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ORIGINAL ARTICLE

A new perspective on evolution of the Baikal Rift

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Abstract A new model is suggested for the history of the Baikal Rift, in deviation from the classic two-stage evolution scenario, based on a synthesis of the available data from the Baikal Basin and revised correlation between tectonic—lithological—stratigraphic complexes (TLSC) in sedimentary sections around Lake Baikal and seismic stratigraphic sequences (SSS) in the lake sediments. Unlike the previous models, the revised model places the onset of rifting during Late Cretaceous and comprises three major stages which are subdivided into several substages. The stages and the substages are separated by events of tectonic activity and stress reversal when additional compression produced folds and shear structures. The events that mark the stage boundaries show up as gaps, unconformities, and deformation features in the deposition patterns.

The earliest Late Cretaceous—Oligocene stage began long before the India—Eurasia collision in a setting of diffuse extension that acted over a large territory of Asia. The NW—SE far-field pure extension produced an NE-striking half-graben oriented along an old zone of weakness at the edge of the Siberian craton. That was already the onset of rift evolution recorded in weathered lacustrine deposits on the Baikal shore and in a wedge-shaped acoustically transparent seismic unit in the lake sediments. The second stage spanning Late Oligocene—Early Pliocene time began with a stress change when the effect from the Eocene India—Eurasia collision had reached the region and became a major control of its geodynamics. The EW and NE transpression and shear from the collisional front transformed the Late Cretaceous half-graben into a U-shaped one which accumulated a deformed layered sequence of sediments. Rifting at the latest stage was driven by

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extension from a local source associated with hot mantle material rising to the base of the rifted crust. The asthenospheric upwarp first induced the growth of the Baikal dome and the related change from finer to coarser molasse deposition. With time, the upwarp became a more powerful stress source than the collision, and the stress vector returned to the previous NW–SE extension that changed the rift geometry back to a half-graben. The layered Late Pliocene–Quaternary subaerial tectonic–lithological–stratigraphic and the Quaternary submarine seismic stratigraphic units filling the latest half-graben remained almost undeformed. The rifting mechanisms were thus passive during two earlier stages and active during the third stage.

The three-stage model of the rift history does not rule out the previous division into two major stages but rather extends its limits back into time as far as the Maastrichtian. Our model is consistent with geological, stratigraphic, structural, and geophysical data and provides further insights into the understanding of rifting in the Baikal region in particular and continental rifting in general.

1. Introduction

The Baikal Rift zone is a large high-latitude Cenozoic continental rift in Asia that formed along the plate boundary between the Siberian craton and a collage of microplates to the southeast. The system of rift basins stretches for over 1600 km from northern Mongolia in the southwest to the Aldan shield (Yakutia) in the northeast and consists of three segments: the largest SW–NE Lake Baikal segment (Baikal Rift proper) following the craton edge between the shortest N–S striking southwestern flank and the ENE northeastern flank. The Baikal Rift basin, in turn, includes three bathymetric sub-basins of Lake Baikal (South, Central, and North Baikal) separated by the Selenga Delta and Academichesky Ridge (Fig. 1).

The mechanisms of Cenozoic rifting in southern Siberia have been debated for more than three decades (e.g., Khain, 1990). Some authors have argued for local sublithospheric sources (Logatchev and Zorin, 1987; Logatchev, 1993, 2003; Zorin et al., 2003), others have invoked far-field effects from the India–Eurasia collision (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979; Zonenshain et al., 1979), while integrated models have reconciled the "active" and "passive" scenarios suggesting various combinations of internal and external forces (Das and Filson, 1975; Popov, 1990; Popov et al., 1991; Solonenko et al., 1997).

Much less debatable has been the timing of the onset of rifting, placed more or less unanimously within the Oligocene (Logatchev and Zorin, 1987; Zonenshain et al., 1995; Delvaux et al., 1997; etc.). However, there has been no dispute that rift evolution has included two major stages with slow and fast rifting (Logatchev and Zorin, 1987). The history of the Baikal Rift was divided into two stages proceeding from the structure of subaerial Cenozoic sedimentary sections with two units of lower and upper molasse (e.g., Logatchev, 1993, 2003) which were correlated with the early and late orogenic events.

There were some attempts before to refine the two-stage model, in terms of both age and structure. For instance, Logatchev (1993, 2003) suggested a longer history of rifting, possibly since 50 or 40 Ma ago, but proceeded mainly from modest palynological evidence. The model by Delvaux et al. (1997) based on paleostress reconstructions included a pre-rift stage of "initial destabilization" since the Eocene, a proto-rift stage in a transpression–transtension context since the Late Oligocene, and an extensional active rift stage since the Late Pliocene, with two additional substages of a Late Miocene–Early Pliocene transition (8–3 Ma) within the earlier major stage and a modern rift (1–0 Ma) within the later stage. Hutchinson et al. (1992) identified proto-rift, middle-rift, and modern-rift deposits in multi-channel seismic reflection images of the basin fill. The seismic stratigraphy by Moore et al. (1997) yielded two major sets of seismic sequences, but with several subsets and three faulting intervals. The authors of the seismic stratigraphy-derived models (Hutchinson et al., 1992; Moore et al., 1997; etc.) admitted their division was only relative and devoid of chronostratigraphic control. They tried to fit their data to the existing evolution scheme with reference to Florensov, Logatchev, and Mats (Logatchev and Florensov, 1978; Logatchev and Zorin, 1987; Mats, 1993) and tentatively counted the rift history from the Late Oligocene or even Miocene. The main problem with these models was the lack of correlation between the submarine section and the surrounding onshore sedimentary sequences, or miscorrelation of the oldest sedimentary sequence with the Tankhoi Formation (Zonenshain et al., 1995) which is actually younger than the lake section base.

Evidence of Late Cretaceous–Early Oligocene lacustrine deposition had been reported from the South and Central Baikal basins and their surroundings earlier (Mats, 1987) than the cited seismic reflection and submarine geological studies during late 1980's–1990's were undertaken. This is a beach facies of quartz gravel and fine pebbles, a hemipelagic facies of dense kaolinitic mudstone with very thin laminations, and a deltaic facies, as well as facies of low watersheds on the periphery of the reconstructed paleolimnic basins (Mats, 1987, 1993, 2001; Mats and Yefimova, 2011; Mats et al., 2004). These relatively widespread limnic deposits with marked facies diversity denote the earliest geomorphic elements of the Baikal Rift. Late Cretaceous (earliest Maastrichtian) – Early Oligocene sediments are redeposited lateritic-kaolinitic weathering derivatives which are stratigraphically lower than the older molasse sequence and constitute another lithologically dissimilar unit that was accumulated in a different earlier setting, besides the two molasse units.

For this reason, we suggest that during the Maastrichtian–Early Oligocene period a rift rather than a pre-rift stage was already in existence: at this time diffuse lithospheric extension that acted over a large area of Asia produced a half-graben in the weak zone of long-lived lithospheric suturing between the Siberian craton and the Baikal folded area (part of the Central Asian orogen). Then, there followed the commonly distinguished two stages of rift development: an older Late Oligocene–Early Pliocene period and the latest stage which has continued since the Late Pliocene.

The deposition history of the Baikal Basin during the three major stages is recorded in the corresponding tectonic–lithological–stratigraphic complexes (TLSC) in subaerial sections distinguished in (Mats, 1987, 1993, 2001; Mats et al., 2004, 2010), and in seismic stratigraphic sequences (SSS) in

