

One RIFT, Two Models

*Two geologists, three minds
(Saying)*

PROLOGUE

After a field season in Tanzania I learned something curious about Russian geologists from my African friends. The first thing a Russian geologist immediately says if asked about the origin of a structure is “don’t know”, and then ... a long explanation follows.

Frankly speaking, I don’t know what is the origin of the Baikal rift. Therefore it is time to set off on a lengthy discussion.

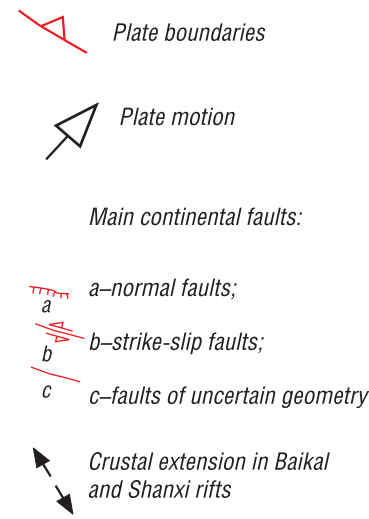
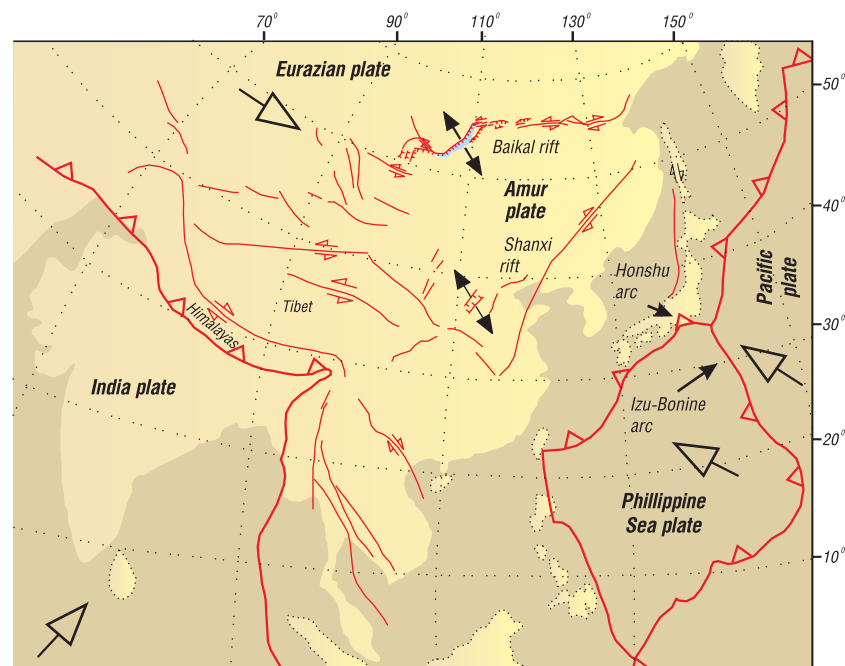
A SORT OF INTRODUCTION

The earliest report on the Baikal geology dates back to the 18th century and belongs to Peter Simon Pallas, a German by birth and a member of the Russian Academy. He wrote in 1772: “Baikal appears to witness a great catastrophe; it is in places immeasurably deep and high rocky cliffs rise from its depths. But no other evidence of breakage is found in the mountains — neither collapse faults, nor volcanoes or lavas — nothing but traces of quite rare and weak earthquakes”. Faults and volcanoes around Baikal were discovered a hundred years later and were attributed to rifting. However, purposeful studies of the Baikal rift started only in the 1950s, especially by scientists from the Institute of the Earth’s Crust (IEC, Irkutsk) where continental rifting became a subject for a science school.

The causes of rifting, including the Baikal rift, were largely discussed in the literature in the earliest 1970s. Peter Molnar from America and Paul Tapponnier from France noted a relationship between the Eocene India/Eurasia collision and crustal deformation in Inner Asia and hypothesized that the collision may have been responsible for ‘passive’ extension in the Baikal rift. This idea became very popular outside of Russia, while many Russian scientists argued that rifting on Baikal was driven mainly by thermal processes in the underlying mantle. This ‘active’ mechanism is indicated by the presence of anomalous low-density mantle beneath the rift revealed by Vera Rogozhina and Vladimir Kozhevnikov



Aleksey IVANOV— senior researcher at the Institute of the Earth’s Crust, Irkutsk, Cand.Sc. in Geology and Mineralogy. Engaged in studies of continental rifting since 1993. His study is currently being supported by grant MK1903.2003.05 from the President of the Russian Federation



Position of Baikal rift in the tectonic framework of Central Asia

STRUCTURE OF BAIKAL RIFT

The Baikal rift system, or shortly Baikal rift, is located in the middle of the Asian continent and separates two stable lithospheric blocks, the Eurasian plate in the north and the Amur microplate in the south. It extends for over 1,500 km from northern Mongolia in the southwest to the Aldan upland in the northeast and consists of several en-echelon rift basins linked by topographic highs. Fields of Late Cenozoic volcanism are found off the rift basins and their mountain borders.

