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Pliocene to Quaternary deformation in South East Sayan (Siberia): Initiation of the Tertiary compressive phase in the southern termination of the Baikal Rift System

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ABSTRACT

The South East Sayan area, W of the Lake Baikal is subjected to a very complex tectonic setting where the extensional stress field of the Baikal Rift System meets the compressional stress field generated by the India–Asia collision further south. Using satellite images, aerial photographs, SRTM DEM, field mapping of geomorphological structures, and published neotectonics and geological data we show that most of the relief in the SE Sayan initiated during Late Pliocene–Pleistocene through compressive reactivation of inherited structures. By Late Quaternary, clockwise rotation of the compressive field generated strike–slip faulting and local, secondary extension still within a general compressional stress field. We demonstrate that the formation of the small-scale extensional basins within the East Sayan range is not linked to general the extension in the Baikal Rift System nor to a possible asthenospheric plume acting at the base of the crust but rather to the rotation of small rigid tectonic blocks driven by the compression.

1. Introduction

Recently published low temperature thermochronology data have shown that relief building in the Altay and Sayan ranges is very recent (less than 5 Ma) and associated to the northward propagation of the compressive deformation driven by the India–Asia collision (De Grave et al., 2003, 2007; Jolivet et al., 2007; Vassallo et al., 2007; Buslov et al., 2007, 2008). The East Sayan region represents the northeastern termination of the Altay–Sayan range, and is connected to the Baikal Rift System (BRS) through the Tunka basin (Fig. 1). Several models have been proposed for the initiation and the evolution of the BRS: (1) the "active rift hypothesis" considers that rifting is driven by mantle processes acting on the base of the crust along the rift axis (Artemyev et al., 1978; Grachev et al., 1981; Zorin, 1981; Logatchev and Zorin, 1987; Gao et al., 2003); (2) the "passive rift hypothesis" implies that the BRS is formed by a series of pull-apart basins opening in response to the India–Asia collision to the south (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979; Zonenshain and Savostin, 1981; Cobbold and Davy, 1988; Petit et al., 1996; Lesne et al., 1998; Petit and Déverchère, 2006). Finally, alternative models link the initiation and development of the BRS to complex interactions between the India–Asia collision and the Pacific–East Asia subduction zone (Delvaux, 1997; Ren et al., 2002).

Jolivet et al. (2009), using apatite fission track data from the northern Lake Baikal and the Barguzin basin demonstrated the occurrence of an initial Upper Cretaceous–Lower Paleocene phase of basin formation in the BRS, potentially linked to the northward propagation of the Transbaikal Graben System. The initiation of the BRS thus appears older than or contemporaneous to the onset of the India–Asia collision in Early Paleocene (Patriat and Achache, 1984; Besse et al., 1984; Patzelt et al., 1996; Ali and Aitchison, 2006) excluding that the two events were link. Only by Late Miocene–Early Pliocene, a strong increase in the exhumation rates around the BRS indicates that the effects of the India–Asia collision reached the BRS and were superimposed to the previous mechanism (Jolivet et al., 2009).

Here we use satellite images, aerial photographs, SRTM digital elevation models associated to field mapping of morphotectonic structures and to a synthesis of published neotectonic, geological and geochronological data to study the Pliocene to Quaternary deformation in the SE Sayan area, between the Kropotkin range and the Tunka basin (Fig. 2).

If the evolution of the BRS is related to mantle processes (the "active rift hypothesis") than these processes must also generate transtensive deformation in the SE Sayan area which is linked to the BRS by the Sayan fault and the Tunka basin. On the contrary, if the opening of the BRS is driven by the conjunction between the India–Asia collision stress field and the triangular geometry of the rigid Siberian platform (the "passive rift hypothesis") then the SE Sayan region must be dominated by compressive or

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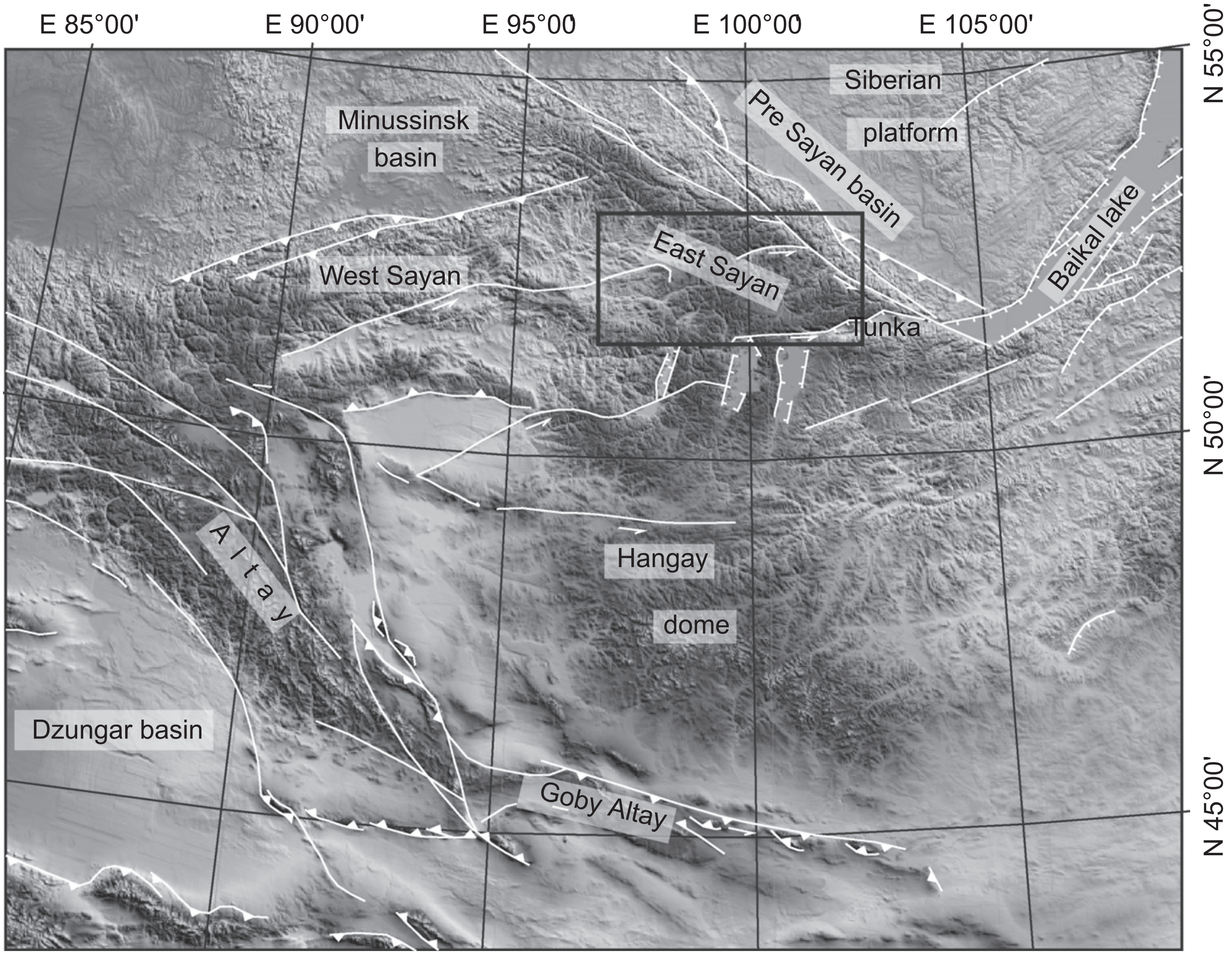

Fig. 1. General topographic and tectonic map of the Altay–Sayan region. The black rectangle corresponds to the study area detailed in Fig. 2.

transpressive deformation at least during the Pliocene–Quaternary period marked by an increase in the extension rate in the BRS (Logatchev and Zorin, 1987; Delvaux et al., 1997; Logatchev, 2003; Mats, 1993; Petit and Déverchère, 2006; Jolivet et al., 2009).

2. Overview of the Cenozoic tectonic evolution and relief building in East Sayan

The detrital sediments deposited within the various intramountain basins of the Sayan region, and especially the south Pre-Sayan basin, the South Minussinsk basin and the Tunka basin (Fig. 1) show a coarsening during the Oligocene, indicating a probable first phase of relief building in the Altay–Sayan (Vdovin, 1976). During the Neogene the tectonic activity decreased, and basaltic volcanism occurred. In Late Pliocene the ongoing phase of relief building initiated and led to the actual topography of the region. This second phase is characterized by strong erosion and deep reorganization of the drainage pattern, deformation of a previously acquired erosion surface and local volcanism (Strelkov and Vdovin, 1969). Jolivet et al., 2007 showed that a peneplenation surface developed in southern and western Mongolia (in the Gobi Altay and Altay ranges) during the Jurassic and has been preserved until the last, Late Tertiary tectonic phase. This surface extended further north to the actual East Sayan ranges and probably corresponds to the actual flat surface forming plateaus in this region. However, because it has been very slowly but continuously rejuvenated by erosion processes (such as wind driven erosion or chemical weathering), the measured age of this surface and especially of the lateritic–kaolinic weathering crust that developed is late-Cretaceous–Palaeogene (Mats, 1993; Kashik and Masilov, 1994; Logatchev et al., 2002).

