasalt volcanism became important in some parts of the belt, together with conglomerates. The major volume of Mesozoic volcanics erupted between 150 and 90 Ma (Late Jurassic - Early Cretaceous), with the most intense activity at the beginning of the Early Cretaceous (e.g. Yarmolyuk and Kovalenko, 1995). This coincides with the main stage of graben formation, with intense uplift of the depression flanks and sedimentation of coarse clastic molasse together with bimodal trachybasalt eruptions (e.g. Gordienko and Klimuk, 1995). During this period, volcanism, intrusive magmatism and dyke swarms well directly associated with the graben systems, controlled by extensional tectonics (Bayanov, 1994; Stupak, 1994; Yarmolyuk and Kovalenko, 1995).

A narrow strip of metamorphic core complexes (MCC) stretches over 700 km in the middle of the Transbaikal province of small basins and ranges (Sklyarov et al., 1994a). They are flanked on both sides by narrow grabens containing Jurassic to Lower Cretaceous molasse and volcanics. They form a domal uplift of mid-crustal metamorphic crystalline rocks, separated from the adjacent molassic basins by low-angle normal faults and mylonites. Shear sense criteria and tectonic lineation in the ductile detachment fabric indicate a NW-SE general extension. Syntectonic intrusions seems to be associated with the detachment fabric, and pseudotachylite veins are also well developed. The available K-Ar and Rb-Sr ages (Sklyarov et al., 1994b) suggest formation of the MCC at 270-290 Ma (Permian), and exhumation at 110-140 Ma (Late Jurassic-Early Cretaceous). In the marginal parts of some MCC, series of Permian, Triassic and possibly Early Jurassic age were involved in the process of mylonitization.

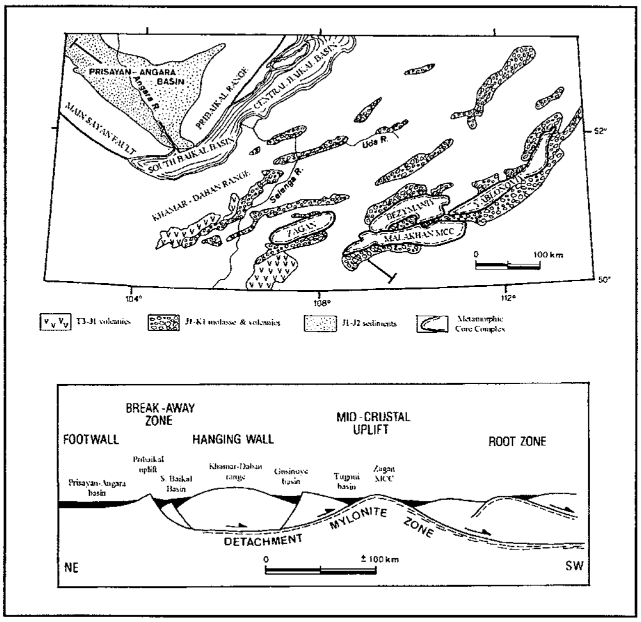

Figure 3. Mesozoic detachment-style tectonics in the southern part of the Baikal Rift System.

Mesozoic sedimentation and denudation in Baikal region

West of Lake Baikal, Early-Middle Jurassic continental molasse was deposited in a large foredeep basin, on the southern margin of the Siberian platform (Ermikov, 1994 & Fig. 3). Deep seismic sounding of the Baikal Rift Zone revealed that the depth of crystalline basement in the South Baikal basin is considerably greater (8-14 km) than previously estimated (Youngsheng et al., 1996). A layer 3-8 km thick of high velocity sediments under the 4-6 km of Neogene-Quaternary sediments might correspond to pre-rift (Mesozoic ?) sediments.

Apatite fission track thermochronology (Van der Beeck et al., 1996) revealed that the main stage of basement uplift and denudation in the shoulder uplifts of the present Lake Baikal depression (Pribaikal and Khamar-Daban ranges) occurred also in the Late Jurassic-Early Cretaceous .

Mesozoic detachment-style extensional tectonics

The close association of volcanism, magmatism, sedimentation, basement uplift and denudation, and MCC exhumation during the Late Jurassic-Early Cretaceous makes it possible to define the Late Mesozoic Pribaikal province as a Highly Extended Terrane, as defined in Olsen and Morgan (1995), with detachment-style tectonics in a thermally weakened lithosphere (Fig. 3). The breakaway zone of the main detachment is presumably situated under the Baikal basin, and the detachment should be rooted to the SE, in the direction of the paleo subduction of the Mongol-Okhotsk oceanic plate. The West-Baikal foredeep, then represents the footwall flexural basin, in front of the footwall uplift. This time-space association is very similar to that found in the Basin and Range Province within the North-American Cordillera (e.g. Parson, 1995) and in other provinces of lithospheric-scale low-angle detachment extension.

Given this long Mesozoic history, the NW-SE upper mantle seismic anisotropy of the Baikal and Transbaikal provinces, revealed by teleseismic investigation (Gao et al., 1994b) can be interpreted in a different way to that originally proposed. This anisotropy might well correspond to NW-SE flow in the upper mantle, but it is unlikely that it has been produced by the Late Cenozoic extension, since true rifting with orthogonal extension only started 3 Ma ago (see below). This texture is more likely to have been inherited from the Mesozoic detachment-style extension, which occurred with the same NW-SE direction of extension, but during a much long time (several dozens of Ma) and with much greater intensity (development of Core Complexes).

Late Mesozoic inversion and peneplenation

Paleostress investigation (Delvaux et al., 1995c) demonstrated an evolution from extensional to compressional tectonics, in the Late Jurassic-Early Cretaceous interval. A strong compressive phase, from the end of the Early Cretaceous to the Late Cretaceous, caused the inversion of the Mesozoic basins, both in Transbaikal and in West Baikal. These results correlate well with the paleomagnetic data, which suggest that China and Siberia were fully accreted in the Late Jurassic (Enkin et al., 1992). The Mesozoic history ended with a long period of tectonic stability and weathering in subtropical climate during the terminal Cretaceous-Paleocene, resulting in a widespread peneplain in Central Asia (Tian-Shan, Altai, Baikal, Mongolia, East China).