Lake Baikal occupies two largest rift basins, South Baikal and North Baikal, separated by the submerged Akademicheskyy Ridge.

(IEC) from changes in seismic velocities. The discussion still continues, but ever more people agree that the two driving mechanisms may act together.

I'd better keep myself from imposing any decided opinion and would rather give a brief account of recent data — important in my view — on tectonics, volcanism, sedimentation, and deep structure of the Baikal rift. Note, however, that these data are often ambiguously interpreted.



Nikolay A. Logachev at the portrait of Nikolay A. Florensov, his teacher. Autumn 2002 (Photo by V. Korotkoruchko)

Continental rifting studies at the Institute of the Earth's Crust, Irkutsk

Systematic studies of the Baikal rift and continental rifting in general at the Institute of the Earth's Crust, Irkutsk, developed into a science school founded by Nikolay Aleksandrovich Florensov and Victor Prokopievich Solonenko, geologists, and Andrey Alekseevich Treskov, geophysicist. Florensov wrote: "My doctor thesis includes elements of coal geology, young volcanism and, especially, Late Mesozoic and Cenozoic tectonics of the Baikal and Trans-Baikal regions, all brought together. Before I was trying to find evidence of their difference from the typical African rifts but I found out that the Baikal and African rifts obviously had much in common. Fortunately, my error just remained with me, while the data cited in the thesis and later in my book <...> made a starting point for years-long comprehensive research into rifting which involves almost all people in our Institute" (Florensov, 1960).

Nikolay Florensov was the founder and the first director of the Institute of the Earth's Crust (Institute of Geology before 1962). When he left, Nikolay Alekseevich Logachev, his closest fellow scientist and devoted disciple, took over the rifting studies. Under Logachev (1976—1998) the Institute became widely known in Russia and abroad due to work on rifting-related problems. This line of science is now continued by Florensov's and Logachev's students and colleagues.

References

Mordvinova V. V., Vinnik L. P., Kosarev G. L., Oreshin S. I., and Treusov A. V. Teleseismic Tomography in Central Asia, from P and PKP Waves, in Stress-Strain State and Seismicity of Lithosphere, Izd. SO RAN, GEO, Novosibirsk, 2003.

Logachev N. A., History and geodynamics of Baikal rift, *Geologiya i Geofizika* (Russian Geology and Geophysics), 2003.

Rasskazov, S. V., Logachev, N. A. Brandt I. S., Brandt S. B., and Ivanov, A. V., Late Cenozoic Geochronology and Geodynamics. (Southern Siberia — Southern and Eastern Asia), Nauka, Novosibirsk, 2000.

Rasskazov, S. V., Saranina E. V., Demonterova E. I., Maslovskaya M. N., and Ivanov A. V., Mantle components of Late Cenozoic volcanics, East Sayan (from Pb, Sr, and Nd isotopes), *Geologiya i Geofizika* (Russian Geology and Geophysics), 2003.

San'kov V. A., Lukhnev A. V., Miroshnichenko A. I., Levi K. G., Ashurkov S. B., Bashkuev Yu. B., Dembelov M. G., Calais E., Deverchere J., Vernol M., Bechtur B., and Amarzhargal Sh., Recent crustal movements in Mongolia and Siberia from GPS data, *Doklady AN SSSR*, 2003.

Horiuchi K., Goldberg E. L., Matsuzaki H., Kobayashi K., and Shibata Y., ¹⁰Be signature in the Miocene section of BDP cores (Lake Baikal): Testing magnetostratigraphic age models, *Geologiya i Geofizika* (Russian Geology and Geophysics), 2004.

Yarmolyuk V. V., Ivanov V. G., Kovalenko V. I., and Pokrovsky, B. G., Magmatism and geodynamics of the South Baikal volcanic province (mantle hotspot), from geochronological, geochemical, and isotope (Sr, Nd, O) data, *Petrologiya*, 2003.

Barry T. L., Saunders A. D., Kempton P. D., Windley B. F., Pringle M. S., Dorjnamjaa D., Saandar S., Petrogenesis of Cenozoic basalts from Mongolia: evidence for the role of asthenospheric versus metasomatized lithospheric mantle sources, *J. Petrol.*, 2003.

Litasov K. D., Taniguchi H., Mantle Evolution beneath Baikal Rift. Center for Northeast Asian Studies, Tohoku University, Japan, CNEAS Monograph Series, 2002, V. 5.

Zorin Yu. A., Turutanov E. Kh., Mordvinova V. V., Kozhevnikov V. M., Yanovskaya T. B., and Treusov A. V., The Baikal rift zone: the effect of mantle plumes on older structure, *Tectonophysics*, 2003.