The East Sayan topography presents a block-like structure with large variations in mean altitude of the different blocks. The SE area of East Sayan is characterized by higher altitudes with ranges such as the Tunka, Kitoy and Munku–Sardyk culminating at 3491 m. Further to the north the Kropotkin range also reaches 3149 m (Fig. 2). Those ranges, like the Great Sayan range to the southwest show a typical alpine topography with deep glacial incision. However, active glaciers are only preserved in the Munku–Sardyk and the southern Great Sayan ranges.

Blocks of lower mean altitudes are spread between the high ranges. They are characterized by preserved remnants of the old peneplanation surface of probably middle to late Jurassic age (Jolivet et al., 2007). The larger occurrence of this surface forms the 400 km square, 2000–2500 m high Oka plateau (Fig. 2).

Cenozoic faulting is responsible for the differential uplift between the blocks. The Main Sayan fault separates the Sayan ranges from the Siberian craton and participates to the relief building within the whole Sayan area (Florensov, 1989). The Baikal–Mondy and Ikhorogol–Mondy fault systems are responsible for the uplift of the high-elevated ranges in the south Sayan region. To the north, the SW margin of the Oka plateau is separated from the Munku–Sardyk and Great Sayan ranges by the Yamaatinskiy fault. Finally, the Oka-Jombolok fault system limits the Oka plateau to the north and controls the uplift of the Kropotkin range (Fig. 2).

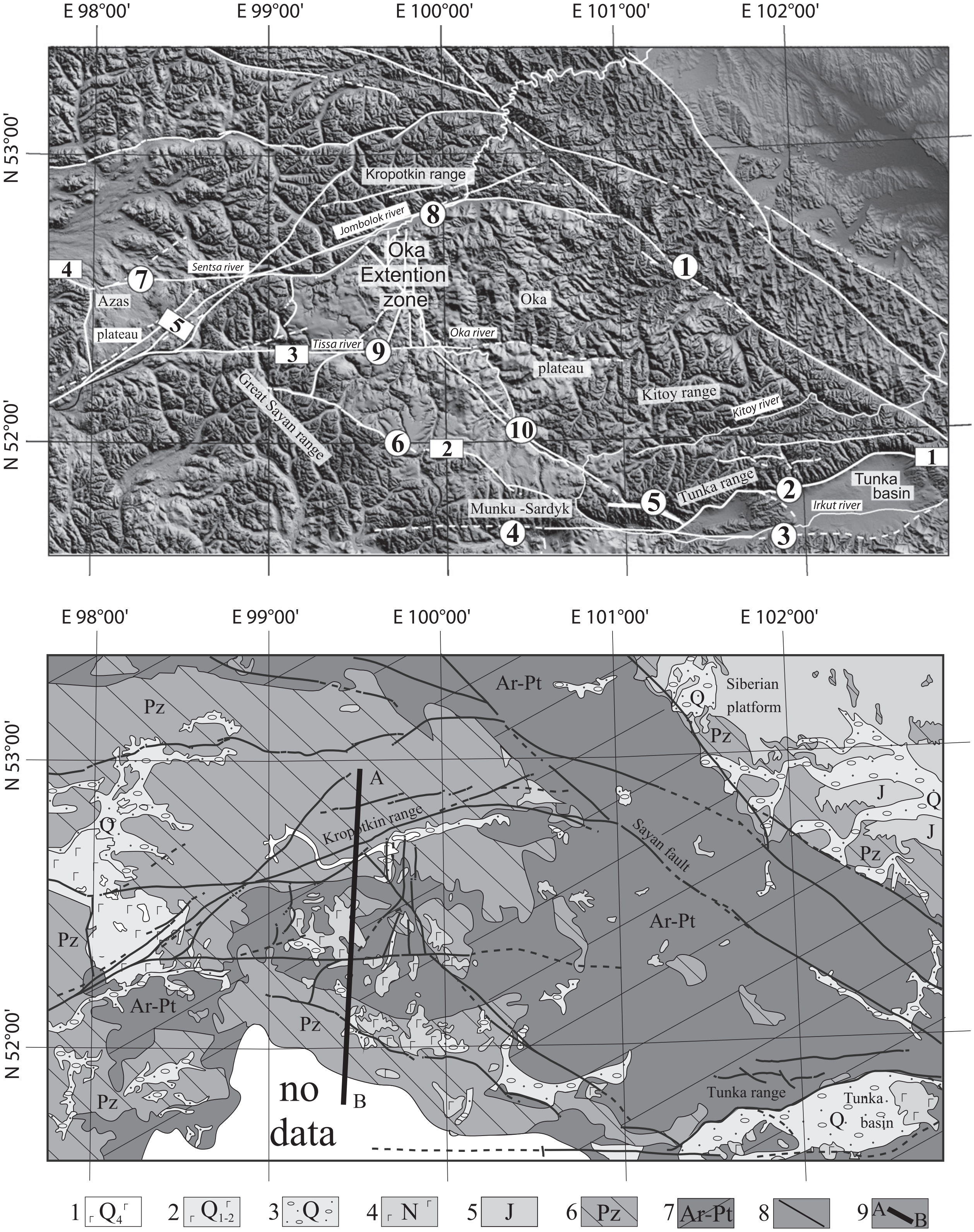

Fig. 2. Topogaphic (top) and geological (bottom) map of the study area in the south-east East Sayan region. *Top*: The numbers in circles indicate the main faults: 1 – Main Sayan, 2 – Tunka, 3 – Baikal–Mondy, 4 – Ikhorogol–Mondy, 5 – Ikhe–Ukhgun, 6 – Yamaatinskiy, 7 – Azas-Sentsa, 8 – Oka-Jombolok, 9 – Biykhem-Tissa, 10 – Oka. The numbers in squares indicate the post-Pliocene structures described in the text: 1 – Deformed basalts with evidences of NE compression (Ruzhich, 1975), 2 – S–N thrusting of the Late Pliocene basalts (Rasskazov, 1990), 3 and 4 – Deformation of basalts by E–W faults (Grosvald, 1965), 5 – Folds in the supposed Pliocene sediments indicating a SE compression phase (Grachev and Lopatin, 1978). *Bottom*: 1 – Holocene basalts, 2 – Pleistocene basalts, 3 – Quaternary sediments, 4 – Tertiary basalts, 5 – Jurassic sediments, 6 – Paleozoic series, 7 – Archean and Proterozoic series, 8 – Main Cenozoic faults, 9 – Position of the cross-section of Fig. 6.

2.1. Kinematic of the main fault systems in SE East Sayan

2.1.1. The Main Sayan fault

The Main Sayan fault is the major tectonic structure of the whole Altay–Sayan region. Since pre-Cambrian times this fault participated to the accommodation of tectonic movements along the edge of the Siberian platform, its kinematic varying through time from strike–slip to reverse or normal (Berzin, 1967). During the Cenozoic, the Main Sayan fault was mostly sinistral with locally a minor normal or reverse component (Lamakin, 1968; Chipizubov et al., 1994; Chipizubov and Smekalin, 1999). The sinistral component is perfectly imaged by the offset of the numerous river systems that cross the fault (Bolshaya Belaya, Malaya Belaya, Onot, Urik, Erma, etc.). The amplitude of the offset varies from 3 to 6 km with a potential maximum of 11 km across the SE portion of the fault in the Zyrkuzunskaya meander along the Irkut river (Lamakin, 1968). However this high offset value should be considered carefully for it may derive from a combination of effective tectonic displacement and of differential erosion. Finally, paleoseismologic studies have shown the existence of paleoseismic structures along a 45 km long portion of the Main Sayan fault indicative of the strong tectonic activity of the fault (Chipizubov et al., 1994; Chipizubov and Smekalin, 1999). Morphological studies coupled with trench analysis show a reverse-sinistral movement along the fault during the Late Quaternary period.

In the East Sayan region, a series of E–W faults are connected from the west to the Main Sayan fault, the most important ones being the Tunka fault and the Azas-Sentsa–Oka-Jombolok fault system (Fig. 2). Within the same region, the Biykhem-Tissa fault also appears well expressed within the topography but does not show any clear connection to the Main Sayan fault. All those E–W faults represent the eastward termination of larger regional systems that appear to control both the vertical and horizontal movements of large crustal blocks.

