Evolution of the Academician Ridge Accommodation Zone in the central part of the Baikal Rift, from high-resolution reflection seismic profiling and geological field investigations

Article *in* International Journal of Earth Sciences · September 2000

DOI: 10.1007/s005310000094

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Int J Earth Sci (2000) 89:229–250

ORIGINAL PAPER

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Evolution of the Academician Ridge Accommodation Zone in the central part of the Baikal Rift, from high-resolution reflection seismic profiling and geological field investigations

Received: 26 November 1999 / Accepted: 12 March 2000

Abstract New high-resolution seismic reflection data from the central part of Lake Baikal provide new insight into the structure and stratigraphy of Academician Ridge, a large intra-rift accommodation zone separating the Central and North Baikal basins. Four seismic packages are distinguished above the basement: a thin top-of-basement unit; seismic-stratigraphic unit X; seismic-stratigraphic unit A; and seismic-stratigraphic unit B. Units A and B were cored on selected key locations. The four packages are correlated with a series of deposits exposed on the nearby western shores: the Ularyar Sequence (Oligocene); the Tagay Sequence (Lower to Middle Miocene); the Sasa Sequence (Upper Miocene to Lower Pliocene); the Kharantsy Sequence (Upper Pliocene); and the Nyurga Sequence (Lower Pleistocene). Based on stratal relationships, sedimentary geometries, distribution patterns and principal morphostructural elements – both onshore and offshore – we propose a new palaeogeographic evolution model for the area. In this model progressive tectonic subsidence of the Baikal basins and successive pulses of uplift of various segments of the rift margins lead to: (a) formation of the ridge as a structural and morphological feature separating the Central and North Baikal basins during the Middle to Late Miocene; (b) gradual flooding of the main parts of the ridge and establishment of a lacustrine connection between the two rift basins during the Late Miocene; and (c) total submergence of the top parts of the crest of the ridge during the latest Pleistocene. This new model helps to better constrain numerous phases in the structural evolution of the Baikal Rift, in which the Academician Ridge as an accommodation zone plays a crucial role.

Key words Seismic data · Rift basins
Sedimentation · Tectonics · Asia

Introduction

In recent years a large amount of interdisciplinary research has been carried out on Lake Baikal, mostly in the framework of large, international programmes dealing with the study of, for example, the origin and evolution of intra-continental rifts, or of global climate change. For various reasons much of this research has focused on the Academician Ridge Accommodation Zone, a major structural feature located in the central part of the Baikal Rift that is expressed as a large, oblique morphological high separating two deep rift basins (Fig. 1). The ridge represents a major tectonic boundary and is very likely to contain primary information about the rifting process and about the main stages in the rift's history.

The accommodation zone and its structural connection to the western rift margin comprise a whole series of structural elements (Fig. 1, inset B) that played a key role in the morphological and structural development of the rift. For this reason they have been the subject of extensive onshore geological fieldwork (Logachev et al. 1964; Mats et al. 1982; Ufimtsev 1992; Agar and Klitgord 1995) and of several offshore expeditions involving a.o. multi-channel and high-resolution single-channel seismic profiling, underwater visual observations and sampling using the "Pisces" submersible, and

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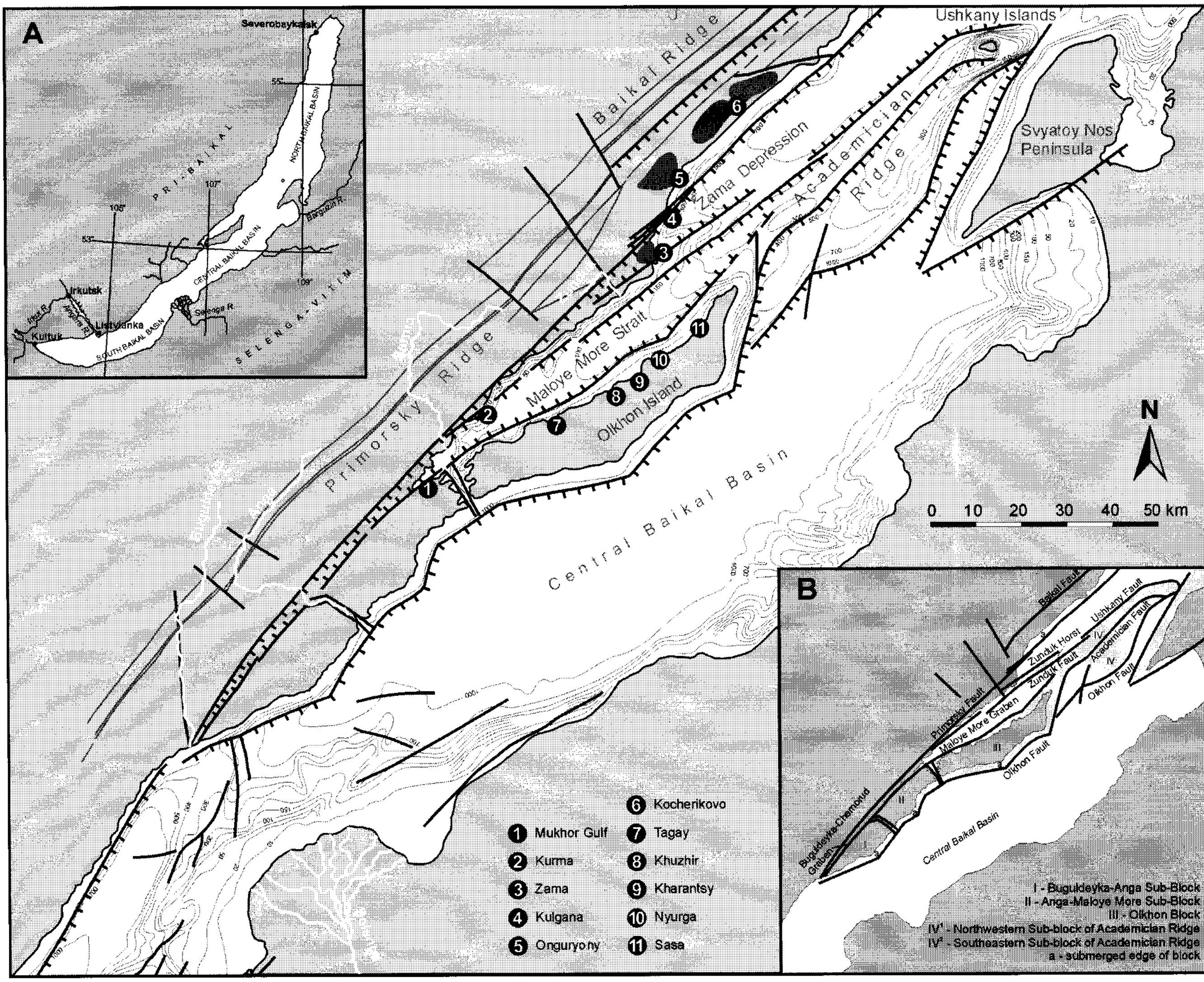


Fig. 1 Map of the central part of the Baikal Rift, showing simplified bathymetry (after USSR Ministry of Defense 1992), main faults and structures (after Kazmin et al. 1995, Agar and Klitgord 1995 and Scholz and Hutchinson, this volume), and key locations. *Inset A:* geographical overview map; *inset B:* morphostructural map

analysis of the ridge's sedimentary cover by shallow coring and deep drilling (Zonenshain et al. 1992, 1993; Kazmin et al. 1995; Bukharov and Fialkov 1996; Moore et al. 1997; Kuzmin et al. 1997; Williams et al. 1997; Grachev et al. 1997, 1998; BDP Members 1998). These studies have addressed various general questions regarding the large-scale structure and long-term evolution of the accommodation zone. However, numerous details still remained unclear, and in particular the relationship between the offshore and onshore segments of the accommodation zone has never been investigated. In this study a new grid of high-resolution reflection seismic profiles was acquired together with sediment core transects across the crest of Academician Ridge. The data were integrated with previous results and new onshore geological field observations. Our interpretation provides new insight into the evolution of the entire Academician Ridge Accommodation Zone within the general context of the Baikal Rift system.

Data and methods

During three joint Belgian–Russian expeditions in the summers of 1995, 1996 and 1998, a dense grid of high-resolution reflection seismic profiles (total length >500 km; Fig. 2) was acquired across the crest of Academician Ridge. This grid also extends into Maloye More, where seismic profiles were shot very close to several key outcrops along the shore of Olkhon Island. The seismic data were acquired using RCMG's "Centipede" fresh-water sparker as seismic source (frequency range of 400–1500 Hz when operated at 500 J), and a single-channel streamer as receiver. The data were recorded digitally using an Elics Delph2 system, and processed at RCMG with Phoenix Vector and ProMax software. Processing routines applied to the data

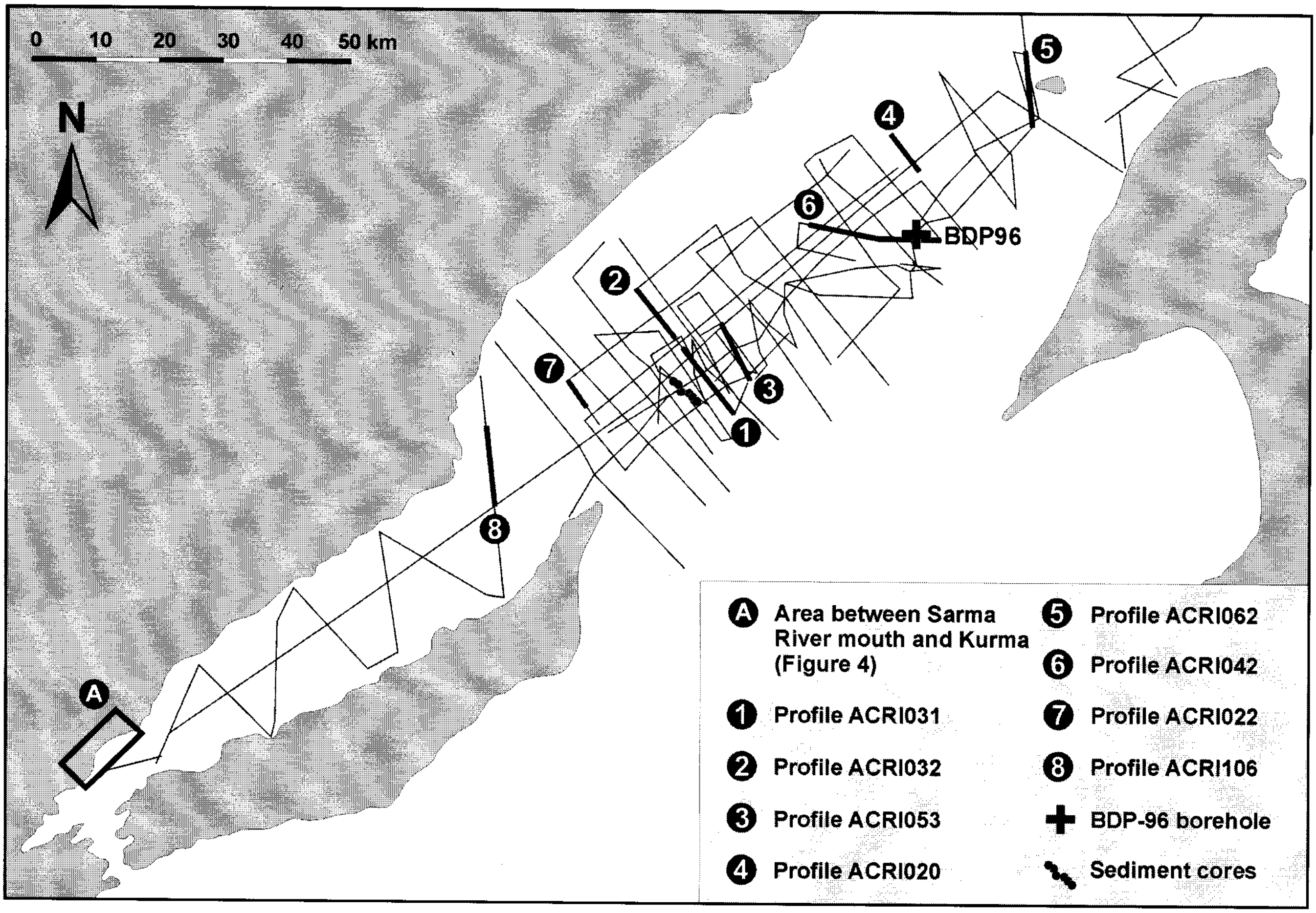


Fig. 2 Location of the seismic profiles used in this study, the geological cross sections, the sediment cores and the BDP-96 borehole

include band-pass frequency filtering, spiking deconvolution and, for some of the profiles, migration. The seismic sections have a penetration of over 400 ms, and a theoretical vertical resolution of approximately 50 cm in the upper sedimentary layers.