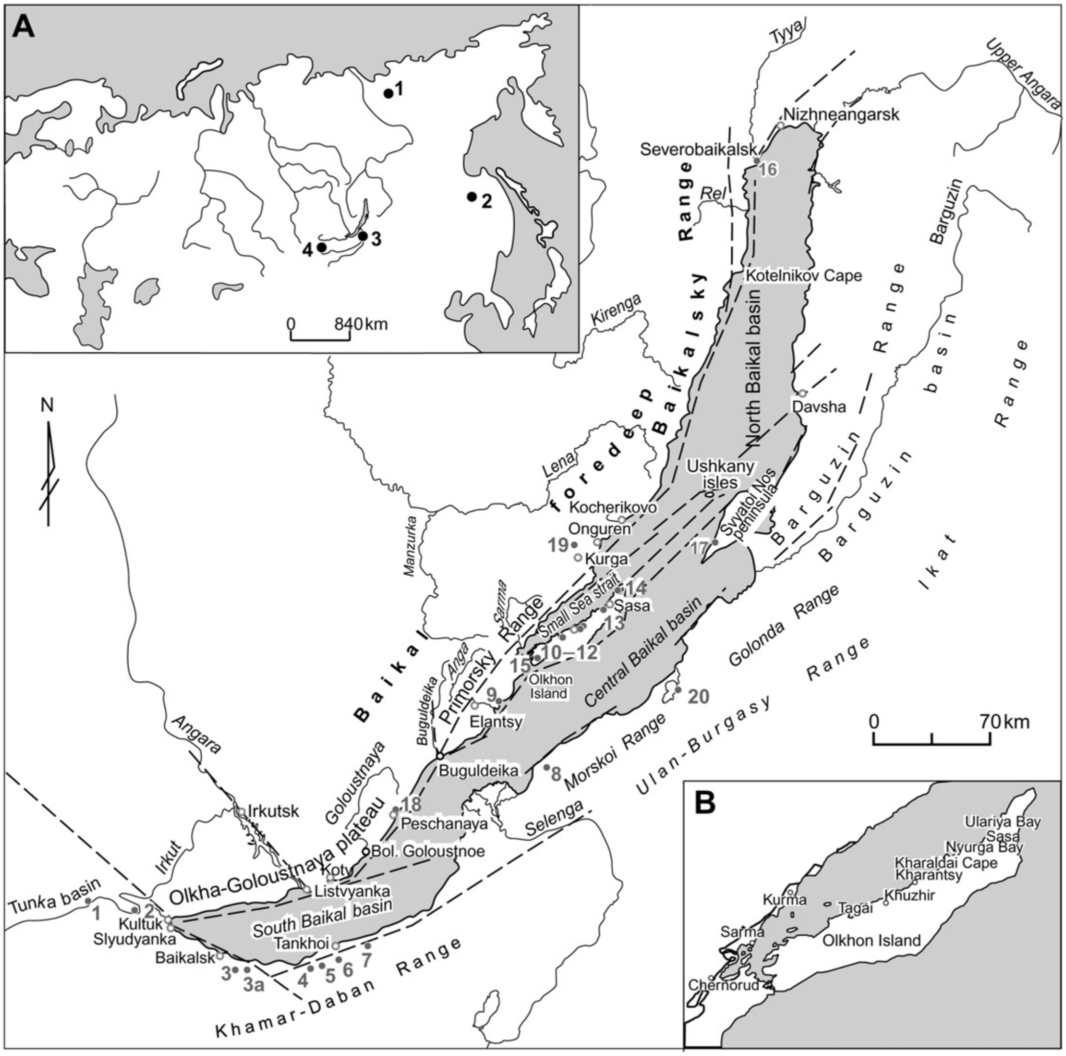

Figure 1 Location map of the Baikal Rift. Numerals from 1 to 19 mark locations of reference sections, keyed as Zamaraikha River (1); Irkut River, Anchuk (2); Shankhaikha River (3); Osinovka Kedrovskaya River (4); Anosovka River (5); Osinovka Tankhoi River (6); Polovinka River (7); Oimur Village, a 120 m terrace (8); Aya Bay (9); Tagai Bay (10); Sarai (Odonim) Bay (11); Cape Kharantsy (12); Nyurga (Peschanka) Bay, Cape Sasa (13); Ulariya Bay (14); Zagli Bay (15); Tyya River–Severobaikalsk city (16); Svyatoi Nos Peninsula (17); Peschanaya and Babushka bays (18); Mindei Basin (19); Lake Kotokel (20). Dashed lines = major faults. Inset map in top left-hand corner (A) shows distribution of heat-loving animals in the Pliocene–Eocene Sinian-Indian zoogeographic province (Martinson, 1998). Numerals 1–4 mark regions of Arctic (1); Russian Far East (2); Lake Baikal (3); Kola Peninsula (4). This distribution provides evidence for the absence of mountain barriers and the position of climate zones farther to the north relative to the present ones. Inset map in bottom right-hand corner (B) enlarges Olkhon Island and its surroundings.

lake sediments (Hutchinson et al., 1992; Kazmin et al., 1995; Colman et al., 1996; Moore et al., 1997).

The ~70 Ma tectonic history of the Baikal Rift included multiple events associated with changes in stress and rift architectonics, geometry, and lithology of basin sediments that are revealed as deposition gaps, unconformities, and deformation features. The existence of such events was recognized by Florensov fifty years ago (Florensov, 1960, 1974; Logatchev and Florensov, 1978), but more recent attention has been given to a single compression event between two evolution stages (Logatchev and Zorin, 1987; Logatchev, 1993, 2003; Sankov et al., 1997).

This paper presents a synthesis of data (Mats, 1987, 1993, 2001; Mats et al., 2004, 2010) from around Lake Baikal (Fig. 1), which has allowed the compilation of stratigraphy (Table 1) and correlation (Table 2). Evidence from subaerial sections is correlated with reflection profiling (Figs. 2 and 3) and geological data from the lake sediments (Hutchinson et al., 1992; Zonenshain et al., 1993, 1995; Kazmin et al., 1995; Bukharov and Fialkov, 1996; Colman et al., 1996; Moore et al., 1997; Mats et al., 2000a; Ceramicola et al., 2001; Khlystov et al., 2001) and deep drilling results (Baikal Drilling Project Members, 2000; Kuzmin et al., 2000; Bezrukova et al., 2004; etc.) to provide a more complete account of the rifting history.

The systematic lithological–stratigraphic study of sedimentary sections from Lake Baikal and its surrounding area forms the basis for a new model of Baikal Rift evolution which comprises three major stages separated by tectonic events. The major stages and corresponding terrestrial and submarine sedimentary units (TLSC and SSS) are subdivided into several substages. For convenience, the oldest sedimentary complexes are labeled TLSC-1 and SSS-1 and the following are TLSC-2, TLSC-3 and SSS-2, SSS-3; the more detailed stratigraphic division is TLSC-2-1 and 2-2, SSS-2-1, 2-2, 2-3.

Table 1 Upper Cretaceous–Cenozoic stratigraphy of the Baikal region (modified after Mats, 2001).

Period	Epoch/stage		Base ages are in Ma according to Geological Time Scale (2008)	*SSS	**RCS	Correlation of local stratigraphic units		
							South and Central Baikal	Northern Baikal (Olkhon area and North Baikal basin)
Quaternary	Pliocene	Ionian	0.7	Undeformed layered	Nyurga	Ust'-Selenga sequence: lacustrine and deltaic clay, siltstone, sandstone, conglomerate, with molluscs, diatoms, spore-pollen assemblages, > 3000 m	Lacustrine, fluvial, and fluvial-proluvial sand and pebble of relict submontane plain and terraces of Lake Baikal	Sand and pebble of Baikal terraces **Nyurga Formation**: lacustrine and proluvial sand; sand and pebble, with fossils of small and large mammals, mollusc shells, pollen assemblages; diatoms; Brunhes-Matuyama paleomagnetic reversal at base of section, 20 m
		Calabrian	1.80					**Zagli Formation**: sand, loam, fossils of Late Calabrian-Ionian small mammals 5 m **Soil-loess** sequence, with fossils of Early Calabrian small mammals 4–6 m
Neogene	Miocene	Paicenzian	3.6	Deformed layered	Shankhaikha		**Shankhaikha Formation**: fluvial-lacustrine pebble and sand, with fossils of Late Pliocene small mammals, spore-pollen assemblages, and diatoms (including *Aulacoseira baicalensis*) 100 m Weathering mantle	**Kharantsy Formation**: subaerial reddish-brown and dark-brown clay, synsedimentary soils, with signature of glaciation in upper part, proluvial sand, debris, with fossils of Late Pliocene small mammals and molluscs; lower half of Matuyama chron; Gauss-Matuyama polarity reversal below, Olduway chron above 12–15 m Red weathering mantle and paleosols
		Zanclean	5.3		Tankhoi		**Tankhoi Formation**: Lacustrine and lacustrine-bog clay, siltstone, sandstone, coal; upper part: turbidite, with pollen assemblages; mollusc shells (including *Baikaliidae*), fishes, leaf imprints. 1200 m **Osinovka Formation**: fluvial-proluvial-deltaic-lacustrine sand and pebble, conglomerate, and siltstone, with diatoms and spore-pollen assemblages 1000 m	**Sasa Formation**: lacustrine clay, siltstone, sand, subaerial red sand, loam, and soils, with fossils of Late Miocene and Early Pliocene small mammals, molluscs, ostracods, and diatoms; lacustrine cobble, pebble, and debris at base < 120 m Red weathering mantle and paleosols
		Tortonian	11.6					**Tagai Formation**: gypsum-bearing lacustrine and lacustrine-bog montmorillonite limy clay, sand, brown coal, including gypsum-bearing varieties, with abundant fossils of Early and Late Miocene mammals, water birds, amphibians, fishes, molluscs, diatoms, and spore-pollen assemblages < 20 m
		Langhian	16.0					
		Aquitanian	23.0					
Paleogene	Oligocene	Chattian	28.4				Kaolinite weathering mantle	Montmorillonite weathering mantle
		Rupelian	33.9	Transparent	Kamenka			
	Eocene	Ypresian	55.8				Quartz-quartzite lacustrine pebble in bays of Peschanaya, Babushka, and Sennaya; pre-Tankhoi siltstone with Pliocene-Eocene miospores; slope-wash red kaolinite clay on watersheds of Primorsky Range; quartz alluvium of ancient valleys; iron-manganese concretions, laterite-bauxite rocks, metasomatic phosphorite; kaolinite breccias and clay deposited in small lakes < 10–15 m Peneplain and laterite-kaolinite weathering mantle, < 100–120 m in linear zones and 5–10 m in relict surfaces	Slope-wash, proluvial, and lacustrine (deposited in a large lake) red goethite-illite clay, kaolinite phosphorite, and halite, with fossils of Early Oligocene small mammals < 25 m
	Paleocene	Selandian	61.1					
		Danian	65.5					
Cretaceous	Maastrichtian		70.6				Kaolinitic weathering mantle	

*SSS: seismic sequences, after Hutchinson et al. (1992)
**RCS: regional correlation stage

Table 2 Correlation of Upper Cretaceous–Cenozoic sedimentary sequences in Baikal Rift.

Period	Epoch	Stage	Base ages are in Ma according to Geological Time Scale(2008)	Regional correlation stage	Substage	Seismic-stratigraphic sequence (Hutchinson et al., 1992; Kaz'min et al., 1995)	Tectonic event	Ma	Reflector
Quaternary	Holocene		0.01	Nyurga		undeformed layered SSS-3	Tyya	0.15 – 0.12	A-2. U-1
	Pleistocene	Late Pleistocene	0.13				Primorsky	1.0 – 0.8	A-1. U-2
		Ionian	0.7						
		Calabrian	1.80				Nyurga Olkhon	2	B-10. U3
Neogene	Pliocene	Paicenzian	3.6	Shankhaikha		upper deformed layered SSS-2-2		3 – 4	B-6. U-4
		Zanclean	5.3	Tankhoi	Sasa substage			10	B-2.U-5
	Miocene	Tortonian	11.6		Tagai substage	lower deformed layered SSS-2-1	North Baikal		
		Langhian	16.0						
		Aquitanian	23.0					27 – 25	
Paleogene	Oligocene	Chattian	28.4				Tunka		U-6
		Rupelian	33.9	Kamenka		transparent SSS-1		70 – 60	
	Eocene	Ypresian	55.8						
	Paleocene	Selandian	61.1						
		Danian	65.5						
Cretaceous		Maastrichtian	70.6				Late Mesozoic		
		Basement		Basement		Basement	Mesozoic orogen		

A, B = reflectors, after Moore et al. (1997); U=unconformities in lake sediments, after N.K. Wong (personal communication)

All data reported in this paper were obtained from the Baikal Basin and in its flanking mountains referred to jointly as "the Baikal Rift". Data from the southern (Khamar–Daban Mountains) and central (Olkhon Island area) parts of the Baikal Basin have especially important implications for stratigraphy and lithology of syn-rift deposits. Geological data from the Olkhon Island area have reliable biostratigraphic constraints due to multiple finds of Miocene–Quaternary faunas of mammals and land mollusks (Logatchev et al., 1964; Popova, 1981; Mats et al., 1982; Pokatilov, 1985; Vislobokova, 1990). Onshore and submarine sections of the central part of the basin provide valuable data for understanding the stress evolution as the strike of Cenozoic structures closely follow the general strike of the rift zone. Perfect exposures in many onshore sections in Olkhon Island and in the area of the Primorsky Range (uplifted western rift shoulder) clearly show pronounced deformation patterns.