2.1.2. The Tunka fault

The morphology of the scarp along the Tunka fault indicates that this Cenozoic normal-sinistral fault, which separates the Tunka range from the Tunka basin is one of the most active E–W trending fault in the region (Sherman et al., 1973; Larroque et al., 2001; Chipizubov et al., 2003; Arzhannikova et al., 2005). The Tunka fault participates to the accommodation of the general extension within the BRS. The opening of the Tunka basin started in Oligocene–Miocene times, contemporaneously with the first uplift phase recorded in the Altay–Sayan ranges (Mazilov et al., 1993; Logatchev, 2003). This first tectonic activity was slow and led to the deposition of fine-grained sediments (the Tankhoyskaya Fm.) within the proto-Tunka basin. A second, more active extension phase initiated in middle Pliocene time, marked by the deposition of the coarse-grained Anosovskaya Fm. The maximum thickness of the Cenozoic deposits in the Tunka basin is estimated around 2700–2800 m (Zorin, 1971). Associated to the 2000 m high scarp along the Tunka range this sedimentary sequence indicates a Cenozoic vertical offset of about 4500 m distributed on the Tunka fault and its related segments inside the basin.

Morphotectonic and paleoseismologic studies have shown that the transtensive regime that prevailed in the basin since Oligocene became transpressive during Late Quaternary (Larroque et al., 2001; Arjannikova et al., 2004; Arzhannikova et al., 2005, 2007). Compressive deformations are observed on the Tunka fault (Chipizubov et al., 2003). Using trenching and analysis of geomorphological structures along the Tunka fault Chipizubov et al. (2003) provided a precise description of the Late Quaternary kinematic of the various segments of the fault: W–E orientated segments show a left lateral strike–slip movement associated to a reverse component while SW–NE directed segments show a left lateral strike–slip movement associated to a normal component. Cenozoic NW–SE compressive structures have been described within the Tunka range: along the southern edge of the range, Late Miocene to Pliocene basaltic dykes are cut by NE verging thrust faults whereas basaltic flows are clearly deformed with a SW–NE direction of compression (Ruzhich, 1975). Transpression also occurs between the Baikal–Mondy and Ikhe–Uhgun faults (Fig. 2) developing compressive flower structures (Arjannikova et al., 2004).

Towards the west, the Tunka and Baikal–Mondy faults are connected to the Ikhorogol–Mondy fault which controls the southern edge of the Munku–Sardyk range, separating the Sayan region from the Hovsgol and Darkhat basins themselves belonging to the BRS (Fig. 1). Arzhannikova et al. (2003) have shown the occurrence of recent (Holocene?) sinistral strike–slip movements along the Ikhorogol–Mondy fault system. Microtectonic indicators show top-to-the-south reverse movements along E–W directed fault planes. On the northern side of the Munku–Sardyk range, Rasskazov (1990) reported late Pliocene north-directed thrusting along the Yamaatinskiy fault system (Fig. 2) that separates the

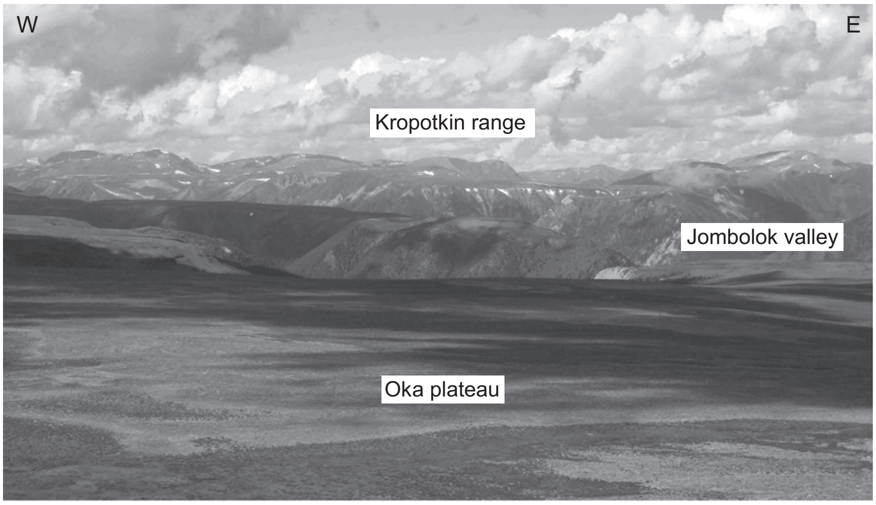

Fig. 3. View towards the north from the northern edge of the Oka plateau. Fragments of the erosion surface in the foreground are preserved at various altitudes within the Kropotkin range on the other side of the Jombolok valley.

Munku–Sardyk and Great Sayan ranges from the Oka plateau (see below). The Munku–Sarkyk range thus developed as a pop-up structure during Late Tertiary–Quaternary.

2.1.3. The Yamaatinskiy fault

Geological data indicate that the Yamaatinskiy thrust fault offsets the pre-Cambrian structures of about 2000–3000 m (Volkolakov, 1971). The fault also affects 2.6 Ma basalts that contain numerous sediment deposits and especially coarse conglomerates derived from a nearby developing relief. This indicates that the Yamaatinskiy fault was active during Late Pliocene and possibly after, inducing northward thrusting and uplift of the Munku–Sardyk range, in conjunction with the regional magmatic activity (Rasskazov, 1990). Rasskazov (1990) reported the occurrence of a buried graben below the basalt flows and estimated that the volcanic activity in that area was linked to extensional structures. The compressive deformation in the S East Sayan region would thus appear later at the end of the magmatic activity period (regionally the youngest volcanics are dated at 1.9 Ma (Rasskazov et al., 2000)), probably putting an end to it by stopping the extension. Following that hypothesis, the age of 2.6 Ma would be approximately the age of onset of the compressive deformation in the Oka region.

Morphological studies of Late Tertiary basalt flows also attest of the Late Pliocene onset of relief formation in the Sayan,

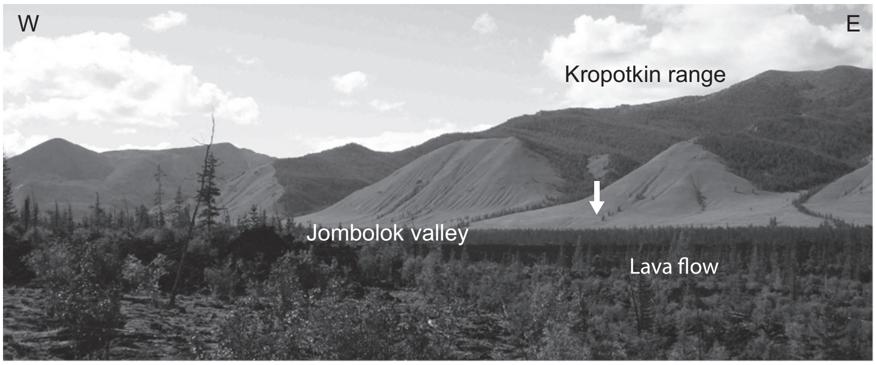

Fig. 4. Facetted spurs along the Oka-Jombolok fault on the northern termination of the Oka Extension Zone. The Jombolok valley is filled with lava flows (see text and Fig. 12). The white arrow indicates the location of the paleosismic study area in Figs. 6 and 7.