In order to provide a basis for ground-truthing the high-resolution seismic data and for correlation with onshore information, sediment cores were collected at numerous key locations on the ridge. The cores were taken with the Limnological Institute's piston and gravity corers. In total, 14 cores were taken, with lengths between 0.6 and 12.0 m. They were cut into 2-m sections and sealed on board. Core analysis, including visual description, grain-size analysis, heavy-mineral analysis, petrographic analysis on thin sections, palynological analysis and diatom stratigraphy, was performed at the Limnological Institute.

These data were integrated with all available information from previous studies (Logachev et al. 1964; Pleshanov and Romazina 1981; Mats et al. 1982, 1989; Mats 1987, 1993), as well as with new onshore geological and geomorphologic field observations from Olkhon Island and adjacent areas.

Geological setting

Geological framework

The Baikal Rift is an active continental rift zone that consists of narrow, elongate rift basins, high mountainous rift shoulders and broad low-relief fault zones, extending over 2000 km in the Siberian interior from 50° to 58°N latitude and 98° to 120°E longitude (Florensov 1968; Logachev 1974). The rift zone developed during the past 70 Ma (Mats 1993) along the boundary between the Archean Siberian craton and the structurally complex high-grade metamorphic basement of the Sayan-Baikal mobile belt (Zonenshain et al. 1990; Balla et al. 1991). Small basins occur along the entire length of the rift zone, but three major rift basins developed in its central part (Fig. 1). They form the present-day Lake Baikal, the deepest (1637 m) and most voluminous (23,000 km^3) lake on Earth (Galaziy 1993). The three rift basins – the South, Central and North Baikal Basins – are highly asymmetrical, with a major steeply eastward-dipping border fault system on their western side. They are separated by two intra-basin highs or accommodation zones.

The Academician Ridge Accommodation Zone is situated in the central part of the Baikal Rift and separates the Central and North Baikal basins. The accommodation zone and its structural connection to the western rift margin consist of a series of major morphostructural elements (Fig. 1, inset B): the entirely submerged Academician Ridge Block proper, the Olkhon Block, and a complex border-fault overstep, the Buguldeyka-Maloye More Block, which can be further subdivided into two sub-blocks: the Buguldeyka-Anga and the Anga-Maloye More Sub-Blocks (Pleshanov and Romazina 1981).

Basement geology in the central part of the Baikal Rift

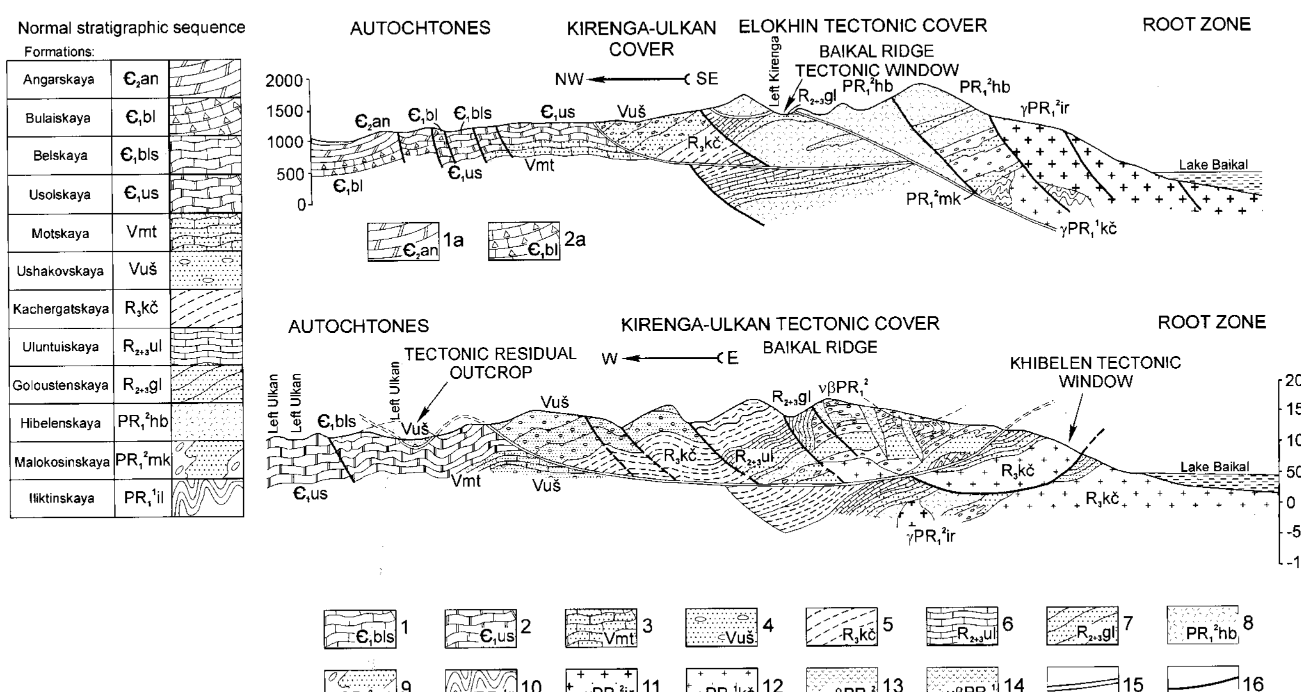
The Cainozoic development of most structures in the central part of the Baikal Rift was influenced by the presence of an old Proterozoic to Paleozoic, structurally complex suture zone between the Siberian craton and the Sayan-Baikal mobile belt (Zonenshain et al. 1990; Mats 1993). The structural complexity of the suture zone results from the fact that the area has acted as a major crustal boundary through most of its geological history (Zonenshain et al. 1990; Mats 1993; Ermikov 1994; Melnikov et al. 1994): in the Early Proterozoic it was the site of subduction of oceanic crust of the Paleo-Asian Ocean under the Siberian palaeo-continent, in Riphean times it was a zone of rifting, and in Paleozoic to Mesozoic times it was an area of continental collision and of accretion of the Barguzin micro-continent onto the Siberian palaeo-continent.

As a result of this complex and long history, a large variety of basement rock types and structures occur within this suture zone: mylonites; cataclastics; batholithic intrusions of rapakivi granites and diabase dikes; zones of dynamic-thermal metamorphism (muscovite-disthene-garnet slates); zones of high-pressure granulite-amphibolite metamorphic facies (eclogites, spinel, garnets of the pyrope-almandine series, macro-boudins of ultrabasites and ultramylonites); tightly pressed isoclinal folds, thrusts and stacked overthrust sheets (Fig. 3); and large strike-slip faults (Alexandrov 1990; Alexandrov et al. 1988, 1996; Bukharov et al. 1992; Fedorovsky 1997; Fedorovsky et al. 1995; Mats et al. 1979; Melnikov et al. 1994; Vakhromeev et al. 1982; Zamaraev 1967). The presence of these pre-rift structures has influenced and facilitated the formation of extensional structures of the Cainozoic Baikal Rift.

Main Cainozoic faults in the central part of the Baikal Rift

The dominant faults in the central part of the Baikal Rift are Primorsky Fault and Olkhon Fault (Fig. 1). Primorsky Fault is one of the principal border faults of the Central and North Baikal basins. Further to the

Fig. 3 Thrust structures in Baikal Ridge (after Alexandrov et al. 1996). *1* Lower Cambrian: limestones and dolomites; *2* Lower Cambrian: dolomites and salt; *3* Vendian: dolomites, marls and sandstones; *4* Vendian: sandstones and conglomerates; *5* Upper Riphean: sandstones and clayey slates; *6* Middle–Upper Riphean: limestones, sandstones and clayey slates; *7* Middle–Upper Riphean: sandstones, quartzites, conglomerates and limestones; *8* Upper Lower Proterozoic: quartz porphyres, sandstones and conglomerates; *9* Upper Lower Proterozoic: basalts, sandstones, conglomerates and argilites; *10* Lower Lower Proterozoic: green slates and sandstones; *11* granite porphyres; *12* plagiogranites; *13*, *14* diabases; *15* overthrust faults; *16* reverse faults and thrust faults



north, it is replaced as rift border fault by Baikal Fault, and to the south by Obruchev Fault. Primorsky Fault became active during the Cainozoic rifting phase. It represents a major structural divide between the fundamentally different geological provinces of the Siberian craton and the Sayan-Baikal mobile belt (Melnikov et al. 1994), although both provinces have a similar crustal thickness (Zonenshain et al. 1993). Olkhon Fault, with a maximum throw of approximately 10 km (Mats 1993), also represents a major boundary (Logachev 1993). It separates the North Baikal Basin, which is the youngest basin in the Baikal Rift with a crustal thickness of up to 40–44 km (Zonenshain et al. 1993), from the Central Baikal Basin, which has a crustal thickness of approximately 34–36 km (Krylov et al. 1981).

Morphology and structure of Pri-Olkhon

The region at the foot of the Primorsky and Baikal Fault scarps, from the Buguldeyka River mouth in the south to Kocherikovo in the north, is generally referred to as Pri-Olkhon (Fig. 1). This area is part of the Pri-Olkhon Block, a major morphostructural element in the Baikal Rift system bounded by two sub-parallel faults: Primorsky Fault in the northwest and Olkhon Fault in the southeast. In map view it appears as an area with a distinct wedge shape (Fig. 1). It occupies an intermediate hypsometric position between the >1000-m-deep basin floors of the Central Baikal Basin and the up to 1700-m-high tops of the western rift margin.

Primorsky Fault is a listric fault and its offset increases along-strike from southwest to northeast, from nearly zero in the area of the Buguldeyka River mouth to several hundreds of metres in the northeast (Agar and Klitgord 1993; Pleshanov and Romazina 1981). Strata of coarse-grained deposits of Early Pleistocene age are displaced by the fault, indicating an age younger than Early Pleistocene. Seismotectonic cracks and ruptures in recent, unconsolidated sediments witness the present-day activity of the fault (Solonenko 1977).

Due to the listric character of Primorsky Fault, the Buguldeyka-Maloye More, Olkhon and Academician Ridge Blocks represent a series of tilted blocks whose surfaces are inclined towards the northwest (Pleshanov and Romazina 1981). On the northwestern side of these blocks an elongated structural depression occurs (Fig. 1), which becomes deeper and wider towards the northeast with increasing offset of the Primorsky Fault: the Buguldeyka-Chernorud Graben (Zamaraev and Mazukabzov 1978; Agar and Klitgord 1993). The morphology and structure of the Buguldeyka-Chernorud Graben is characterised by a series of small horsts, grabens and tilted blocks. In the southwestern part of Pri-Olkhon, where Primorsky Fault has its minimum offset, the graben structure affects a nearly horizontal surface, a relic of a Cretaceous to Paleogene peneplane. Towards the northeast, the Buguldeyka-Chernorud Graben develops along-strike into the Maloye More Graben, which includes the shallow-water basin of Maloye More Strait (Fig. 1). The water depth of Maloye More increases towards the northeast, from only a few metres in the southwest to approximately 250 m in the northeast, whereas the height of Primorsky Ridge decreases. In the southwestern part of the Maloye More Strait, the relics of isolated horst-like structures, comparable to those observed in the Buguldeyka-Chernorud Graben, stand out as a chain of small islands. Similar structures, although entirely submerged, are present also further to the northeast, as observed on the high-resolution seismic profiles. The morphology and structure of the entire Maloye More Graben is therefore believed to be similar to that of the Buguldeyka-Chernorud Graben, with a succession of small horsts, grabens and tilted blocks. In the southwestern sub-basin of the Maloye More Graben, Mukhor Gulf, there are indications for a propagation of the graben towards the southwest: at Cape Ulan-Khoda, situated at the outlet of Mukhor Gulf into Maloye More Strait, an archaeological site of Neolithic age (^{14}C-dated at 7000 years B.P.; Vorobyova et al. 1990) is presently submerged suggesting recent subsidence and enlargement of the gulf.

The Buguldeyka-Chernorud Graben and Maloye More Graben are bordered to the southeast by the up to 1270-m-high crests of the tilted blocks that lie between the Primorsky and Olkhon faults: the Buguldeyka-Anga and Anga-Maloye More Sub-Blocks, and the Olkhon and Academician Ridge Blocks. Transverse structures, which are clearly expressed in the relief, separate these different blocks. The Buguldeyka-Anga Sub-Block is only slightly tilted and at almost the same level as the Primorsky Fault footwall, the fault scarp being only a few tens of metres high. The Anga-Maloye More Sub-Block is clearly tilted towards the northwest and the Primorsky Fault scarp reaches a height of several hundreds of metres. The Olkhon Block is also clearly tilted towards Primorsky Fault. Its northwestern flank is subsided below water level in Maloye More.