Cenozoic Rifting and Stress Field

The Baikal Rift Zone in Central Asia is a type region for studying processes of rift basin formation in an intraplate setting dominated by far-field compressive stresses. During its evolution, it has been submitted both to periodical changes in far-field stress regime, governed by modifications of kinematic processes at the plate boundary, and to the growing influence of locally generated

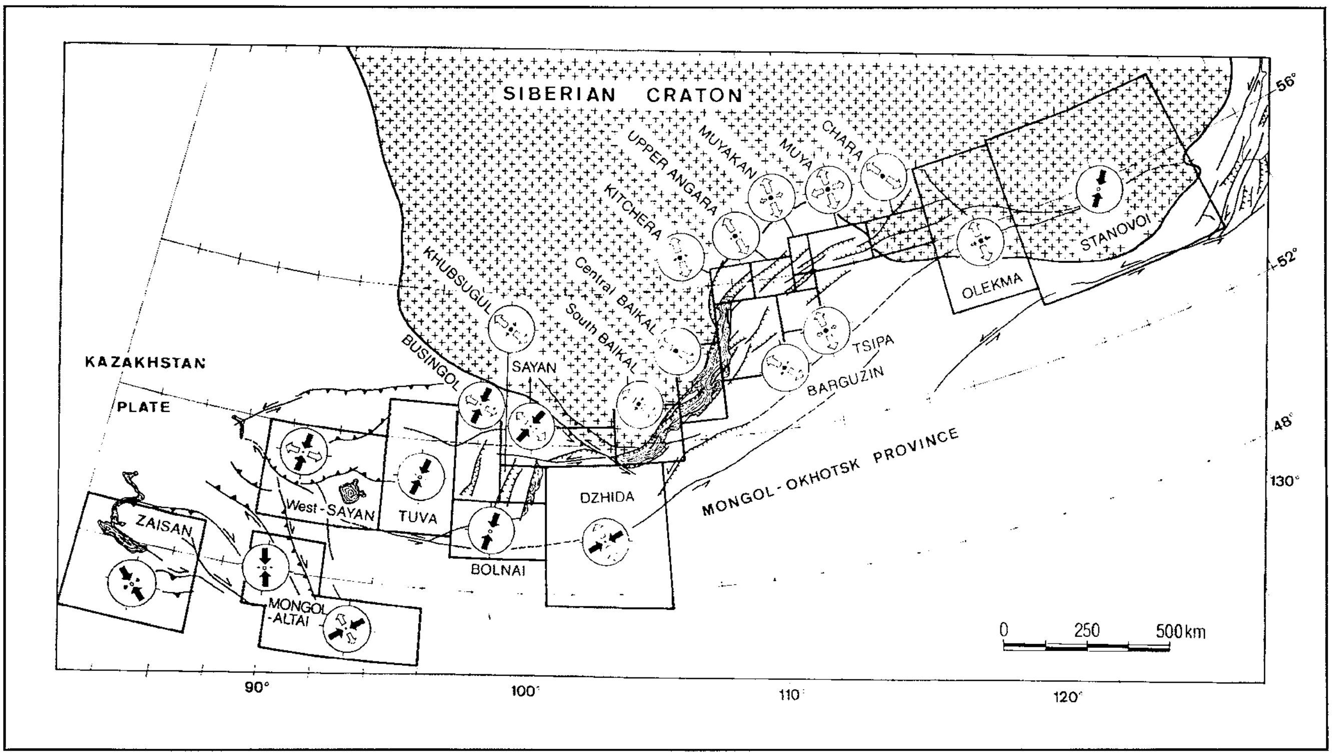

Figure 4. Present-day stress field change from Altai to Stanovoi areas, from the inversion of more than 400 focal mechanisms, including the data of Petit et al. (1996). Map projection of stress tensors with azimuth of S_{Hmax} and S_{hmin} (black for compressional and white for extensional deviatoric stresses).

extensional stresses, supposedly related to the progressive ascent of an asthenospheric diapir.

In the last few decades, there has been a considerable debate about the role of extensional stresses generated by asthenospheric diapirism and far-field stresses generated by the distant India-Eurasia collision. The distinction between "passive" and "active" rifting mechanisms appears no longer appropriate, as the tectono-stratigraphic, volcanic and stress state evolution of the Baikal Rift Zone suggest that rifting was initiated as a "passive" mechanism, from which it evolved progressively into an "active" mechanism.

Rift initiation

The integration of existing conventional geological data and reconstruction of stress field through time by stress tensor inversion from fault kinematic data (Delvaux et al., in press) shows that the Baikal rift zone originated under conditions of a continental-scale compressive stress field, linked to the combined effects of the India-Eurasia collision and convergence, and to the Pacific-East Asia subduction. Rifting started in the Late Oligocene with the development of transtensive basins, in a stress regime dominated by NE-SW to ENE-WSW horizontal compression ("proto rift" of "slow rifting" stage). This was reactivating pre-existing basement discontinuities along the suture zone between the Siberian platform and the Caledonian Sayan-Baikal fold belt. In the course of rifting, the kinematic regime changed progressively from passive transtension to active extension. In the Late Pliocene, a strong increase in tectonic activity and the installation of a pure extensional regime in the central part of the rift zone marks the onset of the "active rift" or "fast rifting" stage.