The evolution trends of the Baikal Basin, the largest and oldest part of the Baikal Rift zone, provide clues to the history and dynamics of the entire rift system, as well as to continental rifting as a whole.

2. Tectonic phases

The patterns of deposition in subaerial and submarine sedimentary sections reveal five major (Late Mesozoic pre-rift, pre-Maastrichtian early rift, Middle Oligocene Tunka, Middle Pliocene Olkhon, and Early Quaternary Nyurga), and three secondary (Middle Miocene North Baikal, Middle Quaternary Primorsky, and Late Pleistocene Tyya) tectonic phases, with residual post-tectonic activity during the Tyya event.

2.1. Late Mesozoic pre-rift event

The evolution of the Baikal Rift was preceded by Late Mesozoic tectonic activity correlated with Stille's Neocimmerian orogenic phase, which involved Jurassic ranges and molasse basins (Sayan and Baikal foredeeps).

2.2. Earliest rift tectonic phase, Early Maastrichtian

The Mesozoic orogen was denuded, and its denudation went through its final stage in the early Maastrichtian (70 Ma) during a deposition hiatus. This was followed by the formation of a primary rift-related peneplain and the development of a laterite–kaolinite weathering mantle derived, among other rocks, from the Mesozoic molasse of the Sayan and Baikal Basins. Surface planation and weathering continued until the Middle Oligocene (Mats, 2001; Mats et al., 2004). Earliest basaltic volcanism (~70 Ma) appeared in the basement of the Tunka basin (Rasskazov, 1993). Graben basins subsided and accumulated volcanic-sedimentary detritus which was subject to Paleocene–Eocene lateritic weathering (Florensov, 1974).

The initial events that mark the beginning of the Baikal Rift comprise the early rift tectonic phase and correlate with Stille's

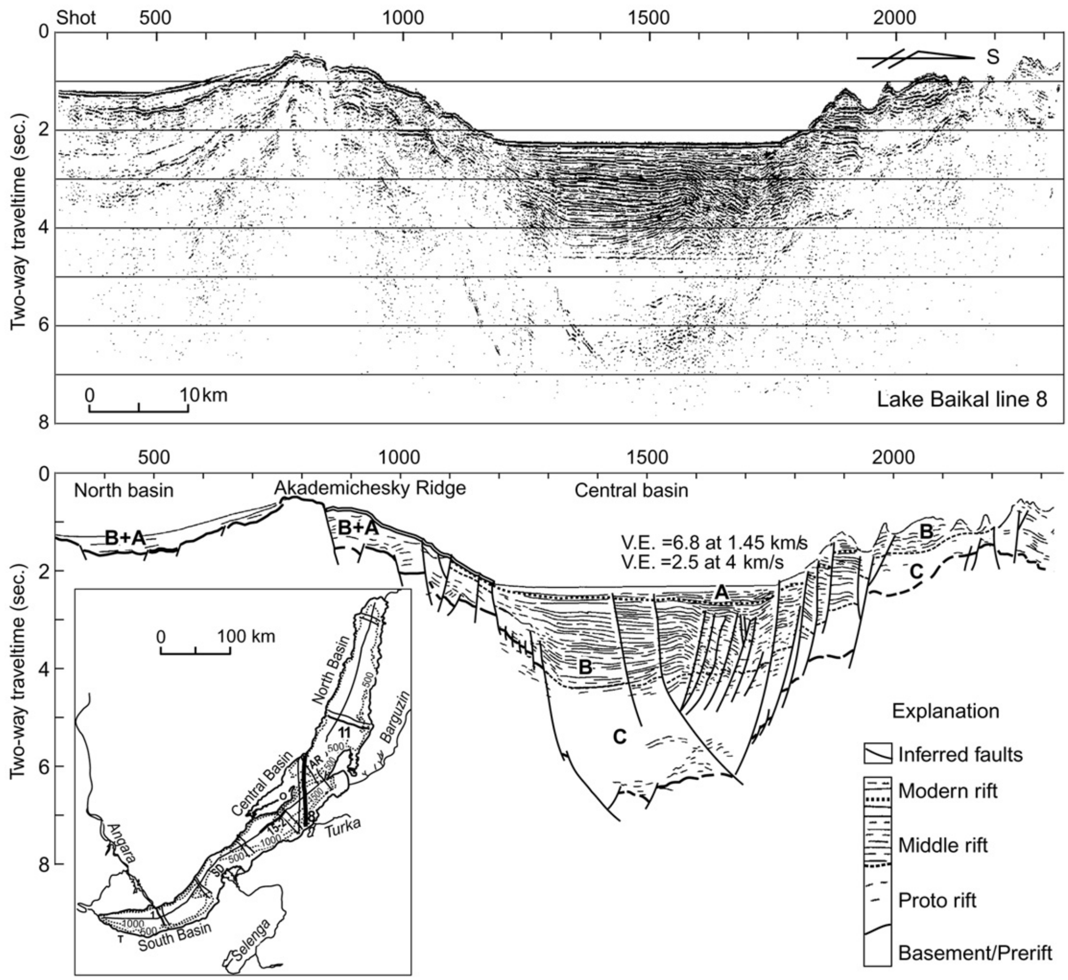

Figure 2 Multi-channel seismic reflection profiling data (modified after Hutchinson et al., 1992). Profile 8 across submerged Akademichesky Ridge (northeastern prolongation of Olkhon Island) and the flanking North and Central Baikal sub-basins. Letters label seismic stratigraphic units: A = undeformed layered unit SSS-3 (Quaternary); B = deformed layered unit SSS-2 (Upper Oligocene–Pliocene); C = unit SSS-1 (Upper Cretaceous-Lower Oligocene); A + B are combined SSS-2 and SSS-3. Inset map shows trackline locations in Lake Baikal. Thick line = profile 8; thin lines = other profiles. Explanation is according to Hutchinson et al. (1992).

Laramide orogeny. This is marked by an unconformity at the base of the Maastrichtian sequence associated with the onset of surface planation. The unconformity is especially prominent in the Baikal foredeep (Pavlov et al., 1976; Zamaraev et al., 1976). In subaerial sections around Lake Baikal, unconformities and gaps appear as "telescoped" features in the Cretaceous–Paleogene weathering profile and as hiatuses at the base of Late Cretaceous–Early Oligocene sections. Stratigraphic equivalents of the pre-Maastrichtian weathering profile proper have been reported from Olkhon Island (Fig. 1, inset B) (Mats, 2001), where Upper Cretaceous lacustrine kaolinitic mudstone overlying pre-Maastrichtian white kaolinitic weathered rocks fills a small graben which is now exposed at Cape Kharaldai (Fig. 4), and is apparently a consequence of the Tunka event (see below). Furthermore, pre-Maastrichtian white kaolinite at Ulariya Bay underlies Paleogene clay with Early Oligocene small mammal fauna, and is overlain by Upper Miocene clay (Sasa Formation). The early Maastrichtian event was the beginning of a ca. 40 Myr period of Late Cretaceous–Early Oligocene peneplanation and weathering associated with the formation of laterite–kaolinite.

The Baikal Basin originated as a half-graben with a detachment zone marked by a system of listric faults, known collectively as the Obruchev Fault (Lamakin, 1955), along an old zone of weakness at the craton edge. Upper Cretaceous–Early Oligocene half-graben fill forms an acoustically transparent syn-rift unit SSS-1 (Fig. 2), which is >4 km thick wedge with deposition centers adjacent to the detachment zone (Hutchinson et al., 1992).

2.3. Tunka phase, Middle Oligocene

The Tunka phase of basin subsidence and denudation is indicated by a regional unconformity, a deposition gap, and a weathering profile at the base of the Late Oligocene–Miocene section. The unconformity at the Oligocene–Miocene boundary, a feature of the Tunka event, is the most prominent at the base of the Tunka basin (Fig. 1) where the section begins with the Tankhoi Formation (Table 1) which lies discordantly over a graben with volcanic-sedimentary fill and related Paleocene–Eocene lateritic rocks but immediately overlies the basement on the rift basin sides (Florensov, 1974). The paratype of the Tunka event is found at the boundary between the Upper Oligocene–Miocene section (Tankhoi and Osinovka Formations) and the weathered (kaolinitic)