With increasing tilting and separation of the individual blocks towards the northeast, the morphology and structure of the Primorsky Fault becomes more complex. In the southwest the fault is expressed as a single steep scarp. Towards the northeast, Primorsky Fault splays off into numerous sub-faults forming a zone of four to five narrow blocks or steps (Fig. 4). The different sub-faults accommodate the total offset of the Primorsky Fault Zone among them. Further to the northeast, adjacent to Maloye More, the width of these steps increases. Northeast from Zunduk River valley, the southwesternmost sub-fault of the Primorsky Fault Zone forms the Zunduk Fault. This fault defines the coastal scarp along Maloye More between the Zunduk River valley and Zama (Fig. 1), whereas Primorsky Fault forms a second scarp further inland. The blocks between the Zunduk Fault and the Primorsky Fault develop along-strike into the Zama Depression (Fig. 1).

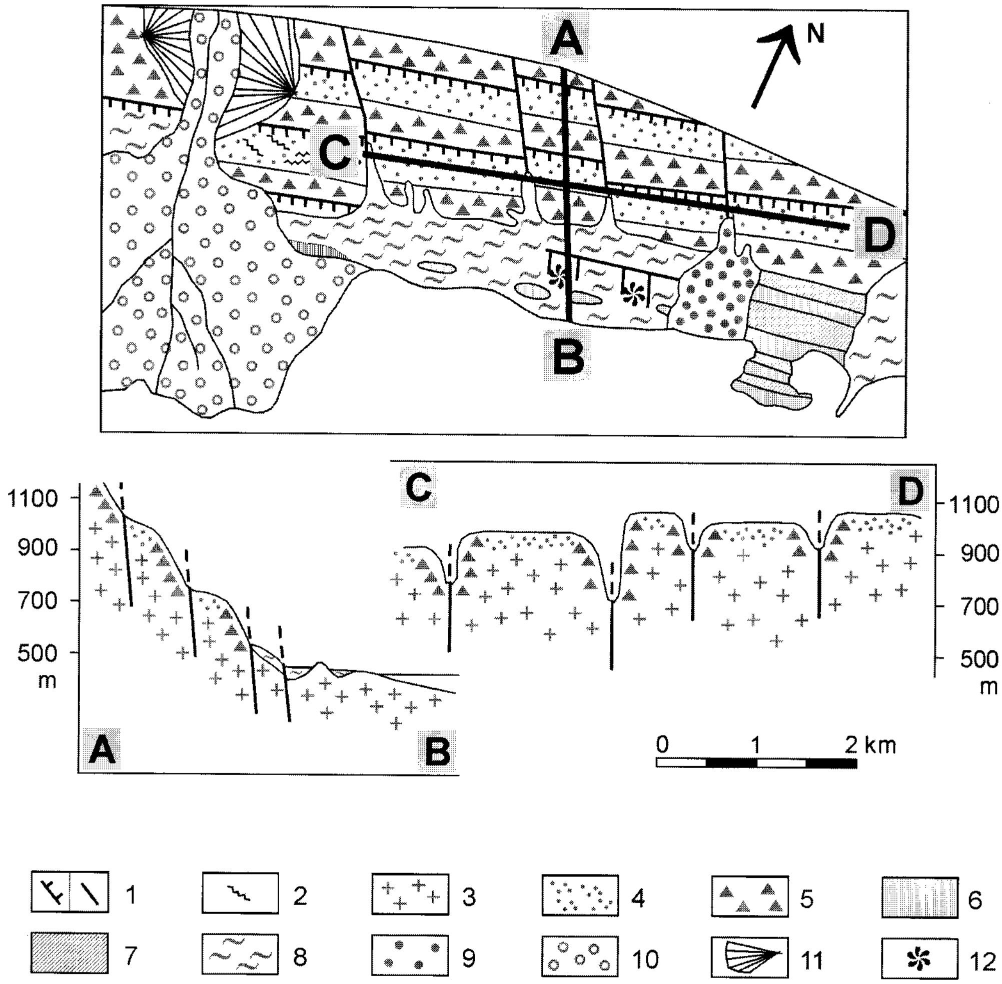


Fig. 4 Morphostructural map and cross sections of the area between the Sarma River mouth and Kurma illustrating the complex structure of the Primorsky Fault Zone. For location see Fig. 2. *1* Faults expressed in the relief, in map view (*dashes* along downthrown side) and on cross sections; *2* seismic dislocations; *3* crystalline rocks; *4* relatively flat surface of the individual fault blocks or steps; *5* tectonic scarps; *6* relic relief: ridges; *7* relic relief: depressions; *8* Piedmont terrain; *9* mudflow fan; *10* Sarma River valley and delta; *11* cirques; *12* springs

The thickness of the depression's sedimentary infill increases towards the northeast. High-resolution seismic profiles show that the Zama Depression, the Zunduk Fault and Maloye More all extend along-strike into the southern part of northern Lake Baikal. The Zunduk Horst (Fig. 1) has only a thin sedimentary cover, indicating that the structure originally formed a sub-aerial high separating the northeastern parts of the Maloye More and Zama depressions, and that it submerged only recently. This observation suggests that also the Zama Depression is characterised by enlargement and subsidence propagation towards the southwest.

The Maloye More and Zama Depressions can be traced over a distance of approximately 15 km into the southern parts of northern Lake Baikal (Fig. 1). Further to the northeast, the Maloye More Depression terminates against the Zunduk-Ushkany Fault system, and the Zama Depression gradually deepens and widens into the southwestern termination of the North Baikal Basin. Thus, the Zama Depression appears to be a small-scale equivalent of the Maloye More Graben. Both formed on the hanging-wall sides of tilted fault blocks between the main Primorsky Fault and one of its fault splays, and both widen and deepen along-strike towards the northeast. Similar structures occur also north of Zama. Between Zama and Onguryony, Primorsky Fault splays off again in numerous secondary faults whose offsets increase towards the northeast. The blocks between these faults are tilted towards the rift margin and deepen along-strike towards the northeast. As a result, several depressions developed (Fig. 1). The Kulgana Depression is one example of such a feature. Geological field data suggest that it formed during post-Pliocene times (ca. 1.6–1.3 Ma). The crests of the tilted blocks form, for example, Cape Kaltygey and Cape Kulgana (Fig. 1). Further to the northeast, the Onguryony and Kocherikovo depressions are marked by similar structures. The Kocherikovo Depression developed on the back of a relatively large fault block that is located between Primorsky Fault and Baikal Fault and tilted towards the northwest.

Along the southeastern border of the Maloye More Graben there are numerous small depressions, a few hundreds of metres wide and a few tens of metres deep, that formed on the back of tilted basement blocks. Some of these depressions are expressed in the relief, others are completely filled by Cainozoic deposits. The development of these depressions is caused by a second system of listric faults with a polarity opposed to that of Primorsky Fault. The origin of these smaller-scale antithetic faults is most likely related to extensional reactivation of pre-existing thrust faults in the Olkhon Island basement.

The along-strike evolution of the lake margin into the accommodation zone does not only involve tilting of fault blocks and northeastward deepening of structural depressions, but also involves a clockwise rotation of 15° of old structural features on Olkhon Island (Pleshanov and Romazina 1981).

Cainozoic stratigraphy of Pri-Olkhon

Cainozoic strata and formations occur throughout Pri-Olkhon (Logachev et al. 1964; Rybakov 1964; Logachev 1974; Pavlov et al. 1976; Mats et al. 1982, 1989; Mats 1987, 1993). They generally comprise a Cretaceous-Neogene weathering crust, Upper Cretaceous to Eocene, Oligocene, Neogene and Quaternary deposits. General structural/stratigraphic relationships are illustrated in Fig. 5.

Weathering crust

All across Pri-Olkhon occurs a laterite-kaolinite crust (Fig. 5) that results from long periods of sub-aerial weathering of the basement. Its age, ranging from Cretaceous to Neogene, was estimated by correlation to a similar weathering horizon in the Pri-Baikal Depression that was dated mainly by palynological data (Pavlov et al. 1976). The crust is preserved where it is overlain by Oligocene and Neogene deposits, and where relics of the Upper Cretaceous to Paleogene peneplane are exposed.

Upper Cretaceous–Eocene

Very locally, some lacustrine reddish-brown kaolinite clays have been observed. Based on lithostratigraphic arguments, their age is believed to range from Late Cretaceous to Eocene (Mats 1993).

Oligocene

Oligocene deposits, such as those of the Ularyar Sequence, occur only in some small outcrops on Olkhon Island (Fig. 5). They consist of continental and lacustrine red clays with a high kaolinite content, deposited in small tectonic depressions. The age of these deposits was determined on the basis of paleontological arguments (Pokatilov and Nikolaev 1986) and of stratigraphic relationships with Neogene strata (Mats 1987).

Neogene

The Neogene forms the main part of the Cainozoic strata in Pri-Olkhon. It occurs in isolated small outcrops along the Buguldeyka-Maloye More marginal step, localised on Olkhon Island, and in a series of small Cainozoic depressions (i.e. Kurma, Zama, Ongu-ryony, Kocherikovo) along the foot of the Primorsky Fault scarp. High-resolution seismic profiles suggest that Neogene deposits might also be present in the Maloye More Depression. Mats (1993) subdivided the Neogene into three sequences: the Tagay (Lower to Middle Miocene), Sasa (Upper Miocene to Lower Pliocene) and Kharantsy (Upper Pliocene) sequences.

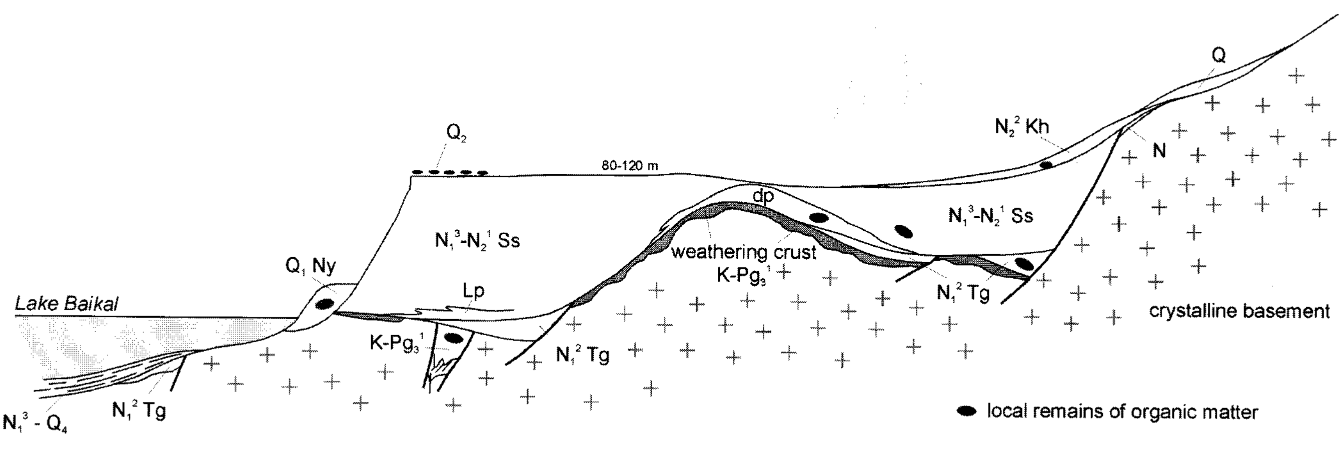


Fig. 5 Cross section illustrates the structural and stratigraphic setting on Olkhon Island. *K-*Pg_3^1 Upper Cretaceous–Lower Oligocene; continental and lacustrine deposits. N_1^2 *Tg* Lower to Middle Miocene, Tagay Sequence; continental and lacustrine deposits. N_1^3-N_2^1 *Ss* Upper Miocene–Lower Pliocene, Sasa Sequence; lacustrine deposits. N_2^2 *Kh* Upper Pliocene, Kharantsy Sequence; deluvial-proluvial deposits. Q_1 *Ny* Lower Pleistocene, Nyurga Sequence; lacustrine and continental deposits. Q_2 early Late Pleistocene; lacustrine pebbles. *Q* Quaternary sands. *Lp* lacustrine–proluvial deposits. *Dp* deluvial-proluvial deposits. N_1^3-Q_4 Upper Miocene–Holocene, seismic stratigraphic Unit B

The Tagay Sequence (Lower to Middle Miocene) overlies the crystalline basement and its weathering crust, and locally – where they are present – Oligocene clays. The sequence is generally preserved in small tectonic depressions (Fig. 5). Its thickness usually does not exceed a few tens of metres. Most of the depressions occur along the Maloye More shore of Olkhon Island and in the central part of the island, but some also occur along the northwestern shore of Maloye More, such as the Kurma Depression in the southwest and the Kocherikovo Depression in the northeast. The Tagay Sequence consists of continental or lacustrine (small- and medium-sized lakes) green montmorillonite clays, sands that are often cemented by carbonates and gypsum, and thin layers of brown coal. These strata have a sub-parallel bedding and gently dip towards the surface of the tilted basement blocks. The thickness and stratigraphic volume of the sequence decrease towards the basement highs. The age of the Tagay Sequence is determined biostratigraphically on basis of rich collections of fossils found at the Tagay site (Logachev et al. 1964; Vislobokova 1990).

