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Basin structures and sediment accumulation in the Baikal Rift Zone: Implications for Cenozoic intracontinental processes in the Central Asian Orogenic Belt

S.K. Krivonogov *, I.Y. Safonova

Sobolev Institute of Geology and Mineralogy SB RAS, Koptyuga Ave. 3, Novosibirsk 630090, Russia
Novosibirsk State University, Pirogova St. 2, Novosibirsk 630090, Russia

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ABSTRACT

In this paper we present a review of sedimentological, geomorphological, lithological, geochronological and geophysical data from major, minor and satellite basins of the Baikal Rift Zone (BRZ) and discuss various aspects of its evolution. Previously, the most detailed sedimentological data have been obtained from the basins of the central BRZ, e.g., Baikal, Tunka and Barguzin, and have been used by many scientists worldwide. We add new information about the peripheral part and make an attempt to provide a more comprehensive view on BRZ sedimentation stages and environments and their relations to local and regional tectonic events. A huge body of sedimentological data was obtained many years ago by Soviet geologists and therefore is hardly accessible for an international reader. We pay tribute to their efforts to the extent as the format of a journal paper permits. We discuss structural and facial features of BRZ sedimentary sequences for the better understanding of their sedimentation environments. In addition, we review tectono-sedimentation stages, neotectonic features and volcanism of the region. Finally, we consider the key questions of the BRZ evolution from the sedimentological point of view, in particular, correlation of Mesozoic and Cenozoic basins, bilateral growth of the Baikal rift, Miocene sedimentation environment and events at the Miocene/Pliocene boundary, Pliocene and Pleistocene tectonic deformations and sedimentation rates. The data from deep boreholes and surface occurrences of pre-Quaternary sediments, the distribution of the Pleistocene sediments, and the data from the Baikal and Hovsgol lakes sediments showed that 1) BRZ basins do not fit the Mesozoic extensional structures and therefore hardly inherited them; 2) the Miocene stage of sedimentation was characterized by low topography and weak tectonic processes; 3) the rifting mode shifted from slow to fast at ca. 7–5 Ma; 4) the late Pleistocene high sedimentation rates reflect the fast subsidence of basin bottoms.

1. Introduction

The Baikal Rift Zone (BRZ) is a SW–NE oriented active tectonic zone aligned along the southern margin of the Siberian Platform, within the Central Asian Orogenic Belt (CAOB), the world largest accretionary orogen (Zonenshain et al., 1990; Kröner et al., 2007; Windley et al., 2007; Safonova et al., 2011) (Fig. 1). Compared to other segments of the CAOB, the BRZ is characterized by the wide occurrence of Mesozoic to Cenozoic rift-type sedimentary basins, Cenozoic volcanic fields and active seismicity (e.g., Rasskazov, 1993; Logatchev et al., 1996; Rasskazov et al., 2000, 2003; Petit and Déverchère, 2006; Ivanov et al., 2015) (Fig. 1). Several authors considered the BRZ a boundary zone or lithospheric suture zone formed in relation to the evolution and closure of the Paleo-Asian Ocean (e.g., Zonenshain et al., 1990; Dobretsov et al., 1995; Kovalenko et al., 2004). Consequently, the recent tectonic structure of the BRZ inherited many previous major stages of the regional geological history, which included the accretion of numerous island arcs and microcontinents to the active margins of the Siberian continents, the closure of the large archipelago-type Paleo-Asian Ocean that ended in the late Paleozoic and the subsequent collisions of the Siberian, Tarim and North-China cratons, Tuva-Mongolia, Amurian and other microcontinents (e.g., Zonenshain et al., 1990; Petit and Déverchère, 2006, Wilhem et al., 2012; Safonova and Maruyama, 2014; Safonova, in press). Those stages of accretion, ocean closure and collision formed numerous foldbelts or orogenic belts consisting of late Neoproterozoic to Mesozoic terranes of various geodynamic origins and were followed by the onset of intracontinental environment in early Mesozoic time.

The Mesozoic intra-continental orogeny resulted in extensive syn- and post-collisional magmatism and rifting (e.g., Yarmolyuk and Kovalenko, 1991; Jahn, 2004; Yarmolyuk et al., 2005; Kröner et al., 2014). The intra-continental orogeny ceased by the end of the Mesozoic and was followed by peneplanation, which resulted in the formation of plain surfaces and laterite-kaolin weathering crusts over almost whole Central Asia (e.g., Jolivet et al., 2013 and references therein). In the Baikal

* Corresponding author at: Sobolev Institute of Geology and Mineralogy SB RAS, Koptyuga Ave. 3, Novosibirsk 630090, Russia.
E-mail address: carpos@igm.nsc.ru (S.K. Krivonogov).

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region, those peneplain surfaces are of upper Cretaceous–Paleogene age (Florensov, 1960). Mesozoic extension tectonics formed rift-type basins in Transbaikalia and Mongolia (Logatchev et al., 1996; Yarmolyuk and Ivanov, 2000; Mats et al., 2001; Logatchev, 2003; Jolivet et al., 2009).

The Mesozoic extension of the BRZ was followed by the Cenozoic intracontinental rifting or riftogenesis, which resulted in extensive basaltic volcanism and formation of sedimentary basins in place of crustal extension zones. Three major driving mechanisms of rift extension have been proposed: the effect of the ongoing India-Eurasia collision (Molnar and Tapponnier, 1975), asthenospheric upwelling (Logatchev et al., 1983; Zhu, 2014) or mantle plumes (Windley and Allen, 1993; Yarmolyuk et al., 1995, 2000; Safonova and Maruyama, 2014) or both the collision and the plumes (e.g., Petit and Déverchère, 2006).

The BRZ has been studied by many research teams of the former Soviet Union, Russia and of other countries with foci made to its geological history (e.g., Logatchev, 1983; Logatchev et al., 1996; Zonenshain et al., 1990), tectonic structure (e.g., Logatchev et al., 1978; Delvaux et al., 1995; Jolivet et al., 2009, 2013; Ufimtsev et al., 2009), deep seismic structure (Zhao et al., 2006; Koulakov, 2011; Zhu, 2014), GPS-geodesy (Ashurkov et al., 2011), and magmatism (Rasskazov, 1993; Yarmolyuk and Ivanov, 2000; Rasskazov et al., 2003; Yarmolyuk et al., 2005; Ivanov and Demonterova, 2009; Ivanov et al., 2015). However, its origin remains debatable, in particular, in terms of its Meso-Cenozoic history. Of special importance are the rift basins, in particular, their sedimentary infill, geomorphological features and tectonic structure. The sediments of those basins represent the only continuous archives of sedimentation and regional geological evolution and hence are necessary for the correct understanding of the origin and evolution of the BRZ.

Many papers and monographs have been published about the structure and composition of sedimentary basins (e.g., Florensov, 1960; Logatchev et al., 1964, 1974; Mats et al., 2001; Shchetnikov and Ufimtsev, 2004) in general, and on the seismic-based deep structure and sedimentology of the BRZ largest lakes of Baikal and Hovsgol, in particular (e.g., BDP Members, 1998; BDP Group, 2000; Kuzmin et al., 2001; Krivonogov, 2006; Fedotov et al., 2007; Prokopenko et al., 2009; HDP Members, 2009). In addition, there have appeared several reviews, which were focused on a limited number of basins, e.g., Baikal, Tunka, Barguzin (e.g., Mats et al., 2001; Mats and Perepelova, 2011; Shchetnikov et al., 2012), or restricted by this or that age interval, for example, the Tertiary (e.g., Kashik and Mazilov, 1994) or the Late Pleistocene–Holocene (Krivonogov, 2010). The huge amount of sedimentological data obtained from all the rift basins of the BRZ by Soviet geologists, but published in Russian, in limited book series or conferences materials, so far remains hardly accessible for international readers. However, no reviews of sedimentological data from the whole BRZ have ever been published.

This paper represents a review of the available sedimentological data from major and minor, central and peripheral basins of the BRZ. We pay a tribute to the researchers who obtained many original data many decades ago and who generated the first ideas on BRZ evolution. We present data from deep boreholes and from subsurface pre-Quaternary and Quaternary sediments and discuss the evolution of the BRZ in terms of the general structure of the BRZ and specific structural features of rift basins, and the relationships between tectonics, volcanism, and sedimentation. Foci are made to correlations between Mesozoic and Cenozoic basins, the bilateral growth of the Baikal rift, Miocene sedimentation, Pliocene and Pleistocene tectonic deformations, the late Pleistocene fast subsidence of the basins and others. Finally, we make an attempt to link the major stages of sedimentation and tectonics and to highlight those more significant for the better understanding of the tectonic evolution of the whole Baikal region.

2. Morphological setting of the Baikal Rift Zone

The main structural features of the BRZ are rift valleys (consist of two or more basins separated by topographic rises, e.g., ridges, spurs and other horst-type structures), major and minor rift basins and surrounding mountain ranges. The rift valleys of the BRZ can be several hundred kilometers long and include both major (typically 200–100 km long and 20–40 km wide) and minor (10–20 km long and 1–10 km wide) basins and interbasin horsts (Ufimtsev, 2002) (Figs. 1 and 2). An exception is the Baikal rift valley, which is around 800 km long and 40–50 km wide. The rift basins are either normal grabens or half-grabens bounded by ca. two kilometers high horst-like linear mountain ranges. The rift basins and valleys form chains extending to a distance of ca. 1800 km to the north-east. There are two main chains: the first includes Tunka, Baikal, Upper Angara, Muya and Chara and the second includes Barguzin, Upper Muya and Tsipa-Baunt. The majority of the basins in the central and north-eastern BRZ are aligned along the margin of the Siberian Craton. In the south-western BRZ, the Darhad and Hovsgol basins meet the Tunka Basin under an almost right angle and look separated from the main chains (Florensov, 1960) (Fig. 1).

The major basins of the BRZ are filled by thick Cenozoic sediments. Most of the basins are typically dry (compensated); only lakes Baikal and Hovsgol represent basins with water (not compensated). The major rift basins and valleys are separated from each other by interbasin horsts, which represent basement elevations. The horsts can be dozens to several hundred meters high, in places covered by sediments. Structurally, the horsts consist of one or several variably uplifted blocks and may include minor basins (Ufimtsev, 2002). The main structural features of the major basins are border (boundary) faults or detachment faults in case of half-grabens, intermediate tilted fault blocks (listric fault fans), and intrabasin horsts (Fig. 2). The intermediate tilted fault blocks are located close to the surrounding mountain ranges and could have been either subsided or uplifted since their formation. For example, in the Baikal rift valley, the Rel'-Sludinka block in the North Baikal Basin was subsided and the Tankhoi in the South Baikal Basin was uplifted (see Section 3 for details). The tilted surfaces of those blocks, which are half-grabens, can be filled by up to 300 m thick Cenozoic sediments and are also considered as minor or satellite basins (Mats, 1990; Kulchitsky et al., 1993).

The major basins are drained by rivers and have flat bottoms dipping down their hosted river; their separating interbasin horsts are cut by those rivers. In addition, the bottoms can be tilted toward main border/detachment faults. The bottoms show signatures of local subsidence, which together with intrabasin highs in the central parts of the basins suggest a blocky structure of the basement and variable directions of block movements (Lopatin, 1972; Ufimtsev et al., 2006). Several basins show signs of tectonic inversion which resulted in reduced sediment thicknesses and stratigraphic breaks (Ufimtsev, 2002; Ufimtsev et al., 2009).

The minor basins occur away from the rift valleys and are characterized by lower-rate border faults and thinner sediments, several hundred meters (Florensov, 1977). For example, the Bystraya and Mondy minor basins of the Tunka rift valley are topographically higher than the major basins and show signs of inversion. Stratigraphically the Bystraya minor basin is similar to the neighboring Tory major basin (Fig. 2C), but the thicknesses of its sedimentary unit are reduced and the Miocene–lower Pliocene sediments are strongly dislocated and exposed to the surface at basin flanks. The Mondy minor basin is very shallow and is filled by late Pleistocene glacial deposits only (Ufimtsev, 2002).

The mountains framing the rift basins represent recently uplifted ranges. The highest ranges are 2500–3500 m a.s.l. and possess Alpine-type topography. That recent uplifting happened at the boundary of the middle and late Pleistocene and resulted in the shift of cup-type glaciation to valley-type glaciation and in an increased rate of denudation (Mats et al., 2001). The ranges are transversally asymmetric (Figs. 2–4): the slopes of the ranges facing the basins from the west and north are typically much steeper than those facing the basins from the south and east (Figs. 3 and 4). Not all mountain ranges of the BRZ underwent the mid-late Pleistocene uplifting: the Primorsky and Ulan-Burgasy ranges bounding the South Baikal Basin are located within the Selenga saddle, which separates two huge dome-shaped uplifts, the

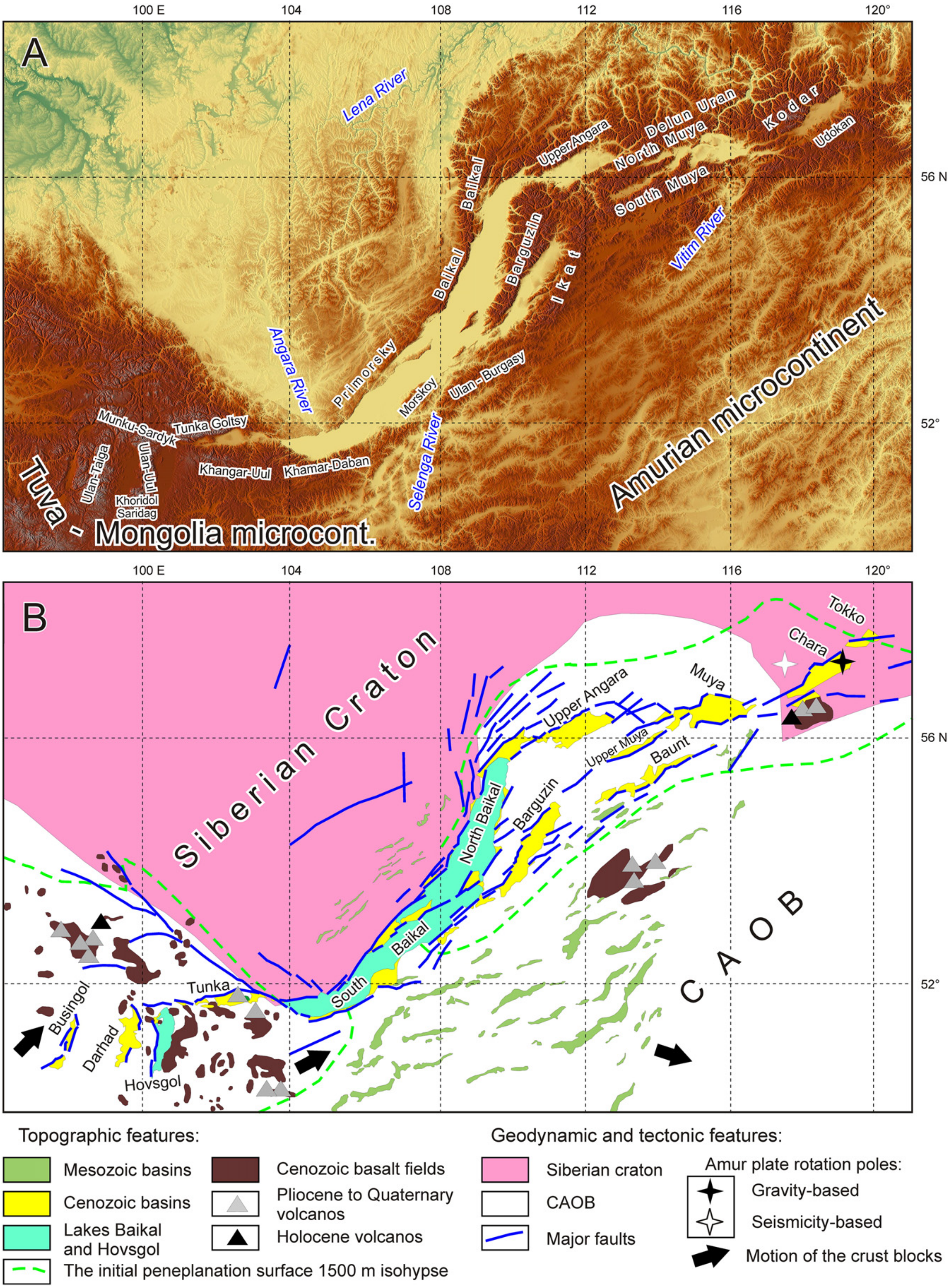

Fig. 1. A. Orography of the Baikal Rift Zone (BRZ) and adjacent areas. Data from Free Relief Layers for Google Maps (http://maps-for-free.com/). B. Major elements of the BRZ and adjacent areas: Cenozoic and Mesozoic basins, bounding faults and large regional faults, fields of Cenozoic volcanism, the directions of movement and the rotation poles of crustal blocks. Based on data from Logatchev (2003), Jolivet et al. (2013) and Ivanov et al. (2015). CAOB, Central Asian Orogenic Belt.