Late Pliocene-Early Pleistocene tectonic activation in Central Asia

The Late Pliocene - Early Pleistocene in Central Asia is a period of high tectonic activity. Most of the modern tectonic structures, mountain ranges and sedimentary basins were initiated during this period. Detailed investigation of the Late Cenozoic tectonic, stratigraphic and morphologic evolution of selected intra-mountainous sedimentary depressions from Central Asia shows that a plate-scale change in tectonic activity occurred at the beginning of the Late Pliocene. This change affected simultaneously a very wide territory, over most of the Central and East Asia. In the Baikal Rift Zone, it marks the transition between the "proto rift" and the "active rift" stages, with the formation of deep uncompensated lacustrine rift basins (Delvaux et al., in Press). In the Altai-Sayan and the Tian Shan Mountains this change occurred after a first stage of Paleogene-Neogene basin formation in transtensional to extensional context, and a period of decreasing tectonic activity in the Late Miocene-Early Pliocene. The next tectono-stratigraphic cycle started abruptly in the Late Pliocene, with a strong intensification of faulting activity, uplift and subsidence, erosion and sedimentation, and by a major modification of the stress field. Intense tectonic activity continued until the end of the Early Pleistocene, after which faulting activity decreased even though uplift and subsidence continued. In East China, extension in the Shanxi rift also started in the Late Pliocene.

This event caused major uplifting and mountain building in Central Asia. It corresponds precisely to the termination of faunal exchange between Siberia and Southeast Asia, and to a global climate cooling (Zykin et al., 1991; 1995). This event seems to be related to the formation of mountain ranges separated by desert depressions in Central Asia, which could have had a strong influence on atmospheric circulations. Following Chinese works, it is contemporaneous to the uplifting of the Tibet plateau, as recorded in the marginal tectonic basins (Yechun, 1996).

Late Cenozoic to present-day kinematics and stress field

The time-space variations of stress field and fault kinematics during the Late Cenozoic "active rifting" stage have been investigated for the Neotectonic period and for the Present-day (Delvaux et al., in press). The neotectonic and present-day stress fields have been reconstructed using modern techniques of stress inversion, from fault-slip data and focal mechanisms of earthquakes respectively. The neotectonic stress field is defined as the last first-order stress regime, which operated since the Late Pliocene, to the Holocene, and has been recorded at outcrop-scale by minor fault-slip data. Such data were measured in the field, in the Altai, Sayan and Baikal regions of Southern Siberia either in dated sedimentary rocks, or in the basement along major active faults (Delvaux et al., 1995a, 1995d; Delvaux et al., in press).

The present-day stress field has been reconstructed from a data-set composed of more than 300 focal mechanisms from the East Sayan and Baikal regions (Petit et al., 1996). This last analysis was enlarged to include the surrounding regions, West of the Baikal Rift Zone (Altai and Sayan Mountains), and east of it (Stanovoy belt). More than 400 focal mechanisms are available for all this region, mainly from the Russian data of Irkutsk and Novosibirsk (including those already reported by Petit et al., 1996). The present-day stress pattern (Fig. 4) shows a continuous lateral evolution from a strike-slip regime in the Altai and Sayan regions, to pure extension in southern part of the rift, with the same S_{Hmax} and S_{hmin} directions. The modern opening of the rift appears to be controlled by the far-field stress-induced reactivation of the lithospheric weakness zone at the southern margin of the Siberian Platform, and by the particular shape of the Platform, with a southwards-pointing wedge which acts as a passive oblique indentor.

As explained above, the last Cenozoic tectonic stage in Central-Asia was initiated by a major change in stress and kinematic regimes in the Late Pliocene. In Central-Baikal, the stress field changed from transtension to pure extension, with similar NW-SE S_{hmin} directions, orthogonal to the rift trend. Similarities with the present-day stress field inverted from focal mechanisms indicate that this last paleostress stage recorded in the sediments is still active now and represents the neotectonic stage.

Rifting mechanism

What induced rifting in the middle of the Central-Asian continent? The new results suggest that the Baikal rifting occurred in a cold and strong lithosphere, as a result of the particular geometry of the lithospheric-scale discontinuities at the margin of the Siberian Craton, and the action of far-field intraplate stress field produced at the plate boundaries. It was controlled by the presence of lithospheric discontinuities that can be tensionaly reactivated and rheological contrasts between the lithospheric blocks, on both side of the suture zone at the margin of the Siberian Craton.

The asthenospheric diapirism under the Baikal Rift Zone is induced by lithospheric destabilisation along a major discontinuity, rather than being the cause of extension. The history of the Baikal Rift System starts in the Late Oligocene-Early Miocene by a transpressional destabilisation of the lithosphere along the suture zone between the south-eastern margin of the Angara-Lena platform.. This may have caused adiabatic decompression and partial melting of the lower lithosphere and upper asthenosphere. This magmatic process is likely to have contributed to the thinning of the lithospheric mantle and "passive" upwelling of the asthenosphere in the zone of lithospheric thinning. The transition from transpressional to transtensional setting in the Late Miocene-Early Pliocene can be related to the progressive appearance of extensional stresses related to the development of an asthenospheric diapir and which interact with plate-scale compressive stresses.

The tectonic intensification in the Late Pliocene corresponds to a plate-scale tectonic change. This suggests that the beginning of the "active rift" stage, with fast orthogonal extension in the Baikal rift zone, is related to an external influence, rather than to the arrival of the asthenospheric diapir at the base of the crust, as generally proposed (Logatchev, 1993). It appears therefore that the major controlling factors for the Baikal rift development during the Cenozoic are: (1) the pre-rift crustal heterogeneity and shape of the Siberian Craton, (2) the onset extensional forces generated as the consequence of lithospheric destabilisation in a compressive stress regime and (3) the fluctuation of the intraplate stress field.

The Cenozoic extension generated a narrow zone of deep rift basins, rather than a detachment-style extension as during the Mesozoic. This difference can be explained by different factors, such as differences in rheology and thermal regime of the lithosphere, in strain rate, in stress field history, and by the availability of old lithospheric discontinuities that can be tensionaly reactivated. The results of Déverchère et al. (1991; 1993), Burov et al. (1994), Lysak (1995) and Petit and Déverchère (1995) and van der Beeck (1997) showed that the crust under the Baikal rift is relatively thick, with relatively low heat flow and high lithospheric strength. This suggests that the lithosphere is rather cold and is strongly elastic, thus favouring the development of a true rift system with significant brittle faulting of the upper crust.