The Sasa Sequence (Upper Miocene–Lower Pliocene) overlies the crystalline basement and its weathering crust, or the Paleogene, or the Tagay Sequence, and forms as such a more or less continuous cover unit (Fig. 5). The sedimentary conditions during development of the Sasa Sequence were considerably different from those of the Tagay Sequence, and both sequences are separated by an unconformity. The Sasa Sequence is composed of lacustrine (large lakes) carbonate-free clays, silts, sands and gravels. More marginal facies include gravely shoreline deposits, calcareous lagoonal clays, and red mottled sandy-loamy deposits representing paleosols (Vorobyova et al. 1987) calcified during sub-aerial diagenesis. The age of the Sasa Sequence is Late Miocene to Early Pliocene, as determined on basis of biostratigraphy and paleomagnetic data (Mats et al. 1982, 1989; Pokatilov 1985; Mats 1987).

The Kharantsy Sequence (Upper Pliocene) is composed of continental reddish to dark-brown clays, with deluvial-proluvial and pedosediments. It overlies the Sasa and Tagay Sequences, but often it rests directly on the crystalline basement (Fig. 5). Locally, remnants of a thick red-brown soil containing an uninterrupted caliche-like carbonate horizon are preserved below the Kharantsy Sequence. Deposits of the Kharantsy Sequence, with thicknesses between 10 and 15 m, occur discontinuously in the area and at different altitudes, but mostly at the foot and along lower slopes of the pre-Quaternary relief. A phase of uplift between deposition of the Sasa and Kharantsy sequences is responsible for the occurrence of the Sasa Sequence at altitudes of 20–80 m above the present-day water level of Lake Baikal. The age of the Kharantsy Sequence is Late Pliocene, as determined on basis of biostratigraphic and paleomagnetic data (Mats et al. 1982, 1989; Pokatilov 1985; Mats 1987).

Quaternary

Various types of continental Quaternary deposits occur at different altitudes across the present-day relief (Fig. 5). They include deposits of Early Pleistocene age – dated on basis of paleontological information (Pokatilov 1985) – that occur in places near the present-day Baikal shore. Lacustrine deposits of the sandy-gravely Nyurga Sequence occur at the same altitude. This sequence was paleontologically dated as approximately 1.0–0.7 Ma (Mats et al. 1982, 1989). Deposits of early Late Pleistocene age, also dated on the basis of paleontological information, are found at altitudes of 80 m above the present-day Baikal level, suggesting a significant early Late Pleistocene lake-level rise (Mats 1993).

Morphology and structure of Academician Ridge

The Academician Ridge Accommodation Zone is a sediment-covered asymmetrical structural high and acts as a major morphological divide in the relief of the Baikal lake floor. It has a steep and high (>1000 m) southeastern slope, and a more gentle and lower (200–400 m) northwestern slope. Multi-channel seismic profiles show that this asymmetry is expressed even more clearly at the top of the basement (Hutchinson et al. 1992; Scholz et al. 1993; Kazmin et al. 1995; Moore et al. 1997). The eastern part of the ridge is separated by a narrow structural depression from the Svyatoy Nos Peninsula intra-rift high (Fig. 1).

A major longitudinal fault, Academician Fault, which is generally sub-parallel with Olkhon Fault, divides the Academician Ridge Block along its axis into two sub-blocks: the Northwestern Sub-Block and the Southeastern Sub-Block (Figs. 1, 6). At its extremities, near Olkhon Island and to the northeast of the Ushkany Islands, Academician Fault changes its trend and links up with Olkhon Fault. In addition to this first-order structural segmentation, Academician Ridge Block is also affected by numerous secondary transverse or diagonal faults. Seismic profiles also show that the morphology of the top of the basement is highly irregular, especially on the Northwestern Sub-Block.

The Southeastern Sub-Block of Academician Ridge forms the hanging-wall margin of the Academician Fault. It represents a marginal step between Academician Fault and Olkhon Fault, and the top of the basement gradually deepens from Academician Fault to Olkhon Fault along numerous step-like longitudinal fault blocks. The entire sub-block is covered by an up to 1.0- to 1.5-km-thick package of sediments with numerous unconformities (Moore et al. 1997). The morphology is regular and smooth, at a depth of 250–700 m.

The Northwestern Sub-Block forms the footwall margin of the Academician Fault. The top of the basement is tilted towards the northwest. The flanks of the

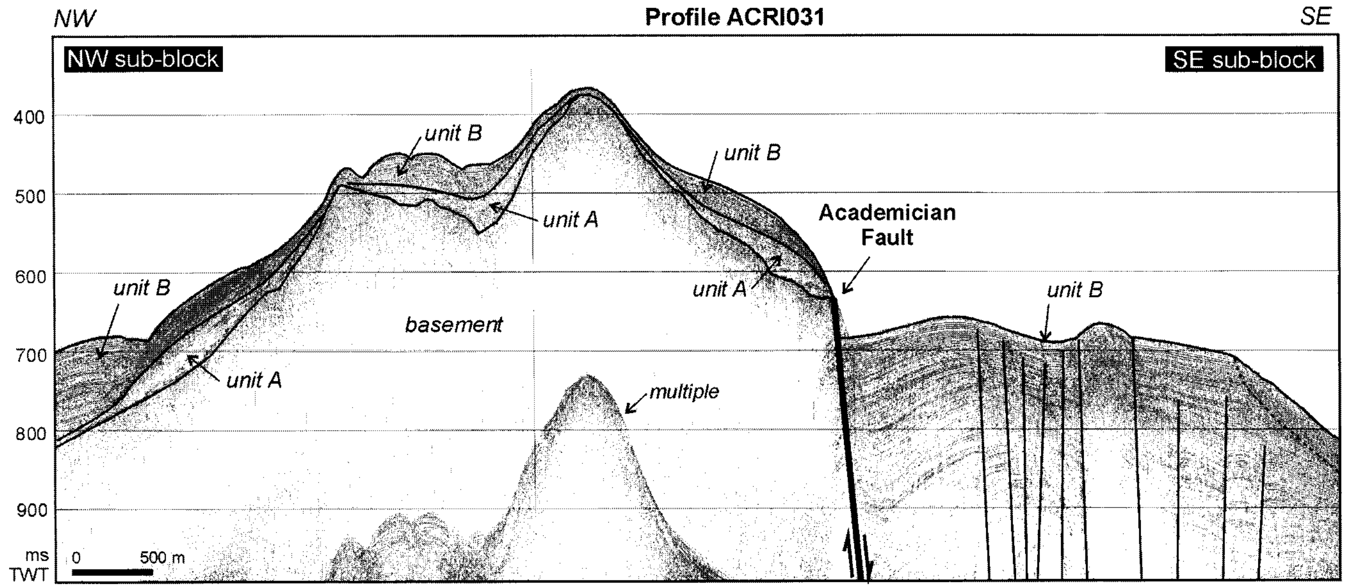


Fig. 6 Seismic profile ACRI031. For location see Fig. 2

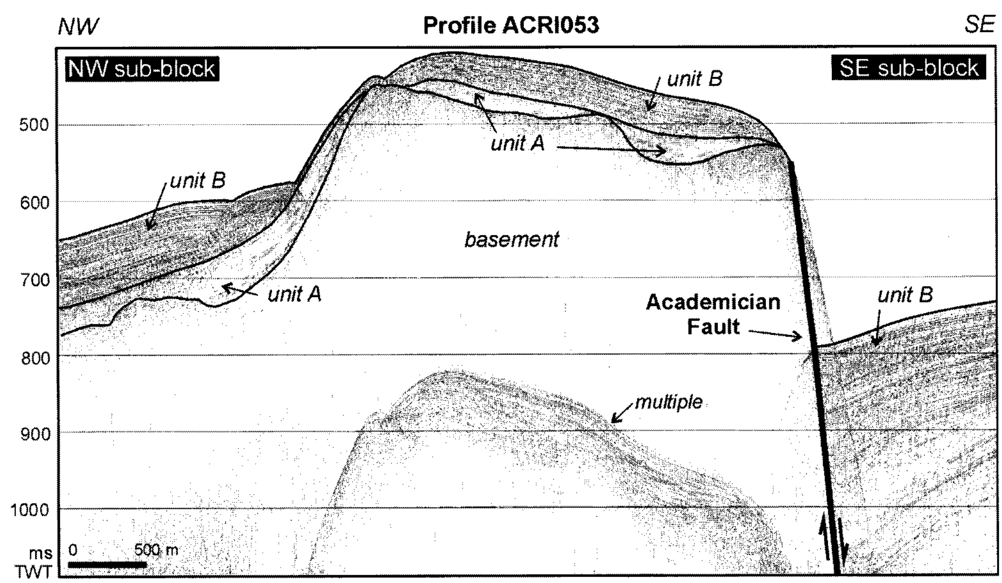
sub-block are marked by secondary faults. The thickness of the sedimentary cover varies from nearly zero to a few hundreds of metres. The morphology is highly variable due to intense faulting. The depth ranges from 500 to 200 m, the highest point being represented by the Ushkany Islands.

The movements along Academician Fault have a hinge character. Near Olkhon Island, the height of the scarp is at its maximum (ca. 300 m), and the sedimentary cover of the Southeastern Sub-Block is separated from the Northwestern Sub-Block by basement rocks outcropping at the fault scarp (Fig. 7). Towards the northeast, the height of the scarp decreases to approximately 20 m. Here, the fault scarp is smoothened by overlying sediments (Fig. 8). Further to the northeast, the height of the Academician Fault scarp increases again (Fig. 9), which finally results in exposure of basement rocks on the Ushkany Islands. The knick-point in the Academician Fault scarp is probably located on the intersection with one of the larger oblique faults. The depth to the top of the basement in the Northwestern Sub-Block therefore changes considerably across strike.

Cainozoic stratigraphy of Academician Ridge

Moore et al. (1997) subdivided the thick sediment package on the Southeastern Sub-Block into several seismic-stratigraphic sequences separated by unconformities. The lower sequences represent obliquely