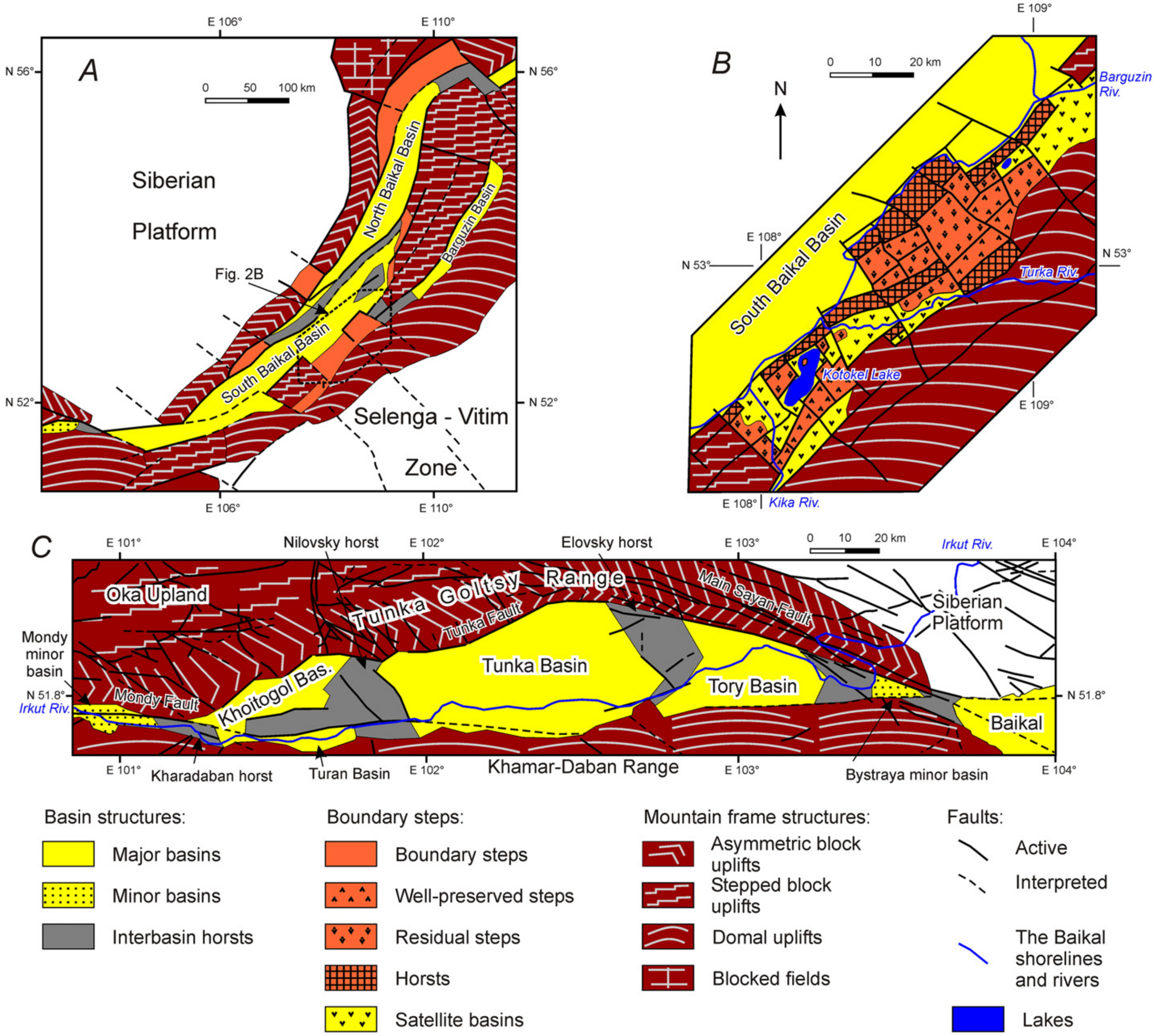

Fig. 2. Structural elements of Baikal rift basins and their mountain frame. A. General structure of the Baikal Rift Valley. B. Blocky structure of the Kika–Turka intermediate step of the eastern part of the South Baikal Basin. C. Major and minor basins and inter-basin horsts of the Tunka Rift Valley. Based on the interpretation by G.F. Ufimstev from Mats et al. (2001).

Sayan-Tuva in the south-west and the Baikal in the north-east (Logatchev et al., 1978; Logatchev, 2003) (Fig. 1).

3. Structural features of major sedimentary basins

In this section we present brief information about main structural features of BRZ major rift basins and rift valleys (from north-east to south west): Chara, Muya, Upper Angara, Barguzin, Baikal, Tunka, Hovsgol and Darhad (Fig. 1). In addition, we characterize environments of rift sedimentation.

3.1. North-eastern cluster: Chara, Muya, Upper Angara, Barguzin

The Chara Basin is located in the north-easternmost part of the BRZ and has a typical rift structure of asymmetric half-graben (Fig. 5A). Its basement is dipping from the southern edge bounded by the Udokan Range to the northern edge bounded by the Kodar Range, along which the detachment fault formed. The basement is broken into blocks, some of which are 200–250 meter high hills, intrabasin highs (Lopatin, 1972). The basin is drained by the Chara River sourced in the Kodar. The Kodar Range is the highest mountain system in the northern BRZ providing a big sediment flow. According to geophysical data the thickness of the sediments ranges from 2000 to 1000 m in the central part of the Chara Basin (Zamaraev et al., 1979; Logatchev and Zorin, 1992). In the southern part of the basin, in the piedmonts of the Udokan Range there are Ingamakit and Lurbun satellite basins.

The Muya Rift Valley is a complicated system of rift basins of different morphologies and origins (Fig. 5B). In includes the Muya, Muyakan, Ulanmakit, Parama, Kuanda and Taxima-Dzhilinda basins, which are separated by interbasin horsts and intermediate mountain spurs (Ufimtsev, 2005). The Muya, Kuanda and Parama basins are drained by the Vitim River and together compose a major area of sedimentation, which, in literature, is often called the Muya Basin and which hosts most complete stratigraphic sections. The southern Muya-Kuanda and northern Parama segments are separated by an EW-striking horst. The Muya-Kuanda segment includes two satellite basins: the western satellite is in

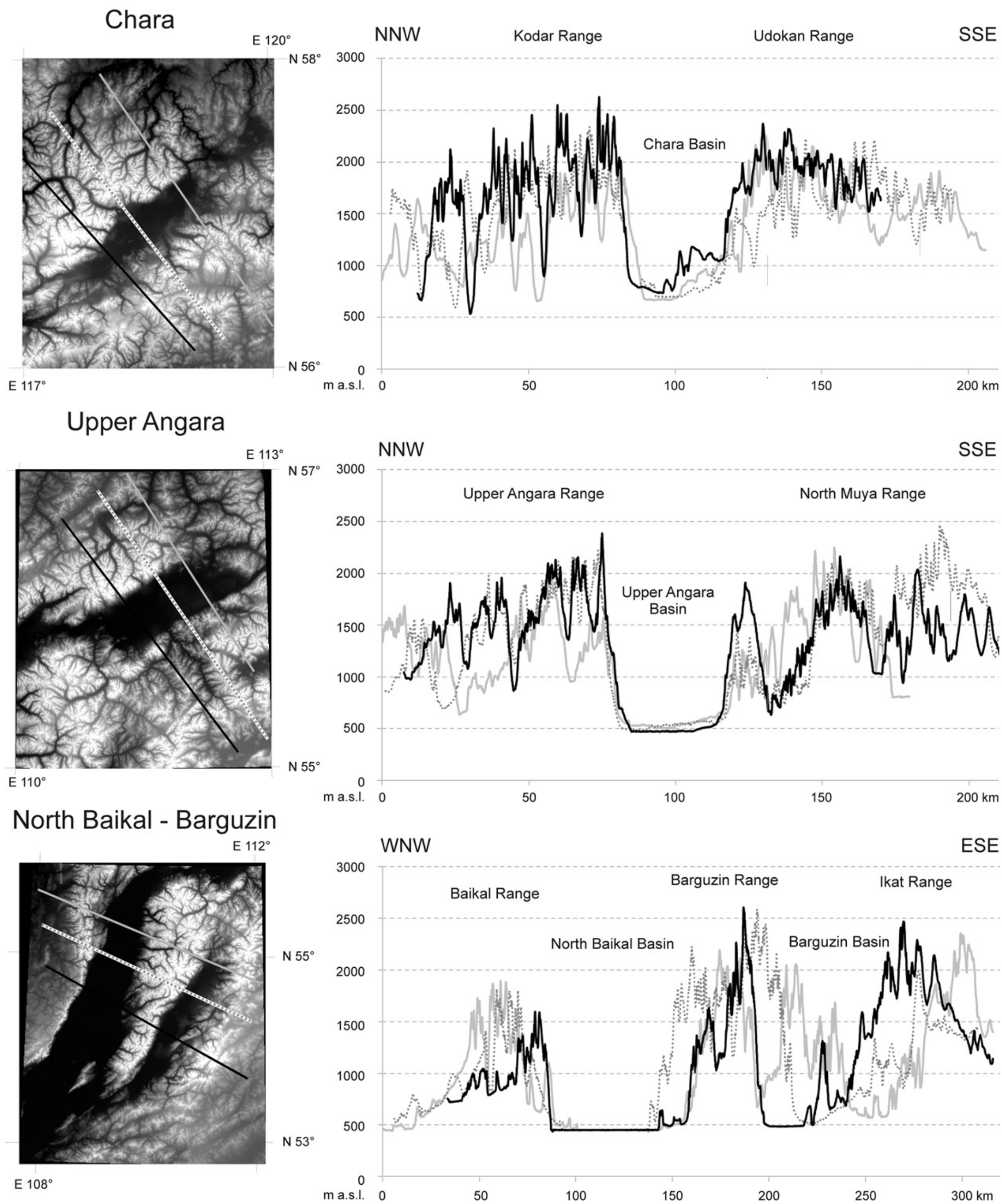

Fig. 3. Sample topographic transects across the BRZ basins (northern half) showing asymmetry of their bounding mountain ranges. Extractions from the SRTM Digital Elevation Model (left parts of the drawings).

the upper streams of the Mudirikan, Anya and Anevirkan rivers and the eastern satellite is aligned along the Sulban River (Zamaraev et al., 1979). The Muya Basin is bounded by the South Muya Range (2000–2100 m a.s.l.) in the south and by the Vitim upland (1500 m a.s.l.) in the north. The high North Muya and Kodar ranges are situated at a distance from the Muya Basin, but belong to its catchment area. The largest Vitim River and its tributaries Muya (with Muyakan) and Kuanda (with Sulban) provide a major flow of sediments from the areas outside the Muya Basin. The estimated thickness of Muya Basin sediments is 1000–1500 or 2200 m according to Zamaraev et al. (1979) and Logatchev and Zorin (1992), respectively.

The Upper Angara Basin is drained by the Upper Angara River and has a simple half-graben structure (Fig. 5C). The main fault zone stretches along the Upper Angara and Delun-Uran ranges located in the northern edge of the basin. The ranges are 2600 m a.s.l., possess Alpine-type topography and are clearly asymmetric. The southern edge of the basin is gentle and shows gradual transit to the highlands of the North-Muya Range. The basin morphology suggests tectonic

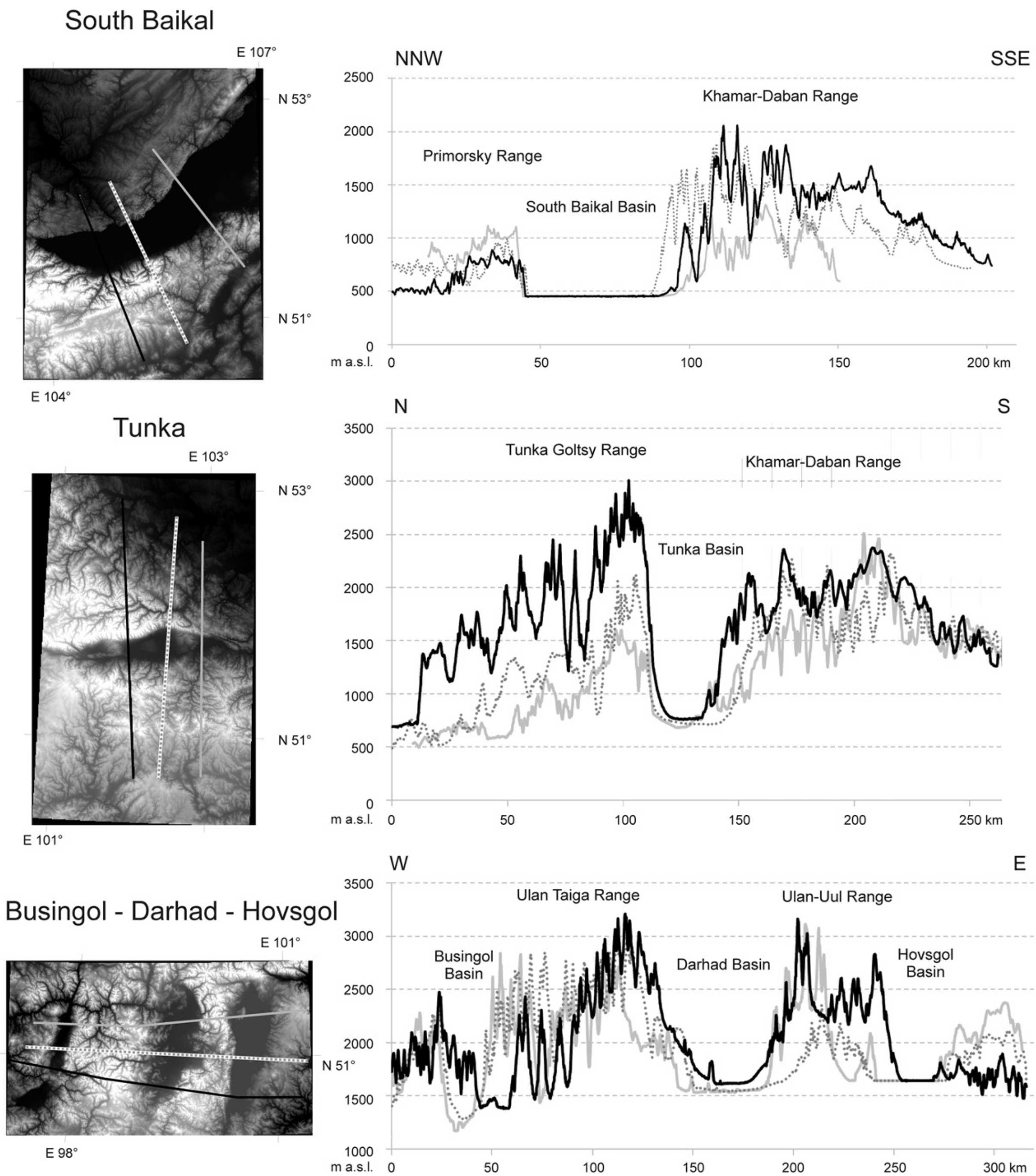

Fig. 4. Sample topographic transects across the BRZ basins (southern half) showing the asymmetry of their bounding mountain ranges. Extractions from the SRTM Digital Elevation Model (left parts of the drawings).

steps moving in different directions, e.g., Ust'-Kotera and Yanchuy moulds and Churok intermediate step (Zamaraev et al., 1979; Ufimtsev, 2002). The south-western side of the basin also shows traces of strong tectonic activity which formed the Irkana graben and the Kumora and Chenchin spurs. The Upper Angara Basin is separated from the North Baikal Basin by the Kyron horst which can be considered as a block in the end of the Barguzin Range. The bottom of the Upper Angara Basin is flat; its central part is elevated to 460–550 m a.s.l. The western part of the basin is maximally subsided as marked by the vast alluvial plain with several running lakes (Fig. 5C). Its north-eastern part is relatively high; it is characterized by a reduced thickness of sediments and is composed of Pleistocene sands (Solonenko, 1968). According to different evaluations the average thickness of the sedimentary fill is estimated as 2500 (Zorin, 1971), or 2000 (Logatchev and Zorin, 1992) or 700–1500 m (Logatchev, 1983).