Conclusion

The evolution of the geodynamic setting of the Baikal Rift Zone during geological history, since the early stages of the amalgamation of microcontinents around the Siberian

Craton, is responsible for the formation of lithospheric scale discontinuities surrounding the Siberian Craton. In the succession of stress fields that acted during the Paleozoic-Mesozoic, none succeeded in forming a true rift system, despite three compressive phases with different orientation of horizontal principal compression, one strongly extensional phase in the Early-Middle Mesozoic and a tectonic inversion in the Cretaceous. The Mesozoic extension generated a highly extended terrain in Transbaikal with metamorphic core complexes, narrow volcano-sedimentary basins, dyke swarms, intense volcanic and magmatic activity and important denudation, but no true rifting (Olsen and Morgan, 1995).

True orthogonal rifting was successful only in the Late Cenozoic, after a long period of lithospheric destabilisation and rift initiation in the Early Cenozoic. In the Late Cenozoic, rifting was triggered by a marked change in plate-scale stress conditions. This caused a lateral extrusion mechanism in the south-western part of the rift system, superimposed on the long-term opening mechanism driven by the presence of density anomalies in the lithosphere. The present-day stress field in the Baikal Rift System and surrounding area can be explained by the superposition of extensional stresses, locally generated by the anomalous lithosphere, on a continental-scale compressional stress field.

Discussion

Mesozoic Detachment-style Extension Versus Cenozoic Rifting

The evolution of the Baikal and Transbaikal areas since the Paleozoic presents marked similarities with the tectonic evolution of the Basin-and-Range Province (see e.g. Parson, 1995; Baldridge et al., 1995). In the Baikal and Transbaikal areas, the succession of geodynamic conditions is very similar to that in the Basin-and-Range Province, but over a longer time. It started with the subduction of the Mongol-Okhotsk oceanic plate under the southern margin of the Siberian Craton. Collision in the Silurian caused crustal thickening by compressional tectonics and large-scale granitic magmatism. In the Late Paleozoic - Middle Mesozoic, extension was triggered by plume magmatism. This extensional stage was blocked by the closure of the Mongol-Okhotsk ocean and the subsequent tectonic inversion. A second stage of extension started in the Paleogene in a cold and strong crust. Rifting was induced by transcurrent movements along the intracontinental boundary between the stable Eurasia (Siberia and Kazakhstan) and Southeast Asia.

This provokes the following question: why did not a true narrow and deep rift develop in this region during the Mesozoic? A broad zone of extension is predicted in a thermally weakened lithosphere with a shallow brittle-ductile transition, while narrow and deep rifts are likely to form in a cold and strong lithosphere with a relatively deep brittle-ductile transition (Baldridge et al., 1995; Parsons, 1995). In Transbaikal, it seems clear that the lithosphere was thermally weakened during the Mesozoic, while the Cenozoic extension occurred in a strong and cold crust.

Another question concerns the possible sources of stress for the Mesozoic extension. The following sources of stress are generally proposed for the Basin and Range Province (Parsons, 1995):

- back-arc setting at the early stage of extension;
- lithospheric thickening during long-term subduction of hot oceanic lithosphere;
- extensional spreading after orogenic thickening by collision followed by magmatism;
- the role of a mantle plume, triggering extension by thermal weakening of the lithosphere, broad uplifting and generation of buoyancy with extensional deviatoric stresses.

All these factors have been present in the evolution of the Baikal region since the Early Paleozoic, and might have influenced the development of the Transbaikal highly-extended province during the Mesozoic. It had a similar tectonic setting in a back-arc environment, it endured a collisional stage in the Silurian, followed by post-collisional magmatism. The Mesozoic extension started first with widespread volcanism, before the development of molassic grabens.

Effects of the Late Pliocene Tectonic Intensification on Rifting

Once initiated, the rifting process in the Baikal rift was progressively -intensified by lithospheric thinning which generates in-situ buoyancy extensional stresses. In the meanwhile, the Baikal Rift System remained sensitive to plate-scale geodynamic forces. Unlike in the Tian Shan and Altai-Sayan regions, the Late Pliocene event initiated a strong extension in the Baikal Rift Zone. This resulted in rapid subsidence of the rift basins and uplift of the rift shoulders. This plate-scale change intensified the slowly developing extensional process. It definitely changed the transpressional phase in to a pure extensional phase. It is therefore this plate scale kinematic process, rather than the effects of a local asthenospheric diapir under the Baikal rift, which is responsible for the rapid deepening of the Baikal basin and its evolution into a deep and uncompensated rift basin.

Crustal Extension and Extension Rates

Direct estimates of the upper crustal extension across the Baikal Lake basin, from depth-converted seismic sections (e.g. Scholz et al, 1993) have not been presented yet, but Zorin and Cordell (1991) estimated a maximum of 19.3 km of crustal extension for the South Baikal basin, from the analysis of the gravity field. Using kinematic modelling, Van der Beek (in press) obtained 13 to 16 km of extension in a pure shear lithospheric necking model and 12.5 km in a detachment model. GPS measurements in 1994-1996 show a general extension rate across the rift, between Irkutsk and Ulan-Ude of 13 +/- 3 mm/yr. (Lesne, 1996; Déverchère et al., this volume). This rate of extension is larger than generally expected, but it is of the same order of magnitude as the 19 mm/yr. Kong and Bird (1996), obtained by finite element modelling.

If the GPS extension rate can be confirmed after a longer period of observation, it has important implications for Central Asian kinematics. An extension rate of 13 mm/yr., if constant since the beginning of the "active rifting" stage (3 Ma), would imply 39 km of crustal extension for the southern half of the Baikal basin, between Irkutsk and Ulan-Ude. This amount of extension appears to be too large in the light of results obtained by Zorin and Cordell (1991) and Van der Beek (1997). This implies either that the duration of extension is shorter that 3 Ma, and/or that the extension rate is increasing with time. In both cases, the occurrence of such a fast extension rate is very recent, confirming the idea that the present-day rift is a young feature.

Influence of India-Eurasia Versus Pacific-Eurasia convergence and the role of the Tibet Plateau Uplift

According to the plate-tectonic theory, changes in the development of a region in the center of a continent are related to changes in boundary conditions at the plate boundaries. Therefore, Central- and East Asia should have been influenced not only by the India-Eurasia continental collision and convergence (e.g. Molnar and Tapponnier, 1975), but also by the Pacific-Eurasia convergence (e.g. Northrup et al., 1995). Both convergent plate boundaries are situated ~2500 km away from the center of the Baikal Rift Zone.