Fig. 7 Seismic profile ACRI053. For location see Fig. 2



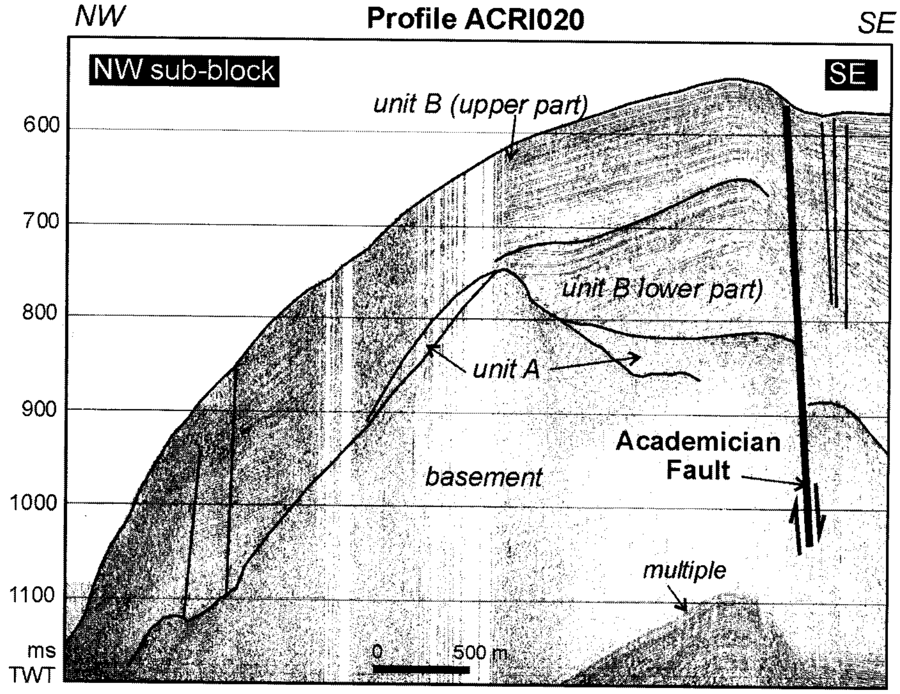


Fig. 8 Seismic profile ACRI020. For location see Fig. 2

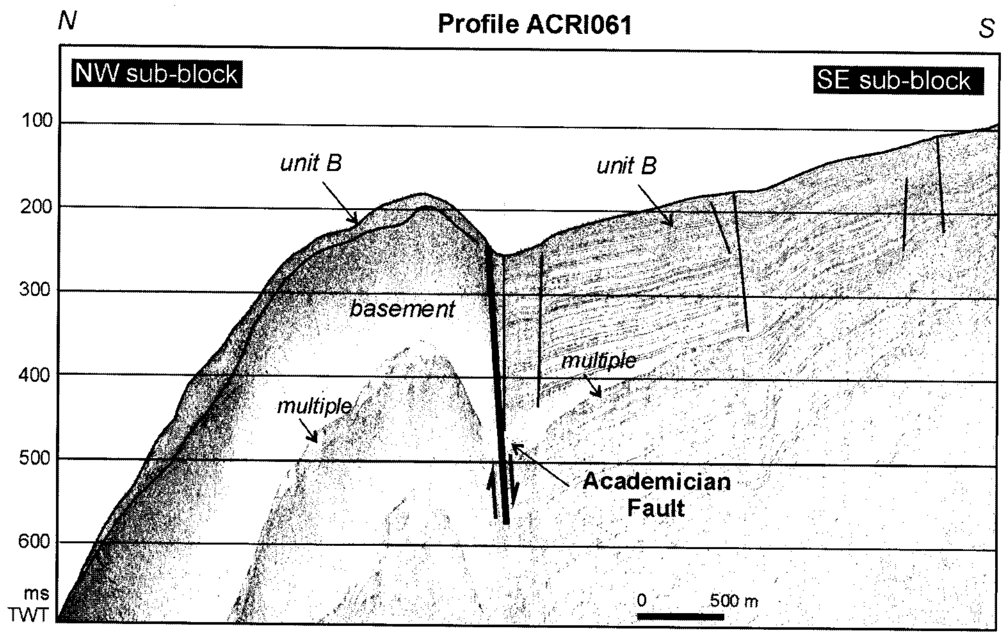


Fig. 9 Seismic profile ACRI061. For location see Fig. 2

prograding, shallow-water deposits of the paleo-Barguzin River delta (Moore et al. 1997). Underwater observations by submersible (Zonenshain et al. 1993) and correlation to outcrops on the nearby Svyatoy Nos Peninsula (Mats et al. 1975) suggest that these units overlie a thick weathering crust at the top of the crystalline basement. The age of the sediments at the base of the deltaic package is estimated to be Early Miocene to Middle Miocene (Kazmin et al. 1995). The upper sequences represent acoustically stratified, continuous hemipelagic deposits typical for sedimentation on a bathymetric high in a deep lacustrine environment (Moore et al. 1997). These deposits were penetrated by the BDP-96 borehole to a depth of 300 m (Kuzmin et al. 1997; BDP Members 1998). The upper 200 m were cored, and proved to consist of a rhythmic alternation of clay layers that are enriched in siliceous diatom frustules, spores and pollen, and of clay layers that are virtually barren. Paleomagnetic analyses suggest that the sediments at 200 m depth have an age of 5 Ma (earliest Pliocene). The age model also shows that the average sedimentation rate has been virtually constant, i.e. 4.0 cm/ka, during this entire period (Kuzmin et al. 1997; BDP Members 1998).

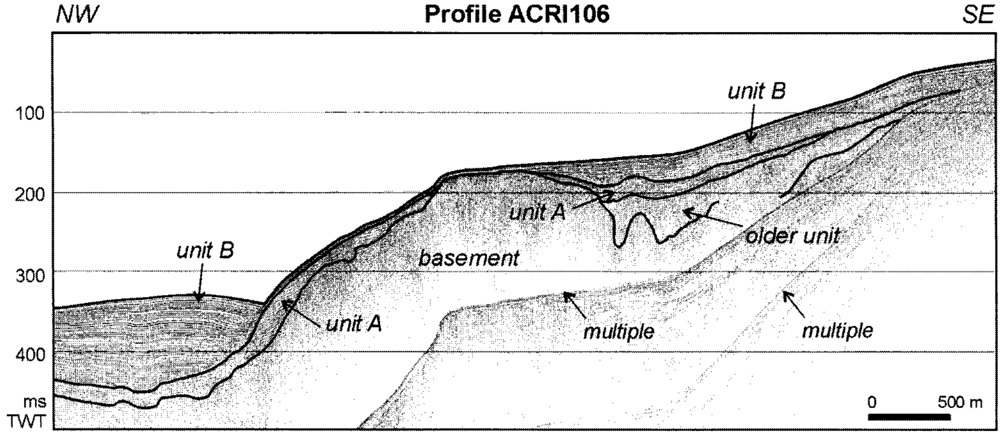


Fig. 10 Seismic profile ACRI106. For location see Fig. 2

The sedimentary cover of the Northwestern Sub-Block was imaged in detail by the new high-resolution reflection seismic profiles. This allowed us to define numerous seismic packages that are of regional importance. They were cored on selected key locations. From base to top we observed: the basement; a thin top-of-basement unit; seismic-stratigraphic unit A; seismic-stratigraphic unit B (Fig. 6); and – although only very locally – an additional seismic package below seismic-stratigraphic unit A (Fig. 10). Because of its limited distribution and the lack of any core information regarding its nature, we preliminarily named this additional package seismic-stratigraphic unit X.

Basement

In agreement with the submersible underwater observations (Zonenshain et al. 1993), we interpret the acoustic basement on the seismic profiles as crystalline basement, consisting of gneisses, granites, crystalline schists and marbles comparable to those exposed in the Zunduk cross section.

Weathering crust

The thin top-of-basement unit, which is expressed on the seismic profiles as a bundle of short, discontinuous, high-amplitude reflections, represents a weathering crust that formed on top of these basement rocks. It was observed in underwater outcrops during submersible dives by Zonenshain et al. (1993), and Goldyrev (1982) collected cores from it. We were also able to sample it in core VER-96-1-St.3-PC, in which it proved to consist of autochthonous granite grains with a clayey mass in the interstitions. Grain sorting is poor to very poor. These characteristics suggest that the crust was formed by cracking of primary basement material by physical weathering due to freezing and strong insolation (G. Stoops, pers. commun.). There are no indications for chemical weathering. The clayey mass in the interstitions is attributed to the alteration of feldspars. The presence of phytolites in our samples indicates that the weathering crust formed sub-aerially.

In the cores the weathering crust is overlain by a thin layer of sediments with a comparable composition. In these sediments, however, numerous allochthonous granite grains occur and the clayey mass is much more abundant than in the underlying crust. The sediment layer has a dark brown colour and is interpreted to represent a hydromorphic soil formed in conditions of stagnant water. Traces of neither sub-aerial nor underwater life are found in the sample, and it was not possible to date it.

Seismic-stratigraphic unit X

High-resolution seismic profiles in Maloye More show the presence of a sedimentary unit, unit X, which occurs as the infill of a small, isolated basement depression at the entrance of the Maloye More Strait (Fig. 10). Unit X's seismic facies is characterised by discontinuous, stratified reflections of variable amplitude. No cores were obtained from this unit.

Seismic-stratigraphic unit A

In all other places in the study area, the oldest deposits overlying the basement and its weathering crust belong to unit A. They do not form a continuous cover but occur in isolated patches (Figs. 6–8, 11, 12). They onlap the substratum, or they fill erosional or structural half-graben-like depressions. Unit A's seismic facies is characterised by parallel-stratified reflections of variable amplitude. It locally grades into an almost reflection-free, transparent facies (e.g. see Fig. 7). A prominent higher-amplitude reflection sometimes occurs in the upper part of the unit.

In order to sample unit A, a series of sediment cores were taken in an area where the seismic profiles showed unit B to be of minimal thickness. In core VER-96-1-St.3PC parts of the weathering crust were retrieved, but it is uncertain if this core also contained

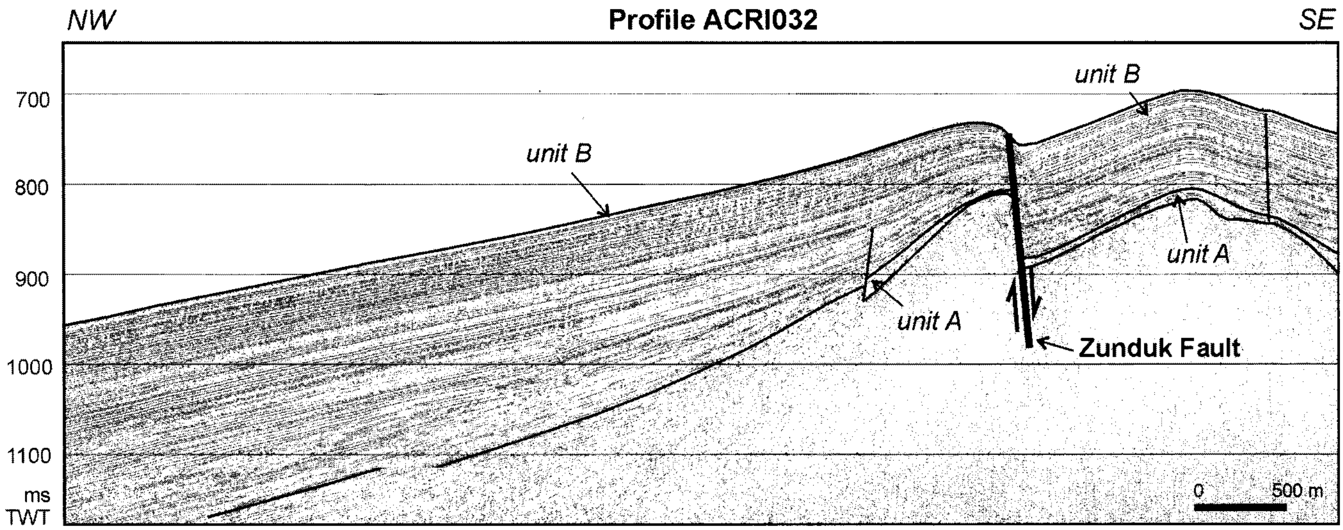


Fig. 11 Seismic profile ACRI032. For location see Fig. 2

sediments of unit A. At the bottom of core VER-96-1-St.6GC, at a depth of 0.78 m, a layer of coarse-grained spotted red sand occurs that might represent unit A. The sands have a high (up to 22%) content of free iron oxide, and also contain heterogeneously distributed goethite and hydrogoethite. The sands are composed of quartz (34–38%), mica (up to 38%) and feldspar (20–27%), with fresh amphiboles and pyroxenes in the heavy fraction. The feldspars are considerably altered, and along fissures they contain aggregates of clayey micas. Hydromicas, Ca-montmorillonites with an admixture of vermiculite, and chlorite dominate in the fine fraction. The rock fragments contain a considerable amount of authigenic carbonate replacing the feldspar-mica component of the rocks and corroding quartz grains. In general, the sands are intensively argillised, which we attribute to geothermal processes. The presence of hematite also suggests a hydrothermal influence. Most probably, these sands were formed as a product of sub-aerial diagenesis. The age of the sands could not be determined. It therefore remains possible that these red sands are not part of unit A but instead belong to the basal layers of unit B.

Seismic-stratigraphic unit B

Unit B overlies either unit A, or the basement and its weathering crust. The unconformity between units A and B is a tectonically controlled angular unconformity, highlighted by numerous onlap terminations of unit B strata onto unit A (Fig. 11). Unit B occurs everywhere on the Northwestern Sub-Block. Locally, it can be subdivided into a lower part and an upper part (Fig. 8). While the upper part is laterally continuous, the lower part occurs locally as onlapping infill of isolated erosional depressions in the basement. At these locations, unit B is characterised by an increased thickness.

Unit B usually dips towards the northwest, except on some broad flat parts on the crest of the Northwestern Sub-Block, where it occurs sub-horizontally. The thickness of Unit B is minimal on top of the basement highs and increases gradually towards the deeper parts of the North Baikal Basin (Fig. 11). Here, the thickness exceeds 300 m, which is more or less the penetration limit of the seismic data. The thickening towards the northwest is a combined effect of gradual onlap onto ridge at the base of the unit, and of stratigraphic thickening of individual reflection packages towards the principal border fault. The oldest deposits of Unit B occur only on the deeper parts of the ridge.