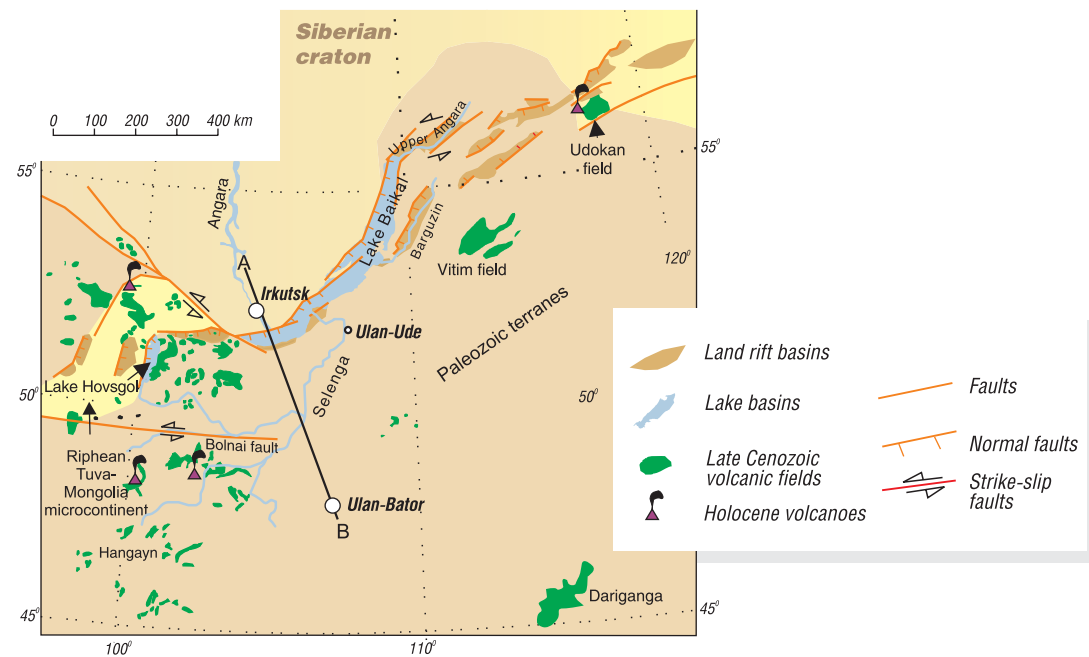
AGE OF SEDIMENTARY FILL

The Baikal basin is filled with 75,000 km³ of unconsolidated sediments, which is about 70% of the total fill of all basins in the rift system (Logachev, 2003). The South Baikal basin is apparently the oldest. Florensov and Logachev placed its age at the Late Eocene – Early Oligocene (30–35 Ma) in the 1970s. Since then this date has been traditionally cited in papers and books, though Logachev thought later that rifting possibly began much earlier.



Barge with a drilling rig making its way to Akademichesky Ridge through hummocky ice (Photo by M. Mitichkin)

Structure of Baikal rift system and distribution of Late Cenozoic volcanism. Line AB is seismic tomography profile



Pliocene-Quaternary time, inferred from variations in the sections of land rift basins. The surprising change in sedimentation rate may have been caused by tectonic uplift of the Akademichesky Ridge 5–4 myr ago which isolated the deposition area from the fluvial sediment input of the Selenga, Barguzin, and Upper Angara rivers.

To time exactly the onset of basin subsidence, one has to reach the bedrock buried under many kilometers of sediments. The sedimentary archive of Lake Baikal was investigated by the Baikal Drilling Project run for over a decade jointly by Russian, American, Japanese, and European scientists. Cores which store a unique millions-year long record of continuous deposition were recovered from deep subbottom boreholes drilled in winter seasons (1993 to 1999) from an ice-based barge. The longest record was obtained near the Akademichesky Ridge far offshore, away from land sediment sources, where the sedimentation rate is the lowest. The basal age of the 585 m core approaches 8.3 myr, and this is the oldest proven age of Lake Baikal (Horiuchi et al., 2004).

According to recentmost estimates (Horiuchi et al., 2004), bottom sediments in Lake Baikal have been accumulating at about 0.04 mm/yr for the past 4.5 myr, and before the rate averaged about 0.1 mm/yr, i. e., was over twice as fast (!). This unexpected result is apparently at odds with the common division of the rifting history into a 'slow' Oligocene-Miocene stage and a stage of 'fast' rifting in



Maloye Morye Strait, Central Baikal (Photo by V. Korotkoruchko)

ONGOING MOTIONS OF LITHOSPHERIC BLOCKS

The rate of horizontal extension in the Baikal basin was a subject of a serious discussion till recently when the problem was resolved with the use of *GPS*, satellite-based Global Positioning System. A decade of continuous and campaign *GPS* monitoring at stations in Siberia shows that the stable blocks of the Siberian craton and the Amur plate are diverging at 4 mm/yr and crustal strain is concentrated along the rift axis (San'kov et al., 2003).