The Barguzin Valley is located east of Lake Baikal, over the Barguzin Range elevated to 2700 m a.s.l. (Figs. 1 and 5D). The mountain frame also includes the North Muya, South Muya and Ikat ranges 2500 m a.s.l. high. The valley is 200 km long and 40 km wide and includes the major Barguzin Basin and two minor basins, Ust-Barguzin and Amut (Fig. 5D). The Barguzin Basin has a typical rift asymmetric structure: the main faults are aligned along the eastern side of the Barguzin Range (Fig. 3). The bottom of the basin gently decreases from 600 to 470 m a.s.l. downstream the Barguzin River. The river tracks the right side of the valley suggesting tectonic tilting and sinking. The south-western tip of the basin is complicated by the fault steps of the

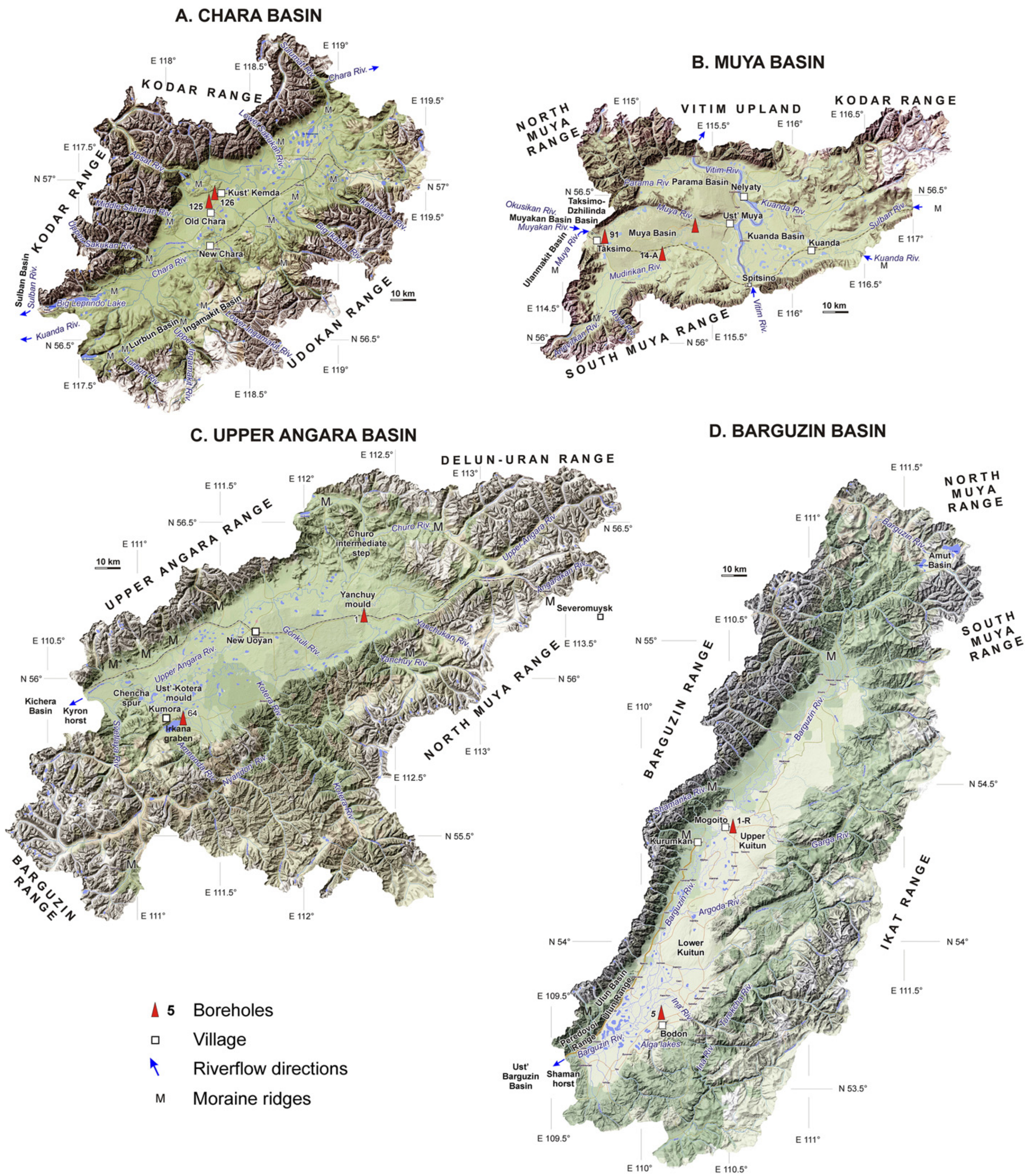

Fig. 5. Google Maps based detailed topography of the northeastern BRZ basins and their catchments showing the geographic names and boreholes used in the text. A - Chara, B - Muya, C - Upper Angara, D - Barguzin.

Peredovoi and Ulyun ranges elevated to 1300 m a.s.l. and separated from the Barguzin Range by the Ulyun minor basin. The rate of displacement along the main fault zone in the Barguzin Basin can reach 500, in places 700–800 m (Florensov, 1960). The geophysically estimated thickness of sediments of the Barguzin Basin is 1500–1800 m with a maximum of 2500 m near Kurumkan Village (Solonenko, 1981). The borehole, which was drilled near Mogoito Village, reached the crystalline basement at a depth of 1400 m (Florensov, 1960). In addition, the geophysical data show several sharply contoured convexities and depressions (Epov et al., 2007).

3.2. Lake Baikal

Lake Baikal consists of two basins: southern and northern, which are separated by the Academic Ridge, an asymmetric horst structure striking at an acute angle to the rift axis and dipping to the west (Logatchev, 2003) (Figs. 1, 2 and 6). The basins are asymmetric grabens, which main fault zones are aligned along their western sides. The surrounding the Baikal, Barguzin and Khamar-Daban high mountain ranges are connected with the Sayan-Khamar-Daban and Baikal-Stanovoy domed structures. The Primorsky and Morskoy low mountain ranges meet the Selenga Saddle, which is located between the domes (Logatchev et al., 1974) (Fig. 1). The peripheral part of the basin represents a fault bounded keyboard-like structure consisting of 10–15 km sized tectonic blocks (Zamaraev and Mazukabzov, 1978). The planes of the faults dip either toward the basin axis or toward the mountain frame (listric faults). The listric faults bound the satellite basins filled by Miocene to Pleistocene sediments (Mats, 1990; Kulchitsky et al., 1993). The main sedimentation area is the bottom of Lake Baikal. The thickness of Cenozoic sediments is ca. 7500–8000 m in the South Baikal Basin, at the underwater edge of the Selenga River delta, and 4000–4500 m in the North Baikal Basin, at the Upper Angara River mouth (Logatchev et al., 1974; Zonenshain et al., 1992, 1995; Hutchinson et al., 1992; Moore et al., 1997). There are also alternative estimates of the sediment thickness: ca. 4500 in the Southern basin and 1000 m in the Northern basin (Mats et al., 2001).

Of special interest are the deltas of the Selenga and Upper Angara rivers, which extend 15 and 10 km inside the Baikal to reach depths of 300 and 500 m, respectively. The thickness of the Selenga delta deposits reaches 5000 m (Zamaraev and Samsonov, 1959). The Upper Angara delta sediments form the Angara-Kichera accumulative plain in the north-east part of the North Baikal Basin.

The steep rocky shores of Lake Baikal lack sediments as the material delivered by rivers and streams from the surrounding mountains is easily reworked and disseminated by waves. Sediments of different ages

Fig. 6. Free Relief Layers for Google Maps based detailed topography of the Baikal rift valley and its catchments showing the geographic names and boreholes used in the text.

occur at the intermediate fault steps. The Maloe More and Olkhon steps host small spots of denudated Miocene, Pliocene and Pleistocene sediments. The Tankhoi step hosts thick Oligocene to Pliocene deposits but thin Pleistocene sediments. The satellite basins, Rel-Slyudinka, Davsha-Bolshaya Recka, Maximikha, Turka and others, have been subsiding since the Miocene or Pliocene (see Section 4 for details) and host better preserved Pleistocene sediments.

3.3. South-western cluster: Tunka, Hovsgol, Darhad

The Tunka Valley consists of four major basins: Tory, Tunka, Khoitogol and Turan, which are separated by interbasin horsts, Elovsky and Nilovsky (Figs. 1, 2 and 7A). In addition, there are two minor basins at the opposite ends of the valley: Bystraya and Mondy, which are separated by large horsts, Bystrinsky and Kharadaban, respectively. All

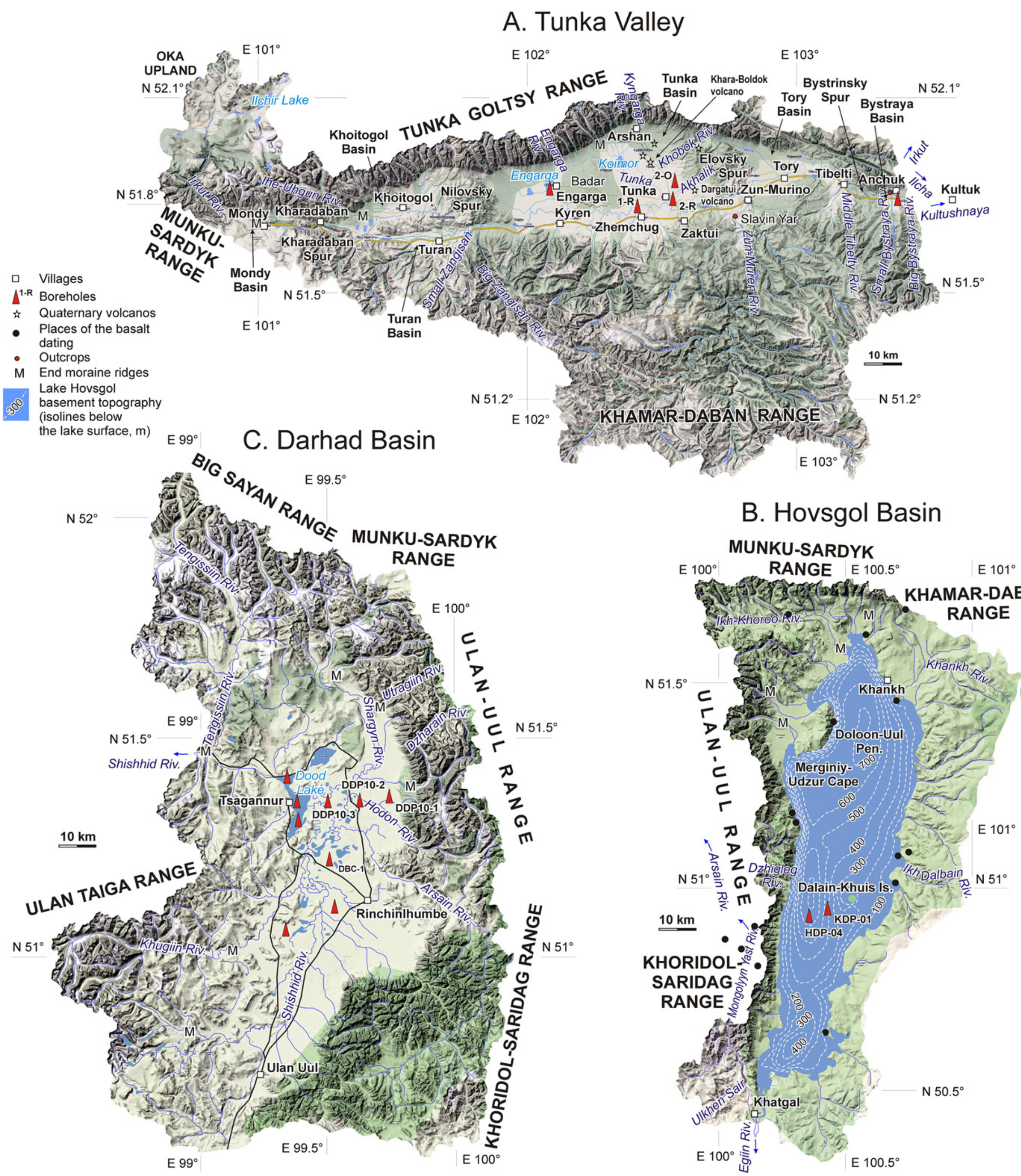

Fig. 7. Google Maps based detailed topography of southwestern BRZ basins and their catchments showing the geographic names and boreholes used in the text.

basins except the Khoitigol are aligned along their draining Irkut River. The Khoitogol Basin is aligned parallel and to the north of the Turan Basin. The total length of the Tunka Valley is 200 km. The minor and major basins are 3 to 30 km wide. The bottom of the valley is dipping from 1000 to 500 m a.s.l. in a WE direction. The morphology of the basins is typical: the asymmetric graben is bounded by a more than 3000 m a.s.l. high asymmetric block of the Tunka Goltsy Range in the north and by the Khamar-Daban Range dome uplift in the south (Figs. 1, 2 and 7A). The basins experienced both extension and strike-slip displacement along the Main Sayan Fault. The depth of the basement varies from 150–200 m in the Bystraya Basin to 3000 m in the Tunka Basin (Lunina et al., 2009).

Lake Hovsgol together with the Darhad and Busingol basins are also thought to belong to the BRZ, although they are oriented perpendicularly to the Tunka and South Baikal basins (Fig. 1). The main structures of the whole Hovsgol region are dome-shaped uplifts broken by NS- and SW–NE-striking faults. The Hovsgol faults meet the EW-striking Irkut-Kyzylkhem fault system in the north and gradually attenuate in the south (Ivanov, 1953, Ufland et al., 1969, Zolotarev et al., 1981). The Hovsgol Basin is a normal graben located in the central part of that dome uplift . The basin and its mountain frame are clearly asymmetric (Fig. 7B). The eastern side of the basin is lower, weakly deformed and covered by Miocene plateau basalts. The western side, the Ulan-Uul Range, is more than 3000 m a.s.l. high and carries remnants of Miocene lava flows on the top suggesting their former connection with the eastern side (Rasskazov et al., 2003). Geophysical and bathymetric data-based GIS modeling shows three deeper parts of the basin basement, up to 700 m below the lake surface (Krivonogov, 2006). The bottom is divided into two sub-basins by a NW–SE horst with Dalain-Khuis Island on the top. The thickness of sediments is 550 m in the northern and 350 m in the southern subbasins (Zorin et al., 1989).

The Darhad Basin is located west of Lake Hovsgol and has similar structure and size, 110 km long and 40 km wide (Fig. 7C). However, the Darhad is completely filled by sediments, i.e. compensated. The bottom is flat, elevated to 1540–1600 m a.s.l. The Shishhid River is draining the basin along its western side. The basin is framed by more than 3000 m a.s.l. high and steep Ulan-Uul and Khoridol-Saridag ranges having blocky structures in the east, and by the 3200 m a.s.l. high Ulan-Taiga Mountains in the west. The basin is bounded by EW- and NS-striking faults. The basement consists of three depressions separated by up to 200 m high horsts (intermediate steps) which are seen as hills on the surface. The thickness of sediments varies between 300 and 500 m and is maximal in the northern part of the basin (Zorin et al., 1989).

4. Sediment stratigraphy, lithology and facies

Many scientists agree that the beginning of sedimentation in the BRZ remains a debatable issue although a lot of boreholes have been drilled over the whole BRZ and dozens of research teams have studied BRZ sediments on the surface. In this section we will characterize the sedimentary sections of deep boreholes to understand the early stages of sedimentation and proportions of strata of different ages, the surficial occurrences of pre-Quaternary sediments and Pleistocene sediments. Finally, we will discuss drilling project data from the region largest Baikal and Hovsgol lakes, as the sedimentary records of these lakes are different from other rift basins of the BRZ.

4.1. Deep boreholes

In the middle of the 20th century, deep boreholes were drilled in several BRZ basins (Figs. 8 and 9) in the frame of oil and gas prospecting and geological survey projects. The boreholes opened sedimentary sequences in basin depocentres, however, most of them did not reach the basement. The age of the sediments was typically constrained by pollen and diatom data (e.g., Faizulina and Kozlova, 1966).