Kong and Bird (1996) simulated by finite element modelling the effects of these two boundaries on the kinematics of Asia. The modelling results appear to be very sensitive to friction coefficients for faults within Asia and to the amounts of shear traction applied to Asia in the Himalayan and the Pacific subductions. To model the present-day kinematics, the shear traction of the Pacific subduction has to be kept to a very low level (2 MPa), in order to prevent thrusting in the Shanxi and Baikal Rift systems. For the Himalayan thrust, the shear traction should be much higher (15 MPa), in order to prevent Tibet from collapsing.

Kong and Bird (1996) concluded that the distribution of stresses around Tibet, with S_{Hmax} radiating away from the plateau suggests that the weight of the plateau and the related potential energy is a very important mechanism in driving the neotectonics of Asia. Material is moving away from Tibet, towards the eastern boundary of Asia. The eastwards motion is mainly SE of a line from Pamir to Baikal, and the crust is very stable north of it. In the best model obtained, the Baikal rift is presently opening by normal faulting with up to 19 mm/a of general spreading, slightly less than the 23 mm/a of the surrounding block. This implies that rifting is primarily "passive", driven by microplate motions rather than by local density anomalies.

It is not precisely known when the eastwards extrusion of Central and East Asia started, nor the timing of the uplift of Tibet. In southern Tibet, Mercier et al. (1987) assessed the change from Tertiary N-S compression to Quaternary E-W extension to the Late Miocene (10-5 Ma). Progressive and continuous increasing of the Tibet uplift rate has been demonstrated by data on neotectonics, geomorphology, paleontology and sedimentology (e.g. Xiao and Li, 1995), specially since the late Pliocene- Early Pleistocene (3-2 Ma). The transition, in the last 5 Ma, from N-S compression to E-W extension in the Tibet Plateau, is explained by England and Houseman (1989), who considered the convective instability of the thickened continental lithosphere. Replacement of the colder and denser lower part of the lithosphere by hot asthenosphere (delamination) would raise rapidly the surface elevation of the Tibet, and increase its gravitational potential energy. This would happen only after a long period of lithosphere thickening. This delamination of Tibet is believed to have occurred in the Late Pliocene, concurrent with the rapid uplift of Tibet.

The gravity contrast induced by the uplift of Tibet above 3000 m is generating extensional stresses in the center of the Plateau and compressional stresses in the surrounding crust. The low level of deviatoric stress generated by plate boundaries in the best model of Kong and Bird (1996) suggests that stress induced by topography plays a major role in the Asian plate.

A review of recent ideas on the timing of tectonic activation and uplift in Asia shows that the Late Pliocene is also a critical period for the whole of Central Asia. It corresponds to the transition between the "slow rifting" and the "fast rifting" stages in the Baikal rift zone (Logatchev, 1993; Delvaux et al; in press), to the onset of the Shanxi rift system in NE China (Xiwei et al., 1996), to the transpressional tectonics and mountain building in the Altai Mountains (Delvaux et al; 1995d Cunningham et al., 1996a, 1996b), and to the compressional tectonics in Tian-Shan.

No major plate kinematic changes occurred in the neighbourhood of the Asian plate during the last 5 Ma: the direction and rate of convergence of both the Indian and Pacific plates, relative to Eurasia, remained constant. The timing of tectonic activation and uplift in most of Asia suggests that the Late Pliocene-Quaternary evolution of the Baikal Rift Zone is only indirectly related to the India-Eurasia convergence, but could be strongly influenced by the Late Pliocene delamination of Tibet and concurrent uplift of the Plateau.

The earlier history of the Baikal Rift Zone during the "slow rifting" or "proto-rifting" stage is more difficult to relate to far-field effects or plate boundary changes. Paleostress investigation showed that this period is characterised by Late Oligocene-Early Pliocene transpressional to transtensional evolution, not only in the Baikal Rift Zone (Delvaux et al., 1995), but also in the Altai Mountains (Delvaux et al., 1995d). Moreover, the S_{Hmax} direction for this period is E-W rather than N-S. In the eastern extremity of the Baikal Rift Zone, Rasskazov (1993) even suggests that the the stress field fluctuation with time in the Udokan volcanic area might be influenced by the Pacific margin. Therefore, the Pacific margin might have generated compressive intraplate stress field in the Oligocene-Miocene time in Central Asia, causing the initial destablisation of the NE-margin of the Siberian plate, and the onset of the "Proto-rift" stage in the Baikal rift. However, this needs to be documented by more detailed observations in the eastern extremity of the Baikal Rift Zone and in the Stanovoi belt.

This hypothesis should be also tested in the lights of the new estimation of the Motion of Pacific plate relative to Eurasia by Northrup et al. (1995). From a reduced convergence rate of 30-40 mm/yr. in Eocene time, the Pacific-Asia convergence increased to 70-95 mm/yr. from Oligocene to Early Miocene. At that time, the Pacific plate was subducting directly under the Asian plate, in the area of the future Sea of Japan (Shimazu et al., 1990). Suitable conditions might thus have exited for a stronger coupling between the Pacific and the Asian plate, generating compressional stresses with E-W trending S_{Hmax} in East- and Central-Asia, as in one of the model of Kong and Bird (1996). This model was considered unsuccessful in predicting present-day Asian tectonics since it generates compressional faulting in the Shanxi and in the Baikal rift system, which is not observed at present. However, in the pre-Late Pliocene period, compressional faulting was observed in the Baikal Rift zone and the Shanxi rift was not yet developing.

Future Perspectives

We hope that this discussion may give new insights into the geodynamics of Baikal rifting in a plate-tectonic environment. As a result of new developments in the geology and geophysics of the Baikal Rift Zone and surrounding areas, it seems clear that the traditional debate between "active" rifting as a consequence of a mantle diapir alone and "passive" rifting as a consequence of the India-Eurasia collision and convergence alone, has to be revised, by integrating the interaction of the Pacific-Eurasia boundary, the uplift of Tibet and the action of mantle plumes.