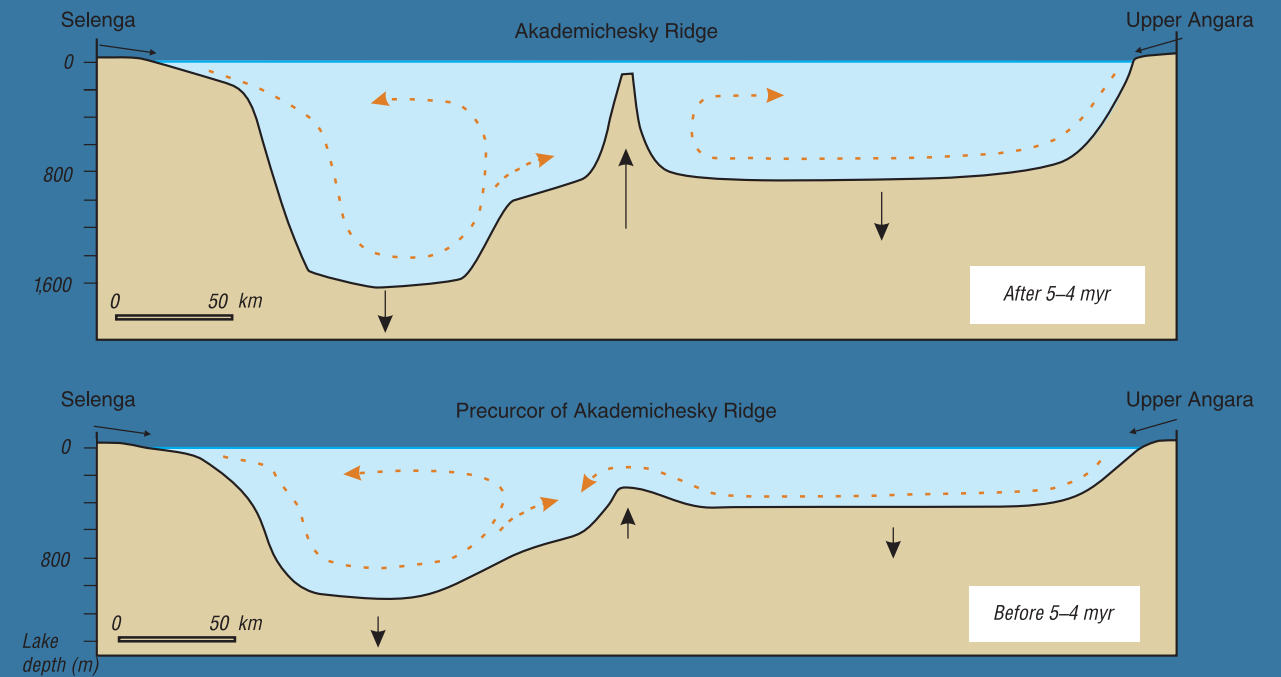
DEEP STRUCTURE

Geophysical methods provide important tools for rifting studies as they can image the present state of crust and mantle. In the three-dimensional P-wave velocity structure obtained in a joint Russian-American experiment in 1992 (Mordvinova et al., 2003), one low-velocity anomaly is detectable immediately below Baikal and another low-velocity zone is much farther south beneath Mongolia where no crustal extension was recorded. Then a reasonable question arises what slows down seismic velocities in the mantle: high temperature or composition changes? Many people give more credit to the former cause (Zorin et al., 2003).

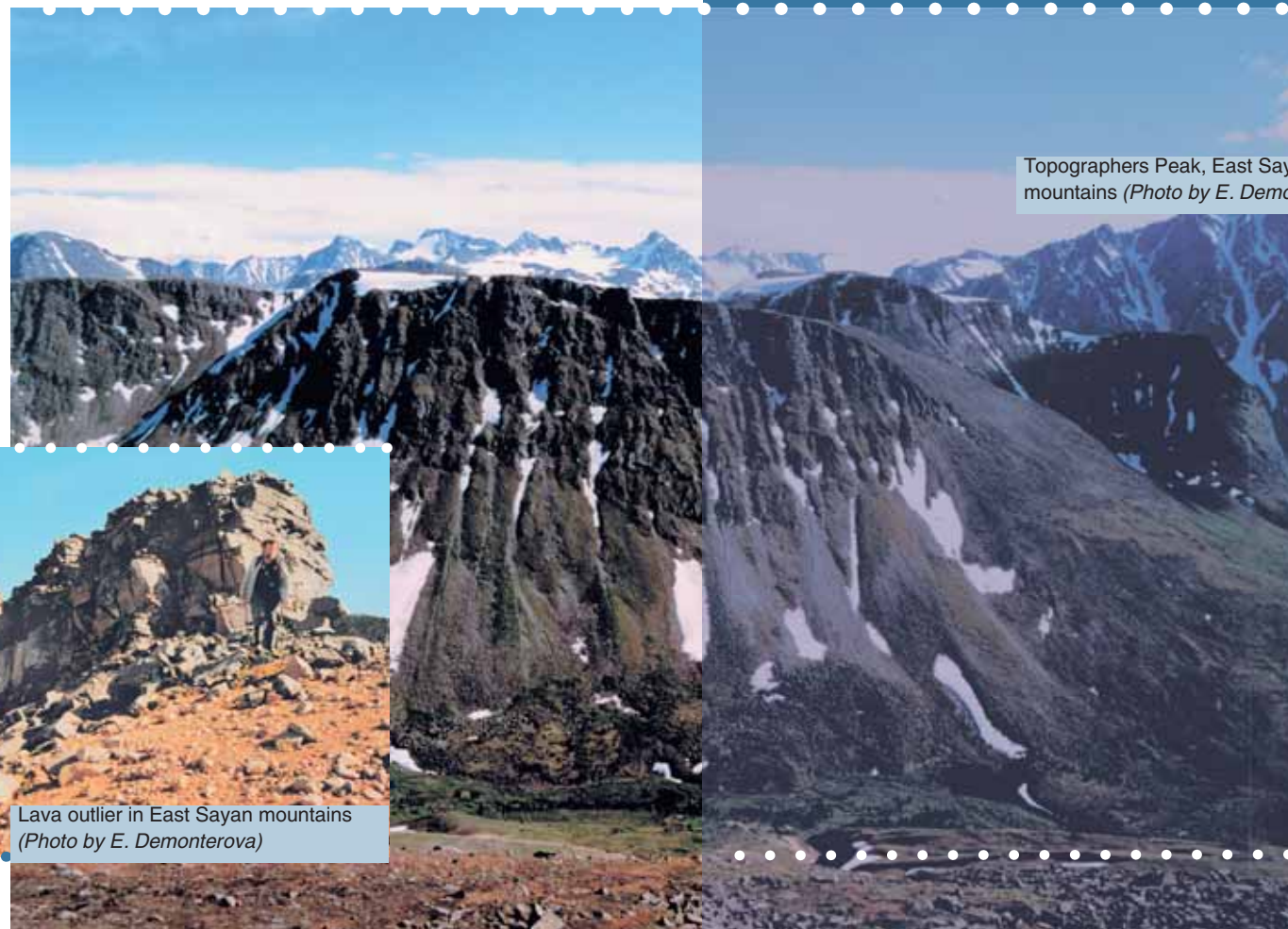
EVOLUTION OF DEEP LITHOSPHERIC THERMAL REGIME