In the South Baikal Basin, several boreholes were drilled at the delta of the Selenga River, i.e. close to the edge of the rift (Figs. 6, 8 and 9). The deepest hole (S-3: 3100 m) was drilled near Stepnoi Dvorets Village (Zamaraev and Samsonov, 1959) and did not reach crystalline rocks, but the neighboring S-1 and S-2 boreholes reached the basement at depths of 1800 and 1340 m, respectively. The age of the sediments ranges from the Paleogene to the Quaternary (Faizulina and Kozlova, 1966). Although there has been big confusion about the depths of stratigraphic boundaries (Mats et al., 2001), the oldest units of the S-3 sedimentary sequence have certainly Eocene age. In general, four main series have been recognized: Eocene–Oligocene (ca. 500 m), Miocene (1000 m), Pliocene (1000 m) and Pleistocene (500 m) (Fig. 9). The sediments of S-3 are deltaic facies dominated by silt, sand and gravel. As the geophysical data suggest 7–8 km thick sediments in the South Baikal basin (see Section 3), at least two more kilometers of much older sediments beneath the bottom of S-3 borehole, possibly down to the late Cretaceous, are suggestible (Mats et al., 2001).

The boreholes of the Tunka Basin documented probably most complete sedimentary sequences in the BRZ (e.g., Sarkisyan, 1958; Logatchev, 1956, 1958a; Logatchev et al., 1964). The two deepest boreholes, 2-O and 1-R, show sediments formed in different environments. The 1961 m deep 2-O borehole was drilled 10 km south of the northern margin of the basin, close to the Elovsky interbasin horst (Figs. 7A, 8 and 9). The borehole did not reach the basement. The core consists of up to 60 basaltic flows interbedded with sand and sandstone. The age of the sediments is constrained by diatom and pollen data suggesting the late Oligocene–early Pliocene age for the lower ca. 800 m Coal-bearing Group, the late Pliocene age for the middle 400 m Ochreous Group and the Pleistocene age for the upper ca. 400 m Sandy Group (Fig. 10). The 2120 deep borehole 2-R drilled nearby the 2-O showed a similar sedimentary section (Kashik and Mazilov, 1994).

The 1026 m deep borehole 1-R drilled about 30 km south-west of borehole 2-O, near Zhemchug Village, showed a lithologically different sequence (Figs. 7A, 8 and 9). The core is dominated by lacustrine clay in the lower part and by sand in the upper part and lacks basalts (Fig. 9). The borehole reaches the basement and spans the same stratigraphical interval as borehole 2-O.

In the Barguzin Basin, the 1402 m deep 1-R borehole drilled near Mogoito Village reached the basement (Figs. 5D, 8 and 9). The sediment sequence consists of three groups (Sarkisyan et al., 1955; Sarkisyan, 1958; Logatchev, 1956, 1958a, 1958b; Florensov, 1960; Khlystov and Dekhtyareva, 1970). The Miocene–lower Pliocene Lower Group (ca. 800 m thick) is dominated by kaolinite and diatomite clays and siltstones with coal, sand and gravel layers. The late Pliocene–early Pleistocene Middle Group (200 m) consists of yellow silts, sands and gravels cemented in parts. The Pleistocene Upper Group (400 m) is lithologically similar but contains more coarse clastic beds of gray gravel, pebble and boulders (Fig. 10).

In the Chara Basin, a 1180 m deep borehole (no. 126) was drilled near Kust-Kemda Village (Enikeev, 2008) (Figs. 5A and 8–10). The Miocene coal bearing mudstones, siltstones and sands of the Anarga Group take an interval of 1180–1036 m. The Pliocene pebble and sand/sandstone of the Turuntai Group (1036–874 m) suggest an isostatically compensated basin with dominant subaerial sedimentation. The Pliocene clays and sands of the Luksugun Group (874–550 m) probably formed in a deep lake, similar to the Baikal. The lower Pleistocene silt, sand and gravel of the Oibon Group, (550–425 m) represent a final stage of such a lake. The middle Pleistocene boulder- and pebble-bearing mixtites of the Tarynak Group (425–180 m) and the late Pleistocene sand of the Topalakh Group (180–0 m) have glacial origin (Fig. 10).

4.2. Exposed and shallow-buried pre-Quaternary sediments

Pre-Quaternary sediments often occur at the peripheral parts of main rift basins, over their intermediate steps and in minor and satellite basins formed in variable tectonic settings. The Maloe More step,

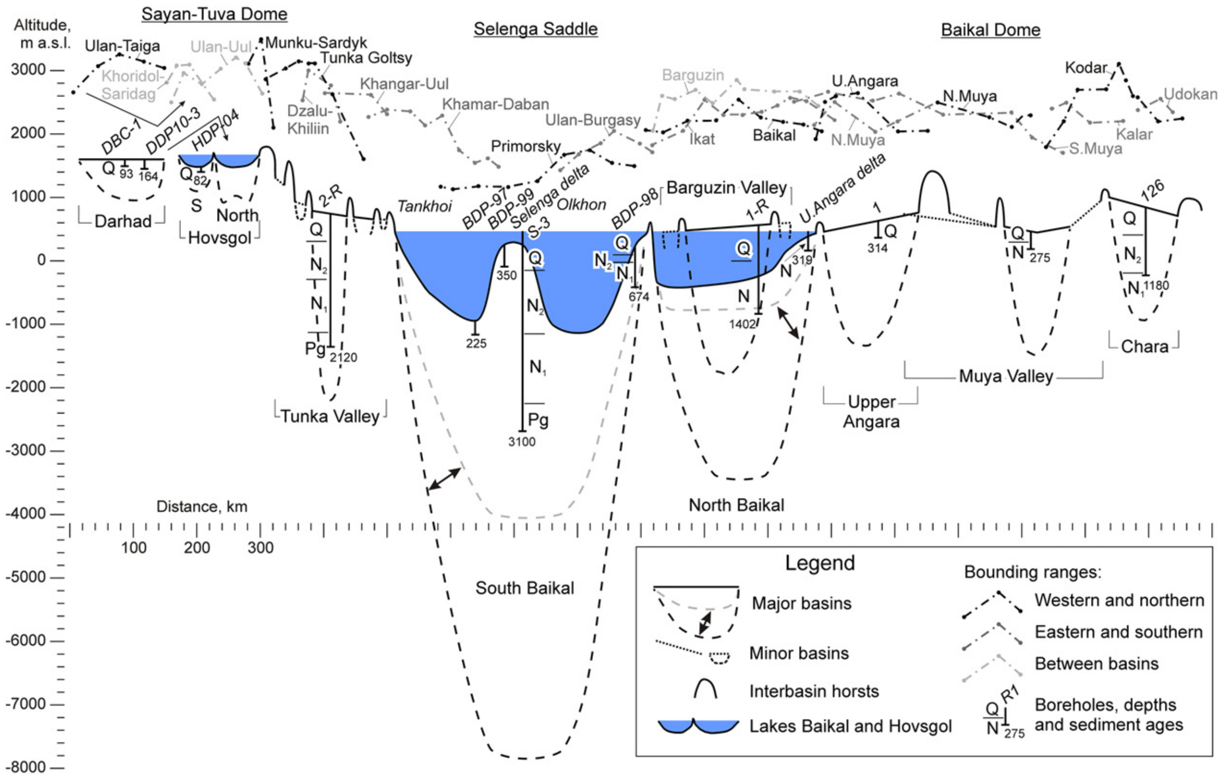

Fig. 8. Profile along the BRZ showing geometry and altitudes of major and minor basins, their separating interbasin horsts and geophysics derived basin contours (two-side arrows show alternative estimates for the South Baikal and North Baikal basins, see details in the text). The upper dash-dot lines show profiles along bounding mountain ranges illustrating two dome-shaped uplifts, the Baikal and Sayan-Tuva, separated by the Selenga Saddle. Additionally, we show the deepest boreholes and their depths.

Olkhon Island and Svyatoi Nos Peninsula of the Baikal Basin (Fig. 6) host sporadic exposures of pre-Quaternary and early Pleistocene sediments. The outcrops of the Olkhon Island and nearby show well preserved sedimentary sections making that area a stratotype section of the whole middle Baikal region (e.g., Mats et al., 2001; Mats and Perepelova, 2011). All these localities are parts of the interbasin horst separating the South Baikal and North Baikal basins, also hosting the underwater Academic Ridge.

The Tankhoi intermediate step bounding the South Baikal Basin from the south (Fig. 6) hosts a relatively complete section of upper Oligocene–lower Pliocene sediments. The Tankhoi step includes a 2–5 km wide and 50–150 m high plain at the southern shore of the Baikal and a 5–10 km wide part of the lake shelf. The sediments are tilted to ca. 20° to the north and broken into several tectonic blocks (Mats et al., 2001). The sedimentary sequence was divided into four groups: Tankhoi, Osinovka, Anosovka and Shankhaikha (Fig. 10). The Tankhoi and Osinovka groups

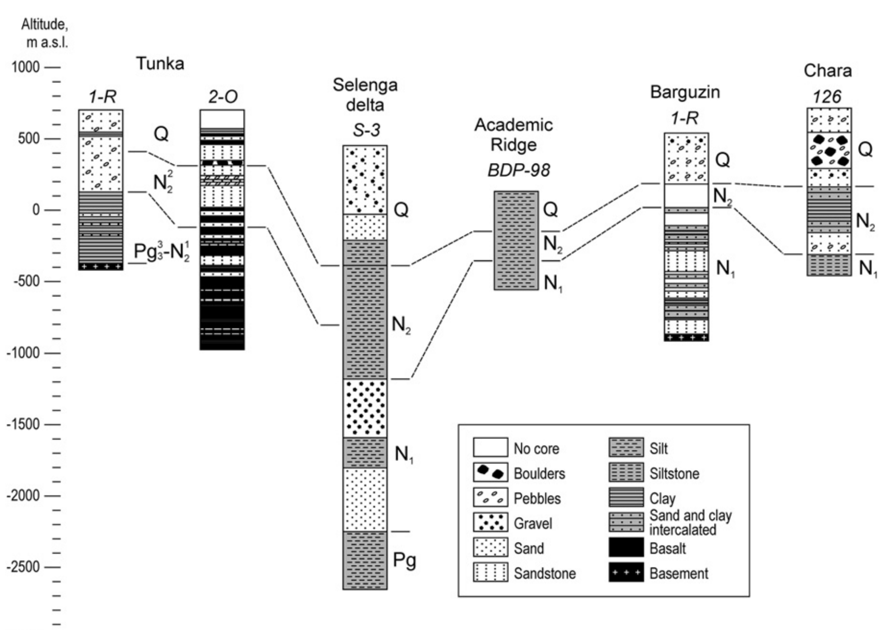

Fig. 9. Summarizing stratigraphic columns of the deepest boreholes of the BRZ basins. For details see the text.

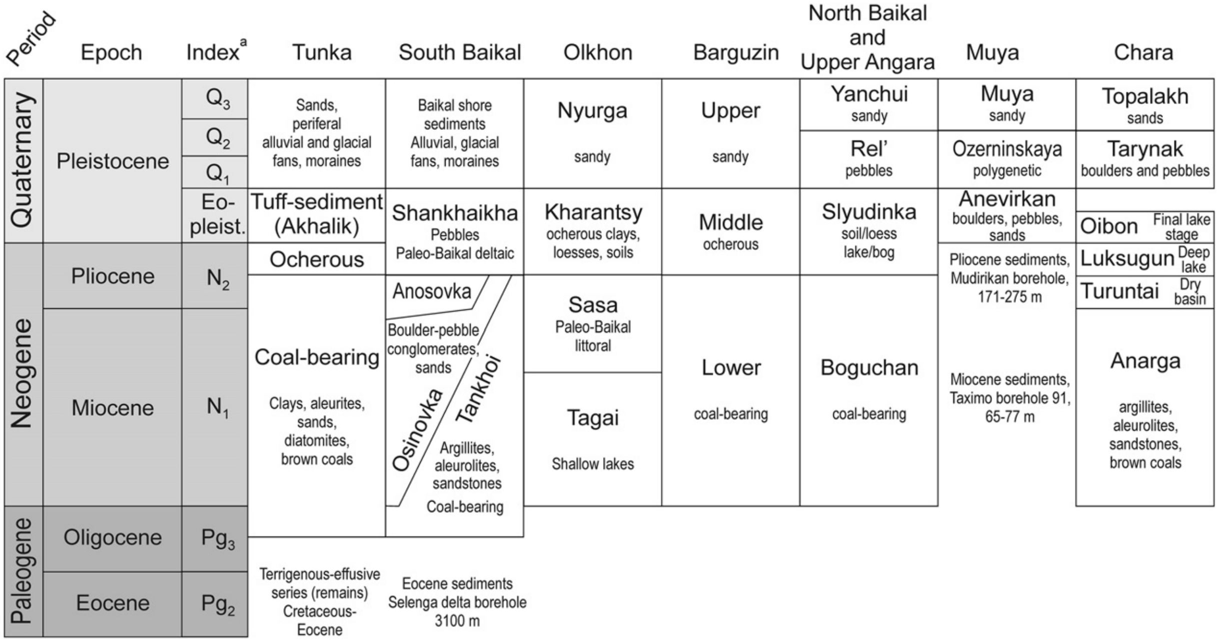

Fig. 10. Stratigraphic schemes of different areas of the Baikal Rift Zone (see details in the text) [a] The indexes match those from original publications.

are lithologically different but coeval. The Tankhoi Group is dominated by mudstone, siltstone and sandstone with subordinated, clays, sands and brown coal and organic-rich layers. The Osinovka Group consists of boulder-pebble conglomerates with intrebeds of siltstone, sandstone and brown coal. The Tankhoi and Osinovka sediments formed in shallow lake/swamp and river delta environments, respectively. Unlike many other localities, the late Ologicene–early Pliocene age of the sediments was constrained by rich flora and fauna. The upper Miocene–lower Pliocene Anosovka clayish Subgroup atop the Tankhoi-Osinovka assemblage suggests a deeper lake environment. The upper Pliocene–lower Pleistocene Shankhaikha Group consists of pebbles and boulders probably formed at a Baikal paleo-shore (Mats et al., 2001).

A borehole (no. 5) drilled in the Rel-Sludinka satellite basin, which is related to a listric fault along the north-western side of the North Baikal Basin (Kulchitsky et al., 1993), opened a 295 m long sedimentary sequence overlying the Cretaceous–Paleogene weathering crust (Fig. 11). The sequence includes two paleontologically constrained series: the upper Miocene shallow lake and swamp Boguchan Series and the lower Pleistocene lacustrine Sludinka Series. The two series are separated by loess-like silts with paleosoils which are well correlated with the Pliocene subaerial sediments of the Olkhon. The upper parts of the sequence are middle and upper Pleistocene glacial and periglacial deposits (Fig. 10).

The Chara Basin (Fig. 5A) includes pre-Quaternary sediments covered by thick Quaternary series, whereas the neighboring Sulban

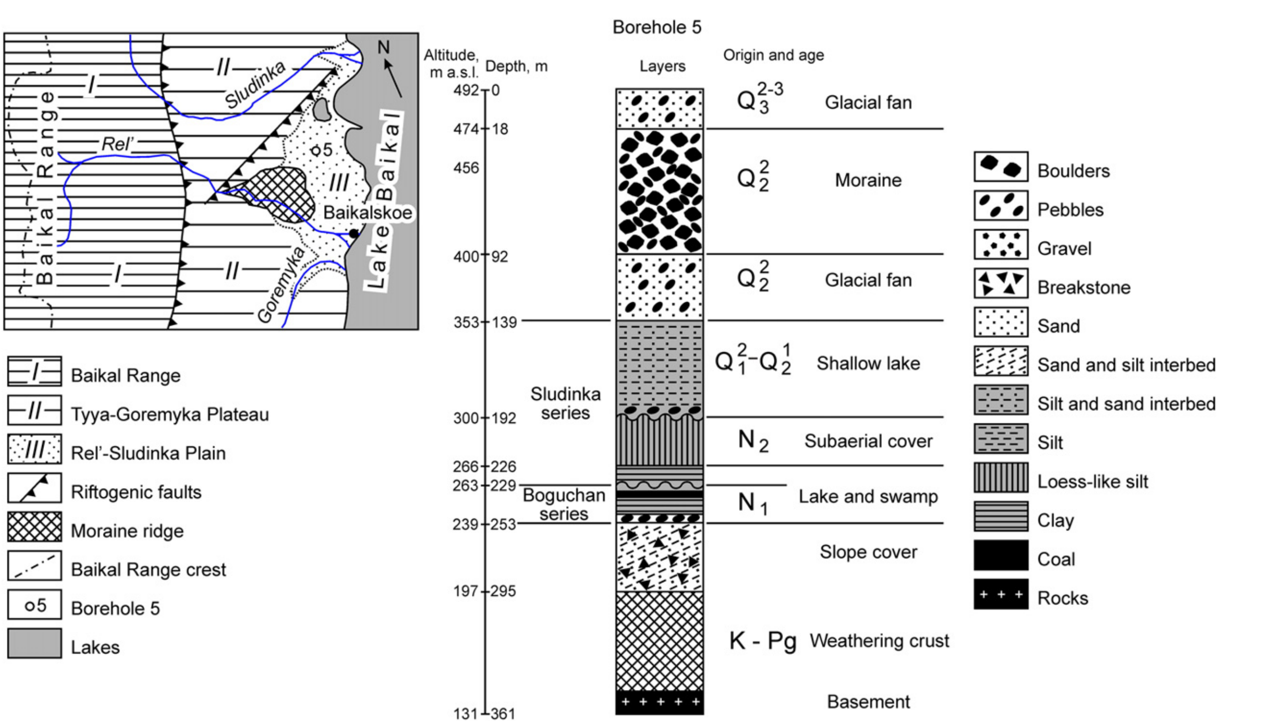

Fig. 11. Stratigraphy of Borehole 5 drilled in the Rel-Sludinka satellite basin of the North Baikal and its geomorphological position (left panel). Modified from Kulchitsky et al., 1993.

minor basin and the Lurbun and Ingamakit satellite basins are filled mainly by Miocene sediments. Early palinological data suggested the presence of Miocene sediments in the western Chara Basin, however they appeared wrong (Endrikhinsky, 1989). Nevertheless, older sediments possibly occur in deeper parts of the upper Chara sedimentary sequence, along the junction zone of the Kodar and Udokan ranges, which is broken to many uplifted and subsided tectonic blocks .The uplifted blocks carry fragments of Cretaceous - Paleogene red-color weathering crust (Logatchev, 1983).