A list of topics which were selected during the workshop, as being of major importance for future research, and which are expected to contribute to the geodynamics of Baikal rifting, are listed below:

1. Inheritance from Paleozoic orogeny and crustal thickness before Mesozoic extension;
2. Mesozoic extensional tectonics and Cretaceous inversion, in relation to the progressive closure of the Mongol-Okhotsk ocean;
3. Geodynamics of volcanism, in Mongolia and Baikal (dating, composition, structural relationship);
4. Time-space evolution of fault kinematics and stress field in the BRZ and surrounding areas (synthesis of existing data, acquisition of new field data);
5. Neotectonics and seismotectonics (focal mechanisms, seismicity, paleoseismicity, Quaternary movement rates and slip directions);
6. Direct measurements of the present-day displacement field using geodetic techniques (GPS);
7. Significance of the Hangai and Khentey domes in Mongolia (crustal structure, volcanism, stress field, gravity);
8. Rift basin architecture from multichannel and high-resolution seismic data;
9. Morphology, climatology and relative to tectonic activity and uplift;
10. Geodynamic modelling(uplift, thermal evolution, dynamics of rift opening, finite element modelling of present-day deformation...);
11. Importance of the transition zones between the rift zone and the surrounding areas, specially to the NW (Altai-Sayan belt) and to the NE (Stanovoi - Okhotsk junction);
12. What have plumes to do with rifts and vice-versa?.

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References

Baldridge, W.S., Keller, G.R., Haak, V., Wendlandt, E., Jiracek, G.R. and Olsen, K.H., 1995. The Rio Grande Rift. In: Olsen, K.H. (Editor), Continental rifts: Evolution, structure, tectonics. Elsevier, Amsterdam, pp.233-275.

Baljinnyam, I., Bayasgalan, A., Borisov, B.A., Cisternas, A., Dem'yanovich, M.G., Ganbaatar, L., Kochetkov, V.M., Kurushin, R.A., Molnar, P., Philip, H. and Vashchilov, Y.Y., 1993. Ruptures of Major Earthquakes and Active Deformation in Mongolia and Its Surroundings. Geol. Soc. Am., Mem. 181, 62pp.

Bayanov, V.D., 1994. The Late Mesozoic Shoshonite-Latite Series in the Dzhida Orefield, Southwest Transbaikalia. Doklady Rossiyskoy Akademii Nauk, 339(3): 374-377 (in Russian). English translation: Transactions (Doklady) of the Russian Academy of Sciences, earth science sections, 1996, 342(4): 111-115.

Burov, E.B., Lobkovsky, L.I., Cloetingh, S. and Nikishin, A.M., 1993. Continental lithosphere folding in Central Asia (Part II): constraints from gravity and topography. Tectonophysics, 226: 73-87.

Burov, E.B., Houdry,F., Diament, M., and Déverchère, J., 1994. A broken plate beneath the North Baikal rift zone revealed by gravity modelling. Geophys. Res. Lett. 21: 129-132.

Cobbold, P.R. & Davy, PH., 1988. Indentation tectonics in nature and experiment. 2. Central Asia. Bulletin of the Geological Institutions of Uppsala, N.S., 14: 143-162.

Cunningham, W.D., Windley, B.F., Dorjnamjaa, D., Badamgarov, G. and Saandar, M., 1996. A structural transect across the Mongolian Western Altai: active transpressional mountain building in Central Asia. Tectonics, 15(1): 142-155.

Cunningham, W.D., Windley, B.F., Dorjnamjaa, D., Badamgarov, J. and M. Saandar. 1996. Late Cenozoic transpression in southwestern Mongolia and the Gobi Altai-Tien Shan connection. Earth and Planetary Science Letters, 140: 67-81.

Delvaux, D., Fernandez-Alonso, M., Klerkx, J., Kuzmin, A., Matton, C., Selegei, V., Theunissen, K., and Vysotskii, E, 1995a. Evidences for active tectonics in Lake Teletskoye (Gorny-Altai, South-Siberia). Russian Geology and Geophysics, 36(10): 100-112.

Delvaux, D., Dobretsov, N., Berzin, N., San'kov, V., and Miroshnichenko, A., 1995b. To what extent are the Baikal rift system and the Cenozoic depressions of Gorno-Altai (South-Siberia) related to the India-Eurasia collision ? In: D.A. Spencer, J.-P. Burg and C. Spencer-Servato (editors), 10th Himalaya-Karakoram Tibet Workshop, 4-8 April, 1995, Ascona (Switzerland), abstract volume. Mitt. Geol. Inst. Eidgenössischen Tech. Hochschuhle Univ. Zürich, Neue Folge, Nr. 298.

Delvaux, D., Moeys, R., Stapel, G., Melnikov, A. and Ermikov, V., 1995c. Paleostress reconstructions and geodynamics of the Baikal region, Central Asia. Part I: Paleozoic and Mesozoic pre-rift evolution. In: S. Cloetingh, B. D'Argenio, R. Catalano, H. Horvath and W. Sassi (eds), Interplay of extension and compression in basin formation, Special Issue, Tectonophysics, 252: 61-101.

Delvaux, D., Theunissen, K., Van der Meer, R. and Berzin, N., 1995d. Formation dynamics of the Gorno-Altaian Chuya-Kurai depression in Southern Siberia: paleostress, tectonic and climatic control. Russian Geology and Geophysics, 36(10): 26-45.

Delvaux, D., Moeys, R., Stapel, G., Petit, C., Levi, K., Miroshnichenko, A., Ruzhitch, V. and Sankov, V., in press. Paleostress reconstructions and geodynamics of the Baikal region, Central Asia. Part II: Cenozoic tectonic stress and fault kinematics. Tectonophysics.

Déverchère, J., Houdry, F., Diament, M., Solonenko, N.V. and Solonenko, A.V., 1991. Evidence for a seismogenic upper mantle and lower crust in the Baikal rift, Geophys. Res. Lett., 18(6): 1099-1102.