Basaltic partial melts in rising mantle flows occasionally uptake fragments of the surrounding rocks and carry them up to the surface. These inclusions in volcanic rocks, called *xenoliths*, bear important signature of the composition and the 'life conditions' of the Earth's depths. The heaviest crop of mantle xenoliths from the eastern Vitim volcanic field belongs to Igor Ashchepkov and his colleagues from the United Institute of Geology, Geophysics and Mineralogy (Novosibirsk).

Mantle xenoliths in the Vitim Miocene lavas show evidence of origin at great depths under a broad range of pressures, whereas xenoliths in Quaternary lavas record a narrower pressure range and shallower depths. Therefore, lithosphere beneath the Vitim field was thicker in Miocene than in Quaternary time, and the thinning was estimated as ~ 15 km for 13 myr. The boundary between the crystallization depths of garnet and spinel, two indicator



Change of sedimentation rate on submerged Akademicheskoye Ridge because of tectonic uplift at 5—4 myr

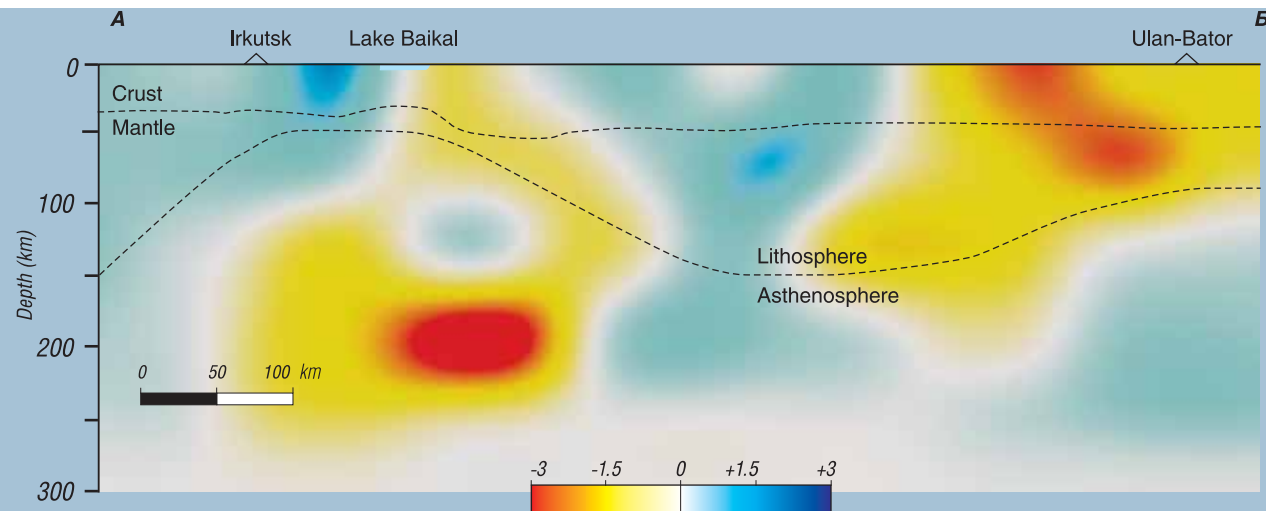


Topographers Peak, East Sayan mountains (Photo by E. Demonterova)

Lava outlier in East Sayan mountains (Photo by E. Demonterova)

minerals, deepened for about 8 km, which, according to experiments, corresponds to higher temperatures.