Unit B is characterised by a stratified seismic facies with continuous, medium-amplitude, parallel to sub-parallel reflections. There is a striking resemblance in seismic facies and an apparent stratigraphic continuity (Figs. 8, 12) between Unit B and the uppermost sequences identified by Moore et al. (1997) on the Southeastern Sub-Block, i.e. the sequences encountered in the BDP-96 borehole (Kuzmin et al. 1997; BDP Members 1998). The suggested correlation is confirmed by analysis of piston and gravity cores that penetrated the uppermost 8–10 m of Unit B on the Northwestern Sub-Block (Colman et al. 1995; Grachev et al. 1997). All cores retrieved from water depths of more than 300 m contain the typical deep-water diatom-rich and diatom-barren clay rhythms that were also encountered in the BDP-96 borehole. Analysis of the rhythmic signature of these deposits has allowed Grachev et al. (1997) to correlate these layers with stages 1 to 7 of the SPECMAP-curve, and some of the cores probably even extend further in time, down to the uppermost Lower Pleistocene (Colman et al. 1995). These correlations yield average sedimentation rates for the late Early Pleistocene to Holocene period of 4.0 cm/ka, which is in agreement with the results of the

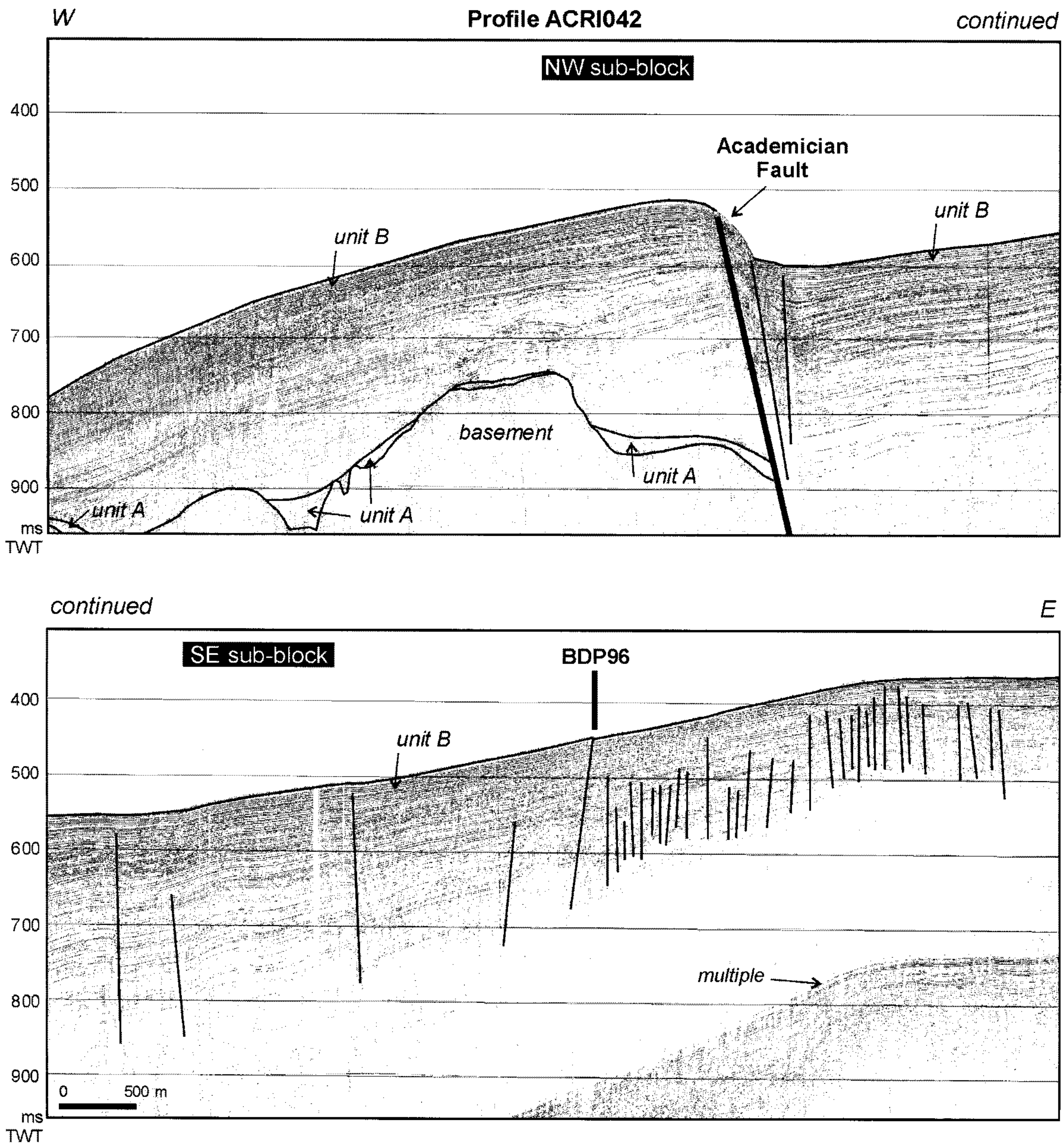


Fig. 12 Seismic profile ACRI042, through the BDP-96 borehole. For location see Fig. 2

BDP-96 borehole (Kuzmin et al. 1997; BDP Members 1998).

However, not all cores of Unit B on Academician Ridge show the same lithology. Some cores taken from the crest of the Northwestern Sub-Block, at water depths of 250–300 m (Fig. 13), where the total thickness of Unit B is often less than 10 m, show a different composition. E.g., the upper part of core VER-96-1-St.8PC,GC comprises the diatom-clay rhythms that are typical for Unit B, but in the middle part a series of dark streaks occur that are enriched with Fe-Mn concretions. These probably represent periods of non-deposition or of strongly reduced sedimentation rates (Granina et al. 1994; Deike et al. 1997). The lower part of the core consists of coarse- and medium-grained, poorly-sorted quartz-feldspar sands. Grain size increases towards the bottom of the core, where gravel and small quartz and slate pebbles appear. This type of deposits was also observed during underwater geological investigations by submersible, along profiles I, II, IV, VI and XI that crossed the Zunduk and Ushkany Fault scarps along the northwestern flank of the ridge (Zonenshain et al. 1993). During these dives, a layer of pebbles and boulders overlain by dense cavernous clays was observed immediately on top of the crystalline basement and its thick weathering crust (Zonenshain et al. 1993). Submersible profiles IV and XI are very close to seismic profile ACRI022 (Fig. 14), on which Unit B

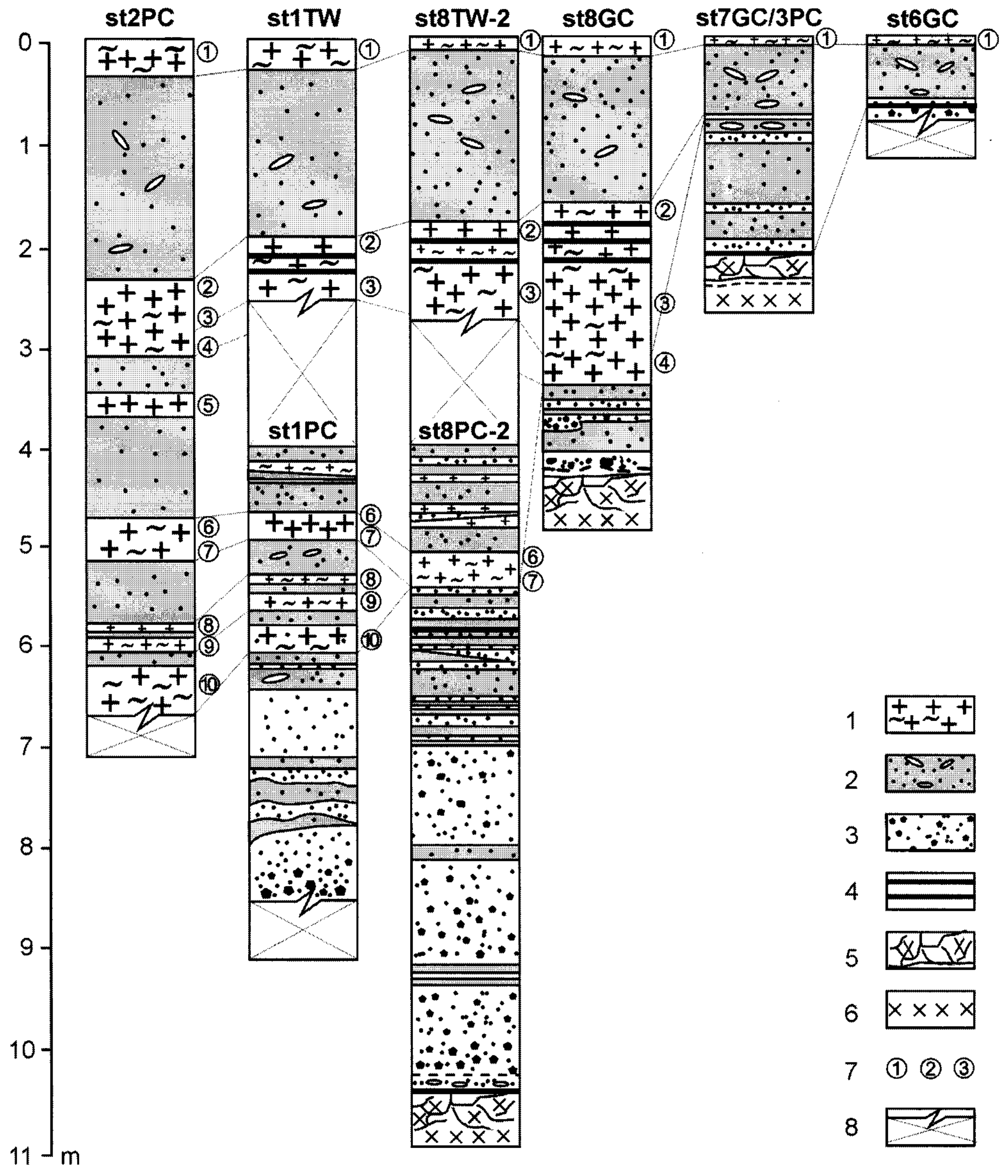


Fig. 13 Lithologs of a series of cores taken along a section across the crest of the Northwestern Sub-Block. For location see Fig. 2. *1* Pelitic diatom ooze; *2* silty clay; *3* sand; *4* Fe–Mn crust; *5* weathering crust; *6* probably basement; *7* ordinal number of diatom layer, according to the diatom stratigraphy of Grachev et al. (1997); *8* lost section

is shown to be directly overlying the basement at the fault scarp. This indicates that the pebbly beach facies described by Zonenshain et al. (1993) might represent the basal layers of Unit B at this location.

Correlation between Pri-Olkhon and Academician Ridge Accommodation Zone

In order to be able to use the deposits of the submerged part of the Academician Ridge to reconstruct the evolution of the entire accommodation zone and its structural connection to the western rift margin, it is necessary to establish a correlation between these sub-aqueous deposits and those observed in Pri-Olkhon (Table 1). We combined information provided by the new seismic data and by the analysis of new shallow cores from the crest of the ridge, with:

1. Results from previous studies using multi-channel seismic profiles (Kazmin et al. 1995; Moore et al. 1997)
2. Underwater geological observations by submersible and palynological analysis performed on the samples taken during these dives (Zonenshain et al. 1993; Kazmin et al. 1995)
3. Analysis of sediment cores (Grachev et al. 1997) and deep drilling on the ridge (Kuzmin et al. 1997; BDP Members 1998)
4. Geological field observations on Olkhon Island (Mats et al. 1989; Mats 1993) and on Svyatoy Nos Peninsula (Mats et al. 1975)

Seismic-stratigraphic Unit X occurs as the infill of a small, isolated depression in Maloye More (Fig. 10). We therefore tentatively correlate it with the Oligocene Ularyar Sequence, which is outcropping in the immediate vicinity, along the shores of the Ularye inlet.

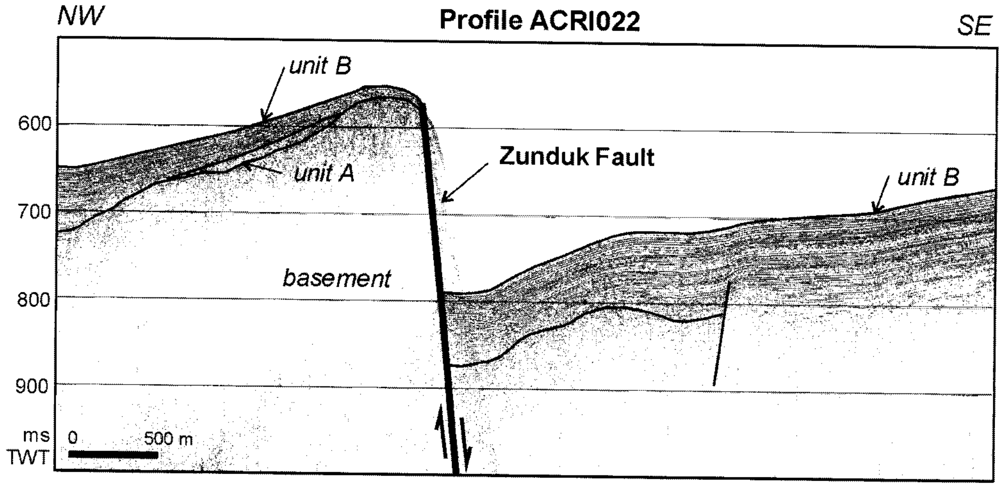


Fig. 14 Seismic profile ACRI022. For location see Fig. 2

Seismic-stratigraphic Unit A occurs on the Northwestern Sub-Block of Academician Ridge in isolated patches, often infilling erosional or structural, half-graben-like depressions. Based on this typical pattern, on the stratigraphical relationships with the overlying Unit B, and on the seismic facies, we tentatively correlate Unit A with the Lower to Middle Miocene Tagay Sequence of the Pri-Olkhon area.

The thickness of seismic-stratigraphic Unit B is highly variable. It increases from a few tens of meters on the crest of the ridge to more than 300 m in the southern part of the North Baikal Basin (Fig. 11). The average sedimentation rate on the Southeastern Sub-Block of Academician Ridge is 4.0 cm/ka (Kuzmin et al. 1997; BDP Members 1998). It is very likely that sedimentation rates on the lower-lying northern slopes of the ridge are slightly higher, but, if we assume for the sake of estimation a similar sedimentation rate for the southern part of the North Baikal Basin, the age of the basal layers of Unit B at that location would be about 7 Ma. This is more or less the age of the Saray Member at the base of the Sasa Sequence that represents the first occurrence of widespread lacustrine environments in the area (Mats et al. 1989). The high-resolution seismic data allow us to extend the seismic stratigraphy from the northern flank of Academician Ridge into Maloye More to Cape Sasa, where the type-section of the Sasa Sequence occurs. Here, Unit B can be correlated with the subaerial exposures of the Sasa Sequence.