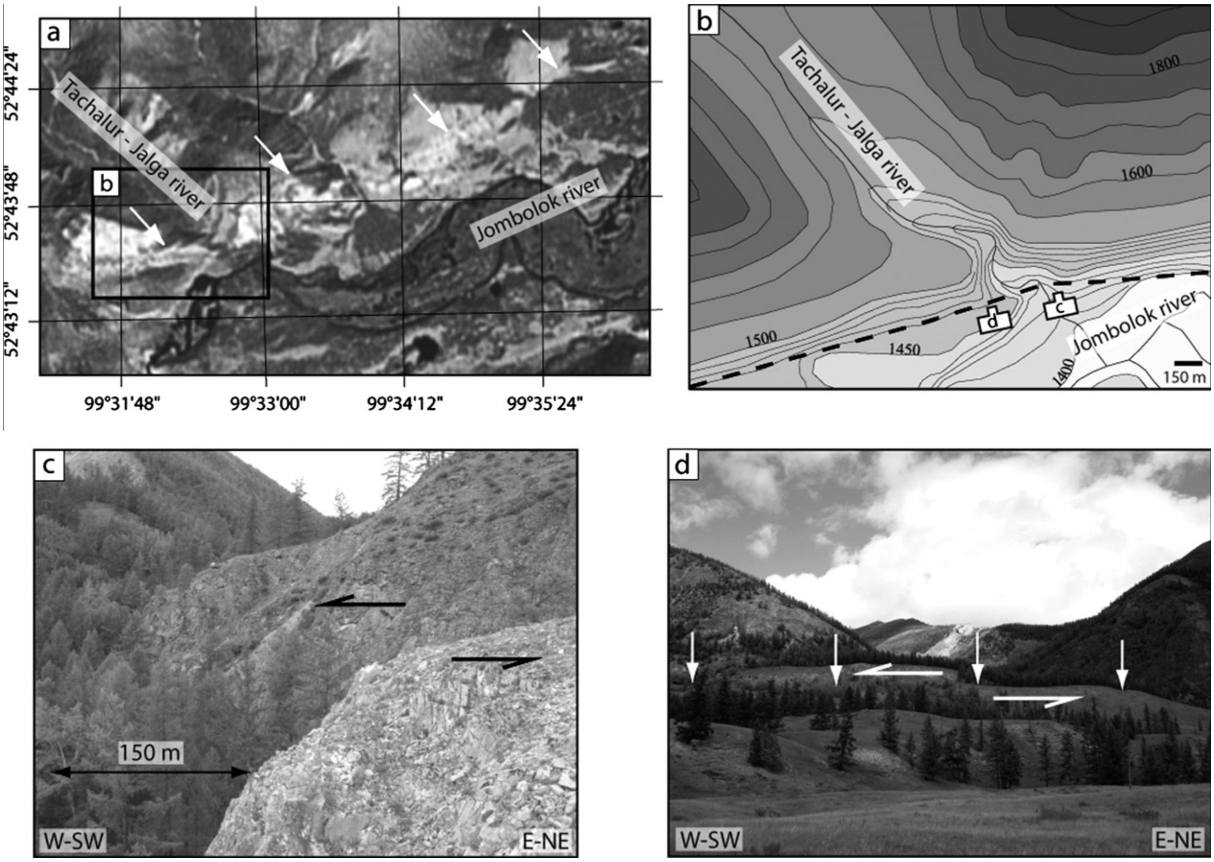

Fig. 5. Examples of evidences for active strike–slip faulting along the Oka-Jombolok fault. (a) Fragment of a Landsat image showing the trace of the Oka-Jombolok fault (white arrows). (b) Morphology of the Tachalur–Jalga fault when it crosses the Oka-Jombolok fault. (c) Evidences for sinistral displacement near the output of the Tachalur–Jalga valley. (d) Sinistral offset of the Late Pleistocene moraine at the output of the Tachalur–Jalga valley. See text for discussion of these elements.

Hamar-Daban and Hangay regions (Yarmolyuk and Kuzmin, 2006; Yarmolyuk et al., 2008). Before 3 Ma the basalts were emplaced as plateau-like structures. Around 3 Ma their shape change as they started to fill developing river valleys. This change is interpreted as a consequence of the onset of relief building and of the formation of a new drainage system. The older valley-filling basalts are 2.8 Ma in East Sayan, 3.1 Ma in Hamar-Daban and 2.9 Ma in Hangay (Yarmolyuk and Kuzmin, 2006). These ages are coherent with the estimated age of activation of the thrust faults around the Oka plateau.

2.1.4. The Biykhem-Tissa and Azas-Sentsa faults

NW of the Yamaatinskiy fault, the Biykhem-Tissa and the Azas-Sentsa faults are two major sinistral transpressive structures (Fig. 2). Both faults vertically offset Pliocene basalts with amplitudes of 500 m and 700 m respectively, based on the vertical displacement of the base of the volcanic flows (Grosvald, 1965). While the Azas-Sentsa fault merges to the east with the Oka-Jombolok fault which itself connects further east with the Main Sayan fault, the Biykhem-Tissa fault is difficult to follow after its connection with the Oka fault (Fig. 2).

2.1.5. The Oka-Jombolok fault

The Oka-Jombolok fault is the main structure that controls the uplift of the Kropotkin range, north of the Oka plateau (Fig. 3). While most authors that worked on the Oka-Jombolok fault agree that it presents a sinistral component (Grosvald, 1965), its vertical motion is still debated. Based on palaeoseismology data, Chipizubov and Serebrennikov (1990) reported a normal component. On the contrary, studying the fracturation system within the fault zone Parfeevets and Sankov (2006) reported Late Pleistocene–Holocene NE directed transpressive movements. In order to precise the kinematic of this fault and its possible variations through time we conducted new fieldwork which results are presented below.

2.2. Recent tectonic deformation within the Oka-Jombolok fault system

The Oka-Jombolok fault separates the approximatively 3000 m high Kropotkin range to the north from the about 2500 m high Oka plateau to the south (Fig. 2). Movements on the Oka-Jombolok fault led to the vertical displacement of the ancient erosion surface still largely preserved on the Oka plateau but also at various altitudes in the Kropotkin range, forming flat-topped massifs (Fig. 3). Well-expressed faceted spurs north of the Jombolok valley indicate a normal component along the fault (Fig. 4). However, these faceted spurs are only localized on a NE directed segment of the fault along the northern edge of the Jombolok valley, below the Oka plateau. They thus seem to have formed after the onset of the vertical movements that displaced the original erosion surface.

Sinistral strike–slip movements are also clearly observed on several locations along the Oka-Jombolok fault system. For example, at the outreach of the Tachalur–Jalga valley, ridges formed of bedrock (marble and granite) are offset by about 150 m (Fig. 5c). On the same location, a Late Pleistocene moraine (Olyunin, 1965) is also affected by the fault with a sinistral offset of several tens of meters (Fig. 5d). The main valleys that cut the Oka-Jombolok fault, such as the Tachalur–Jalga valley, formed in response to the uplift of the Kropotkin range, driven by transpressive tectonic regime. However, their morphology, and especially the fact that their width does not change dramatically when crossing the main

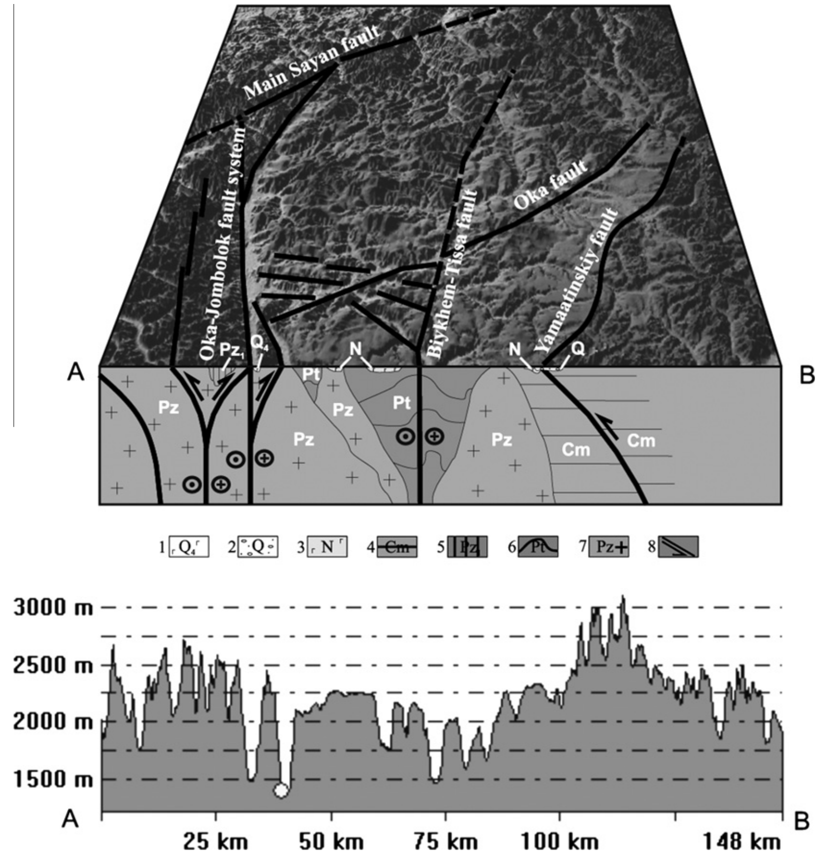

Fig. 6. *Top*: General tectonic model of the Oka region between the Oka-Jombolok fault system and the Yamaatinsky fault. 1 – Holocene basalts, 2 – Quaternary sediments, 3 – Tertiary basalts, 4 – Cambrian series, 5 – Lower Paleozoic series, 6 – Proterozoic series, 7 – Undifferentiated Paleozoic granitoids, 8 – Active faults. *Bottom*: General topographic profile along the section (see Fig. 2 for location of the profile) drawn from SRTM topographic data.

fault seems to indicate that during their main period of development, movements along the Oka-Jombolok fault were mainly vertical with small horizontal component. The large offset of the Late Pleistocene moraines implies that horizontal motion along the fault increased at least in Pleistocene times. The general cross-section of Fig. 6 presents a structural and morphological interpretation of the Oka plateau where the Kropotkin ridge formed as a positive flower structure along the Oka-Jombolok fault system. The development of faceted spurs localized on a NE directed segment of the fault may also be a consequence of this increase of strike–sleep motion on the fault. This last hypothesis will be explored below.