Note that although attenuated, the lithosphere beneath the Vitim volcanic field did not experience significant extension. The sediment-filled basins detected by drilling beneath the lavas are no wider than a few tens of kilometers and no deeper than a few hundreds of meters (Rasskazov et al., 2000).



Three-dimensional velocity structure (seismic tomography) of crust and mantle (Mordvinova et al., 2003; Zorin et al., 2003). Color shows relative variations in P-wave velocities. Crust and lithosphere thicknesses (after Zorin et al. 1989; 2003)

VOLCANISM

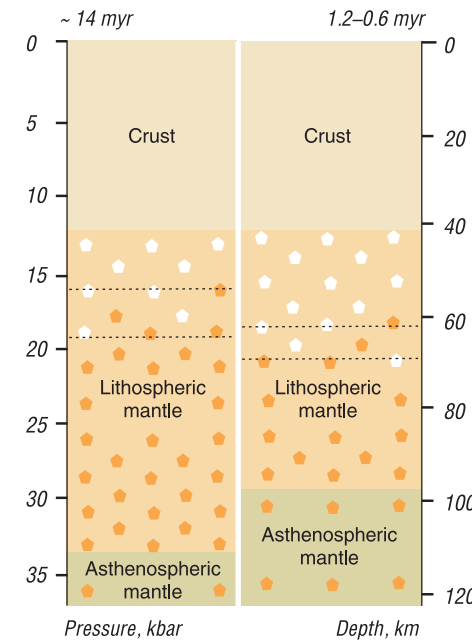
Dating of volcanics from the East Sayan and Udokan mountains revealed intricate migration paths of volcanism. Volcanism in both regions moved with time along intricate pathways, generally westward, i.e., actually in the counter direction relative to the Eurasian plate motion. This may be evidence of tectonic control of magma ascent at the junction of compressional and extensional structures. On the other hand, the westward volcanism migration is consistent with the existence of an immobile hot magma source in the asthenosphere.

Partial melting is possible in the mantle when it is heated or decompressed or enriched with volatiles. Pressure in the mantle beneath a passive rift, with lithosphere as thick as under Baikal extended at 5 mm/yr, is never low enough to initiate melting in the absence of volatiles. However, even small temperature and pressure changes can trigger melting of low-melting mantle zones containing water-saturated minerals or carbonates.

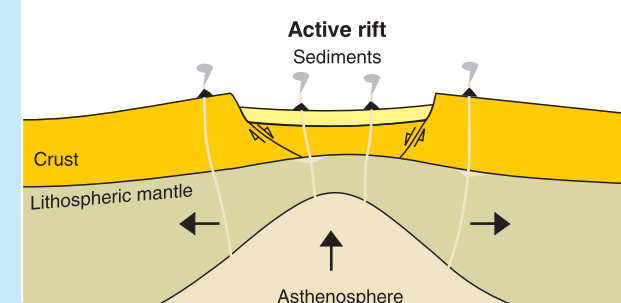
The pattern of volcanism in the region agrees neither with the position of rift basins nor with gravity lows that may correspond to abnormally hot regions. The Darigan-ga volcanic field in Mongolia is especially far off the rift. Therefore, melting of mantle beneath the Baikal rift and its surroundings may be primarily controlled by composition.

The composition of molten mantle is investigated using isotope ratios of elements. $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios measured in xenoliths from lavas in the southwestern Baikal rift were compared to those from the Hangayn mountains in Mongolia and showed that the melting mantle

zone can be divided into three parts, conventionally coded as A, B, and C components. A is sublithospheric mantle (asthenosphere) and the two others represent lithospheric mantle. B corresponds to deep garnet-bearing mantle and C to shallower spinel-bearing mantle or mantle-crust transition.

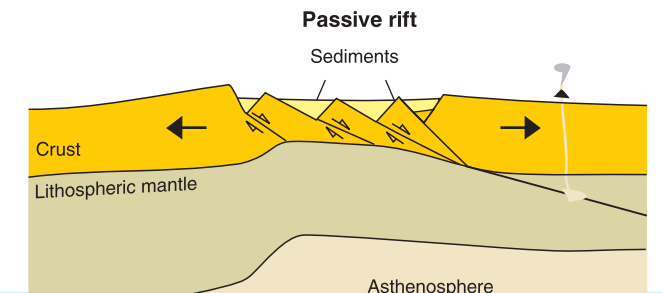


Petrological cross section of Miocene and Quaternary lithospheric mantle beneath eastern Vitim volcanic field. Mantle structure after (Litasov, Taniguchi, 2002), ages (after Rasskazov et al., 2000). Black and rose pentagons mark the presence of spinel and garnet, respectively, in lherzolite. Dashed line shows depth range where the two minerals coexist



There are two extreme views of the driving mechanism of lithospheric extension referred to as 'active' and 'passive' rifting models.