About 700 boreholes were drilled in the Muya Basin, but no one opened pre-Miocene sediments. Near Taksimo, Borehole 91 documented Miocene sands with subordinate silts and clays at 77–65 m (Figs. 5B and 10) (Logatchev, 1983). The 275 m deep borehole drilled near the mouth of the Mudirikan River (Fig. 5B) opened Pliocene sediments at 275–171 m (Zelenskii, 1971). A 10 m thick upper Pliocene–lower Pleistocene lacustrine silt sequence of the Spitsino Group outcrops at the right bank of the Vitim River entering the basin (Popova et al., 1989).

In the Upper Angara Basin (Fig. 5C), there are no outcrops of older sediments; geological prospecting reached a depth of ca. 200 m to find Miocene–lower Pliocene clays, siltstones and diatomites (Belova and Endrikhinsky, 1979; Logatchev, 1983). A 110–140 m high terrace-like accumulative body extended along the Gonkuli River in the southern part of the basin has a Pliocene age (Zolotarev, 1981; Bazarov, 1986). In the western part of the basin, a borehole opened Pliocene sediments at depths of 144–211 m (Bazarov, 1986).

In the Barguzin Bazin (Fig. 5D), a 86.8 m deep borehole 5 drilled near Bodon Village documented Mio-Pliocene coal-bearing sediments covered by only 5.6 m thick Pleistocene sands (Bazarov, 1986). In addition, Pliocene ochreous clays and silty sands occur near the Alga salt lake (Zaklinskaya, 1950; Lamakin, 1952) and on the slopes of the Shaman interbasin horst (Zamaraev et al., 1979).

The basins of the Tunka Rift Valley host many outcrops of pre-Quaternary sediments. The Anchuk stratotype section of the Bystraya minor basin is located at a terrace of the Irkut River (Fig. 7A). The section consists of three groups of sediments, which are tectonically tilted to 45–55°. The first Coal-bearing Group is 50 m thick and includes upper Oligocene–Miocene sand and loamy sand with brown coal interbeds and lenses. The second group is represented by basaltic flows extended to a distance of 250–300 m along the river bank. The third Ocherous Group includes upper Pliocene alluvial pebbles, sands and conglomerates. The ages of the first and third groups were constrained by pollen and micromammal data, respectively (Adamenko et al., 1983, 1984). The Pliocene Ocherous Group conglomerates are also exposed in the Tory Basin in the Slavin Yar outcrop extended along the Zun-Muren River (Shchetnikov et al., 2009). The Tunka Basin is the largest field of pre-Quaternary sediments of the Tunka Rift Valley. The older sediments were buried under thick Pleistocene series, but then partly exhumed to the surface by tectonically uplifted blocks. The Neogene sediments are exposed at the Elovsky interbasin spur/horst, along rivers Akhalik and Khobok (Fig. 7A), and are intercalated with Miocene basaltic flows (Logatchev, 1956) (see Section 7).

The southernmost Hovsgol and Darhad basins (Fig. 7B, C) cover a large field of Miocene basalts. The basalts are exposed east of the Hovsgol (Ivanenko et al., 1989; Rasskazov et al., 2003). The sediment fill of the basins is probably as old as late Miocene–Pliocene. The older layers are buried under thick Pleistocene sediments. Previously researchers suggested the Pliocene age for an uplifted tectonic block in the central Darhad Basin (Ufland et al., 1971), however recent studies have scarped this interpretation (Krivonogov et al., 2012).

4.3. Quaternary sediments

4.3.1. The problem of Eopleistocene

The thickness of the Pleistocene sediments in the rift basins reaches 400–500 m (Fig. 10). In general, the sediments are dominated by gray medium-to-coarse boulders, pebbles and sands. The gray color is a special feature of BRZ Pleistocene sediments because Pliocene sediments are typically yellow, brown or red due to iron oxide (e.g., Florensov, 1960; Logatchev et al., 1964; Mats et al., 2001). The 2015 version of the IUGS stratigraphic chart shows the lower boundary of the Pleistocene at 2.588 Ma, i.e., it now includes the sediments, which were formerly classified as Eopleistocene. In the BRZ, the Eopleistocene deposits previously attributed to a lower stage of the Pleistocene are yellow-brownish sediments, i.e. facially similar rather to the Pliocene deposits than to the Pleistocene. Their “true” stratigraphic position has not been revised since then. The facies can be variable in different basins. In the Barguzin Basin, the deposits are a polygenetic yellow-brownish group (Fig. 10).

In the North Baikal Basin and Olkhon Island, these are loess and soil sequences of the Sludinka and Kharantsy groups, respectively (Trofimov, 1994; Mats et al., 2001). In the South Baikal, they compose the upper part of the Shankhaikha pebble Group, which is interpreted as a paleo-Baikal shore series (Mats et al., 2001). The sand units of the Davsha, Maksimikha and Turka satellite basins (Fig. 6) are probable analogues of the Shankhaikha Group (Logatchev et al., 1974; Imetkhenov, 1987). In the Tunka Basin, the lower Pleistocene volcanic tuff of the Akhalik Group occurs at the Elovsky spur and probably formed during the same event as the volcanic cones on the bottom of the basin (see Section 7). Some researchers compare the Akhalik Group with the Anosovka Group thus shifting the age of the former to the upper Pliocene (Mats et al., 2001).

4.3.2. Sedimentary facies and deposition environments

The Pleistocene deposits of the BRZ margins are glacial, periglacial, alluvial and eolian. The sediment grain-size is, in general, coarser than that of the pre-Quaternary sediments. The gray color Pleistocene deposits suggest a much colder climate than that of the Pliocene. The middle Pleistocene series are dominated by boulder-pebbles, while the late Pleistocene ones are sandier, probably because the glaciation indicating this was stronger (Enikeev, 2008). Glacial sediments and landforms occur in all basins surrounded by high mountains 2.5–3 km a.s.l. (Figs. 1 and 5–7).

The end moraines are present in piedmonts, in front of mountain troughs (Figs. 5–7). The Pleistocene glaciers and the melt water streams transported material from the surrounding mountain ranges leaving the coarser material in the peripheral parts and carrying the finer particles to the central parts of the basins. A glacier-related facial succession includes end moraine–periglacial fan–sandy outwash. Mountain rivers and temporary streams form numerous alluvial/proluvial fans with similar graded sediment distribution. Rivers meet major rivers flowing along the basin axis. The major rivers form valleys which morphology changes from mountain to plain types. The glacial and fluvial sediments source the up to 200 m high eolian sand ridges which formed in different parts of the basins depending on local wind patterns (Krivonogov and Takahara, 2003; Krivonogov, 2010). Those massifs occur in the Chara, Muya, Upper Angara, Barguzin and Tunka basins, and have their own names. They are called “Sands”, “Kuitun” and “Badar” in the Chara, Barguzin and Tunka basins, respectively (Figs. 5A, D and 7A).

In the basins of Lake Baikal, thick gray Pleistocene sands of variable origin occur in different tectonic and geomorphological settings in the Olkhon Island (Nyurga Group; Mats et al., 2001), in the Turka, Kika and Ust-Selenga satellite basins and at the Selenga delta (Fig. 2B). These units are stratigraphically and lithologically similar to lower–middle Pleistocene Krivoyarskaya Group of Western Transbaikalia (Bazarov, 1986). However the age of a part of the Ust-Selenga sand sequence and of the eolian sands, which may occur high on the mountain slopes is late Pleistocene (Imetkhenov, 1987). Most of those sands formed by the Selenga, Upper Angara and Barguzin rivers in Lake Baikal environment, because they contain the Baikal endemic sponge spicules (Kolomiets, 1994). The unique Svyatoi Nos peninsula tombolo (Fig. 6) formed by the lake waves transporting and re-depositing Barguzin River deltaic sediments (Rogozin, 1993).

Many of the BRZ basins, which are now dry, experienced temporary flooding during the Pleistocene documented by presence of lacustrine beds. Baikal short-term ingressions are recorded in the Upper Angara Basin by sediments containing Baikal endemic diatoms, which occur at depths of 280–180 m (Kulchitsky, 1991). More typical are glacier dammed lakes existed at higher than the Baikal altitudes in the Chara, Muya and Darhad basins (Lungersgauzen, 1965; Muzis, 1966; Enikeev, 1998; Krivonogov et al., 2012). In the Chara and Muya basins the dammed lakes filled with varved silty and sandy deposits (Enikeev, 1998) existed at least four times during the middle and late Pleistocene. In Darhad, the late-Pleistocene damming event resulted in the 30–50 m thick layers of varved silt (Ufland et al., 1971; Krivonogov et al., 2005, 2012; Gillespie et al., 2008; Batbaatar and Gillespie, 2015).

4.3.3. Late Pleistocene and Holocene high-rate sedimentation

The upper Pleistocene sediments are extremely thick in the central parts of the BRZ dry basins. Table 1 shows the radiocarbon and luminescence ages from the basins of the NE cluster (Chara, Muya, Upper Angara, North Baikal) and from Darkhad, which allowed us to evaluate the rate of subsidence of the bottoms of BRZ basins during the late Pleistocene based on the rates of sedimentation. In the Chara Basin, the thickness of the Topalakh Group reaches 180 m and it accumulated at an average rate of 1.4 and 2.8 mm/yr according to the data from borehole 125 (Enikeev and Potyomkina, 1999) and from the borehole near Chara Village (Endrikhinsky, 1989), respectively (Fig. 5A). In the Muya Basin, borehole 14-A (Fig. 5B) showed a sedimentation rate of 3.5 mm/yr (Kulchitsky et al., 1990). In the Upper Angara Basin, the 314 m deep borehole 1 (Fig. 5C) showed a sedimentation rate of 3.7–5.7 mm/yr (Kulchitsky, 1991). Similarly, borehole 49 drilled in the Angara-Kichera plain of the North Baikal Basin (Fig. 6) showed a rate of 5.0–5.4 mm/yr (Trofimov, 1994). Consequently, the bottoms of the basins were subsiding with acceleration from the periphery toward the central parts of the BRZ.

In the Darhad Basin, the 92.6 m deep DBC-1 borehole (Fig. 7C) documented late Pleistocene silts of a glacier-dammed lake underlain by another lake and non-lake sediments (e.g., Gillespie et al., 2005, 2008; Krivonogov et al., 2007, 2008, 2012). Several OSL and IRSL dates (Batbaatar et al., 2008, 2009, 2012) indicate a rate of sedimentation of 0.4–1.8 mm/yr (Table 1).

Intensive Holocene sedimentation has been recorded in vast alluvial plains situated at the places where rivers meet the spurs of interbasin horsts. Those plains are seen on satellite images as floodplains with strongly meandering river channels and numerous oxbow lakes (Figs. 5 and 7). Thick constrative alluvium forms there due to gradual sinking of basin bottoms and/or slow uplifting of interbasin horsts. In addition, there are tectonic depressions away from the axes of the valleys, e.g., the Koimor and Engarga areas of the Tunka Basin (Ufimtsev et al., 2006) (Fig. 7A).

4.4. Sedimentation in lakes Baikal and Hovsgol

4.4.1. The Baikal Drilling Project (BDP, 1989–1999)

First researchers of the BRZ suggested that 400 m deep lakes existed in the place of the modern Baikal in Oligocene–Miocene time (e.g., Kozhov, 1972). However, their sizes and shapes did not coincide with those of the Baikal as the occurrences of pre-Baikal endemic faunas appear far away of Baikal modern shores. In addition, the depocenters of the lakes, which were reconstructed in the Tunka Basin and in the Tankhoi Plain of the South Baikal Basin, do not match the modern topography (Kashik and Mazilov, 1994).

The pre-BDP seismic survey (Hutchinson et al., 1992; Kazmin et al., 1995) yielded the estimates of sediment thickness (see Section 3) and marked main seismostratigraphic borders interpreted as tectonic events, erosional boundaries or sedimentary facies changes. According to Moore et al. (1997), the sediments can be divided into two main seismostratigraphic units: A and B. The top unit (A), sequences A1–A3, is characterized by rather smooth seismic reflection profiles, and the bottom unit (B), sequences B1–B10, has a reflectance pattern disturbed by faults, angular unconformities and clinoforms.

BDP drilling missions retrieved sediment cores from five localities (Table 2). The deepest BDP-98 and BDP-96 boreholes were drilled on the Academic Ridge, a horst separating the South and North Baikal basins (Fig. 6). The antiform character of the ridge provided a shortened sequence of sediments and, as a result, the 670 m deep BDP-98 and the 300 m deep BDP-96-1 boreholes reached sequences B-6 and B-8, respectively (BDP Group, 2000; Antipin et al., 2001). The other boreholes intruded the top seismostratigraphic unit only. The age of the BDP-98 and BDP-96 sedimentary sequences was determined as 8.4 (8.05) and 5 Ma, i.e., late Miocene and early Pliocene, respectively. The ages were determined by paleomagnetic (BDP Members, 1998; BDP Group, 2000; Antipin et al., 2001) and Be^{10} (Horiuchi et al., 2001, 2003; Sapota et al., 2004) methods with a paleontological control (e.g., Derevyanko, 2008; Kuzmin et al., 2009).

In spite of the seismostratigraphic data obtained from the Academic Ridge (Moore et al., 1997), the BDP-98 sediment sequence show no significant stratigraphic interruptions or dramatic structural changes (Fig. 9). The sediments are dominated by silty clay and diatomaceous mud of lacustrine origin; alternation of the sedimentary beds suggests variations in sediment transportation patterns and climate changes (Antipin et al., 2001; BDP Group, 2000). The lower 600–480 m interval contains more sandy layers and gravel particles, than the upper part. The 600–560 m interval (B-6 seismostratigraphic sequence) is characterized by abundant plant remains which include fragments of leaves

Table 1
Evaluation of the late Pleistocene dipping of the BRZ basins bottoms: sedimentation rates inferred from the radiocarbon and luminescence dated boreholes

Site and reference	Dating technique	Lab no.	Depth, m	Sediment type material for dating	Age[a]	Sedimentation rate, mm/yr
Chara Basin, borehole 125 (Enikeev and Potyomkina, 1999)	^{14}C	LU-977	54	Organic-rich sands Wood	38210 ± 870	1.4
Chara Basin, borehole near the Chara Village (Endrikhinsky, 1989)	^{14}C	SOAN-2204	65	Sands Wood	23245 ± 280	2.8
Muya Basin, borehole 14A (Kulchitsky et al., 1990)	^{14}C		127	Sands and silts Peat	36320 ± 3130	3.5
Upper Angara Basin, borehole 1 (Kulchitsky, 1991)	^{14}C	Ri-S2 Ri-S1 Ri-S3	101.7 135.7 189.25	Sand and silt lake and river series Peat layers	27420 ± 540 30450 ± 570 33200 ± 430	3.7–5.7
North Baikal Basin, borehole 49 (Trofimov, 1994)	RTL	RTL-525 RTL-526	238 285	Outwash sands	48 ± 12 ka BP 53 ± 13 ka BP	5.0–5.4
Darhad Basin, DBC-1 borehole (Batbaatar et al., 2008, 2009, 2012)	OSL and IRSL		9.1–9.5 44–47 77	Riverine/eolian sands between the lacustrine series	18–25 ka BP 43–45 ka BP 124–135 ka BP	0.5 1.4-1.8 0.4

[a] Age in years BP for the radiocarbon (^{14}C) dates and in kiloyears (ka BP) for the luminescence (RTL, OSL and IRSL) dates.