Because Unit B gradually onlaps against the relief of Academician Ridge, the basal layers of Unit B higher on the Northwestern Sub-Block are significantly younger than those at the foot of the ridge. On the crest of the ridge, at water depths of less than 300 m, sediment cores showed the presence of hiatuses and significant changes in sedimentation rates in the upper parts of Unit B, and of a coarse-grained sandy-pebbly layer at its base. Lithologically, this layer is very similar to the Lower Pleistocene (1.0–0.7 Ma) Nyurga Sequence outcropping on Olkhon Island.

The sedimentary cover on the Southeastern Sub-Block of Academician Ridge is significantly thicker than that on the Northwestern Sub-Block, and because of the presence of Academician Fault it is not possible to unambiguously correlate seismic-stratigraphic units from one to the other sub-block. Part of the sediment package of the Southeastern Sub-Block was penetrated by the BDP-96 borehole. The upper 200 m were dated paleomagnetically (Kuzmin et al. 1997; BDP Members

Table 1 Proposed correlation between the Cainozoic deposits in Pri-Olkhon and the seismic-stratigraphic units in different settings on Academician Ridge

ONSHORE	OFFSHORE			
Pri-Olkhon	southern part of N. Basin	NW Sub-Block / Maloye More	crest of NW Sub-Block	SE Sub-Block
Nyurga Sequence (L. Pleistocene)			base of Unit B	
Kharantsy Sequence (U. Pliocene)		base of Unit B		
Sasa Sequence (U. Miocene - L. Pliocene)	base of Unit B			base of Unit B
Tagay Sequence (M. Miocene)	*beyond penetration*	Unit A	Unit A	*beyond penetration*
Ularyar Sequence (Oligocene)	*beyond penetration*	Unit X	?	*beyond penetration*

1998) and proved to consist of Quaternary and Pliocene deposits. The Miocene-Pliocene boundary (5.4 Ma) is interpreted to occur at a depth of 220 m.

Kazmin et al. (1995) and Moore et al. (1997) observed a major stratigraphic unconformity on the multi-channel seismic profiles across the Southeastern Sub-Block. Based on our observations and interpretations, we tentatively correlate this unconformity with the unconformity between Unit A and Unit B that we observed on the high-resolution seismic profiles on the Northwestern Sub-Block, and hence with the boundary between the Tagay and Sasa Sequences on Olkhon Island. This unconformity would thus more or less represent the boundary between the Middle and Upper Miocene.

Geological history of the central part of the Baikal Rift

Below, we propose a new paleogeographic scenario for the evolution of the central part of the Baikal Rift. This scenario builds on the models for the Baikal Basin development as proposed previously by Logachev et al. (1974), Mats (1987, 1993) and Mats et al. (1989). The development and evolution of the Academician Ridge Accommodation Zone is a crucial part of this scenario and our new observations from this area allow us to refine a number of aspects of the above models.

The first stage in the geological history of the Baikal Basin is what could be called the "Pre-Rift Stage", which was characterised by extensive basaltic volcanism, hydrothermal activity and deep-crustal circulation of surface waters (Tsehovsky et al. 1996a, 1996b; Kashik et al., in press). The volcanic activity provides age constraints on the "Pre-Rift Stage": it started at about 72 Ma (oldest basalts in the Tunka Basin), and it ended at about 27 Ma (youngest plateau basalts on the Khamar-Daban Ridge; Rasskazov 1993). During this stage, only limited vertical tectonic movements took place. This favoured, under humid-tropical and subtropical climate conditions, the development of an extensive laterite-kaolinite weathering crust.

The initial Baikal Depression was occupied by a series of relatively large lakes, with depths of several tens of meters (Fig. 15a). The areas that now form the uplifted rift flanks were then part of a widespread, low peneplane. Only locally, in areas with residual relief such as in the area of the Khamar-Daban Ridge, altitudes of 200–400 m were reached (Mats 1993). Since there were no large orographic barriers and because climate conditions were favourable, southern species of water animals invaded these northern areas from the Sinic-Indian zoological provinces (Martinson et al. 1986). Molecular analyses (Sherbakov et al. 1998) suggest that the genetic roots of many species of Lake Baikal's rich endemic fauna are over 30 Ma old, and possibly date back to this initial "Pre-Rift Stage".

The rifting stage itself started in the Late Oligocene (27 Ma). It can be subdivided into an Early Rift Stage, the Tankhoy Stage (Late Oligocene to Early Pliocene; 27–3.5 Ma), and a Late Rift Stage (Late Pliocene – Present; 3.5–0 Ma), which are more or less equivalent respectively to the Slow Rifting Stage and the Fast Rifting Stage of Logachev and Zorin (1987). The Early Rift Stage can be further subdivided into an Early Sub-Stage (Late Oligocene to Early Miocene; 27–17 Ma), a Middle Sub-Stage (Middle Miocene; 17–7 Ma), and a Late Sub-Stage (Late Miocene to Early Pliocene, 10–3.5 Ma), and the Late Rift Stage into an Early Pra-Manzurka Sub-Stage (Late Pliocene to Early Quaternary; 3.5–0.7 Ma), a Middle Primorsky Sub-Stage (Early to Middle Quaternary; 0.7–0.15 Ma), and a Late Tyya Sub-Stage (Late Quaternary; 0.15–0 Ma).

During the Late Oligocene to Early Miocene (27–17 Ma), a large, deep-water lake formed in the South and Central Baikal Basins. The northwestern shores of this early Baikal Lake were formed by the Olkhon Fault scarp (Fig. 15b). Not only the Bugul-deyka-Maloye More and Olkhon Blocks, but also the Academician Ridge Block were then part of the land surrounding this lake. The North Baikal Basin remained virtually dry, except perhaps in its northern termination (Logachev et al. 1974; Mats 1993). The first volumetrically significant deposits in the North Baikal Basin are thus younger than those in the Central and South Basins. Here, our model differs from that of Moore et al. (1997). Based on the analysis of MCS data across Academician Ridge, on seismic-stratigraphic correlations across the ridge, and on the assumption that faulting periods were contemporaneous in all sub-basins of Lake Baikal, Moore et al. (1993) postulate that the North Baikal Basin formed during the same period as the Central and South Baikal Basins. This interpretation remains, however, difficult to reconcile with the available field data and other observations, as mentioned in e.g. Mats (1993), Logachev et al. (1974), Hutchinson et al. (1992) and Zonenshain et al. (1993), indicating that the North Basin must be significantly younger.

Paleontological data (M.M. Kozhov, pers. commun.) suggest that this early Lake Baikal reached water depths that were already in excess of 400 m. Arguments for this are derived from the presence of a fauna of warm-water molluscs in outcropping lacustrine strata of Late Oligocene age (Mats 1993). These molluscs, which occurred in a vast area from the southern Sinic-Indian zoological provinces to the northern Lena River mouth (Martinson et al. 1986), are lacking entirely in deposits of the same age from smaller – and shallower – lakes in the Selenga-Vitim and Pri-Baikal Depressions. It seems that these species apparently sought and found refuge from the general climatic cooling that affected the Earth during the Late Oligocene in the deeper waters of Lake Baikal.

During the Middle Miocene (17–10 Ma) a series of narrow fault-bounded blocks started to form within the Southeastern Sub-Block of Academician Ridge. One by one, these blocks submerged and the shoreline of

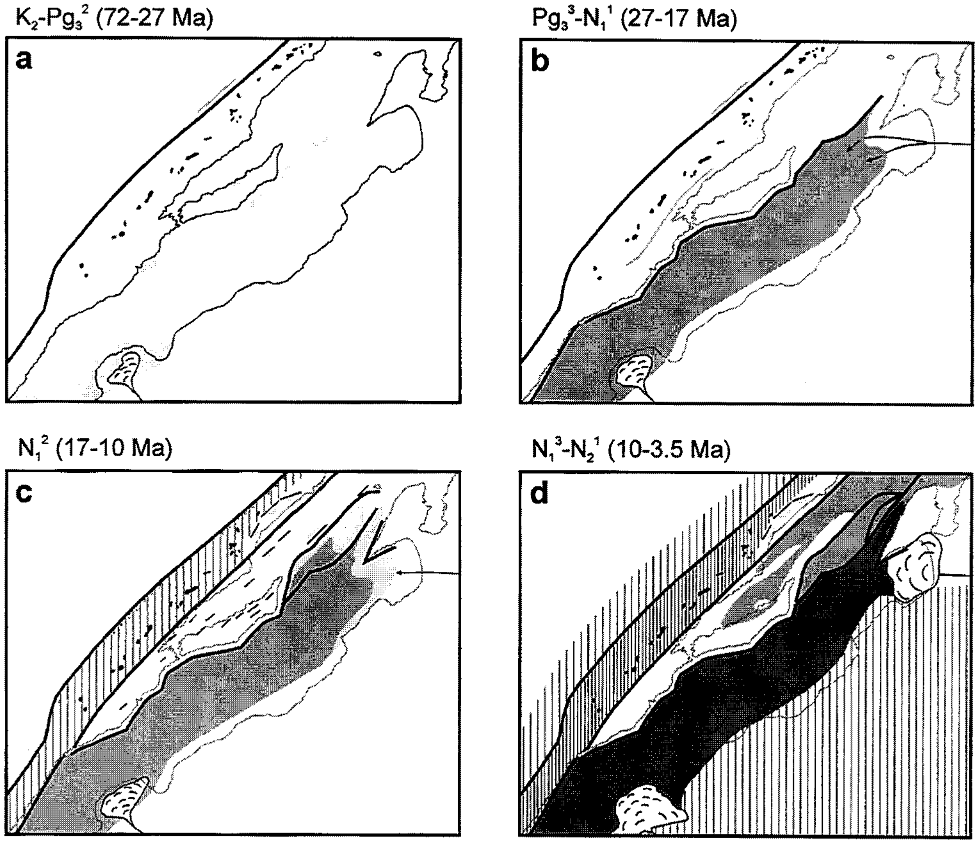


Fig. 15a–d Paleogeographic reconstruction of the environments in the central part of the Baikal Rift. **a** Cretaceous–Middle Oligocene (72–27 Ma); **b** Late Oligocene–Early Miocene (27–17 Ma); **c** Middle Miocene (17–10 Ma); **d** Late Miocene–Early Pliocene (10–3.5 Ma)

the Central Baikal Basin gradually moved northwestwards (Fig. 15c). In the Pri-Olkhon area, half-graben-like depressions started to form. The number of such half-grabens increased from the Buguldeyka-Maloye More Block marginal step in the southwest towards the northeast, i.e. with increasing offset along Primorsky Fault and with increasing enlargement and subsidence of the Maloye More Depression. These depressions were occupied by isolated or interconnected small to medium-sized lakes. They were filled with syn-rift deposits. Because of the semi-arid conditions, the waters of these lakes were highly mineralised, with high concentrations of carbonates and gypsum. In some of the lakes sediment with high organic content accumulated that later developed into brown coal. These deposits form the Tagay Sequence of Pri-Olkhon and seismic-stratigraphic Unit A on the Northwestern Sub-Block of Academician Ridge (Fig. 15c).

During the Late Miocene, the extensional movements intensified, and the small structural depressions that formed during the previous stage gradually evolved into larger ones. The graben separating the Svyatoy Nos Peninsula from the Ushkany Islands deepened and propagated towards the northeast. Through this graben, and also along the area where the Academician Fault scarp had minimal relief, waters from the Central Baikal Basin moved across Academician Ridge into the North Baikal Basin and into Maloye More. The flooding of Maloye More involved the northern parts of Maloye More, up to Khuzhir, and parts of Olkhon Island. The lake basin that formed remained hydrologically connected with the Central Baikal Basin via the narrow Svyatoy Nos and Ushkany Straits, whose morphology was strongly influenced by the structurally controlled flanks of the Olkhon Block and the Northwestern Sub-Block of Academician Ridge.