According to the 'active' model, extension in rifted lithosphere is maintained by a local deep-seated heat source produced by rising mantle flows or **plumes**. Mantle plumes may originate at the upper/lower mantle boundary about 650 km below the Earth's surface or even as deep as 2,700 km at the core/mantle boundary. Active rifting is associated with large-scale regional uplift and subsidence of tectonic basins accompanied by high heat flux and voluminous volcanism. Volcanism in active rifts precedes the regional uplift and the subsidence of rift basins, and the composition of volcanics is uniform over a large territory and independent of the age and composition of the lithosphere.



A sketch of lithospheric structure in 'active' and 'passive' rifts

The alternative 'passive' model attributes extension to tectonic stress on plate boundaries far off the zone of rifting and implies that attenuation of extended lithosphere is passively followed by upbulging of sublithospheric mantle. Passive rifts delineate old boundaries between lithospheric blocks of different ages and show moderate volcanism which postdates extension; volcanic rocks record a non-uniform composition of the lithosphere.

CORRELATION OF TECTONIC EVENTS

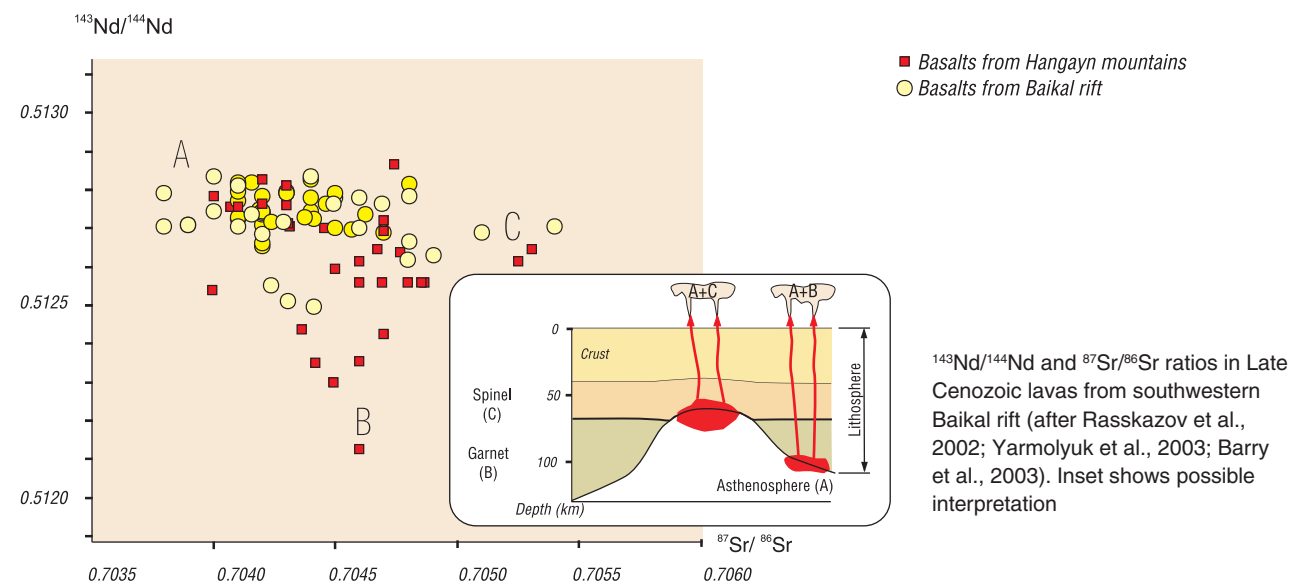
Neither collision-induced crustal stresses nor local mantle heat sources alone could initiate rifting in the Baikal region. According to recently appeared ideas, a certain role may belong to plate interaction on the eastern periphery of Eurasia.

The episodes of compression and extension in the zones of India/Eurasia and Pacific/Asia collisions are remarkably shifted in time relative to one another. The eastern margin of Central Asia experienced extension while the southern margin was compressed, and vice versa, relaxation in the southern margin was accompanied by compression on the eastern margin.