Déverchère, J., Houdry, F., Solonenko, N.V., Solonenko, A.V. and San'kov, V.A., 1993. Seismicity, active faults and stress field of the North Muya region, Baikal rift: New insights on the rheology of extended continental lithosphere. J. Geophys. Res., 98(B11): 19895-19912.

Diament, M. and Kogan, M.G., 1990. Long wavelength gravity anomalies over the Baikal rift and geodynamic implications. Geophysical Research. Letters., 17(11): 1977-1980.

Dobretsov, N. L., Buslov, M.M., Delvaux, D., Berzin, N.A., V.D. Ermikov. (1996). Meso-Cenozoic tectonics of the Central Asian orogenic belt: collision of lithospheric plates and mantle plume. International Geology Review, 38: 430-466.

England, P. and Houseman, G., 1989. Extension during continental convergence, with application to the Tibetan Plateau. Journal of Geophysical Research, 94(B12): 17,561-17.579.

Ermikov, V.D., 1994. Mesozoic precursors of rift structures of Central Asia. Bull. Centr. Rech. Explor. Prod. Alf Aquitaine, 18(1): 123-134.

Enkin, R.J., Yang, Z., Chen, Y. and Courtillot, V., 1992. Paleomagnetic Constraints on the Geodynamic History of the Major Blocks of China From the Permian to the Present. J. Geophys Res., 97(B10): 13953-13989.

Gao, S., Davis, P.M., Liu, H. Slack, P.D., Zorin, Y.A., Logatchev, N.A., Kogan, M., Burkholder, P.D. and Meyer, R.P., 1994a. Asymmetric upwarp of the asthenosphere beneath the Baikal rift zone, Siberia. J. Geophys. Res., 99 (B8): 15319-15330.

Gao, S., Davis, P.M., Liu, H. Slack, P.D., Zorin, Y.A., Mordvinova, V.V., Kozhevnikov, V.M. and Meyer, R.P., 1994b. Seismic Anisotropy and Mantle Flow beneath the Baikal Rift Zone. Nature, 371: 149-150.

Gordienko, I.V. and V.S. Klimuk, 1995. Bimodal volcanism of the Tugnui rift depression (Transbaikalia). Russian Geology and Geophysics, 36(5): 22-36.

Keller, G.R., Khan, M.A., Morgan, P., Wendlandt, R.F., Baldrige, W.S., Olsen, H., Prodehl, C. and Braile, L.W., 1991. A comparative study of the Rio Grande and Kenya Rifts. In: A.F. Gangi (Editor): World Rift Systems. Tectonophysics, 197: 355-372.

Kong, X. and P. Bird, 1996. Neotectonics of Asia: thin-shell finite-element models with faults. In: "The Tectonics of Asia", edited by Yin A. and Harrission, M. Cambridge University Press, 18-36, 1996.

Lesne, O., 1996. Cinématique actuelle du rift Baikal: apport de mesures de géodésie spatiale par Golbal Positioning System et modélisation numérique. D.E.A. Dynamique de la lithosphère, des marges océaniques aux chaînes de montagne. Université de Pierre et Marie Curie (Paris VI). 76p.

Litvinovskii, B.A., Zanvilevich, A.N. and Wickham, S.M., 1994. Angara-Vitim batholith, Transbaikalia: structure, petrology and petrogenesis. Russian Geology and Geophysics, 35(7-8): 190-203.

Logatchev, N.A. History and geodynamics of the Baikal rift (east Siberia): A review., 1993. Bull. Centr. Rech. Explor. Prod. Alf Aquitaine, 17(2): 353-370.

Logatchev, N.A. and Zorin, Yu.A., 1992. Baikal rift zone: structure and geodynamics. Tectonophysics, 208: 273-286.

Lysak, S.V., 1984. Terrestrial heat flow in the South of East Siberia. Tectonophysics, 103: 205-215.

Lysak, S.V., 1995. Terrestrial heat and temperatures in the Upper Crust in South East Siberia. Bulletin des Centres de Recherches Exploration-Production elf-aquitaine, 19(1): 39-58.

Melnikov, A.I., Mazukabzov, A.M., Sklyarov, E.V. and Vasiliev, E.P., 1994. Baikal rift basement: structure and tectonic evolution. Bull. Centr. Rech. Explor. Prod. Alf Aquitaine, 18(1): 99-122.

Mercier, J.L., Armijo, R., Tapponnier, P., Carey-Gailhardis, E. and Han, T.L., 1987. Change from late Tertiary compression to Quaternary extension in southern Tibet during India-Asia collision. Tectonics, 6: 275-304.

Molnar, P. and Tapponnier, P., 1975. Cenozoic tectonics of Asia: Effects of a continental collision. Science, 189(4201): 419-426.

Neymark, L.A., Rytsk, E.Y., Rizvanova, N.G., Gorokhovitskiy, B.M., 1993. Zircon and Sphene U-Pb Data on the Polychronic Nature of the Angara-Vitim Batholith. Doklady Rossiyskoy Akademii Nauk, 333(5): 634-637 (in Russian). English translation: Transactions (Doklady) of the Russian Academy of Sciences, earth science sections, 1995, 335(2): 136-140.

Northrup, C.J., Royden, L.H. and Burchfiel, B.C., 1995. Motion of the Pacific plate relative to Eurasia and its potential relation to Cenozoic extension along the eastern margin of Eurasia. Geology, 23(8): 719-722.

Olsen, K.H. and Morgan, P., 1996. Introduction: Progress in understanding continental rifts. In: Olsen, K.H. (Editor), Continental rifts: Evolution, structure, tectonics. Elsevier, Amsterdam, pp. 3-26.

Parson, T., 1995. The Basin and Range Province. In: Olsen, K.H. (Editor), Continental rifts: Evolution, structure, tectonics. Elsevier, Amsterdam, pp.277-324.

Petit, C. and Déverchère, J., 1995. Velocity structure of the northern Baikal rift, Siberia, from local and regional earthquake travel times. Geophys. Res. Lett., 20: 1677-1680.