After this initial connection between the Central and North Baikal Basins was established, the North Baikal Basin continued to deepen during the Late Miocene to Early Pliocene (10–3.5 Ma). This deepening was the result of a gradual tilting towards the northwest of the Northwestern Sub-Block of Academician Ridge (Fig. 15d). Consequently, its northwestern margin gradually submerged and the shoreline of the North Baikal Basin advanced towards the southeast. Nevertheless, the main part of this Northwestern Sub-Block remained sub-aerial, except for the narrow Ushkany Strait. The sediments deposited during this period form the Sasa Sequence of Pri-Olkhon and probably the lower parts of seismic-stratigraphic Unit B where they onlap the foot of the northern slope of Academician Ridge. The sedimentary facies of the Sasa Sequence indicates that the lacustrine basin in which it was deposited was relatively deep. The lake water was characterised by a low mineralisation and a high oxidation-

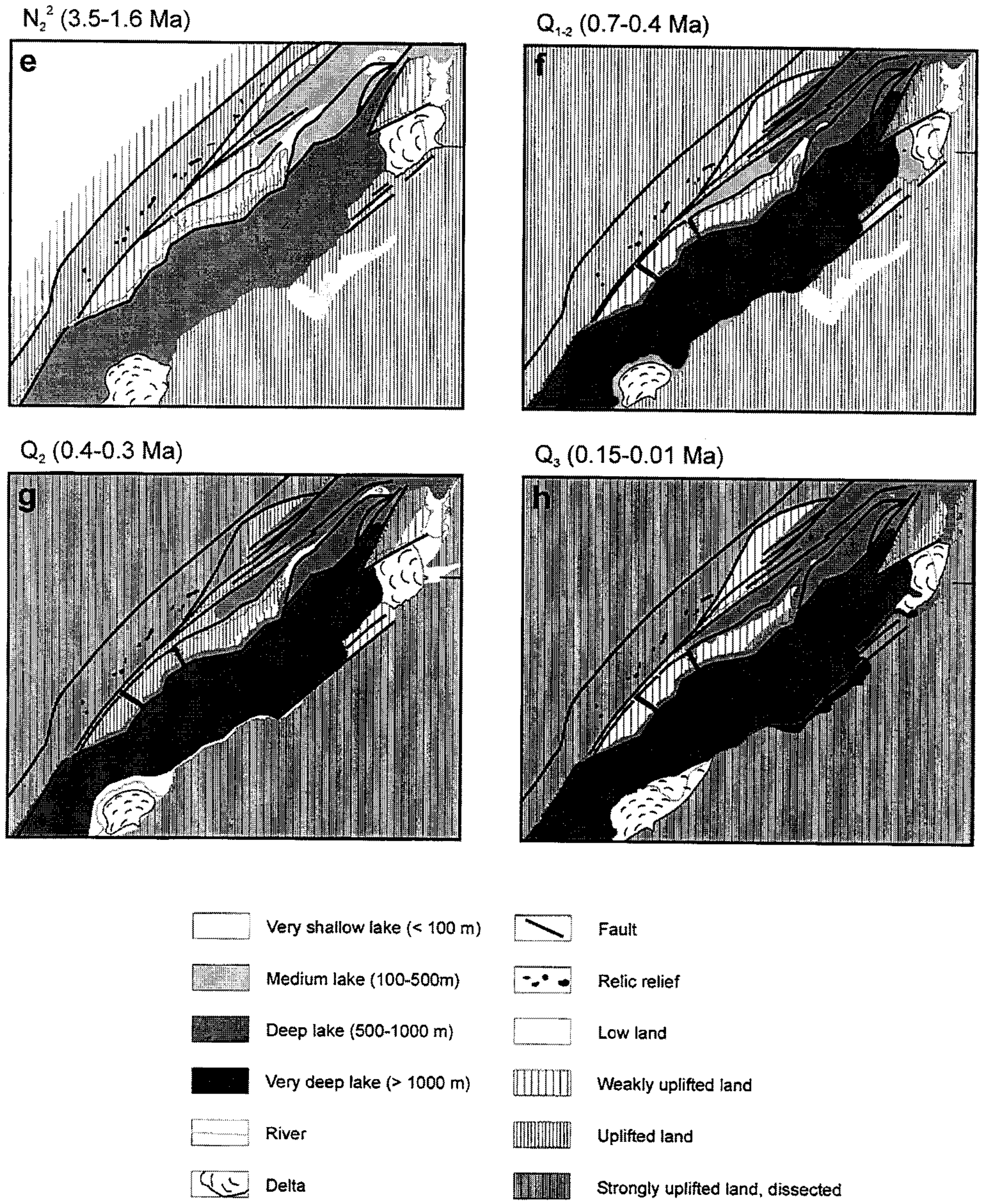


Fig. 15e–h Paleogeographic reconstruction of the environments in the central part of the Baikal Rift. **e** Late Pliocene (3.5–1.6 Ma); **f** Early Late Pleistocene (0.7–0.4 Ma); **g** Middle Late Pleistocene (0.4–0.3 Ma); **h** Late Late Pleistocene (0.15–0.01 Ma)

reduction potential. A series of lagoons with highly mineralised, alkaline waters formed around the main basin.

At the transition between the Early and Late Pliocene (at about 3.5 Ma), the Olkhon Block was uplifted, which caused the complete drying out of the Sasa embayment (Mats et al. 1982) and a major regression in the Maloye More area. Tilted strata of Upper Miocene to Lower Pliocene lacustrine deposits witnessing this uplift are exposed in the northern part of Olkhon Island. The Zunduk Horst and the Northwestern Sub-Block of Academician Ridge remained sub-aerial during this period (Fig. 15e). The Southeastern Sub-Block remained in a stable, deep-water depositional environment (Kuzmin et al. 1997; BDP Members 1998) with open connection to the North Baikal Basin via a shallow-water strait between the Ushkany Islands and Olkhon Island.

Tectonic deformations of Late Pliocene age are documented within the uplifted Baikal Rift shoulders (Florensov 1960; Logachev 1974; Logachev et al. 1974; Mats 1993). As the rift shoulders probably uplifted contemporaneously with rift basin subsidence, it is very probable that such a Late Pliocene (3.5–2 Ma) tectonic pulse was the main cause for the development of the ultra-deep-water basins of Lake Baikal, as they still exist today (Logachev et al. 1974; Mats 1993). By the end of the Pliocene or the beginning of the Quaternary, the uplift slowed down or stopped, which resulted a.o. in the backfilling of the erosional Pra-Manzurka valley, the single outlet of Lake Baikal at that time (Logachev et al. 1974).

During the Early Pleistocene (1–0.7 Ma) another major transgression started from the North Baikal Basin onto the Northwestern Sub-Block of Academician Ridge. During this transgression, the coarse-grained sandy-pebbly layers at the base of Unit B on the crest of the Northwestern Sub-Block were deposited, and also the beach sands of the Nyurga Sequence on Olkhon Island.

Another drastic uplift of the western rift shoulder took place during the early Late Pleistocene (0.7–0.4 Ma). This resulted in the disconnection of the only lake outlet through the Pra-Manzurka valley (Logachev et al. 1974; Mats 1993). Consequently, lake level rose until it reached the altitude of the lowest-lying connection to the surrounding areas, located near Kultuk at the southwestern end of Lake Baikal, from where a new outflow of the Baikal waters was established via the Irkut River valley into the Yenisey River system (Kononov and Mats 1986). The amount of lake-level rise can be estimated from the altitude of early Late Pleistocene lacustrine terraces at Cape Tyya (35–80 m) and of beds of lacustrine pebbles at Cape Sasa on Olkhon Island (80 m). Our data show that during this lake-level rise the Northwestern Sub-Block of Academician Ridge was still not completely submerged (Fig. 15f).

A number of studies (Lut 1964; Galkin 1975; Romashkin and Williams 1997) suggest that the level of Lake Baikal may have fallen again during the middle Late Pleistocene (0.4–0.3 Ma), possibly in response to climatic changes. This could have lead to a drying out of the Ushkany Strait and the re-emergence of the entire crest of Academician Ridge between Olkhon Island and the Ushkany Islands archipelago (Fig. 15g). Such a lake-level fall could help to explain the hiatuses and discontinuous sedimentation rates observed in sediment cores from Unit B retrieved from water depths of less than 300 m on Academician Ridge. However, no sign of such an event is observed in the BDP-96 borehole (Kuzmin et al. 1997; BDP Members 1998), and also Colman (1998) argues against the possibility of such strong climatically-driven lake-level fluctuations.

At the transition between the middle and the late Late Pleistocene (0.15–0.12 Ma), the last phase of major tectonic movements started: the Tyya sub-stage. It involved an increased subsidence in the rift basins and uplift of the rift shoulders, and it resulted a.o. in a rapid submergence of the Northwestern Sub-Block of Academician Ridge. The highest points of the ridge, however, probably only disappeared at the very end of the Pleistocene (Fig. 15h). The latest pulses of this Tyya sub-stage lasted up until the Holocene (Mats and Kulchitsky 1994; Kulchitsky 1994; Levi 1991). The subsidence of the Listvianka Block that resulted in the creation of the present lake outlet via the Angara River (dated at ca. 60–40 ka B.P.) is the result of this late tectonic pulse (Mats 1993).

Conclusion

The following conclusions were reached as a result of this study:

1. In the present-day morphology and structure of the central part of the Baikal Rift, a whole range of rift-related structures (half-grabens, grabens, marginal steps, border fault splays, accommodation zones, ...) can be observed. These occur in different scales and in different degrees of development. Small structures can be regarded as miniature models for their larger-scale equivalents. The striking similarities in morphology and structure between e.g. the Maloye More Graben and the Zama Depression indicate that they have a common origin. The more practical size and accessibility of the small-scale structures also means that they can be studied more easily. Analysis of the structural evolution of the Maloye More Graben, for example with high-resolution reflection seismic profiles, may thus help us to improve our understanding of the earlier phases of Baikal Rift development.
2. The typical structural elements that make up the accommodation zone and its connection to the western rift margin show a very characteristic along-strike evolution in structural style, i.e. from southwest to northeast. The sub-aerial marginal step attached to the rift margin (the Buguldeyka-Maloye More Block) continues laterally into a sub-aerial tilted fault block (the Olkhon Block), which in its turn continues into the fully submerged accommodation zone (the Academician Ridge Block). This spatial evolution seems also to represent an evolution in time, the most mature segment in this series being the submerged Academician Ridge Block. The same applies to the Buguldeyka-Chernorud Graben, which grades laterally into the more evolved Maloye More Graben. Another example of along-strike evolution from one structural feature into another, more mature one is given by Primorsky Fault. A splay of Primorsky Fault evolves laterally into a larger tilted block, then into the Zunduk-Zama marginal step and finally into the Zama Depression. Most of the longitudinal structural elements are segmented by transverse faults systems (i.e. the segmentation of the Buguldeyka-Maloye More Block into sub-blocks).
3. The structural elements that make up the accommodation zone and its connection to the western rift margin also show a distinct across-strike evolution in structural style. The western rift margin evolves – from northwest to southeast – from a single border fault, over a series of border-fault splays, a marginal step, an isolated graben and an accommodation zone to the deep rift basin. Such a step-like structure appears to be characteristic for the entire central part of the Baikal Rift: between the Zama and Maloye More Depressions, between the Kocherikovo, Onguryony and Zama Depressions, and

between the Kaltygey and Kulgana Depressions. Along-strike and across-strike evolution in style appear to be closely related. Lateral changes in morphology and structure may e.g. lead to transverse migration of depocentres or structurally controlled depressions. This is clearly expressed along the northwestern rift margin, between Zama and Onguryony.

4. The observed along-strike evolution in structural style in the central part of the Baikal Rift is mainly to be attributed to the listric character of the faults involved, and to lateral changes in fault offset, imposing a rotational component on the fault movement. Obliquely tilted blocks determine a significant part of the morphology and structure of the accommodation zone and its connection to the western rift margin. The across-strike evolution and observed step-like structures point to a distinct strike-slip component within the fault movement. All observations suggests that distinct changes in the stress field occurred during the Middle Miocene to Present evolution of the Primorsky Fault and Olkhon Faults.
5. Based on new data from Academician Ridge (high-resolution reflection seismic profiles and shallow sediment cores) and on available data from geological and geomorphologic field work in Pri-Olkhon, we have been able to reconstruct in more detail the evolution of the ridge through time, as part of the accommodation zone and in the framework of the evolution of the central part of the Baikal Rift. We have also been able to refine a previously proposed palaeogeographic scenario (Kazmin et al. 1995) involving gradual flooding of Academician Ridge from the North Baikal Basin. We have also shown that the crest of Academician Ridge probably did not submerge until very recently, not until the latest Late Pleistocene. These findings and new age constraints are particularly significant for evolutionary biology research in Lake Baikal.

Acknowledgements This research was carried out under the auspices of BICER, and was partially funded by INTAS Project 94-0134, by INTAS-RFFR Project 95-0646 and by the Flemish Fund for Scientific Research. We thank the Captain and crews of R/V Vereshchagin and R/V Titov, on board of which the seismic and coring data were collected. We are also grateful to M. Grachev, J. Klerkx, P. Otinov, A. Fedotov, S. Vorobyova, W. Versteeg, T. Van Cauwenberghe, K. De Rycker, P. Vanhauwaert and M. Vanneste for their help during acquisition and processing of the data and for helpful discussions at all stages of this study. We also thank the reviewers for their very constructive comments. SC was funded by an EC-grant. MDB is Research Associate of the Flemish Fund for Scientific Research.

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