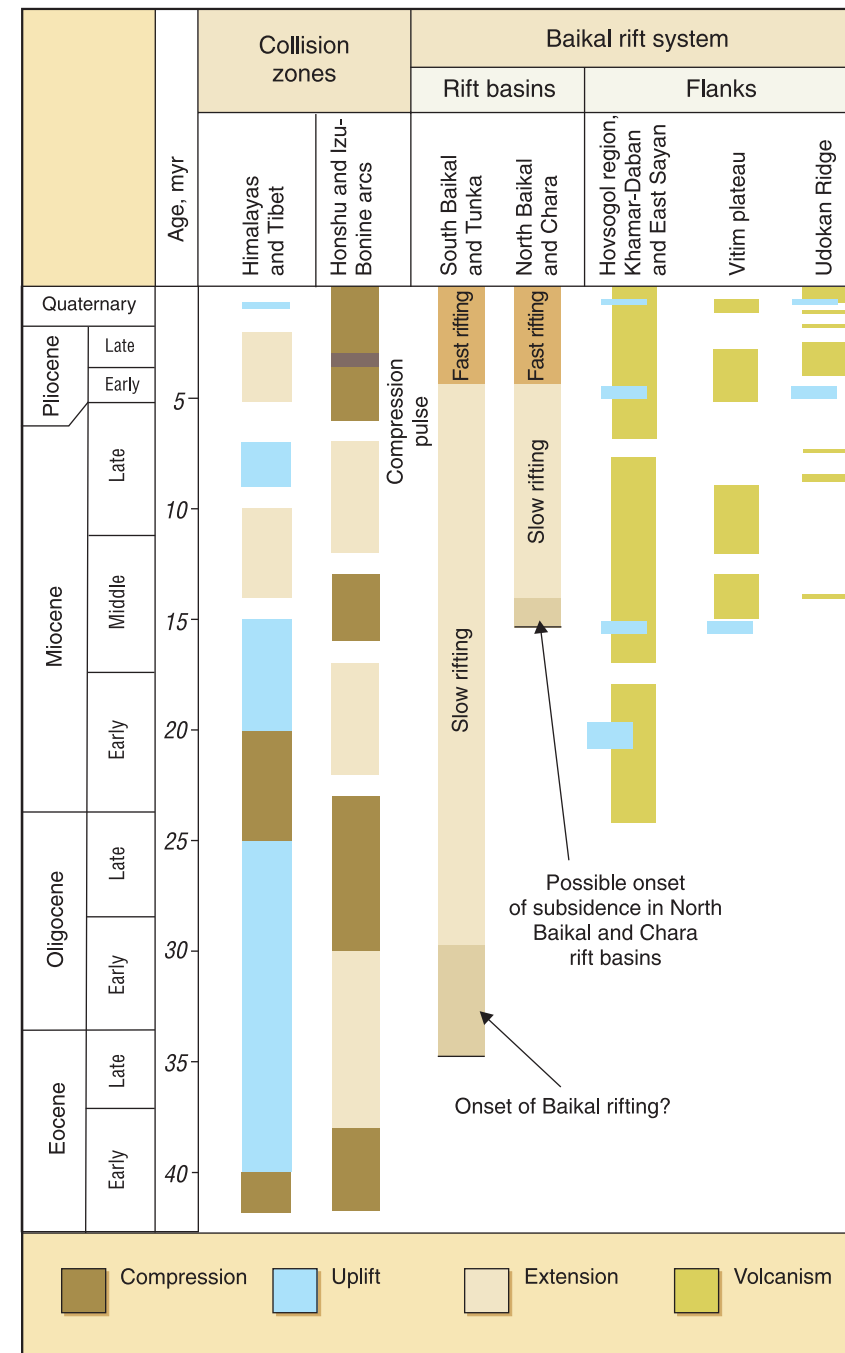
These compression/extension cycles may have loosened the inner part of Central Asia and caused motion of blocks of different geometries with compression or extension on their boundaries. If this is the case, the main tectonic pulses in Central Asia, e.g., rotation of the Amur plate, can be expected to correlate with stress changes on plate boundaries.

Unfortunately, dating of these pulses remains a difficult task.

Periods of uplift in the Baikal rift can be timed from the topographic position of dated lavas (Rasskazov et al., 1998). Four such episodes occurred 21–19, 16–15, 5–4 and ~ 0.8 myr ago. Note that the change in sedimentation rate on the submerged Akademichesky Ridge at 5–4 myr coincided with an episode of tectonic uplift. I wrote earlier that this event may mark the onset of the fast rifting stage. At that time, the front of the India/Eurasia collision was under extension, and compression on the eastern margin of Central Asia started shortly before. Thus fast rifting cannot be genetically related to remote events at the collision front but may be associated either with tectonism on the eastern margin of Asia or with thermal and/or chemical impact on the lithosphere from local mantle heat sources.



$^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in Late Cenozoic lavas from southwestern Baikal rift (after Rasskazov et al., 2002; Yarmolyuk et al., 2003; Barry et al., 2003). Inset shows possible interpretation



Tectonic events in zones of India/Eurasia and Pacific/Asia collisions correlated to tectonic and volcanic events in Baikal rift

EPILOGUE

So what – the reader may ask, – Is the Baikal rift ‘active’ or ‘passive’?

The Baikal rift shows features of both active and passive lithospheric extension: crustal strain and extension are controlled by remote tectonic events on plate boundaries whereas heating, melting, and attenuation of the lithosphere are maintained by deep heat sources or are due to low-melting zones in the mantle. The attempts to view the evolution of the Baikal rift in terms of crustal strain, volcanism, or geophysical evidence taken separately drive us to the known story of the blind sages who examined the elephant by touch.

Which are the predominant driving mechanisms of Baikal rifting and whether their role changed with time? Are crustal extension and magma generation related or independent processes? – these problems can be resolved only through integration of different lines in Earth sciences. The necessity to join the efforts is getting ever increasing understanding. I hope that the first lines of some future paper on the Baikal rift will say we know how and why it originated.