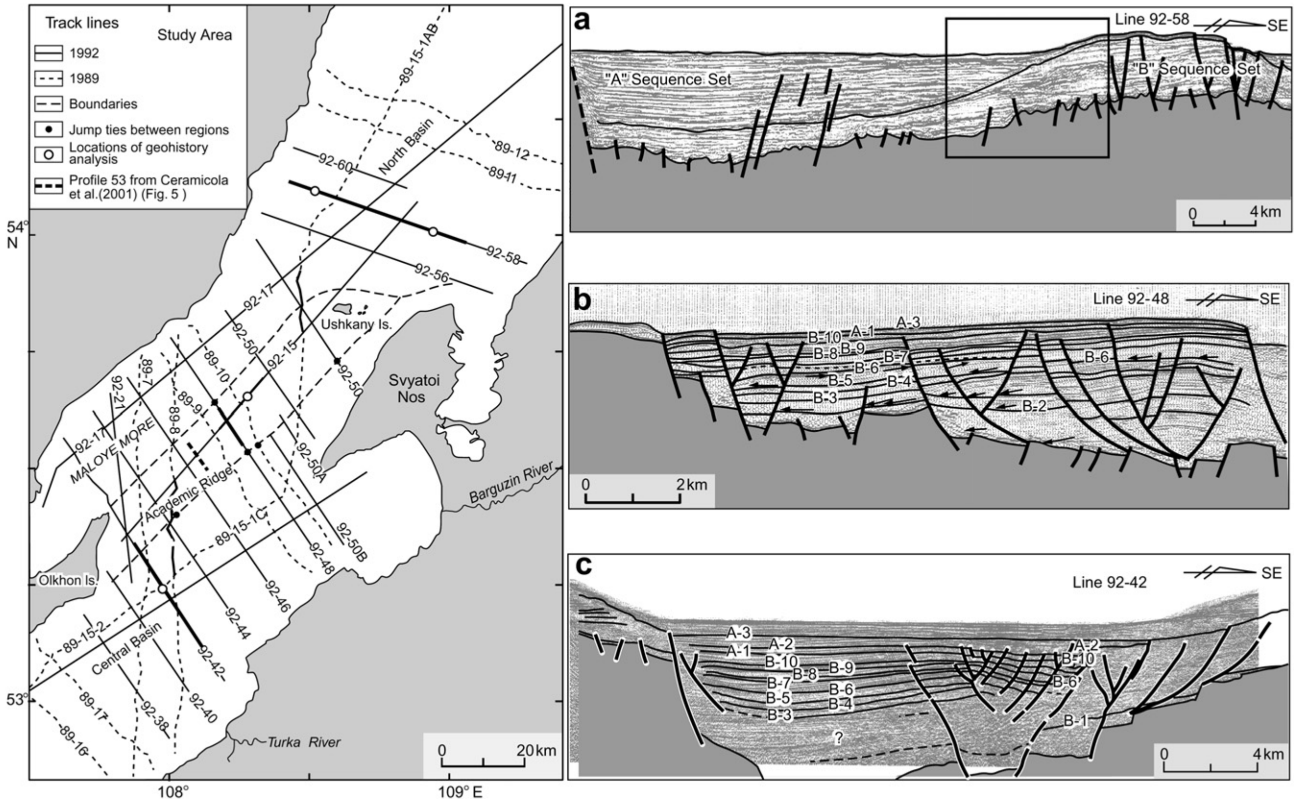

Figure 3 Examples of seismic interpretations of multi-channel reflection profiling data collected in different parts of central Lake Baikal in 1992, with locations of tracklines (Inset map) (after Moore et al., 1997). a: Line 92-58 across the southern North basin; b: Line 92-48 across the Akademichesky Ridge; c: Line 92-42 across the Central basin. Interpretative cross sections are vertically exaggerated. A and B = two sets of seismic sequences. Thin lines = sequence boundaries (reflectors); heavy lines = faults. Heavy dashed line in location map = profile 53 from Ceramicola et al., (2001). The seismic cross section is shown in Fig. 5. Box frame is a fragment enlarged in Fig. 7.

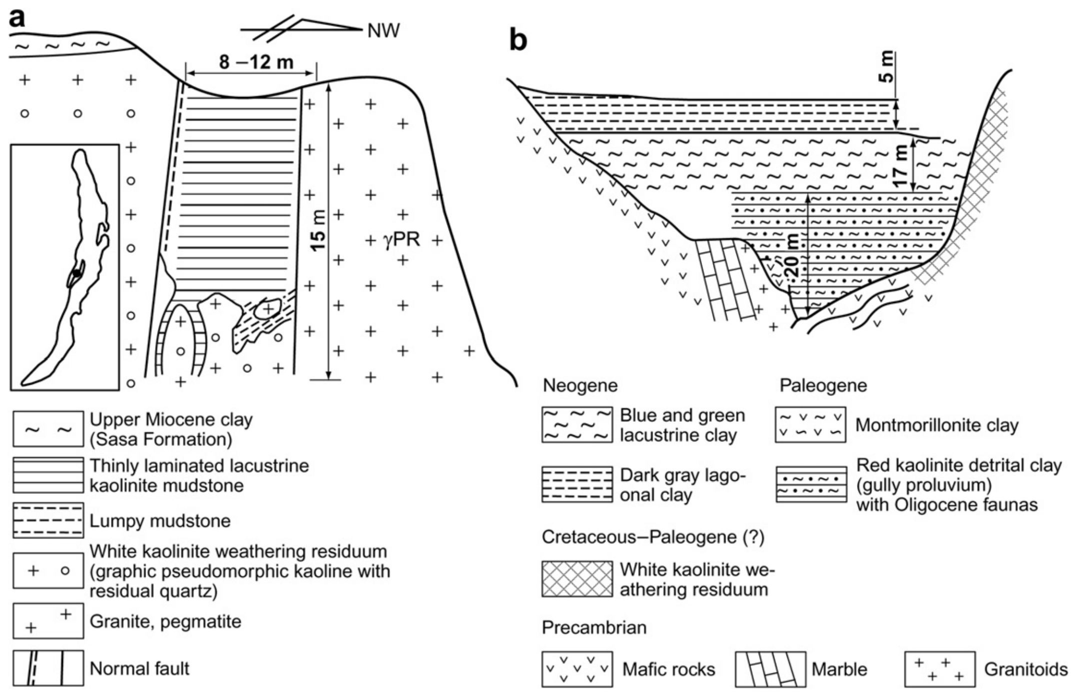

Figure 4 Evidence of pre-Maastrichtian (a) and Tunka (b) tectonic events. (a) Upper Cretaceous−Paleogene mudstone that fills a small graben and overlies a white kaolinitic weathering profile, Olkhon Island, Kharaldai. (b) Lower Oligocene sediments in Ulariya Bay, with fossils of then small mammals *Desmatolagus cf. gobiensis, Cricetops cf. dormikor* (Pokatilov and Nikolaev, 1986), sandwiched between a white kaolinite weathering profile and Upper Miocene−Lower Pliocene Sasa Formation.

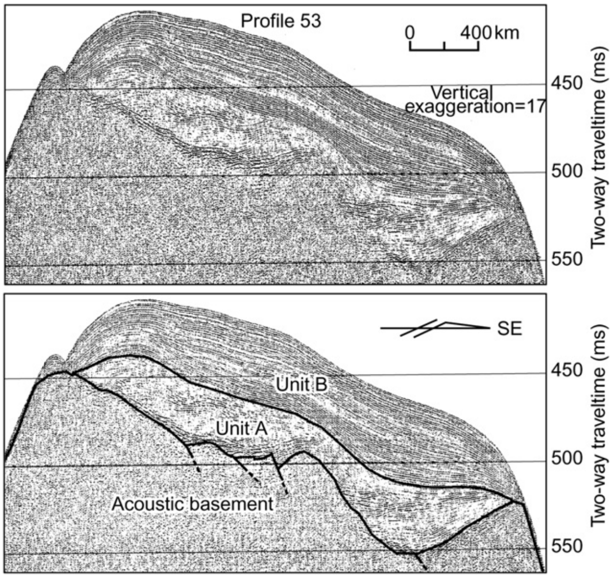

Figure 5 Dip seismic profile ACR 53 across the northwestern horst block of the Akademichesky Ridge (after Ceramicola et al., 2001). Unit A = stratigraphic equivalent of Lower–Middle Miocene (Tagai Formation); Unit B = stratigraphic equivalent of Upper Miocene–Lower Pliocene (Sasa Formation). Marker bed of coarse clastics recognized at the base of Unit B (Zonenshain et al., 1993) was found also at the base of the Sasa Formation, Olkhon Island (Mats et al., 1982). Unit B lies over Unit A with an angular and azimuthal unconformity or locally lies immediately over weathered basement. An azimuthal unconformity is evident from a lower dip angle of Unit A relative to dip of the overlying Unit B. For location of profile see inset map in Fig. 3 (heavy dashed line).

basement along the Osinovka Tankhoi and Osinovka Kedrovskaya rivers in the southern Baikal Basin; it also appears at the discordant boundary of the Miocene (Tagai Formation) and the montmorillonite weathered basement within the Olkhon block (Fig. 1; Table 1). Furthermore, a deposition gap and weathering (a montmorillonite profile) appear at the base of the Upper Paleogene in the Baikal foredeep (Pavlov et al., 1976; Zamaraev et al., 1976).

This major tectonic phase, coeval with Stille's Savic orogeny, separates the complexes TLSC-1 and TLSC-2 and the sequences SSS-1 and SSS-2. At that time, the rift shoulders experienced the earliest notable uplift. As a consequence, pre-erosional flood-basalt eruptions between 72 and 28 Ma (K–Ar ages) in the southwestern flank of the rift system were followed by eruptions of 28–25 Ma lavas that filled deep (up to 100 m) erosional incisions (Rasskazov, 1993). Oligocene erosion produced coarse clastics of the Osinovka Formation, as part of the Tankhoi Stage of the regional stratigraphy (Table 1). The deposition style in the Baikal Basin changed dramatically as well, from monomictic Upper Cretaceous weathering facies to polymictic molasse. During the Tunka tectonic activity, the basin propagated on the account of the gently dipping eastern rift side.

During the Tunka event, the earlier half-graben transformed into a complete U-shaped graben bounded by listric faults (Hutchinson et al., 1992; Zonenshain et al., 1995; Kazmin et al., 1995), with its deposition corresponding to the deformed layered unit of SSS-2 in the lake sediments (Fig. 2) and to the TLSC-2 unit on the shore (Table 1).

2.4. North baikal tectonic phase, Middle Miocene

The North Baikal tectonic phase was was a secondary event within the intermediate stage of the Baikal Rift history that occurred about 10 Ma ago (time of Stille's Styrian orogeny). It is represented by an unconformity and a weathering profile at the base of the Upper Miocene section. The event is evident in the subaerial and submerged parts of the North Baikal Basin and in Olkhon Island (Fig. 1). At the latter site, this is an angular and azimuthal unconformity between the Lower–Middle Miocene Tagai Formation and the Upper Miocene–Lower Pliocene Sasa Formation (Table 1). The Upper Miocene strata lie either immediately over the basement or over the Lower–Middle Miocene Tagai Formation and red weathering residuum, as at Cape Sasa and Ulariya and Kharaldai bays in Olkhon Island (Fig. 4). A marker bed of coarse clastic deposits overlying the basement is present on Olkhon Island (Mats et al., 1982) and the submerged Akademichesky Ridge (Zonenshain et al., 1993, 1995).

In the lake sediments of the North Baikal Basin (Fig. 3a), the Miocene–Lower Pliocene stratigraphic unit (Tankhoi Stage of local stratigraphy) has its equivalent in a deformed layered unit containing a gap and an unconformity (Kazmin et al., 1995; Moore et al., 1997; Mats et al., 2000a). The unconformity correlates with that between the Lower–Middle Miocene and Upper Miocene–Lower Pliocene (Tagai and Sasa formations) at Olkhon Island (Tables 1 and 2). The same unconformity also appears on the slopes of the Akademichesky Ridge (Figs. 3b and 5) where sequence B correlated with the Lower–Middle Miocene deposits of the Tagai Formation (Mats et al., 2000a), overlies the basement and fills small depressions. Sequence B is overlain, with an angular and azimuthal unconformity, by sequence A (Figs. 3b and 5) locally lying directly on the weathered basement surface. Sequence A has a coarse clastic marker bed at its base which was recognized during lake bottom examination with submersibles (Zonenshain et al., 1993, 1995). The marker bed obviously correlates with coarse clastics at the base of the Upper Miocene–Lower Pliocene Sasa Formation on Olkhon Island (Mats et al., 1982).