Table 2
The Baikal and Hovsgol drilling projects missions

Borehole	Year	Locality	Coordinates	Water depth, m	Borehole depth, m	Sediment age at the bottom
Baikal						
BDP-93-1 BDP-93-2	1993	Buguldeika Saddle	N 52.51805556 E 106.15305556	354	98 102	Pleistocene
BDP-96-1 BDP-96-2	1996	Academic Ridge	N 53.69666667 E 108.35166667	321	300 100	Early Pliocene Late Pliocene
BDP-97	1997	South Baukal Basin	N 51.79750000 E 105.48722222	1428	40	Pleistocene
BDP-98	1998	Academic Ridge	N 53.74666667 E 108.40944444	333	670	Late Miocene
BDP-99	1999	Posolsk sandbank	N 52.08972222 E 105.84000000	205.5	350.5	Pleistocene
Hovsgol						
KDP-03	2003	Central (deepest) part of the lake	N 50.97333333 E 100.40916667	232	53	Pleistocene
HDP-04	2004		N 50.95527778 E 100.35888889	239	82	
HDP-06	2006		N 50.90694444 E 100.45083333	230	23	
HDP-09	2006		N 50.88000000 E 100.44166667	222	60	

of terrestrial plants. The middle 480–270 m interval is characterized by a relatively persistent sediment composition and weak lamination; the abundances of diatoms are lower in the 480–370 m and higher in the 370–270 m intervals. The upper 270–0 m sequence is characterized by finely laminated clay and diatom rich layers, which alternation resembles the Pleistocene glacial-interglacial pattern, and by the high concentration of vivianite inclusions suggesting a deficiency of oxygen in the lake. The inferred environments of sedimentation in those three major sedimentary sequences of the Academic Ridge at depths of 600–480, 480–270 and 270–0 m are a submerged distal delta of paleo-Barguzin River, a transgressing and deepening basin, and a hemipelagic basin, respectively (Antipin et al., 2001).

Both, paleomagnetic and ^{10}Be age models yielded concordant pictures for two intervals of relatively constant sedimentation rates with critical points at 240 m (6 Ma) and 200 m (5 Ma), respectively (Fig. 12). The ^{10}Be model based sedimentation rates are 4 cm/ka for the upper and 13 cm/ka for the lower parts of the model. Therefore, a considerable, probably tectonic-related change occurred in the Baikal region at about 7–5 Ma, i.e. at the Miocene/Pliocene boundary.

4.4.2. The Hovsgol Drilling Project (HDP, 2003–2009)

The pre-project investigation was limited by numerous short cores opened the top layer of lake sediments (see a review in Krivonogov, 2006) and gravity survey suggested 550–350 m of sediments in the basin (Zorin et al., 1989). The drilling missions (Table 2) were preceded by a seismic survey. The survey showed seven horizontal to tilted seismic-stratigraphic sequences separated by angular unconformities and suggested at least 180-m sediment thickness (Fedotov et al., 2002).

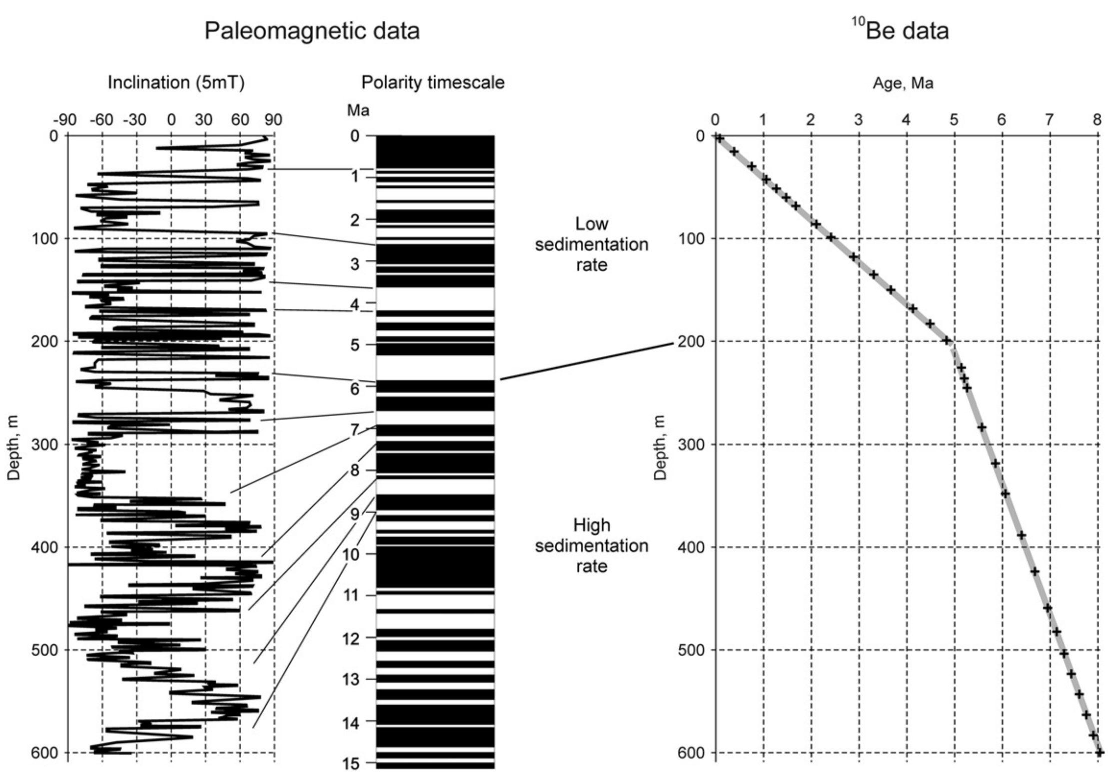

Fig. 12. Paleomagnetic and ^{10}Be-based age models for the BDP-98 borehole. Data from Sapota et al. (2004) and Derevyanko (2008).

The publication of the seismic and drilling results led to hot debates (Fedotov et al., 2007; Prokopenko and Kendall, 2008; Fedotov and De Batist, 2008). The paleotectonic reconstruction of the seismic profiles by Fedotov (2007) suggested the 5.5–6 Ma age of the Hovsgol Basin sedimentary fill as constrained from two major units: tilted (5.5–0.4 Ma) and horizontal (0.4–0 Ma). The angular unconformity between the units matches the major erosional event recorded in the HDP-04 core at a depth of 24 m suggesting a significant break in sedimentation during the middle Pleistocene (HDP Members, 2009).

Two deep boreholes, the 52 m KDP-01 (Fedotov et al., 2004) and 81 m HDP-04 (HDP Members, 2007), were drilled in the deepest part of the lake. Paleomagmatic study of both sedimentary cores showed the ca. 0.8 Ma Bruhnes/Matuyama reversal in their lower parts, and the 1.1 Ma Jaramillo excursion near their bottoms (Kazansky et al., 2005; HDP Members, 2007). The HDP-04 core shows at least eight successions of sediments, each starting from calcareous clayey silt to finely laminated carbonaceous mud and finally to carbonate-free (diatomaceous) mud. Those “cycles” were interpreted as signals of repeated Pleistocene climate-related Hovsgol lake transgressions/regressions (HDP Members, 2009).

5. Sedimentation and tectonics

There have been several stages in the evolution of the Baikal rift recorded in tectonic, topographic and sedimentation changes. According to Logatchev (2003), the sedimentary strata of the BRZ indicate two major stages of sedimentation. The Paleocene–Miocene sediments are dominantly fine-clastic suggesting slow tectonic movements and low topography, i.e. subsidence dominating in respect to mountain growth. The Pliocene–Quaternary sediments are represented mainly by coarse-clastic varieties which reflect high topography and fast mountain growth. These two major stages are separated by tectonic unconformities throughout the whole BRZ. The regime of sedimentation changed in the late Miocene–early Pliocene, at 7–5 Ma, coevally with the onset of the compressional tectonic.

Another scheme of main tectonic stages was proposed by Mats (1989), Mats et al. (2001) and Mats and Perepelova (2011) (Fig. 13). Mats et al. (2001) recognized three tectono-stratigraphic complexes: upper Cretaceous–middle Oligocene, upper Oligocene–lower Pliocene and upper Pliocene–Quaternary. The upper Cretaceous–middle Oligocene complex (70–27 Ma), includes the oldest sediments of the Selenga delta. The upper Oligocene–lower Pliocene complex (27–3.5 Ma) was called Tankhoi (Mats et al., 2001), Paleobaikal or Early orogenic (Florensov, 1960, Logatchev et al., 1974) and includes the Tankhoi, Osinovka, Khalagai, Tagai, Sasa, South Svyatoy Nos sedimentary groups and the Boguchan Series. The complex includes two sub-complexes: Tagai (up to the middle Miocene) and Sasa (upper Miocene–lower Pliocene). The upper Pliocene–Pleistocene complex (3.5–0 Ma), Neobaikal, includes Shankhaikha, Kharantsy and Nyurga sedimentary groups.

Mats and Perepelova (2011) recognized seven main tectonic phases or stages (Fig. 13) which they compared with the seismic-stratigraphic sequences (Hutchinson et al., 1992; Kazmin et al., 1995) and with the major reflectors and unconformities of the Baikal (e.g., Moore et al., 1997). The names of stages match local stratotypes and the names of events match the most representative areas of the Baikal and Tunka basins. The tectonic events mark the beginning of related tectonic phases. The earliest late Cretaceous (Maastrichtian)–middle Oligocene tectonic phase of regional peneplanation at ca. 70–27 Ma laterite-kaolinite weathering crusts formed over Mesozoic rocks and molasses. However, that time early extensional structures probably already existed in the South Baikal Basin (Logatchev, 2003): the early Eocene sediments of the Selenga delta occur at a depth of 1.5–2 km and the total thickness of sediments may reach 7.5–8 km (Hutchinson et al., 1992). Eocene sediments were also suggested in the deepest parts of the Tunka Basin

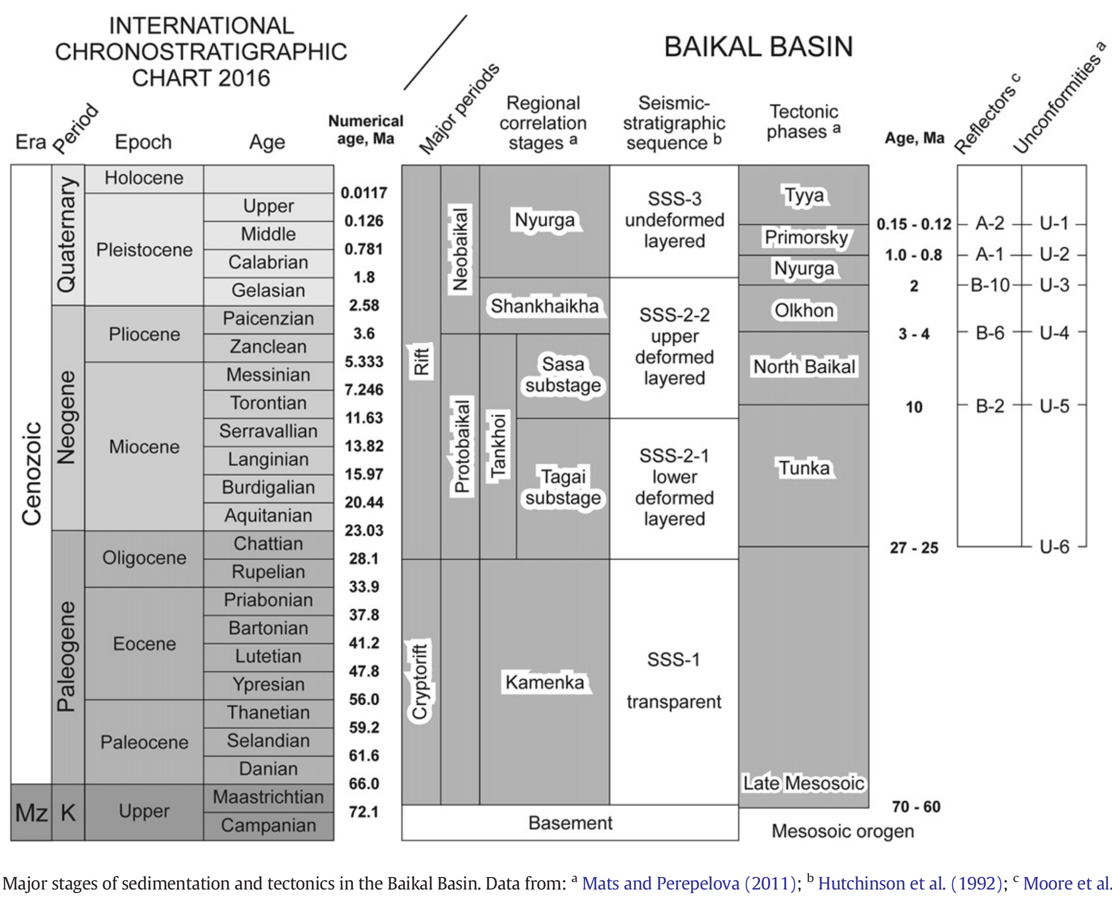

Fig. 13. Major stages of sedimentation and tectonics in the Baikal Basin. Data from: [a] Mats and Perepelova (2011); [b] Hutchinson et al. (1992); [c] Moore et al. (1997).

(Logatchev, 1993). In addition, the initiation of the Baikal rift is often attributed to the onset of basalt volcanism in the Tunka Basin at ca. 72 Ma (Rasskazov, 1993), however this date was questioned (Ivanov et al., 2015).

The middle Oligocene–late Miocene Tunka tectonic phase (27–25 to 10 Ma) formed the bedding unconformities and breaks recorded in the sediments of the Tankhoi intermediate step, Southern Baikal, and Olkhon Island (Mats, 1993). The deposition style changed from kaolinite-rich monomictic to polymictic. The rifting processes became more active: Baikal half-graben basins transformed to grabens bounded by listric faults (Hutchinson et al., 1992; Zonenshain et al., 1995; Kazmin et al., 1995).

The late Miocene–early Pliocene North Baikal tectonic phase (10 to 4–3 Ma) was recorded in the unconformities of the onshore and underwater sediments of the North Baikal Basin and Olkhon Island. The major unconformity is at the boundary between the lower-middle Miocene Tagai and upper Miocene–lower Pliocene Sasa groups. During this phase, the North Baikal basin was deepening and transgressing and became connected with the central and South Baikal basins.

The late Pliocene–early Pleistocene Olkhon phase (4–3 to 2 Ma) was a major shift from a tectonically "calm" period to the active orogeny of the Baikal Rift at ca. 3.5 Ma (Logatchev and Florensov, 1978; Logatchev, 1993, 2003). The dome uplifts of the northern and southern parts of BRZ started to form the mountain ranges and the ultra-deep rift basin of Lake Baikal. The uplift of the Olkhon block shifted the sedimentation environment from lacustrine (Sasa Group) to subaerial (Kharantsy Group). In the Tankhoi intermediate step (Fig. 6), the sediments of the Miocene–upper Pliocene Osinovka Group were overlapped by Shankhaikha Group conglomerates (Mats et al., 2001).

The early Pleistocene Nyurga tectonic phase (2 to 1.0–0.8 Ma) deformed the SSS-2 seismic-stratigraphic unit (Hutchinson et al., 1992) and is seen in the B10 reflection boundary (Moore et al., 1997) (Fig. 13). The large-scale uplifts and subsidence were recorded in the Olkhon Island at the contact of the Miocene–Pliocene Sasa Group and the Quaternary Nyurga Group (Mats and Perepelova, 2011).

The early to middle Pleistocene Primorsky tectonic phase (1.0–0.8 to 0.15–0.12 Ma) was characterized by the rapid uplift of the western mountain frame, which changed the direction of the discharge of Baikal waters from the Lena (via the Manzurka Valley) to the Yenisei (via the Ilcha-Irkut Valley) (Kononov and Mats, 1986). During this phase, the Baikal terraces, which are now elevated to 120–130 m, probably formed (Yefimova and Mats, 2003). However, the sedimentation in the Baikal was probably interrupted at ca. 200 Ka (Bezrukova et al., 2004). Finally, the late Pleistocene Tyya tectonic phase (0.15–0.12 Ma to now) formed the modern high topography of the BRZ and induced the up to 200 m vertical displacements of Baikal terraces (Mats and Perepelova, 2011) and the onset of the discharge via the Angara River due to the collapse of the Listvyanka block (Kononov and Mats, 1986; Mashiko et al., 1997; Yefimova and Mats, 2003) (Fig. 6).