Recent activity of the Oka-Jombolok fault is again attested within the coluvial deposits at the base of the faceted spurs of the Jombolok basin. The general slope (about 15°) of the lower part of the spurs abruptly decreases to a nearly horizontal (6–5°) "flat", interpreted as a active fault scarp, before reacquiring its normal angle at the extreme base of the spurs (Fig. 7). Within this nearly horizontal area, several gullies perpendicular to the fault show a sinistral morphological offset of 7.5–16 m (Fig. 7). A 5 m long and 1.5 m deep trench across the fault scarp (Fig. 8) showed evidences of two seismic ruptures along vertical fault planes that cut the soil horizons at several levels. Those horizons show an abrupt variation in thickness from one side to the other of the fault planes indicative of horizontal displacements along those planes. Given the near verticality of the fault planes it has not been possible to estimate the occurrence of a vertical component within the trench where only the Late Holocene horizons are exposed.

To summarize, the analysis of the kinematic of the Oka-Jombolok fault system indicates that during the main uplift phase of the Kropotkin range, the fault essentially displayed a vertical component which is responsible for the 400 m difference in mean altitude between the range and the Oka plateau. A second phase, that probably initiated around Late Pleistocene times is characterized by an increase of sinistral strike–slip movements associated to local normal motion along NE directed segments of the fault.

3. Late Tertiary–Quaternary crustal structure and deformation style in SE East Sayan

3.1. Mapping of individual tectonic blocks

Using the SRTM topographic database, we mapped the faults and individual tectonic blocks (see description of the method in Orlova (1975)) within the SE East Sayan range (Fig. 9). The tectonic blocks have been identified using both tectonic data (faults) and the variations in envelope altitude. The envelope altitude of a given area was calculated using the altitudes of topographic crests, large sedimentary basin surfaces, plateau surfaces while the data from slopes and small valleys were not considered. The difference in envelope altitude must be at least 200 m to consider the occurrence of different blocks (Orlova, 1975). The blocks derived from topographic analysis were then compared to the tectonic map. When the limits between topographic blocs coincide with faults we estimate that the blocs are independent tectonic blocks. When

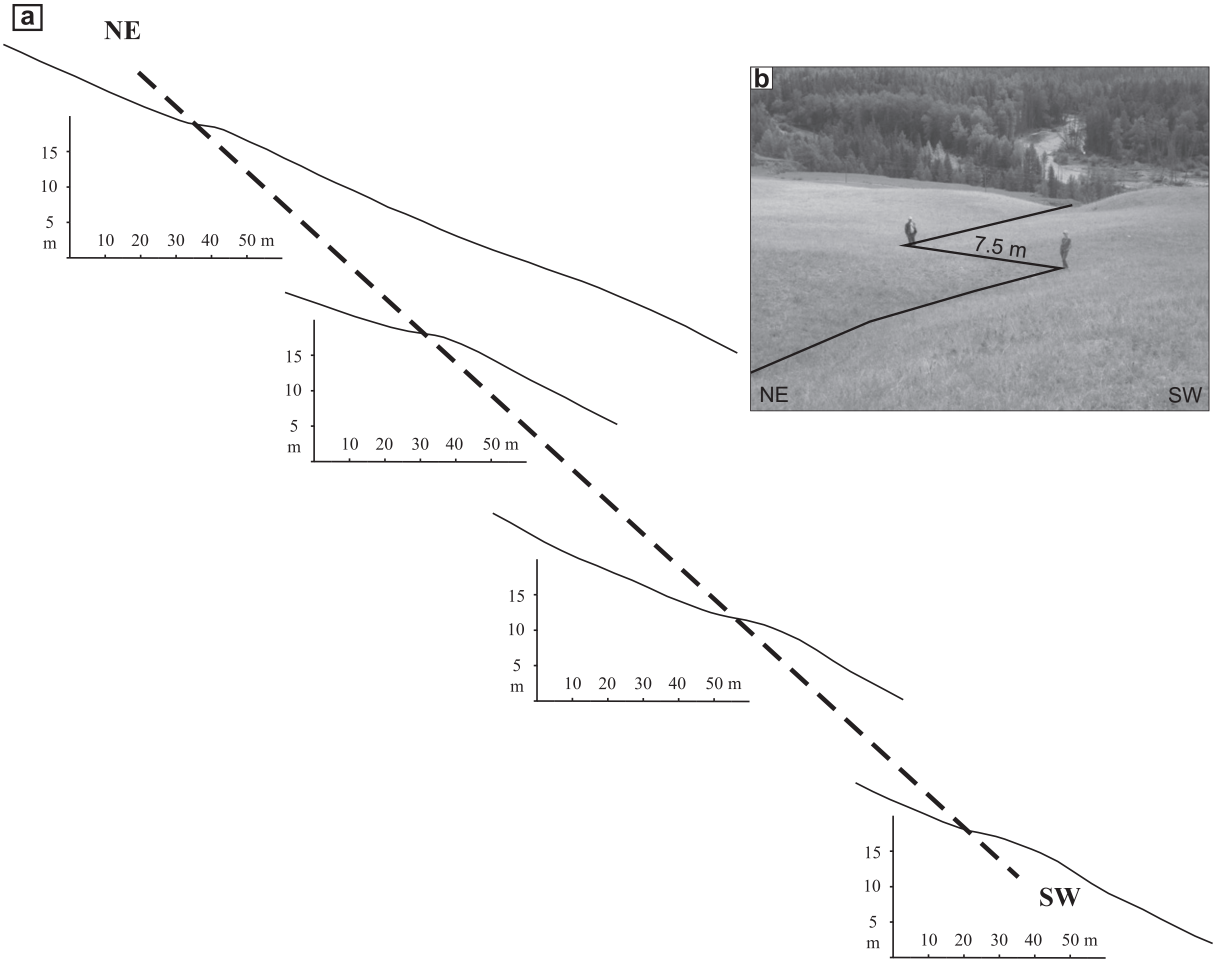

Fig. 7. Topographic profiles perpendicular to the supposed trace of the Oka-Jombolok fault at the bottom of the main facetted spurs. The trace of the fault is marked by the dotted line. *Picture*: 7.5 m left lateral displacement of a small gully indicating active strike–slip movement along the Oka-Jombolok fault.

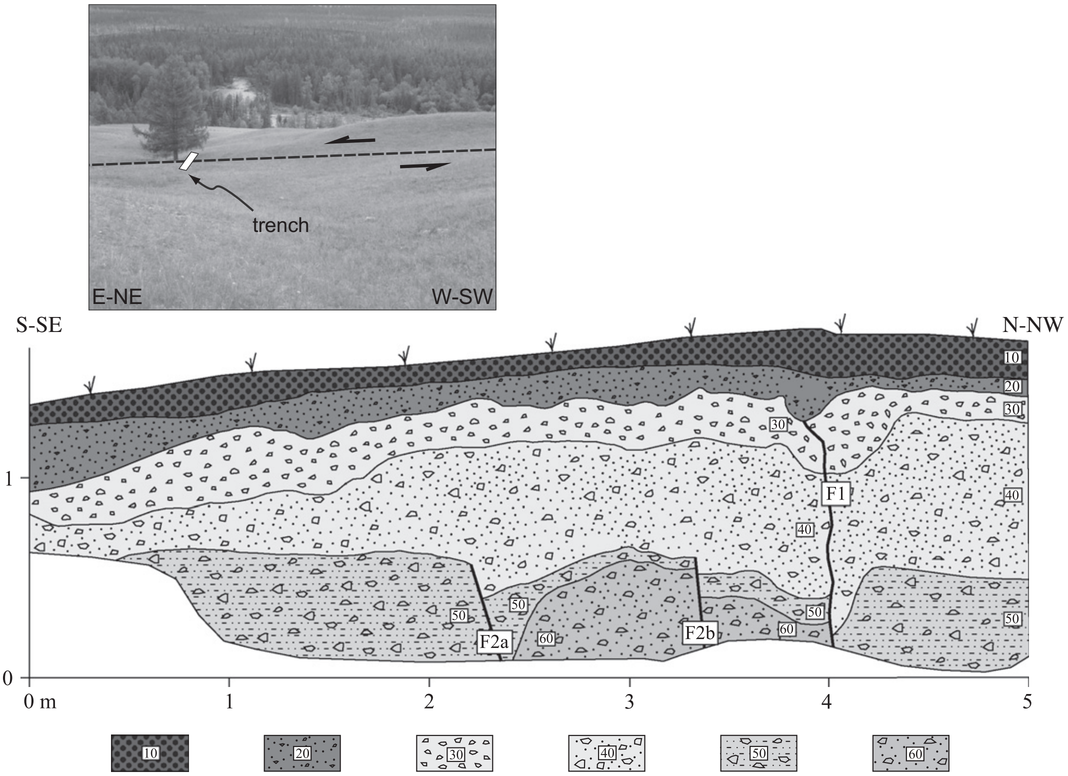

Fig. 8. Log of the northwestern wall of the trench across the Oka-Jombolok fault (location on photograph). Faults are indicated in bold lines. Lithological units are: 10 – Soil, 20 – Sandy soil with landwaste, 30 – Gravel (carbonated horizon), 40 – Gravel with carbonate-rich silt, 50 – Gravels with clayed silt, 60 – sand-rich gravel horizon (old alluvium?).