Unlike the North Baikal Basin (Fig. 3a), the deformed seismic stratigraphic sequence in the South and Central sub-basins (Fig. 3b, c) contains no unconformities (Hutchinson et al., 1992; Kazmin et al., 1995; Moore et al., 1997); neither are there unconformities within TLSC-2 in the subaerial sections (Tankhoi, Osinovka, and other formations).

The North Baikal tectonic event was the time of transgression when the North Baikal Basin (newly formed by that event) became connected with the South and Central Baikal sub-basins by a strait in the middle of the Akademichesky Ridge, similar to the present-day strait of Small Olkhon Gates (Fig. 1, inset B) (Mats et al., 2000a; Khlystov et al., 2001). A fragment of the transgression sequence is preserved at the foot of the western Svyatoi Nos Peninsula: the Late Miocene–Early Pliocene South Sviatoi Nos Formation overlies the weathered basement surface (Mats et al., 1975). Finally, the North Baikal event was responsible for folding of Late Oligocene–Middle Miocene deposits.

2.5. Olkhon tectonic phase, Pliocene

The Olkhon (Khara–Murin) tectonic phase, Middle Pliocene, was a major event between the Early and Late orogenic stages of the Baikal Rift (Logatchev and Florensov, 1978; Logatchev, 1993, 2003), ~3.5 Ma, about the time of Stille's Rhonian orogeny. The event is

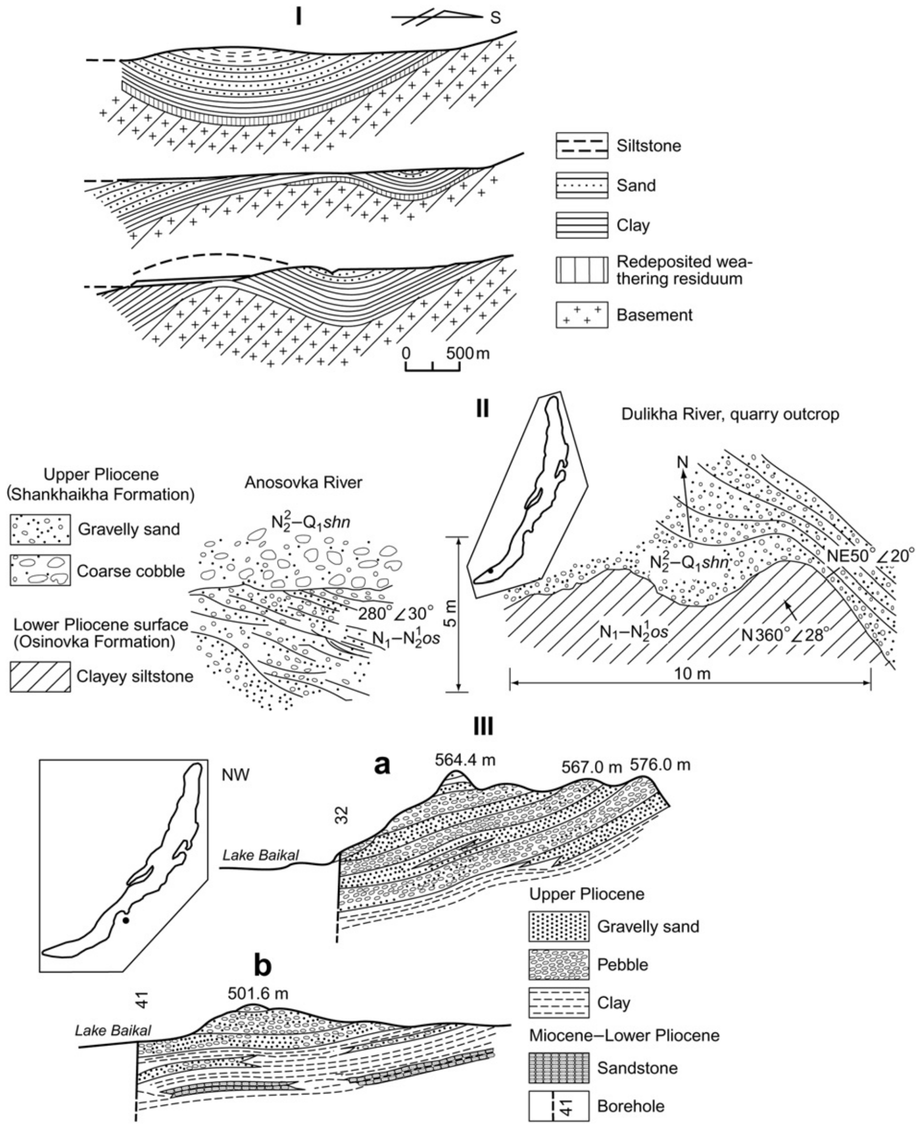

Figure 6 Folding in pre-Quaternary sediments on the southern coast of Lake Baikal, Khamar−Daban Range (Mats, 2001) as evidence of stress reversals. I: Three examples of folding patterns in Upper Oligocene−Lower Pliocene sediments, Tankhoi Formation (Palshin, 1955). II: Early and Late Pliocene deformation, Osinovka and Shankhaikha Formations in sections along Anosovka River (cross section view, a) and Dulikha River (quarry outcrop, plan view, b). See angular and azimuthal unconformities at the base of the Upper Pliocene. III: Miocene−Early Pliocene and Late Pliocene deformation (Imetkhenov, 1987).

traceable throughout the area as a regional gap and an unconformity at the base of the Upper Pliocene. It represents a period of weathering and uplift of the rift shoulders and Olkhon and Sviatoi Nos blocks in the basin interior. Related coarse clastic deposition at the Baikal Basin periphery is marked by a change from the Upper Pliocene lower molasse unit to the upper molasse unit (Adamenko et al., 1984).

The typical structure representing the Olkhon tectonic phase is found in onshore outcrops of Kharaldai Bay, Olkhon Island (Fig. 1, inset B) where the Olkhon block appears to be uplifted above the level of Paleo-Baikal. The event is indicated from a change from Late Miocene−Early Pliocene lacustrine facies (Sasa Formation) to Upper Pliocene subaerial deposits (Kharantsy Formation) (Table 1). The two units are separated by a non-deposition gap during which the earlier deposits became weathered (caliche-type) and deformed (seismite-like soft-sediment deformation structures).

The structures of the Olkhon event, as the Kara−Murin paratype, are especially prominent in the Khamar−Daban (southeastern) coast of Lake Baikal (Fig. 1), where Upper Pliocene deposits (Shankhaikha Formation) overlie the weathered basement surface. The basement/sediment boundary is exposed in several road cuts along the Irkutsk−Ulan-Ude highway between the 265 km mark and the left side of the Khara−Murin River. On the right side of the river, the Shankhaikha Formation extends over the eroded surface of Miocene−Lower Pliocene coarse clastics of the Osinovka Formation. In the section along the Anosovka and Osinovka Kedrovskaya rivers (Fig. 6), the Upper Pliocene Shankhaikha Formation, with conglomerate at its base, overlies the siltstone top of the Miocene−Upper Pliocene section (Osinovka Formation). In a quarry on the Dulikha River, Upper Pliocene sand and pebbles lie, with an angular and azimuthal unconformity (dip azimuth NE 50°; dip angle 20°), over Miocene−Lower Pliocene siltstone dipping at 28° relative to N 360° (Fig. 6II).

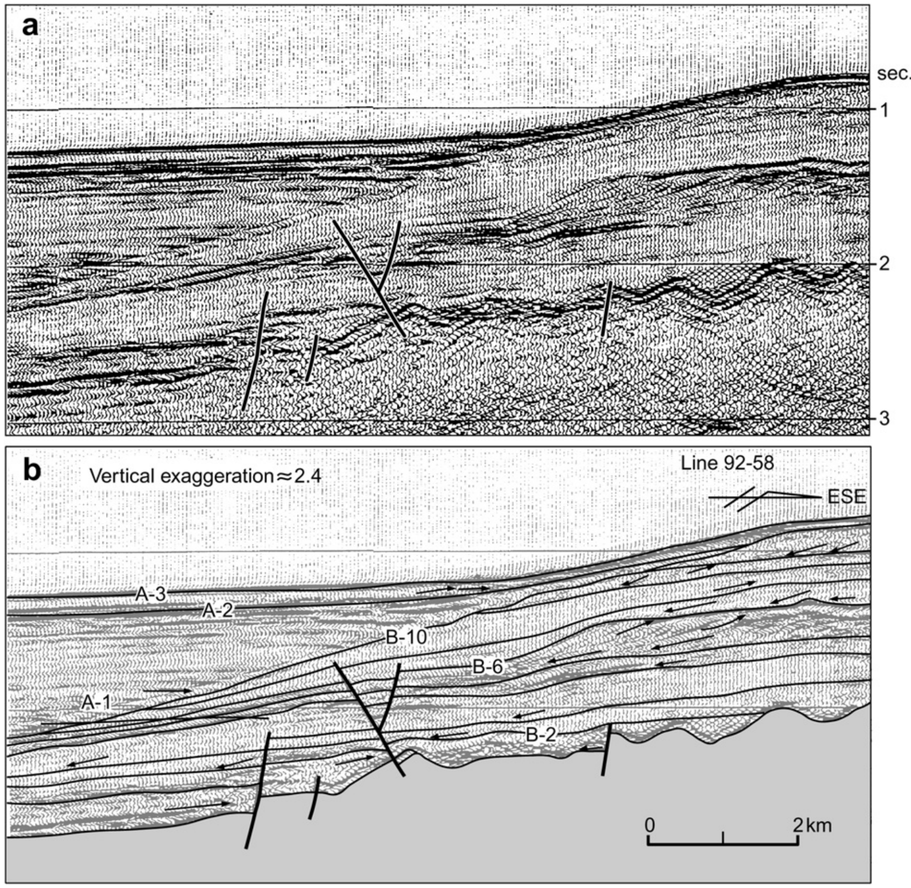

Figure 7 Profile 92-58 across southern North Baikal sub-basin, an enlarged part of Fig. 3 (after Moore et al., 1997): (a) Seismic cross section, and (b) interpretation. A and B in (b) = two sets of seismic sequences. Thin lines = sequence boundaries (reflectors); heavy lines = faults. A = the undeformed layered sequence SSS-3: A-3 is water–bottom interface; A-2 and A-1 possibly correspond to Tyya and Primorsky tectonic events, respectively; B = the deformed layered sequence SSS-2: B-10, B-6, and B-2 are unconformities we interpret as corresponding to the Nurga (Primorsky), Olkhon, and North Baikal tectonic events, respectively.