The major tectonic events can be correlated with the reversals of tectonic modes from extension to compression as shown by structural data (Sherman, 1992; Delvaux et al., 1995, 1997; Parfeevets and Sankov, 2006). In the BRZ basins, those reversals match the early–late Oligocene, middle–late Miocene, early–late Pliocene and Pliocene–Quaternary tectono-stratigraphic boundaries (Mats and Perepelova, 2011).

6. Neotectonic events and processes

The sedimentation and tectonic movements of the BRZ are mutually related: the total rate of vertical neotectonic displacements in the BRZ was about 10 km accounting the 8 km thickness of BRZ sediments and the average elevation of the mountains of around 2 km. The late Neogene–Quaternary tectonics formed the high topography of the BRZ and controlled the sedimentation therein. According to Mats et al. (2001), the sediments of the Shankhaikha tectono-stratigraphic sub-complex (3.5–0.5 Ma) were deformed during the Primorsky tectonic phase, which was responsible for the uplift of the western edge of the Baikal rift, the break of the Manzurka (Lena River) outlet of the Baikal waters and the rise of the Baikal lake level. The Irkut sub-complex (0.5–0.15 Ma) reflects the tectonic events, which caused the up to 120 m rise of the lake level and provided the discharge of Baikal waters to the Yenisei via the Irkut River. The Angara sub-complex (0.15–0 Ma) was formed during the youngest tectonic stage, which reformed and dissected the mountain ranges and, therefore, enhanced the glaciation and transportation of clastic material into rift basins. The growth of the mountain frame was accompanied by the continuing subsidence of the Baikal bottom, which finally reached the modern depths.

The late Pleistocene–Holocene neotectonic events have been recorded in almost all BRZ basins. Three tectonic phases were recognized in the North Baikal and Upper Angara basins (Trofimov, 1994): Tyya (ca. 130–100 ka BP), Kichera (50–30 ka BP) and Upper Angara (20–0 ka BP). The first phase of high-rate uplifting was accompanied by deep incisions of rivers: 40–60 m in the North Baikal upland and 100–120 m in the Angara-Barguzin region (Fig. 5C). The glacial sediments of the Goremyka-Tyya intermediate step were buried. The paleo-Amnunda valley in the Upper Angara Basin was broken by the Severomuysk fault. During the second and third phases, the bottoms of the basins subsided rapidly to accumulate thick sedimentary series of the Karginian and Sartanian age (50–10 ka BP): more than 200 m in the Kichera minor basin and 300 m in the Upper Angara and Muya basins. The estimated rates of the subsidence of the NE cluster of the BRZ basins and related sedimentation were 1.4–5.4 mm/yr (see Section 4.3.3).

Intensive late Pleistocene and Holocene tectonic movements have been reconstructed in the basins and inter-basin faults of the Tunka Valley (Shchetnikov, 2001; Ufimtsev et al., 2004, 2006, 2009). A considerable part of those movements, for example, in the Barguzin Range, was related to glacioeustasy (Levi et al., 1998). The estimates of the rates of Holocene and modern tectonic movements are controversial. For example, in the north-eastern flank of the BRZ, the basins show negative gradients in their central parts and positive in the edges. The rates of subsidence and uplifting were 2 and 4–14 mm/yr, respectively (Levi and Sizikov, 1978; Levi et al., 1998).

Around the Baikal, many researchers used the reference marks of I.D. Chersky reporting on geological and geomorphologic events based on instrumental measurements (Lamakin, 1953). All those data indicate abrupt changes of the Baikal shoreline. Strong evidence for a seismically triggered event comes from the Proval Bay in the Selenga delta (Fig. 6), which formed after the 1862 earthquake (Ladokhin, 1960; Vologina et al., 2007). More evidence comes from archaeology: the subsidence of the oldest 11th cultural layer in the Ulan-Khada Neolithic site (Maloye More) under the water, the 50-m uplift of Onkogon (Chivyrkui Bay) Cape petroglyphs, and the presence of rounded ceramic pebbles together with rock pebbles in the Lysaya Sopka settlement near Nizhneangarsk (Gurulev, 1959) - all suggest that the Baikal shoreline was affected by seismic events (Fig. 6). In addition, there has been recorded a 3 m displacement of the shoreline at the Merginiy-Udzur Cape of Lake Hovsgol (Rogozin, 1993).

Traces of late Pleistocene–Holocene deformations triggered by earthquakes were discovered in the sediments of the basins linked to major active faults, Main Sayan, Tunka, Primorsky and Chersky, during mining campaigns. Radiocarbon dating results indicate strong earthquakes every 130 years during the Holocene (Khromovskikh et al., 1993). Three Holocene seismic rock collapses were recorded in the Okusikan River valley, at the Severomuysk interbasin horst. The largest collapse dammed the river at ca. 9.2 ka BP (Kulchitsky, 1994).

7. Volcanism

Cenozoic volcanism is manifested in many basins and uplifted structures of the BRZ: Udokan Range, Vitim Upland, Khamar-Daban Range, Tunka Rift Valley, Hovsgol-Darhad area and Sayan Mountains. The volcanic formations are both basaltic flows and stand-alone volcanoes. In general, volcanic fields are situated outside rift basins, except for the Tunka and Hovsgol-Darhad (Fig. 1). The majority of volcanoes were active before the main rifting phase; however, there are several Pliocene and Quaternary volcanos coeval with the rifting in all volcanic fields (Fig. 14A) except for the Hovsgol-Darhad (e.g., Ivanov et al., 2015).

According to Ivanov et al. (2015), there have been three major stages of Cenozoic volcanism in the BRZ. 1) The late Cretaceous–early Eocene volcanism of the "crypto-rift" stage was probably linked to the preceding early Cretaceous riftogenesis (Sklyarov et al., 1997; Donskaya et al., 2008; Jolivet et al., 2013). The volcanism probably started in the Mesozoic basins (e.g., Tunka, and Eravna) and continued during the late Cretaceous–Paleogene regional peneplanation. The Tunka Cretaceous to Paleocene sediments intercalate with volcanogenic rocks as seen in drilled cores (Kashik and Mazilov, 1994). A sample of basalt from the Elovsky interbasin horst was dated by the K-Ar method to show an age of 72 ± 1.6 Ma (Rasskazov, 1993), however this age estimate is doubtful (Ivanov et al., 2015). Similar ages of 76.2 ± 1.0 and 74.0 ± 0.9 Ma were obtained from the Mesozoic Eravna Basin, which has not been reactivated in post-Mesozoic time (Ivanov et al., 2015) (Fig. 14A).

2) The Oligocene volcanism of the transitional-rift stage formed the lava flows of the Tunka Basin intercalated with late Oligocene sediments (Logatchev, 1993; Shchetnikov et al., 2012), and those in the southern BRZ and south of it yielded Oligocene ages (Devyatkin and Smelov, 1979; Bagdasaryan et al., 1981; Ivanenko et al., 1989; Kononova et al., 1988; Ashchepkov et al., 2003; Yarmolyuk et al., 2003). However, those ages obtained from the southern BRZ were questioned (e.g., Rasskazov, 1993; Rasskazov et al., 2000, 2003). Ivanov et al. (2015) reported a new Ar-Ar age of 26.8 ± 0.2 Ma from the northern margin of the Darhad Basin (Fig. 14A).

3) The Miocene Baikal rift volcanism formed the majority of basaltic fields of the BRZ (Fig. 1B). The Early Miocene volcanism was manifested in the southwestern BRZ as shown by numerous K-Ar and Ar-Ar age estimates ranging from 22 to 15 Ma (Rasskazov, 1993; Ashchepkov et al., 2003; Rasskazov et al., 2000, 2003; Yarmolyuk et al., 2003; Ivanov and Demonterova, 2009; Tsypukova et al., 2014). The main fields of the Early Miocene volcanism are Tunka and Hovsgol. Two Early Miocene K-Ar dates were obtained from the Vitim volcanic field (Rasskazov, 1993; Ashchepkov et al., 2003) which are thought to be doubtful as well (Ivanov et al., 2015). The middle to late Miocene volcanism was manifested over a wide territory including the Hovsgol, Sayan, Tunka, Vitim and Udokan fields. There are also smaller Miocene volcanic fields in Eastern Tuva and Oka Plateau. The volcanism ceased at around 15 Ma BP (Ivanov et al., 2015). The peak of volcanic activity in the Vitim area was at ca. 9–10 Ma. The Oka volcanism started at ca.12 Ma. The 12–6 Ma large volcanic field of Sayan-Hovsgol extends from the Oka plateau in the north-west to Lake Hovsgol in the south-east. The volumes of early Miocene lavas were much greater than those of late Miocene age (Ivanov et al., 2015). In addition, only plateau-type basalts, also termed "basaltic covers" or "top basalts" in Russian literature, erupted during the early Miocene (22–15 Ma) (Fig. 14A). Since ca. 8 Ma the basalts

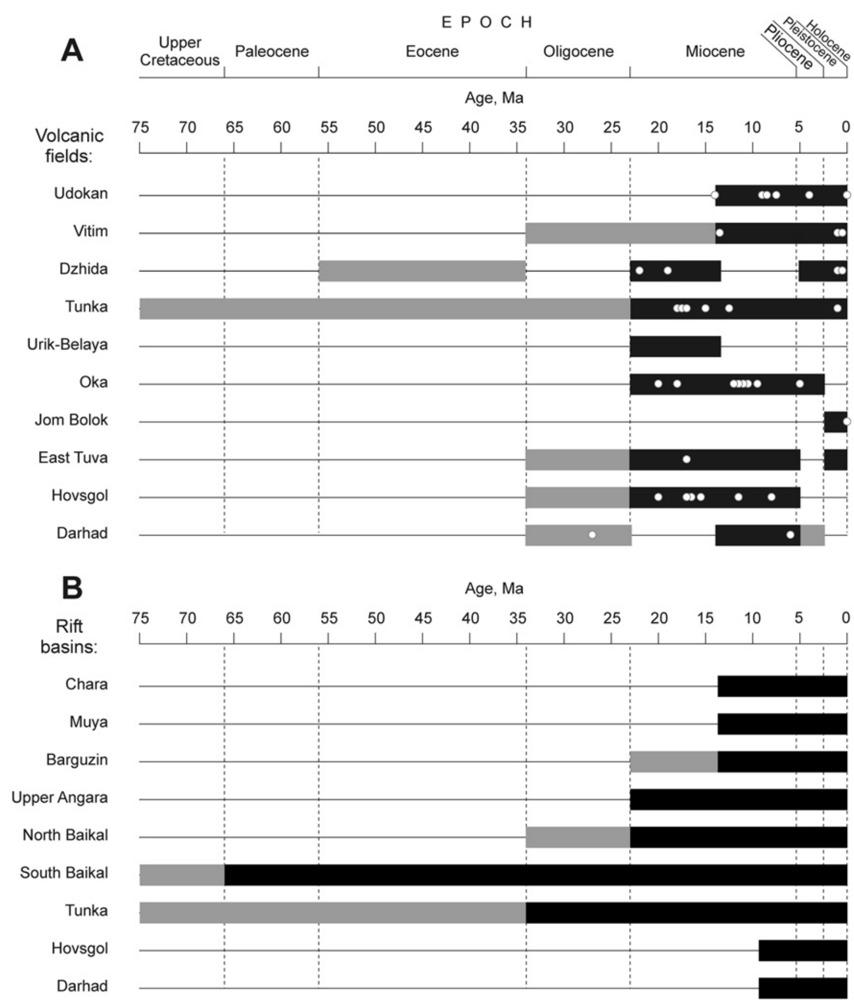

Fig. 14. A. Summary of BRZ volcanic fields versus ages; thick bars are for age intervals: black – proved, gray – questioned; light circles – specific age estimates (the data borrowed from Ivanov et al., 2015). B. Summary of BRZ sedimentary basins versus ages; thick bars are for age intervals: black – recorded, gray – assumed.

filled the river valleys and accordingly are called "valley" basalts (e.g., Ivanenko et al., 1989).

During the Pliocene and Quaternary, the volcanism continued in almost all Miocene basaltic fields (Fig. 14A) to produce lava flows and central-type volcanos. The volume of erupted material decreased except for the Udokan field, which volcanism remained highly active during the whole Pliocene. The Ar-Ar dating of the Udokan basalts yielded ages of 3.9 and 0.1 Ma, whereas the Oka Plateau basalts yielded an age of ca. 5.1 Ma (Rasskazov et al., 2000). The Quaternary volcanism formed the large Azas Plateau in East Tuva. That stage was dominated by sub-glacial eruptions (Grosswald, 1965; Komatsu et al., 2004; Arzhannikov et al., 2012) with subordinate normal interglacial lava flows (Yarmolyuk et al., 2004). Although the ages obtained by different research teams are controversial (Rasskazov et al., 2000; Yarmolyuk et al., 2001), the main peaks of volcanism were more or less well estimated at 2.14–2.07, 1.75–1.65, 0.76–0.565 and 0.235–0.06 Ma (e.g., Komatsu et al., 2004). The Quaternary Vitim basalts have an age of 1.0 to 0.6 Ma (Rasskazov et al., 2000). The youngest Holocene volcanism (0.01–0 Ma) is manifested in two localities: Jom-Bolok of Tuva and in the western Udokan field (Ivanov et al., 2011).

In Tunka, which is the only basin hosting volcanic flows intercalated with sediments, the Miocene and post-Miocene lava flows occur at the Elovsky interbasin horst to form a fan-shaped series of intercalated sedimentary and basalt layers. The volcanic structures include well-preserved pyroclastic cones. The numerous volcanic structures of the Elovsky spur (Figs. 2 and 7A) are exposed at river banks. For example, the basalts exposed along the Khobok River yielded the ages of 4.1 $\pm$ 0.2 Ma (Hase et al., 2003), 2.49 $\pm$ 0.36 and 1.91 $\pm$ 0.3 Ma (Rasskazov et al., 2000); those exposed along the Irkut River yielded 4.4 $\pm$ 0.2 Ma (Hase et al., 2003) and those exposed near a bridge over the Irkut River yielded 2.46 $\pm$ 0.14 Ma ages (Rasskazov et al., 2000). The hawaiites of the Dargatuy scoria cone and Khara-Boldok (Chersky) volcano yielded 0.86 $\pm$ 0.05 Ma and 1.58 $\pm$ 0.14 Ma (Rasskazov et al., 2000) or 0.7 $\pm$ 0.4 Ma (Hase et al., 2003) ages, respectively. The ages of the lavas underlying the Tunka intra-basin scoria cones are 1.57 $\pm$ 0.08 and 1.21 $\pm$ 0.08 Ma (Rasskazov et al., 2000). Shchetnikov and Ufimtsev (2004) suggested that the position of the volcanic cones of the north-eastern Tunka Basin is consistent with the general trend of basin subsidence.

8. Discussion and Summary

In this section we will summarize the data from the Baikal Rift Zone and discuss its evolution. The main foci will be made to the correlations between the Cenozoic and Mesozoic events, the growth of the Baikal rift, Miocene–Pliocene boundary and youngest tectonic processes. In addition, we will address key questions of regional tectonic evolution and speculate about probable links between the Meso-Cenozoic rifting and widely manifested intra-plate magmatism in the BRZ and adjacent territories.

8.1. Regional correlation of Mesozoic and Cenozoic basins

There are a lot of Mesozoic basins in central Yakutia, Transbaikalia and northern Mongolia filled by Jurassic, Cretaceous, Paleogene–Neogene and Quaternary continental sediments (e.g., Sarkisyan, 1958; Rasskazov et al., 2007). Topographically they fit the structures formed during the late Paleozoic–early Mesozoic suturing of the Paleo-Asian or Mongolo-Okhotsk Ocean and continental collision (e.g., Dobretsov et al., 1995; Donskaya et al., 2013; Safonova and Santosh, 2014; Zhao et al., in press). Numerous events of active mantle and crustal magmatism happened during the Early Mesozoic tectonic stage. In the late Mesozoic, the tectonic regime changed to form a system of uplands and basins called the Transbaikalian Mesozoic basin province (Fig. 1B). These landforms experienced denudation during the late Cretaceous–early Paleogene and developed slowly during the Cenozoic, when the Baikal rift basins formed. Morphologically the Mesozoic basins are relatively small and show smooth topography.