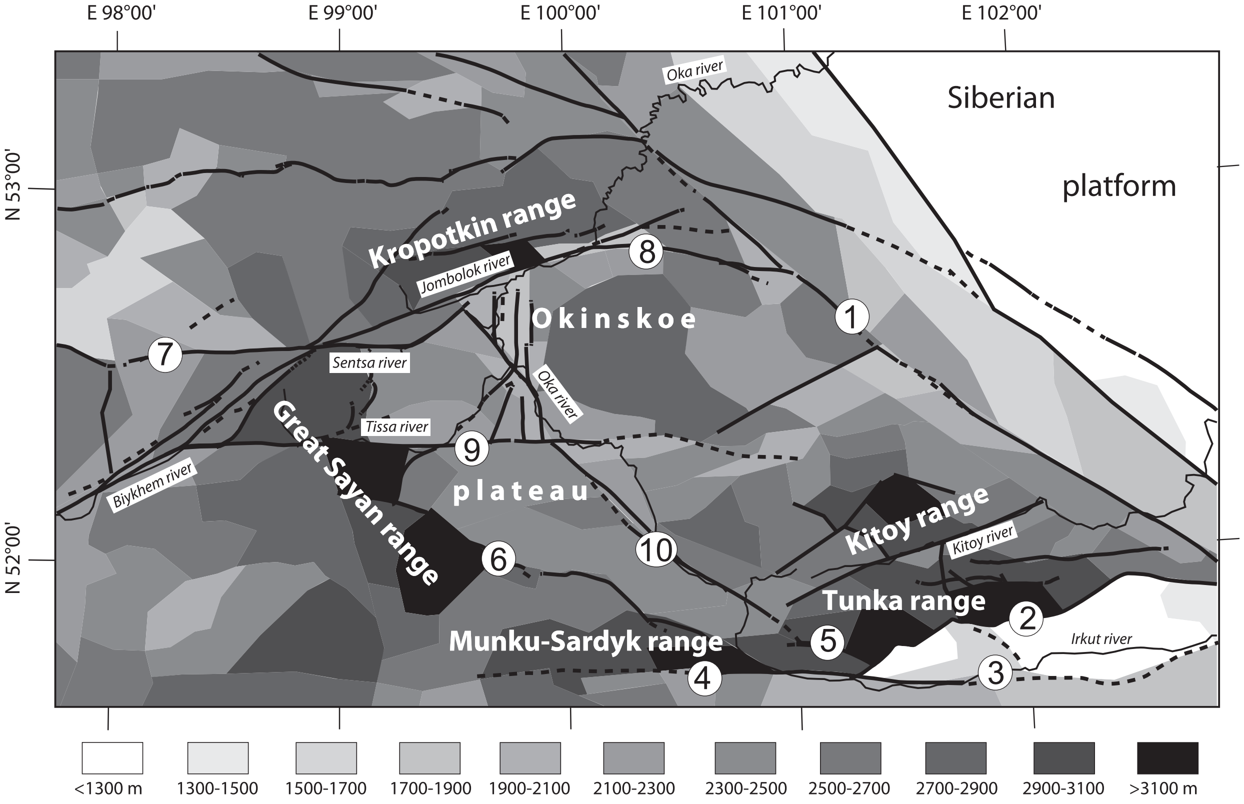

Fig. 9. Map of the various topographic–tectonic blocks defined using the Orlova (1975) method. See text for discussion. Numbers refers to the name of the various major faults as in Fig. 2.

there is no coincidence, the difference in altitude may simply be due to differential erosion and the blocks are not considered as tectonically independent.

Fig. 9 shows that differential vertical movements between individual tectonic blocks played a major role during the formation of the relief. The amplitude of vertical movements relative to the stable Siberian platform (700–800 m high) range from 1400 m on the lowest part of the Oka plateau to 2400 m on the highest ranges such as Tunka, Kitoy, Munku–Sardyk, Kropotkin and Great Sayan. Within the Est Sayan range, preserved remnants of a peneplanation surface on the Oka plateau show a difference in altitude of about 400 m with those on the summits of the Kropotkin range.

3.2. The Oka plateau

The Oka plateau that forms the central part of our study area is a flat, near horizontal surface standing at an intermediate altitude between the Jombolok valley and the surrounding ranges. Two major blocks are individualized within the plateau, separated by the NNW Oka fault running parallel to the Oka river valley (Fig. 10). The eastern Oka block is higher than the western Oka block with maximum altitudes of 2700–2900 m compared to about 2500 m in the west. It is also more eroded by a stronger and more coherent drainage pattern. The 300 m difference in altitude may partially explain the stronger erosion of the eastern block. Furthermore, the eastern Oka block is also slightly tilted towards the east, which probably facilitates the development of the drainage system. Finally, the western Oka block has been surrounded by large Late Pleistocene glacier filling both the Sentsa and Tissa river valleys (Fig. 10) that potentially slowed down the development of the drainage system on the plateau by artificially uplifting the local base level of rivers. Evidences for similar large glacier are not found around the eastern Oka block (no moraine deposits for example).

The difference in altitude between the western and eastern Oka blocks can be explained by westward thrusting along the NW–SE Oka fault during the Late Pliocene tectonic phase. Both blocks remained internally rigid, the eastern one being simply uplifted along the fault. However, the whole Oka plateau mostly behaves as a unique, rigid block compared to the surrounding ranges. It forms a core around which thrust faults develop driven by tectonic compression generating high reliefs.

3.3. Late Pliocene–Quaternary deformation in SE East Sayan

3.3.1. Compression and extension with the Oka-Jombolok area

Analysis of the tectonic blocks and faults patterns shows that the largest and highest ranges within the SE East Sayan region formed along E–W or NW–SE faults bordering the Oka plateau. This regional fault pattern implies Late Tertiary–Early Quaternary NNE–SSW compression coherent with the regional compression field by that time (e.g. Ruzhich, 1975; Rasskazov, 1990; Delvaux et al., 1997). This is also consistent with the general E–W elongation of the various tectonic blocks forming the ranges (Fig. 9).

During that period, the Kropotkin range developed as a transpressive structure along the Oka-Jombolok fault system (Fig. 10). This led to the vertical displacement of a former erosion surface actually preserved on the Oka plateau and on several locations within the Kropotkin range. Vertical offsets between preserved surface remnants inside the Kropotkin range indicate internal deformation (Fig. 3). Only limited strike–slip movements occurred along the Oka-Jombolok fault compared to the vertical motion. A similar setting must have prevailed on the Biykhem-Tissa fault while the Azas-Sentsa seems to have accommodated more horizontal than vertical movements. However this last assumption remains to be verified. West of the Oka plateau, strike–slip motion along the Biykhem-Tissa and Azas-Sentsa was transformed into W–E thrusting along N–S to NW–SE structures such as the Yamaatinskiy fault (Fig. 10). Inside the Oka plateau itself the Oka fault was also activated as a thrust fault.

However, the Quaternary extension along the western section of the Oka-Jombolok fault as well as the numerous NW–SE to nearly N–S normal faults observed within the Oka Extension Zone (Fig. 2) remain to be explained within this general transpressive setting. The rigid behavior of the Oka plateau region (if we except the Oka fault) is a clear evidence that this region is characterized by "block tectonic", most if not all the deformation being accommodated by discrete fault structures. A small clockwise rotation in the direction of the general maximum compression vector would increase the horizontal movement along the three E–W major faults on both sides of the Oka plateau (Oka-Jombolok, Biykhem-Tissa and Azas-Sentsa) (Fig. 10). In this geodynamic context, the Biykhem-Tissa fault propagated eastwards toward the Oka fault. When reaching the Oka fault zone it connected to the north with the Oka-Jombolok fault, creating a new tectonic block that started to migrate toward the east (Fig. 10b). Morphological lineaments visible on satellite pictures and aerial photographs seem to show that the Biykhem-Tissa fault may actually propagate across the Oka fault towards the east. However, field observation did not reveal any active deformation along lineaments that may be either really new and poorly active or inherited, inactive structures. Eastward migration of the newly formed block created extension distributed on several normal faults within the relay zone between the two major strike–slip faults (i.e. the Oka Extension Zone (Fig. 10b). Along the northern termination of the Oka Extension Zone, the subsidence is accommodated by local, normal, movements along SW–NE segments of the Oka-Jombolok fault. This setting explains why only those restricted segments of the fault show a normal component and developed facetted spurs. Extension within the Oka Extension Zone is thus directly linked to the strike–slip movement along the Biykhem-Tissa and Oka-Jombolok faults and not to any regional extensional process such as the opening of the BRS.