In the rift morphostructure, the Olkhon event corresponds to the onset of the Baikal dome uplift, which forms the neotectonic mountain border of the subsiding ultra-deep Baikal Rift basin, and the associated change in the drainage network to its present pattern (Mats et al., 2010). Olkhon (Khara–Murin) activity caused folding of pre-Upper Pliocene sediments (Fig. 6I, III).

2.6. Nyurga tectonic phase, earliest Pleistocene

The Nyurga tectonic phase, 2–1.8 Ma, equated to Stille's Wallachian orogeny, was distinguished from deformation (folding) of Upper Pliocene strata at the top of SSS-2. Inasmuch as the youngest deformed sediments of the Baikal Basin are Late Pliocene and undeformed sediments are Quaternary, there was obviously a post-Pliocene–pre-Quaternary tectonic event. Besides the top of SSS-2, deformation appears in Upper Pliocene subaerial deposits (Fig. 6III) and an unconformity exists at the base of the overlying Quaternary section. This is unconformity B-10 (Figs. 3a and 7) in the lake sediment section of Moore et al. (1997) and a "transgressive onlap" in the classification of Khain and Mikhailov (1985).

The Nyurga event resulted in rapid subsidence of the Baikal Basin, which again became a half-graben and accumulated the sequence SSS-3 (Fig. 2) during the Quaternary. The deposition event is evident in undeformed planar-bedded sediments that onlap the geomorphically-expressed margins of the Baikal Basin composed of SSS-2 (Figs. 2, 3a and 7).

The typical tectonic structure representing the Nyurga event occurs at the boundary between the Quaternary (Nyurga Formation) and the Miocene–Pliocene (Sasa Formation) at Nyurga Bay, Olkhon Island (Fig. 1, inset B). The base of the Quaternary section is below the Baikal Lake level and its top is no higher than 20 m above lake level, while the whole Upper Miocene–Pliocene section is exposed for 60–80 m above lake level. Thus, the younger sediments are hypsometrically lower than the older sediments. At another locality, a landslide near abandoned houses of Kharantsy Village, Olkhon Island, Quaternary sediments overlie the Upper Pliocene surface at about 20–25 m above the lake level. Therefore, Quaternary deposition was preceded by large-scale uplift and subsidence which is identified in this model as the Nyurga tectonic phase.

2.7. Primorsky tectonic phase, early Quaternary

The Primorsky tectonic phase is represented by a deposition gap during rapid uplift in the western shoulder of the Baikal Rift along the craton margin. The uplift interrupted the Manzurka discharge of Lake Baikal into the Lena River system and resulted in a new discharge through the Irkut–Ilcha Valley (Kononov and Mats, 1986;

Mats et al., 2000b; Yefimova and Mats, 2003). It also caused a rise in lake level and the formation of young high terraces at 120–130 m above the present lake level. The timing of the Primorsky event is constrained by the age of the youngest Manzurka Formation filling the erosional incision of the paleo-Manzurka channel. According to paleontological data by O. Adamenko (Zamaraev et al., 1976), the Primorsky event corresponds to the early Pleistocene (Calabrian). Thus, the event occurred at 0.9–0.8 Ma and roughly correlates with the Riss glaciation.

Additional independent time constraints of 0.8–1.0 Ma come from a 200 ka deposition gap in the BDP-99 core of lake sediments at a depth of 134 m (Bezrukova et al., 2004), when faulting occurred in the area of the Selenga Delta and the western rift shoulder experienced further uplift.

The type structure of the Primorsky uplift occurs at Cape Rogovik, northwest of Cape Goloustnaya (Fig. 1), where the Manzurka Formation is cut by the rift master fault. According to reports of Fishbein and Kononov (Kononov and Mats, 1986; Mats et al., 2010), the Manzurka sediments fill an old valley on the uplifted rift shoulder, at elevations ∼1000 m a s l, and their detritus redeposited into the basin and preserved on a fault step about 455 m above the lake level (∼700 m a s l).

Thus, the Primorsky tectonic event is indicated as a deposition gap, as uplift of the western rift shoulder, from the breakup of the Baikal discharge through the paleo-Manzurka River and by the onset of a new discharge through the Irkut–Ilcha Valley, as well as by the formation of young high terraces. During the Primorsky phase and subsequent events, the paleo-Manzurka valley was deformed: drilling evidence indicates that it was either deeply buried or exposed (Logatchev et al., 1964).

2.8. Tyya tectonic phase, late Pleistocene

The Tyya tectonic phase was identified from displacement resulting in a ∼200 m vertical offset of the 80-m Baikal terrace on the stepped border fault of the Baikal Basin. The terrace deposits are currently preserved as pebble debris on fault steps. The late Pleistocene age of the faulting event was constrained by complete mammoth skeleton and other fossils (Bazarov et al., 1982). The offset of sediments along the fault observed at the outskirts of Severobaikalsk city can be taken as a type structure of the Tyya event, and the paratype may be the boundary between the flat land topography and the steep Primorsky fault scarp near Chernorud Village near Olkhon Island (Fig. 1, inset B). At the latter site, the foot of the fault scarp borders a gently dipping planar surface overlain with scattered large (2 m or more) granitic boulders. The boulders apparently rolled downward for short distances, but in some instances even traveled upslope. Such movement is only possible on frozen ground, i.e., during a Quaternary glacial period. The planar surface adjacent to the scarp foot has also been offset by the fault. Granitic blocks like those on the flat land part of the fault footwall are absent from the fault plane but exist in young shallow gullies across it. The same surface with granitic blocks occurs along the fault hanging wall beginning at granitic bedrock outliers and ending before the scarp edge. Immediately below the granite outliers are angular blocks which become progressively more rounded toward the scarp. Thus, the planar surface, with the scattered granitic boulders on it, was obviously disrupted and displaced for about 200 m along the Primorsky Fault during a Late Pleistocene glaciation indicating that the Tyya event must be at 150–120 ka.

The Tyya phase is the youngest major tectonic event affecting the Baikal Rift. It was during this event that Lake Baikal became a deep lake bounded by high flanking mountains, as it is today. It was a period of accelerated head erosion of the Baikal Lake tributaries and related dissection of the uplifted rift shoulders (Mats et al., 2010).

The Tyya activity also included post-tectonic events, such as flooding of the Akademichesky Ridge (Mats et al., 2000a; Khlystov et al., 2001; Granina et al., 2010), and periodic acceleration of deposition in the Angara–Kichera and Upper Angara basins, as determined from radiocarbon-constrained markers (Kulchitsky, 1991). Another post-tectonic event was the collapse of the Listvyanka block which opened the Baikal outlet through the Angara River 60 ka ago (Kononov and Mats, 1986; Mashiko et al., 1997; Mats, 2001; Yefimova and Mats, 2003). Finally, terraces on the eastern side of the Baikal Basin were uplifted in the late Pleistocene (Late Ionian–Tarantian), the amounts of uplift being different in the North Baikal Basin, in the Svyatoi Nos Peninsula, Big Ushkany Island, and the Central Baikal sub-basin (Yefimova and Mats, 2003).

3. Tectonic stress reversals

The history of the Baikal Rift included several events of regional-scale stress reversal when the regime of overall rifting (extension) changed to compression. The periods of deformation apparently reflected global-scale pulses of compression and folding.

The stress reversal events mark the boundaries between tectonic phases and can be inferred from sedimentary gaps, unconformities, and deformation patterns (e.g., Fig. 6I). Folds and strike-slip faults revealed in seismic cross sections of lake sediments (Figs. 2 and 3) correlate with deformation in subaerial sections (see Table 2 for correlation of TLSC and SSS). The recognized reversal events are generally consistent with paleostress reconstructions on the basis of structural data (Sherman and Dneprovsky, 1989; Sherman, 1992; Delvaux et al., 1995, 1997; Sankov et al., 1997; Parfeevets and Sankov, 2006).

In addition to the prominent brief stress reversal at the Early–Late Pliocene boundary (Logatchev and Zorin, 1987; Logatchev, 1993, 2003; Delvaux et al., 1997; etc.), there were other earlier and later episodes of compression and shear in the rifting history (Mats, 2001).

The earliest reversal at the ***Early–Late Oligocene boundary*** has no explicit manifestation in sedimentary sections: SSS-1 is acoustically transparent while TLSC-1 on the shore is only fragmentary. However, it can be inferred from the presence of a distinct unconformity between TLSC-1 and TLSC-2 and from the dramatic change in basin geometry from a half-graben to a graben.

The compression event at the ***Middle–Late Miocene boundary*** occurred during the North Baikal tectonic phase and was responsible for the gap and angular unconformity between the Middle and Upper Miocene strata, between SSS-2-1 and SSS-2-2, and for folding of sediments deposited before the gap (Figs. 2, 3, 5–7).

The reversal at the ***Early–Late Pliocene boundary*** during the Olkhon (Khara–Murin) tectonic phase caused the gap and unconformity between the Lower and Upper Pliocene strata and folding of the pre-gap sediments (Figs. 5–7).

The latest regional change to compression was during the Primorsky tectonic phase, at the ***Pliocene–Quaternary boundary***. It corresponds to the pre-Quaternary gap and folding evident in Upper Pliocene sediments and at the top of SSS-2 (Fig. 7).

In the Quaternary, basinal evolution proceeded in a purely extensional setting, without compressive interventions, judging from the predominantly normal faulting (Zonenshain et al., 1995; Sherman, 1992; Levi and Sherman, 2005) and the layered and undeformed SSS-3 (Figs. 2, 3 and 7).