Petit, C., Déverchère, J., Houdry-Lémont, F., Sankov, V.A., Melnikova, V.I. and D. Delvaux, 1996 Present-day stress field changes along the Baikal rift and tectonic implications. Tectonics, 15(6), 1171-1191.

Rasskazov, S.V., 1993. Magmatism of the Baikal rift system. Nauka, Novosibirsk, 285p. (in Russian).

Richardson, R.M., 1992. Ridge forces, absolute plate motions and the intraplate stress field. J. Geophys. Res, 97(B8): 11739-11748.

Schlupp, A., 1996. Néotectonique de la Mongolie occidentale analysée à partir de données de terrain, sismologiques et satellitaires. Ph.-D. Thesis, Université Louis Pasteur, Strasbourg, 172p, 1map.

Scholz, C.A., Klitgord, K.D., Hutchinson, D.R., Ten Brink, U.S., Zonenshain, L.P., Golmshtok, A.Y. and Moore, T.C., 1993. Results of 1992 seismic reflection experiment in Lake Baikal. Eos, Transactions, AGU, 74: 465-470.

Shimazu, M., Yoon, S., and Tateishi, M., 1990. Tectonics and volcanism in the Sado-Pohang Belt from 20 to 14 Ma and opening of the Yamato Basin of the Japan Sea. Tectonophysics, 181: 321-330.

Sklyarov, E.V., Belichenko, V.G., Mazukabzov, A.M., Melnikov, A.I., and Donskaya, T.V., 1994a. Evolution of the Mongol-Okhotsk ocean and formation of metamorphic core complexes. Proceedings of the International Join Symposium of IGCP Projects 283, 321, 359 in Japan. pp. 72-74.

Sklyarov E.V., Mazukabzov A.M., Donskaya T.V., Doronina N.A. and Shafeyev A.A., 1994b. Zagan metamorphic core complex. Doklady Rossiyskoy Akademii Nauk, 339(1): 83-86 (in Russian). English translation: Transactions (Doklady) of the Russian Academy of Sciences, earth science sections, 1996, 345(8): 53-56.

Stupak, F.M., 1994. Dike-Packet Complexes in Continental Stuctures of Transbaikalia: Morphology and Arrangement. Doklady Rossiyskoy Akademii Nauk, 339(1): 87-90 (in Russian). English translation: Transactions (Doklady) of the Russian Academy of Sciences, earth science sections, 1996, 345(8): 57-61.

Tapponnier, P. and Molnar, P., 1979. Active faulting and Cenozoic tectonics of the Tian Shan, Mongolia and Baikal regions. J. Geophys. Res., 84(B7): 3425-3459.

Van der Beek, P.A., Delvaux, D., Andriessen, P.A.M. and Levi, K.G., 1996. Early Cretaceous denudation related to convergent tectonics in the Baikal region, SE Siberia. Geol. Soc. London, 153: 515-523.

Van der Beek, P.A., 1997. Flank uplift and topography at the Central Baikal Rift (SE Siberia): A test of Kinematic models for continental extension. Tectonics.

Windley, F.F. and Allen, M.B., 1993. Mongolian plateau: evidence for a late Cenozoic mantle under Central Asia. Geology, 21: 295-298.

Xiwei Xu, Xingyuan Ma, Qidong Deng and Zongjin Ma, 1996. Neotectonics, paleoseismology and ground fissures ot the Shanxi (Fen-Wei) rift system, China. 30th International Geological Congress, 4-14 August 1996, Beijing, China, Field trip Guide T314.

Xiao Xuchang and Li Tingdong, 1995. Tectonic evolution and uplift of the Quinghai-Tibet Plateau. Episodes, 18(1-2): 31-35.

Yarmolyuk, V.V. and V.I. Kovalenko, 1995. Late Mesozoic-Cenozoic intraplate magmatism in Central and Eastern Asia (nature, development dynamics and volcanic hazard). Russian Geology and Geophysics, 36(8): 132-141.

Yechun, Z., 1996. Evidence for Uplift of Quinghai-Xizang (Tibetan) Plateau. In: China's Postdoctors's Contribution to the 30th International Geological Congress, Edited by Yanjing, C. and Ziguo, E. China Petroleum Industry Press, Beijing, pp. 279-286.

Youngsheng, S., Krylov, S.V., Baojun, Y., Cai, L., Shixue, D., Tiechen, L., Jingzhi, L., Xingzhui, X., Mishen'kina, Z.R., Petrik, G.V., Shelud'ko, I.F., Seleznev, V.S. and Solov'ev, V.M., 1996. Deep seismic sounding of the lithosphere on the Baikal-Northeastern China International Transect. Russian Geology and Geophysics, 37(2): 1-13, 1996.

Zoback, M.L., 1992. First- and Second-Order Patterns of Stress in the Lithosphere: The World Stress Map Project. J. Geophys. Res. 97: 11703-11728.

Zoback, M.D., Stephenson, R.A., Cloetingh, S., Larsen, B.T., Van Hoorn, B., Robinson, A., Horvath, F., Puigdefabregas, C. and Ben-Avraham, Z., 1993. Stresses in the lithosphere and sedimentary basin evolution. Tectonophysics, 226:1-13.

Zorin, Yu.A., Novoselova, M.R., Turutanov, E.K. and Kozhevnikov, V.M., 1990. Structure of the lithosphere of the Mongolian-Siberian moutainous province. Journal of Geodynamics, 11, 327-342.

Zorin, Yu.A. and Cordell, L., 1991. Crustal extension in the Baikal rift zone. Tectonophysics, 198: 117-121.

Zykin, V.S., Zazhigin, V.S. and Kazansky, A.Yu., 1991. The Late Neogene of the South of the West Siberian plain: stratigraphy, paleomagnetism, major climatic events. Russian Geology and Geophysics, 32(1): 66-72.

Zykin, V.S., Zazhigin, V.S. and Zykina, V.S., 1995. Changes in environment and climate during Early Pliocene in the Southern West-Siberian plain. Russian Geology and Geophysics, 36(8): 37-47