3.3.2. Evidences of extension and compression in the Azas and Khi-Gol region

West of the Oka plateau area, the Azas lava plateau and the Khi-Gol volcanic area (Fig. 11) are also characterized by transtensive structures that control the volcanic activity by allowing the magmas to reach the surface. The Khi-Gol and Jombolok valleys are filled by a 75 km long basaltic flow that reaches the western edge of the Oka Extension Zone (Fig. 12). Kiselev et al. (1979) reported that the eruption center was situated in the upper Khi-Gol and Jombolok valleys. These volcanoes are associated to the Orosoyskiy fault that follows the NW border of the Kropotkin range before crossing the Oka-Jombolok fault towards the Azas plateau (Arsentyev, 1975) (Fig. 2). However Rasskazov et al. (2000) indicate that the morphological structure of the lava flow implies several eruption centers spread along the Khi-Gol and Jombolok valleys and into the northern Oka Extension Zone. This is confirmed by the occurrence of several probably very recent small-scale basaltic flows superposed to the main flow into the Oka Extension Zone (Fig. 12).

Towards the SW, the Orosoyskiy fault merges with a number of parallel, SW–NE directed faults that cut the Azas plateau (Fig. 11). Volcanism in that region occurred in three different phases: 17–16 Ma, 7.9 Ma and 2 Ma (Rasskazov et al., 2000). The last phase that initiated after a 6 Myrs long quiet period, corresponds to the onset of the compressive deformation and to the last volcanics observed SW of the Oka plateau. It also corresponds to the last eruption phase in the Tunka area (3–0.6 Ma) that again initiated after a 8 Myrs long quiet period (Rasskazov et al., 2000). Finally during the same period, the location of volcanism in Hangay (Fig. 1) changed

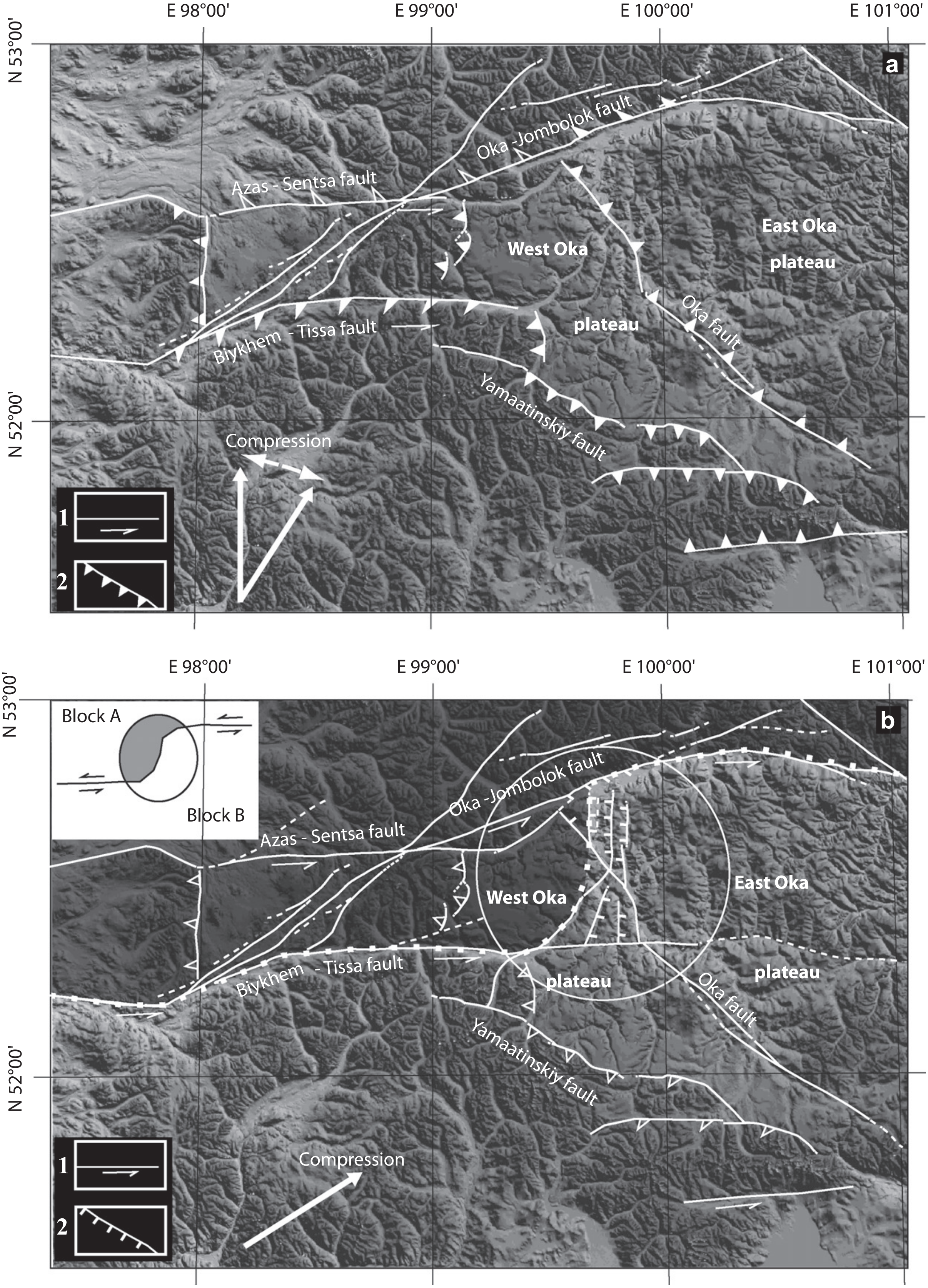

Fig. 10. *Top*: Schematic tectonic setting of the major faults during the first orogenic phase that initiated in Late Pliocene. The bold white arrows show the possible range for the direction of the main compression vector. 1 – Strike–slip fault, 2 – Thrust fault. *Bottom*: Schematic tectonic setting for the Late Quaternary showing the extensive relay zone between the Biykhem-Tissa and Oka-Jombolok fault. The two newly formed blocks are highlighted (separated by the dotted fault line). 1 – Strike–slip fault and 2 – Normal fault.

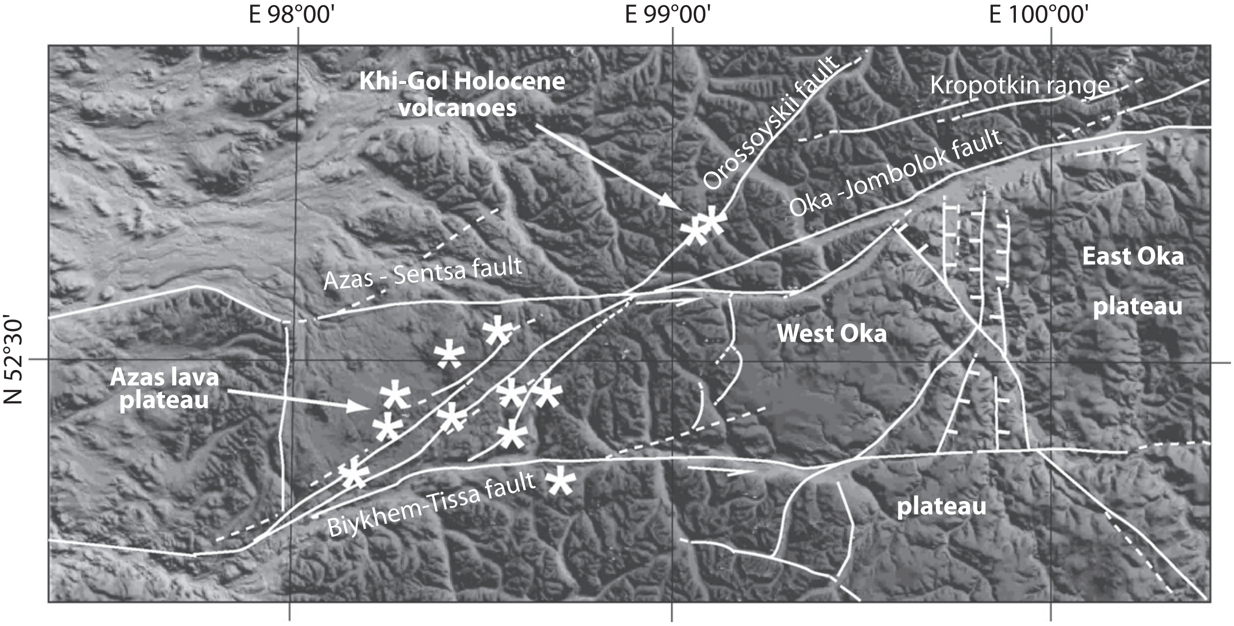

Fig. 11. Main volcanic centers (white stars) within the Azas plateau and the Khi-Gol valley.