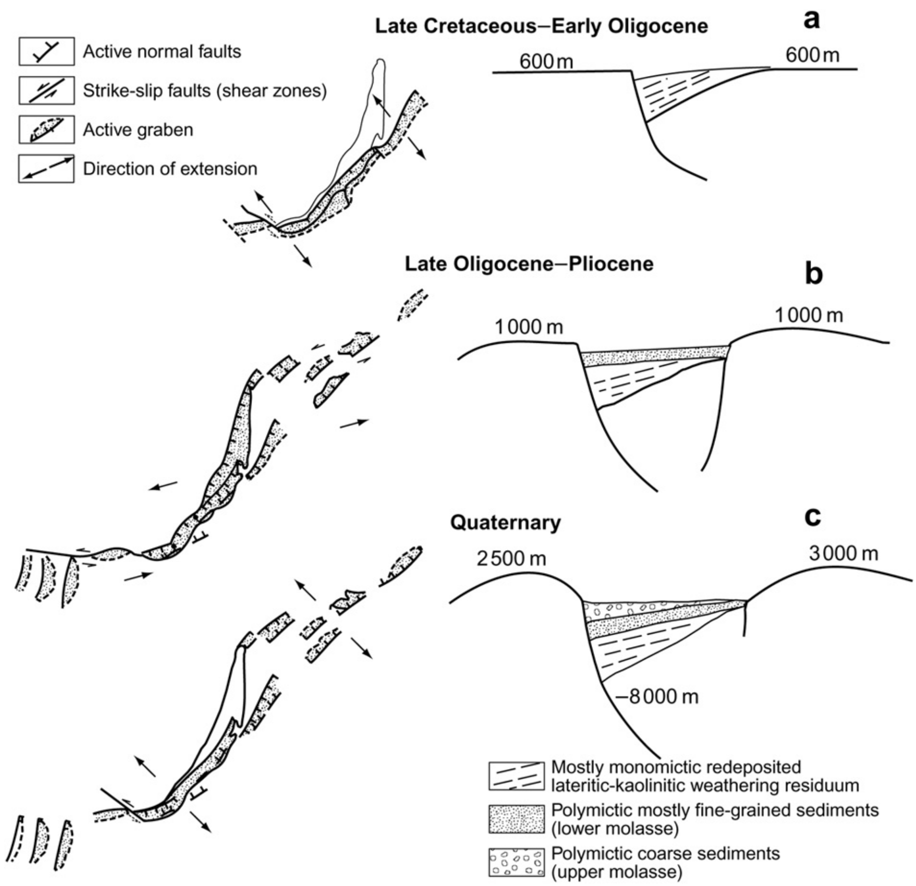

Figure 8 Evolution of Baikal rift system (modified after Zonenshain et al., 1995).

4. History of rifting: a synthesis

Tectonic events divide the history of the Baikal Rift into three major stages and several substages as recorded in the sedimentary sections. The major stages were: an earliest Late Cretaceous–Early Oligocene stage (70–30 Ma), an intermediate Late Oligocene–Early (or Late) Pliocene (30–3.5 Ma or 1.8 Ma), with two substages, and the latest stage since 3.5 (or 1.8) Ma, with three substages.

4.1. Earliest stage 70–30 Ma

The Baikal Rift originated in a zone of a long-lived lithospheric suture at the boundary between the Siberian craton and the Baikal folded area (part of the Central Asian orogen), that preceded the India–Eurasia collision. Uplift to form Late Cretaceous mountains around the incipient Baikal Basin was slow enough to be equaled by the rate of denudation (Nikolaev, 1984). The absence of mountain barriers in Central Asia (Kuzmin and Yarmolyuk, 2006) allowed the extension of warm climate zones as far as the high latitudes and a broad exchange of biotas, with northward shift of animal (Fig. 1, inset A) and plant (Martinson, 1998; Volkova and Kuzmina, 2005; Scherbakov, 2003) communities. Denudation produced an area of low relief (a peneplain) associated with weathering to form a thick monomictic kaolinite–laterite profile. Surface planation was periodically interrupted by localized rapid uplift which dissected the peneplain (to as deep as 50 m) producing steep geomorphic scarps, and eventually resulting in the moving of planation to lower altitudes. Two such uplift events are recognized; one in the Baikal foredeep (Zamaraev et al., 1976), the other in the Baikal Basin (Mats and Yefimova, 2010).

The rifting process began with formation of a half-graben in the peneplain (Milanovsky (1976) used the term *fissure rift* for basins of this kind), bounded in the west by a system of NE listric faults striking at 55° (the present Obruchev Fault). The half-graben became filled with an acoustically transparent wedge-shaped syn-rift sequence SSS-1 recognized in the South and Central Baikal subbasins. The deposition centers of SSS-1 delineate the western fault border of the half-graben (Hutchinson et al., 1992; Kazmin et al., 1995; Zonenshain et al., 1995) where the thickness of SSS-1 exceeds 4 km decreasing to a few hundreds of meters further in the southeast (Figs. 2 and 3).

The surface planation and large-scale weathering (Mats, 2001) are evidence of an extension setting that followed a long period of compression (Delvaux et al., 1995). The signature of earliest volcanic (Eskin et al., 1978; Devyatkin, 1981; Rasskazov, 1993) and hydrothermal (Tsekhovsky et al., 1996) activity, which is possible in a rifted crust, marks the onset of rifting. Late Mesozoic–Cenozoic rifting was most intense in the Middle–Late Cretaceous, as well as in the Paleocene and Eocene (Milanovsky, 1995). Rifting was a regional response to extension overall Central Asia (King, 1967; Nikolaev, 1984; Tsekhovsky et al., 1996). The exact driving mechanism of extension remains controversial but may be linked either with plate interaction, or plume activity (Dobretsov et al., 1996; Rasskazov et al., 2007), or be a global agent which Milanovsky (1995) explained in terms of pulsations of an expanding Earth. Whatever the mechanism of regional extension, it affected the craton-edge weak zone in the NW–SE direction at 140°–145°(Zonenshain et al., 1995)[1], initiated rifting and controlled the orientation of the Baikal half-graben along the NE discontinuity (Fig. 8a). The global-scale extension was a far-field stress source, i.e., the rift evolution followed the classical "passive rifting" scenario.

4.2. Intermediate stage, 30–3.5 (1.5) Ma

The intermediate stage, from about 30 Ma to 3.5 (or 1.5–2.0) Ma, corresponds to the previously distinguished early orogenic stage, or a stage of "slow rifting" (Logatchev and Florensov, 1978; Logatchev and Zorin, 1987; Logatchev, 1993, 2003; Delvaux et al., 1997; etc.). During this stage, the rift shoulders were uplifted whereby the earlier peneplain became exposed to more rapid erosion. Erosion dissected the weathering profile while large amounts of unweathered material were transported to the basin. Thus, the earlier weathering-related formations provided material for the lower molasse.

The transition to the second major stage of Baikal Rift formation corresponds to the Tunka tectonic event, while the North Baikal tectonic event (10 Ma) separates this into two substages. The Tunka event caused the transformation of the half-graben formed under earlier pure extension to a fault-bounded U-shaped graben (Fig. 8b) where the deformed layered lacustrine unit of SSS-2 (Figs. 2, 3 and 7) formed (Hutchinson et al., 1992; Kazmin et al., 1995; Zonenshain et al., 1995; Moore et al., 1997) and the TLSC-2 unit was deposited subaerially. The marked changes in tectonics (uplift and deformation of peneplain) and deposition (from monomictic detritus derived from laterite–kaolinite eluvium to lower molasse), as well as the change in rift basin geometry to a full graben, were a consequence of counterclockwise rotation of the regional stress vector (Fig. 8b) to a W–E orientation, oblique to the strike of the rift (Zonenshain et al., 1995).

The stress regime changed to transpression and shear, and then to transtension (Delvaux et al., 1997; Sankov et al., 1997; Levi and Sherman, 2005; Parfeevets and Sankov, 2006) with related strike-slip faulting considered to be critical for rift formation (Balla et al., 1990). Structural evidence for strike-slip strain and faulting was extensively reported from the Baikal Basin (Sherman, 1992; Delvaux et al., 1997; Levi and Sherman, 2005; Parfeevets and Sankov, 2006; Cheremnykh, 2010). Compression events are recorded by Late Oligocene–Pliocene folds in submarine (SSS-2) and subaerial (Fig. 6) sections. The two substage division with a boundary about 10 Ma (North Baikal tectonic event) approximately agrees with change from the transpression (Late Oligocene–Middle Miocene) to transtension (Middle Miocene–Early Pliocene) substages of Delvaux et al. (1997) and distinguished in their proto-rift stage.

The stress change was consistent with NE compression from the India–Eurasia collisional front slowly propagating northward since the Eocene (Molnar and Tapponnier, 1975). Different estimates of the rate of this propagation and the time of its arrival in southern Siberia are given by Tapponnier and Molnar (1979), Dobretsov et al. (1996) and De Grave et al. (2007), but it is likely that the collisional far-field stress had reached the Baikal region by ~30 Ma, otherwise it would be difficult to explain the changes evident in the patterns of deposition and deformation. Thus, in its further evolution during the second stage, the Baikal Rift experienced the impact of the India–Eurasia collision. In this sense the rift may be equated with "impactogenic rifts" which develop as a foreland reaction to major orogenic events in transtensional systems (Barberi et al., 1982), i.e., rifting remained passive although the source of the far-field stress had changed.

4.3. Latest stage

The beginning of the latest (present) stage was not synchronous throughout the rift. On the periphery, the growth of the Baikal dome gave rise to a change in sediment lithology, from the finer lower molasse unit to the coarser upper one at the Early–Late Pliocene boundary (Adamenko et al., 1984; Mats, 2001). At that point corresponding to the Olkhon (Khara–Murin) tectonic event at 3.5 Ma, slow rifting (early orogenic phase) gave way to fast rifting or late orogenic phase (Logatchev and Florensov, 1978; Logatchev, 1993, etc.).

In the interior of the Baikal Basin, the boundary between the intermediate and recent stages is marked by the transition from deformed to undeformed SSS (Figs. 2, 3 and 7). The deposition of the third seismic stratigraphic sequence (SSS-3) commenced following the Nyurga and Primorsky tectonic events between 2.0 and 1.0 Ma. Thus, the boundary between the intermediate and latest stages has different time constraints in the basin periphery and in the interior, the difference being more than 1.5 Ma.