On the contrary, the Cenozoic Baikal rift basins are larger, actively faulted and tectonically differentiated due to the recent tectonic events. Geometrically, the Cenozoic and Mesozoic basins do not fit excluding their inherited co-development (Florensov, 1960). These two systems of sedimentary basins may partly juxtapose (e.g., Jolivet et al., 2013). Late Cretaceous to early Paleogene sediments may occur in the South Baikal and Tunka basins suggesting a long period of regional subsidence (Mats et al., 2001; Logatchev, 2003). Only late Eocene sediments have been so far identified in the deepest borehole of the Selenga delta (see Section 4), while the four to five kilometers of sediments below the borehole bottom remain uninvestigated. Accordingly, many researchers attributed the initiation of the Baikal rift to the middle Eocene (Logatchev and Florensov, 1978) or late Cretaceous to Eocene (Mats, 1993; Logatchev, 2003) and defined this interval as a crypto-rift or pre-rift stage of BRZ evolution (Mats, 1993; Mats et al., 2001).

8.2. Bilateral growth of the Baikal rift

The South Baikal Basin is typically regarded a major structural element of the Baikal Rift Zone. The structure of the South Baikal Basin suggests a scenario of tectonic evolution different from that inferred from the basins at the periphery of the BRZ. The subsidence of the basin was greater than the uplifting of the surrounding mountain ranges resulting in the deposition of an extremely thick sedimentary sequence (7.5–10 km) in the Selenga delta. The mountains of the western frame of the South Baikal Basin are 1–1.5 km lower than those of the North Baikal Basin (Figs. 6 and 8). In addition, the structure of the South Baikal Basins is not as asymmetric as that of the peripheral basins, which northern and north-western ranges are higher and steeper (Figs. 3 and 4). The South Baikal basin is located within the Selenga Saddle, which is an orographically lower area between the Sayan-Tuva and Baikal dome-shaped uplifts (Logatchev, 2003).

The oldest basins of the BRZ are South Baikal and Tunka as their sedimentary sequences may appear as old as late Cretaceous. The North Baikal Basin is younger: according to Logatchev (2003) it appeared in the Oligocene. The sedimentary sequences of the peripheral basins are much younger, Miocene, although their oldest sediments have not been documented by boreholes. The youngest basins of the BRZ are Hovsgol and, possibly, Darhad, which experienced extension and subsidence since the late Miocene, i.e. at ca. 5.5–6 Ma (Fedotov, 2007). In addition, the depth of the crystalline basement gradually decreases from the center to the periphery of the BRZ. All this allowed Logatchev (2003) to conclude about the bilateral growth of the Baikal rift (Fig. 14B).

8.3. Miocene sedimentation environments

The Miocene tectonic evolution and related sedimentation has been better understood, as the Miocene sediments were documented by many boreholes drilled in most large basins and they are well exposed in the basins of the Tunka Valley, the Tankhoi Plain and the Maloe More–Olkhon–Svyatoi Nos area of Lake Baikal. The sediments are dominated by fine-grained varieties suggesting low topography and weak tectonic activity. The sediments obviously formed at river deltas, accumulative plains and swamps. The layers of brown coal are a diagnostic feature of Miocene sediments. There were big lakes in the Tunka, South Baikal and probably North Baikal which could be up to several hundred meters deep (e.g., Mats et al., 2001). The facial analysis of the Miocene sediments of the Tunka and Tankhoi basins indicates that the contours of the Miocene basins do not fit the modern basin morphology, as their depocenters also do not match (Kashik and Mazilov, 1994). The Miocene strata experience strong tectonic deformations during the North Baikal tectonic event at 10 Ma (Mats et al., 2001; Mats and Perepelova, 2011) or 7–5 Ma (Logatchev, 2003).

8.4. Dramatic events at the Miocene/Pliocene boundary

In Lake Baikal, the BDP-98 core documented an abrupt shift of the sedimentation environment at 6–5 Ma (Derevyanko, 2008): the rate of sedimentation changed from 13 cm/ka in the lower part to 4 cm/ka in the upper part. In the lower part of the core, the 8.4–6 (5) Ma interval of intensive sedimentation can be explained by the proximity of the paleo-Barguzin delta as a source of terrestrial material. That time the lake was relatively shallow and then started deepening gradually. At a level of 6–5 Ma, the influence of the delta ceased and the lake became a deep hemipelagic reservoir (Antipin et al., 2001). The cessation of delta sedimentation was probably caused by the accelerated subsidence of the South and North Baikal basins and the uplifting of the Academic Ridge forming an interbasin horst.

Logatchev (2003) considered the 7–5 Ma interval as a time of dramatic tectonic changes in the BRZ. This interval separates the earlier 40–50 Ma long phase of "slow rifting" and the last 5 Ma long phase of "fast rifting". The first phase was characterized by slow extension and by moderate vertical displacements. The second phase was characterized by accelerated extension and high-rate vertical movements both in the basins and mountains. The 7–5 Ma interval separating the two phases was rather a period of compression than extension and was accompanied by the folding of basin sediments. The folded Miocene sediments are well exposed in the Tunka Valley and in the Tankhoi Plain of the South Baikal Basin.

In Tunka, the shift of the stress pattern from extension to compression at ca. 7–5 Ma (Fig. 12) was attributed to the India-Asia collision which has been affecting the region since the late Miocene (Molnar and Tapponnier, 1975; Arzhannikova et al., 2011; Jolivet et al., 2013). The late Miocene change of the stress field caused the tectonic inversion of the basins, which, however, resulted in the significant changes of sedimentation regimes and landforms much later, in the late Pliocene–early Pleistocene (Larroque et al., 2001; Rasskazov et al., 2007; Arzhannikova et al., 2011).

A deep Baikal-type lake temporarily occupied the Chara Basin during the Pliocene (Enikeev, 2008). The initiation of the deep lake could be linked to accelerated tectonics at the Miocene/Pliocene boundary. The initiation of the Hovsgol Basin was probably also related to that event because the "valley" basalts were incised into a plateau of "top" basalts at ca. 8–7 Ma (Ivanov and Demonterova, 2009). The tectono-stratigraphic record from Hovsgol sediments suggests their 6–5.5 Ma age (Fedotov, 2007). Thus, at the Miocene/Pliocene boundary the stress pattern shifted from extension to compression and the period of slow rifting changed to the period of fast rifting. These changes could initiate the modern plate motions: the drift of the Tuva-Mongolia microcontinent towards the Siberian Craton and the rotation of the Amurian plate (Fig. 1B), which are well documented by the GPS monitoring data (Ashurkov et al., 2011).

8.5. Pliocene and Pleistocene tectonic deformations

The Pliocene–Pleistocene tectonic events in the BRZ have been documented by numerous boreholes and seismic reflectance profiles. The best examples are the seismo-stratigraphic data from lakes Baikal and Hovsgol. The seismic profiling provided more robust data as it clearly shows the reflectors marking the main tectonic events (Fig. 13). However, those boundaries are not well seen in the sedimentary sequences (Derevyanko, 2008). The angular bedding and the unconformities as shown by reflectance profiles suggest sedimentation breaks and basin bottom subsidence. The lower units of the Baikal and Hovsgol seismic-stratigraphic sequences show deformations, whereas their upper units show coherent stratigraphy. In the Baikal, the B-6–B-10 upper package of deformed sequences yielded a late Miocene–early Pleistocene age, 11–1.8 Ma (Hutchinson et al., 1992; Moore et al., 1997). The A1–A3 package of undeformed sequences is of middle to late Pleistocene age. Similarly, in the Hovsgol, the lower tectonically deformed units span 5.5–0.4 Ma and the stratigraphically coherent intervals span 0.4–0 Ma (Fedotov, 2007). However, the borehole data suggest a long break of sedimentation during a part of the middle Pleistocene (HDP Members, 2009) and therefore the age of that unconformity can be older.

In general, the BRZ basins show several sedimentation breaks suggesting uneven or inversed vertical tectonic movements. In the Chara Basin, the sedimentation environments changed from on-land in the Miocene to a Baikal-type basin in the Pliocene; the latter was finally compensated by Pleistocene sediments. However, the borehole data show no lower Pleistocene sediments in the sedimentary sequence. Enikeev (2008) explained that by the erosion of Chara sediments by middle Pleistocene giant glaciers, which filled the basin. This explanation looks doubtful as a thick ice cup would provide an additional stress on the basin and would induce related isostatic movements, which must have buried the previously accumulated layers. Therefore, the tectonic inversions are a more reasonable explanation for those gaps in sedimentation.

Such an inversion is well documented in the Tunka Valley, where the late Miocene compression induced the uplifting of the Tertiary sediments in the peripheral parts of the basins and near the interbasin horsts (e.g., Arzhannikova et al., 2011; Jolivet et al., 2013). The Pleistocene subsidence of the central parts of the Tunka Basin was recorded by the regular subsidence of Quaternary volcanos (Shchetnikov and Ufimtsev, 2004). Large-scale displacements of Quaternary landforms, such as river valleys, terraces and moraine ridges, have been described in many places of the BRZ as well (e.g., Trofimov, 1994; Mats et al., 2001; Shchetnikov and Ufimtsev, 2004).

8.6. The late Pleistocene fast subsidence

The radiocarbon dating of the sediments in boreholes gave estimates of the rates of sedimentation for several dry basins of the northern BRZ. According to those dates (Krivonogov, 2010; Table 1), the sedimentation rates were 1.4 to 5.7 mm/yr. The rates gradually increase from the peripheral Chara Basin to the central South Baikal basin (Logatchev, 2003). The basins of the southern BRZ show no high-rate subsidence. In the Tunka Valley, the subsidence was probably negligible. In the Darhad Basin, despite several boreholes, the estimates appeared doubtful due to the thick permafrost ice layers interbedded with the basin sediments. The presence of ice may increase the total thickness of the sediments up to 20% (Krivonogov et al., 2012). In addition, two age models, paleomagnetic and luminescence, have been applied to the 92.6 m long DBC-1 borehole (Krivonogov et al., 2012; Batbaatar et al., 2008, 2012). By accounting the presence of ice layers within the sedimentary sequence and two age models, the average rate of sedimentation for the upper part of Darhad sediments can be estimated as 0.3 and 0.5 mm/yr, respectively.

8.7. Rifting as a surface manifestation of deep-mantle processes

The role of the Baikal rifting in the development of the whole CAOB and its relation to deep mantle processes can be better understood by considering geology, magmatism and tectonics of BRZ adjacent areas. Two major types of surface manifestations of deep-mantle processes are plate movements and volcanism. Many researchers consider various stages or periods of tectonism and volcanism in the BRZ based on sedimentological and geomorphological data (Sections 5, 7, 8.4 and 8.6). However, in spite of the different alignment of Mesozoic and Cenozoic rifts (Fig. 1), recent publications argue for continuous Mesozoic to Cenozoic deformations (Jolivet et al., 2009, 2013) and practically continuous intra-plate volcanism in the BRZ (Ivanov et al., 2015) (Fig. 14A). The sedimentary and tectonic data show that the BRZ experienced the slow extension prior to 7 Ma, the compression at the Miocene–Pliocene boundary, i.e. at ca. 7–5 Ma, which was probably triggered by the India-Eurasia collision, and the rapid extension after 5 Ma (see Section 8.4). The distribution of volcanic fields and separate volcanoes over the BRZ suggests that the volcanism was hardly related to a certain tectonic reorganization, e.g., India-Eurasia collision (see Section 5).

Compositionally, the Cenozoic volcanic rocks of the BRZ are dominated by basalt, basanite and trachybasalts. There are also melanephelenites, tephrites, trachytes, phonolites, alkaline ultramafic rocks with carbonatites, bimodal basalt–pantellerite series and peralkaline granitoids (Kuzmin et al., 2010). The most widespread variety is OIB-type basalt, which is characterized by increased alkali, TiO_2, Nb and light-rare-earth elements and which origin is typically related to hot spots or mantle plumes (Sun and McDonough, 1989; Hofmann, 1997; Safonova and Santosh, 2014).

In general, the Cenozoic tectonic reactivation was manifested over the whole CAOB (e.g., Windley et al., 1990; Buslov et al., 2004). OIB-type alkaline basalts and bi-modal volcanic series occur in the BRZ (Udokan, Vitim), and South-Khangai volcanic field, located south of the Baikal and in the Dariganga volcanic region (Yarmolyuk et al., 1995; Wiechert et al., 1997; Kuzmin et al., 2010) (Fig. 1B). OIB-type basalts of Quaternary age compose modern volcanic fields of the Jeju Island in South Korea (Tatsumi et al., 2005) and Hainan Island in south-eastern China (Li et al., 2013). Thus, all those manifestations of OIB-type intraplate continental volcanism are sporadically scattered over a huge territory of the CAOB and span a wide range of ages from the Mesozoic to the Holocene (e.g., Rasskazov et al., 2003; Zhao et al., 2014; Yarmolyuk et al., 2005; Simonov et al., 2015). Recently those volcanic occurrences have been linked to hydrous-carbonated plumes generated in the mantle transition zone under the effect of the subduction of oceanic crust, volatiles and crustal rocks to the deep mantle (Safonova et al., 2015).

The mechanism that drove those extensions and related rifts remains debatable though. One model considers an orogenic collapse of the crust thickened by the collision between Siberia and North China (e.g., Xiao et al., 2003; De Grave et al., 2014). Another formerly popular model for their formation connects the rifting with the India-Eurasia collision (Molnar and Tapponnier, 1975). However, the early stage of extension in in the BRZ and the intra-plate volcanism both happened much prior to the main stage of the India–Asia collision at ca. 25–20 Ma (Hall, 2002; Kuzmin et al., 2010). Therefore, we speculate that the Cenozoic intra-plate or OIB-type magmatism and extensions in the BRZ and adjacent areas of south-eastern Transbaikalia, central Mongolia and east Chinacan be linked to the last ca. 200 Ma subduction of the Pacific plate beneath East Asia, which is still continuing (e.g., Windley and Allen, 1993; Kuzmin et al., 2010; Safonova and Maruyama, 2014; Zhao et al., 2014) and that the origin of BRZ rift basins and volcanism can be regarded as surface manifestations of the plumes generated in the transition zone.

9. Conclusions

Major, minor and satellite BRZ basins are filled by Cenozoic sediments and give valuable information about environmental and tectonic evolution of an important segment of the CAOB - Transbaikalia. The structures of the BRZ are superimposed on the previously formed Mesozoic extensional structures and basins, which morphology and geological history are substantially different.

The Mesozoic basins are relatively small and show smooth topography unlike the Cenozoic basins, which are larger, actively faulted and tectonically subsided by recent orogenic events. The Cenozoic and Mesozoic basins are geometrically different thus excluding their inherited development. The available deep drilling data suggest that the oldest basins of the BRZ are South Baikal and Tunka, which sedimentary sequences may appear as old as late Cretaceous. The North Baikal Basin is Oligocene and the peripheral basins are Miocene. The youngest basins are Hovsgol and Darhad in the southern BRZ. These estimates allowed researchers to conclude about a bilateral extension of the rift from its central and largest South Baikal Basin. However, the true age of the Baikal rift is still unknown, as the drilling did not open the lowest parts of basin sedimentary sequences.

Sedimentologists recognize several major and subordinate stages of the evolution of the BRZ, in particular, crypto-rift and major rift stages. The sedimentary sequences of the basins clearly show two formations: the Oligocene–Miocene fine-grained formation is characterized by low topography and related to weak tectonic processes; the Pliocene–Pleistocene coarser-grained formation is related to active mountain growth and basin bottom subsidence.

The most dramatic tectonic shift in the BRZ happened at the Miocene/Pliocene boundary, i.e. at ca. 7–5 Ma. The earlier “slow rifting” stage changed to the later “fast rifting” stage. At this stage the subsidence of the South and North Baikal basins accelerated and the uplifting of the Academic Ridge in Lake Baikal started.

The Pliocene–Pleistocene intensive tectonic deformations were recorded in the Baikal and Hovsgol stratigraphic sequences based on borehole drilling and seismic reflectance data: their lower units show tilting and deformation at 11–1.8 Ma, whereas their upper units show coherent stratigraphy at 0.4–0 Ma.

The tectonically driven changes of sedimentation are typical of the BRZ, which has been experiencing deformations since the late Miocene. At that time, the tectonic regime shifted from extension to compression, resulting in the late Pliocene–early Pleistocene on-land sedimentation and uplifting of the Tertiary sediments in the peripheral parts of the basins and near the interbasin horsts.

In the late Pleistocene most of the basins were subsiding. The rate of sedimentation in the basins of the northern BRZ was higher (1.4 to 5.7 mm/yr) than in those of the southern BRZ (0.3 to 0.5 mm/yr).

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