The latest stage was the period when there was a notable change in geomorphology, due to the growth of the Baikal dome and reorganization of the drainage network. The stage consists of three substages divided by the Primorsky (1–0.8 Ma) and Tyya (0.15–0.12 Ma) tectonic events.

The early substage bracketed between the Olkhon and Primorsky tectonic events was one of rapid uplift of the rift shoulders and basin floor subsidence as a result of the Olkhon activity. Uplift of basin borders favored more intense erosion and denudation and, as a consequence, the deposition change to coarse molasse. Coarse clastics form a belt along the basin sides and grade basinward to progressively finer sediments that become a pelitic hemipelagic facies of alternating diatom-bearing mud and diatom-free clay in the basin interior (Baikal Drilling Project Members, 2000; Kuzmin et al., 2000; Bezrukova et al., 2004).

Onshore, a submontane complex of sediments began to be deposited along the foot of the western mountain border, with a large contribution from head erosion.

The Primorsky tectonic event at 1.0–0.8 Ma marked the onset of the middle substage and another uplift pulse. Uplift was attendant with a deposition gap in the basin interior and with termination of the Manzurka discharge on land. As a consequence of the latter event, lake level rose as high as that of the Irkut–Ilcha Valley, the lake began to discharge into the Yenisei River system, and the young high terraces formed along the western Baikal coast. Along the eastern coast, a lake level rise led to ingression into the Barguzin, Ust'-Selenga, and other basins (Kolomiets and Budaev, 2010), and caused broad deposition of polygenetic Quaternary sand.

The latest substage began with the Tyya tectonic event (0.15–0.12 Ma), when the uplift of the basin border and subsidence of its floor further accelerated, so that the elevation contrast attained its present magnitude. Post-tectonic processes resulted in flooding of the Akademichesky Ridge, abrupt subsidence of the Listvyanka block, formation of a new lake discharge through the Angara Valley, and a fall in lake level. Other post-tectonic events at the end of the Tyya phase were very rapid subsidence of the northern end of the Baikal and Upper Angara basins which produced nearly vertical

[1] Zonenshain et al. (1995) reconstructed extension for the oldest unit in the lake sediments which they miscorrelated with the Tankhoi Formation and the Late Oligocene early rifting stage. This interpretation, however, contradicts the paleostress reconstructions of transpression and shear in Late Oligocene–Pliocene (see below).

coastal escarpments above and below the water, and caused ingression into the northern basin end (Kulchitsky, 2009).

Further uplift acceleration, promoted head erosion. Many valleys of the lake's western inlets, have downstream segments with stepped longitudinal profiles and V-shaped transversal profiles. These valley segments commonly end with waterfalls, upstream of which the rivers become broad, shallow, and calm. This may represent the end of headwater incision associated with the uplift during the Tyya event. The evidence of uplift correlates with the recent submontane deposition in the western border of the Baikal Basin, which is especially well pronounced in alluvial fans. Head erosion propagated not very far into the mountains along small inlet valleys, but in large rivers such as the Buguldeika, the Anga, and the Sarma, it was a cumulative result of several tectonic events and thus dissected the entire Primorsky Range (Fig. 1). The paleo-Manzurka network became gradually destroyed, and the Baikal runoff system took up the Lena River headwaters: some tributaries remained linked with the Lena while some became the Baikal inlets (Mats et al., 2002, 2010).

At the third major stage of its history, the Baikal Rift basin returned to a half-graben geometry as the tectonic setting reverted to one of pure extension (Fig. 8c) oriented across the strike of the rift (Zonenshain et al., 1995; Delvaux et al., 1997; Sankov et al., 1997; Levi and Sherman, 2005; Parfeevets and Sankov, 2006). Note again that the change in the basin geometry and deformation style lagged at least 1.5 Myr behind the growth of the Baikal dome and the sediment facies change that had the same causes (see above). The extension setting uninterrupted by large stress reversals is recorded in the undeformed sedimentary unit of SSS-3 (Figs. 2, 3 and 7), with minor deformation restricted to faults along the basin sides.

Extension was a response to the effect from a plume impinged on the base of the lithosphere beneath the southwestern Baikal Basin. The presence of low-velocity mantle material under the Baikal Basin was discovered in the late 1970's (Logatchev and Zorin, 1987 and references therein) and confirmed by later studies, including teleseismic tomography, which provided better constraints on the position of the plume (Gao et al., 1994, 2003; Zorin et al., 2003; Zorin and Turutanov, 2005; Tiberi et al., 2008). According to the teleseismic data, asthenosphere in the southwestern Baikal region reaches the crustal base in a wedge-shaped upwarp thickening away from the Siberian craton (Tiberi et al., 2008; Mordvinova et al., 2010). The width of the upwarp, in an W–E direction, is estimated to be about 400–500 km from 3D teleseismic tomography and gravity data (Zorin et al., 2003; Tiberi et al., 2008), as well as from the distribution of volcanism (Rasskazov, 1993). The asthenospheric upwarp maintains increasing NW extension by creating gravity instability (Zorin et al., 2003).

The transition to the fast rifting of the last evolution stage from ca. 2–3 Ma appears to be the time when the extension regime created by the rising mantle wedge became prevalent over collision-induced transpression and transtension, and the upwarp became a kind of barrier impeding propagation of the collisional effect into eastern Central Asia (Mordvinova et al., 2010)[2]. The question remains as to whether the effect of the plume has been direct or indirect, but irrespective of the exact mechanism of its influence, the Baikal rifting has been mainly driven by local sources ("active rifting" scenario) since at least the Pliocene.

[2] Mordvinova et al. (2010) deduced that "Cenozoic rifting in the Baikal region has been controlled by mechanisms other than the distant effect from the India–Eurasia collision", but this inference appears to apply rather to the latest evolution stage than to the Cenozoic rifting as a whole.

5. Conclusions

Lithostratigraphic data (Table 1), the architectonics of subaerial sedimentary sections around Lake Baikal, and their correlation with submarine sequences of lake sediments (Table 2) reveal three major stages and several substages in the history of the Baikal Rift. The major stages correspond to tectonic–lithological–stratigraphic units (TLSC) in subaerial sections, which span the Late Cretaceous–Early Oligocene, Late Oligocene–Early Pliocene, and Late Pliocene–Quaternary and correlate with seismic stratigraphic units (SSS) in submerged lake sediments (Figs. 2 and 3): a lowermost acoustically transparent unit and two layered units, a lower deformed unit and an overlying undeformed unit.

Subaerial sections are divided on the basis of deposition patterns, proceeding from changes of early weathering derivatives (early stage) to lower molasse (intermediate stage), and finally to upper molasse (latest stage). The boundary between the intermediate and latest stages in the lake sediments is defined by a change in the SSS structure from the deformed to the undeformed sequence. Because of this difference in diagnostic features, the beginning of the third stage is placed in the Middle Pliocene at the basin borders and in the Quaternary in the interior, indicating a time lag of 1–2 Ma. Deposition during the three major stages was interrupted by intervals of weathering, tectonic activity and stress reversals recorded as gaps, unconformities, and deformation structures (especially folds). There were five major (Late Mesozoic pre-rift, pre-Maastrichtian early rift, Middle Oligocene Tunka, Middle Pliocene Olkhon and Early Quaternary Nyurga events) and three secondary (Middle Miocene North Baikal, Middle Quaternary Primorsky, and Late Pleistocene Tyya) tectonic phases marked by stress changes. The tectonic and stress change events inferred from the patterns of deposition and deformation in sedimentary sections generally agree with paleostress reconstructions from fault slip data. Note that the agreement is quite good in the history of stress settings, but the cited authors distinguished two major stages of rifting since the Late Oligocene. In the reconstructions for the Mesozoic, Delvaux et al. (1995) gave more attention to Early and Middle Mesozoic compression settings, though obtained pure extension at one Cretaceous site (Posolsky fault, Selenga Delta area). In the course of its three-stage history, the Baikal Rift basin changed its geometry from an initial half-graben, to a graben, and finally again a half-graben. The rift geometry changes were due to the action of different stress sources. A fissure-type rift first developed within a peneplain in response to continent-wide NW–SE extension associated either with plate interaction or with a pulse in the evolution of an expanding Earth. That was NW to SE pure extension, controlled by an old zone of weakness at the edge of the Siberian craton. Rift evolution during the intermediate stage was controlled by far-field NE–SW stress regime resulting from the India–Eurasia collisional front which propagated northward since about 50 Ma. The convergence effect may have reached the Baikal region about 30 Ma and was responsible for a transition to transpression, shear, and then to transtension as the stress orientation changed counterclockwise, from SE–NW to W–E or NE–SW. The latest stage of Baikal Rift evolution which has continued since the Late Pliocene, has been driven by a local source associated with hot mantle material rising to the base of the rift. This growing asthenospheric upwarp maintains extension by creating gravity instability, and initiated growth of the Baikal dome and the related change from finer to coarser molasse deposition. From ca. 2–3 Ma, the asthenospheric upwarp has become a more powerful stress source than the collision, and the stress vector has reverted to the previous NW–SE direction and changing the rift geometry back to a half-graben.

Thus the three-stage model of the Baikal rift history offers a new solution to the conflict between the hypotheses of passive and active rifting. The rift evolved through different tectonic regimes and followed subsequently two stages of passive rifting though driven by different far-field forces (a perfectly passive rift and an impactogenic rift, respectively), and finally proceeded to active rifting dominated by an energy source from beneath the basin. Three major units have been distinguished independently in onshore and submarine sedimentary sections, but the age of the oldest unit is Late Cretaceous–Early Oligocene. The lowermost seismic stratigraphic unit is correlated with the oldest subaerial sediments around Lake Baikal, especially the fill of the Baikal Foredeep rather than with the Tankhoi Formation. It was for the latter miscorrelation (Zonenshain et al., 1995) that the lowest sequence was placed within Logatchev's early orogenic stage, which supported the model of two major stages of rifting. The revised correlation, along with the earliest evidence of extension, indicates that Baikal rifting began before Oligocene tectonism and before the India–Eurasia collision.

The three-stage division of the Baikal Rift history does not preclude the previous two-stage division but rather extends its limits back in the time. The new model refines the succession of driving forces that acted at each evolutionary stage and provides reasonable explanations for the tectono-sedimentological changes from stage to stage consistent with geological, stratigraphic, structural, and geophysical data.

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