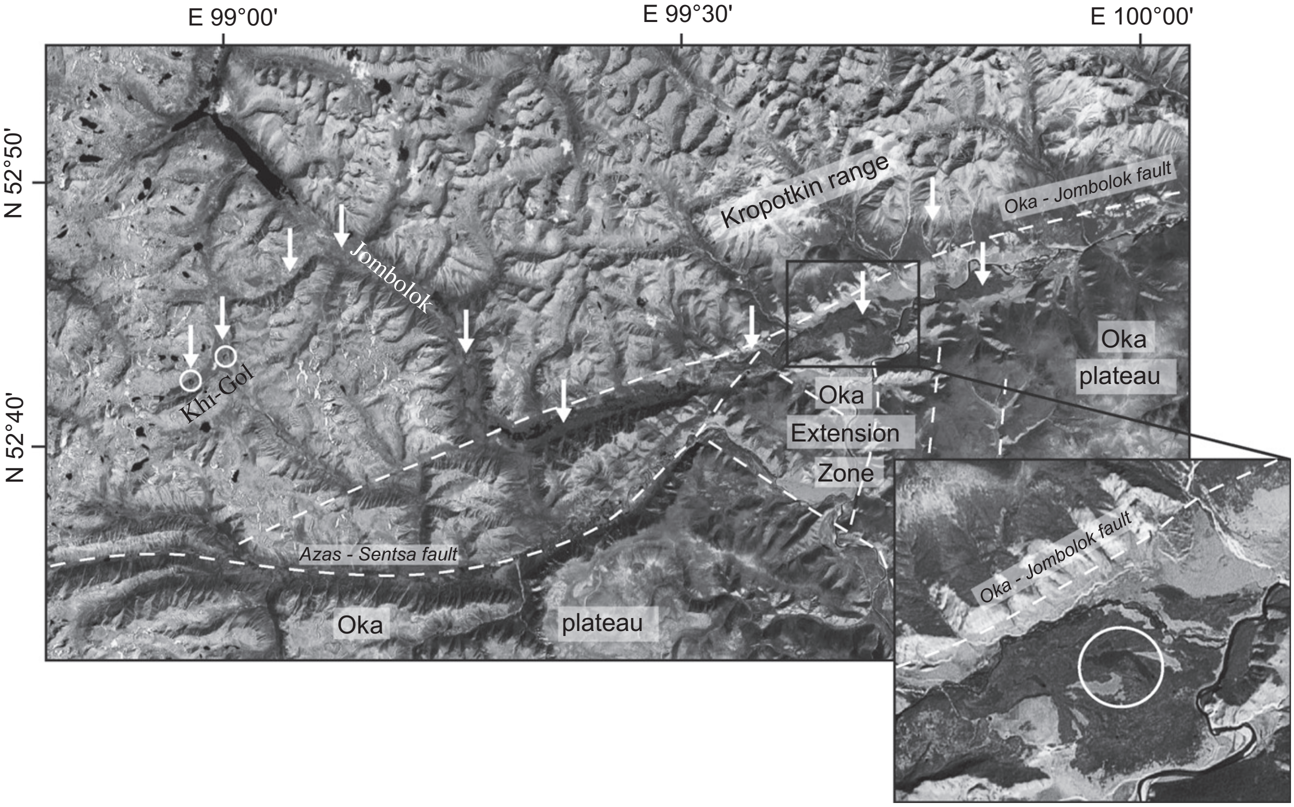

Fig. 12. Satellite image (extracted from Google Earth) showing the 75 km long lava flow filling the Jombolok valley. On the large picture, the small circles indicate volcanic cones near the emission center. White arrows indicate the flow. On the small inset picture, the white circle indicates a small late flow superimposed to the major one. See text for discussion.

from the summit of the relief towards the slopes (Yarmolyuk et al., 2008).

Grosvald (1965) noted that on the Azas plateau, the volcanic centers are located along the secondary SW–NE faults and not along the major E–W faults, the latest being associated with transpressive deformations. On the plateau compression is marked by SW verging folds affecting Pliocene sediments, indicative of a N30°E directed compression (Grachev and Lopatin, 1978). Demonterova and Ivanov (2002) determined the evolution of the direction of compression in the Azas plateau using the orientation

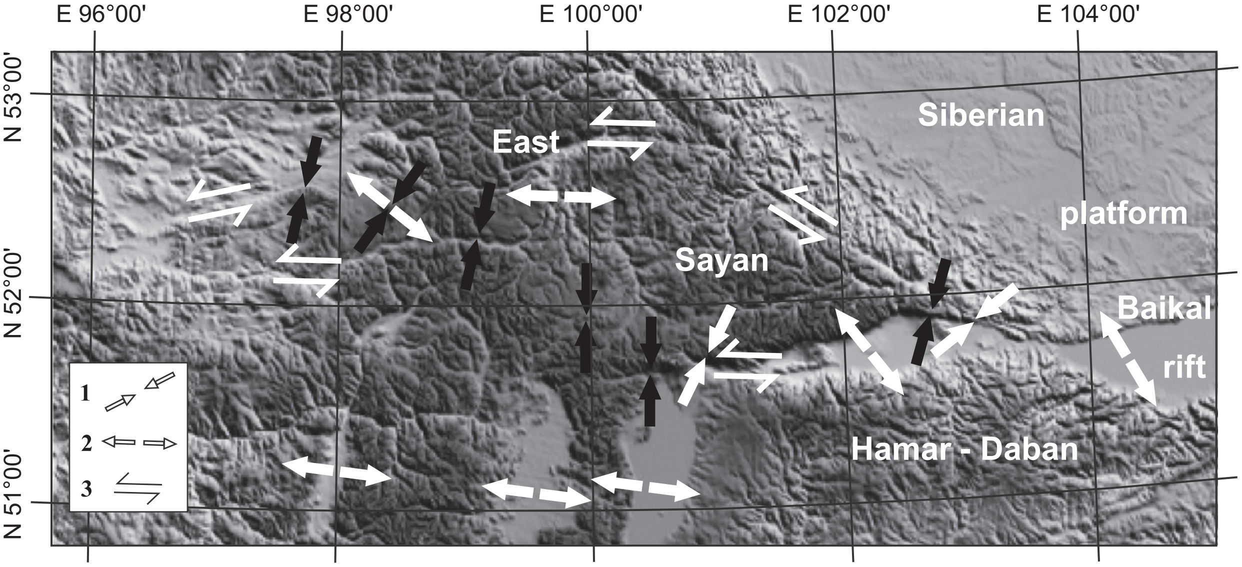

Fig. 13. Summary of the evolution of the deformation pattern within the study area. The black arrows represent the first tectonic phase that initiated in Late Pliocene while the white arrows represent the Late Quaternary phase. 1 – Compressive structures, 2 – Extensive structures, 3 – Strike–slip structures. See text for a complete discussion.

through time of the volcanic dykes (which are generally orientated parallel to the compression). They concluded that during the period 1.2–0.7 Ma the compression was directed between NW to NE with a main NNE direction while after 0.6 Ma the direction shifted to WSW–ENE. This is consistent with a Late Quaternary clockwise rotation of the constraints in the Oka-Jombolok area.

4. Conclusion

The morphotectonic and palaeosismologic analysis of the SE part of the East Sayan area revealed that Plio–Quaternary tectonic deformations are separated in two stages (Fig. 13).

- During the first period from Late Pliocene to Pleistocene, vertical movements predominate together with associated minor horizontal displacements. During that period, the main reliefs developed within the various ranges surrounding the Oka plateau.
- By Late Quaternary the deformation style changed and most displacements were accommodated by sinistral strike–slip movements along E–W faults both to the south (Tunka fault, Mondy fault, Ikhorogol–Mondy fault) and to the north (Oka-Jombolok fault) of the Oka plateau.

The Late Pliocene–Pleistocene compressive reactivation of inherited structures within the Tunka range and along the SW edge of the Oka plateau marks the onset of NNE directed general compressive deformation in that region. This is consistent with the onset of compressive deformation and relief building reported from Goby Altay and Altay (Jolivet et al., 2007; Vassallo et al., 2007) or in the Teletskoye region in western Sayan (De Grave and Van den Haute, 2002) which is considered as a consequence of the northward propagation of the compressive deformation resulting from the India–Asia collision to the south. This regional deformation phase seems to initiate earlier (Late Miocene–Early Pliocene) in the Goby Altay (Jolivet et al., 2007; Vassallo et al., 2007) than in the West Sayan (Late Pliocene–Pleistocene) (De Grave and Van den Haute, 2002) which again is consistent with a northward propagation of the constraints.

This work also demonstrates that the active extensive and transtensive deformation observed locally within the East Sayan area are not linked to the extensive deformation within the BRS. The geometry of the small-scale tectonic blocks as well as the kinematic of the faults around the Oka plateau show that extensive and transtensive structures in that region are secondary, linked to strike–slip movements along major E–W faults still accommodating the general SW–NE compressive deformation. The importance of this transpressive deformation field in the region is also confirmed by microtectonic data (Sankov et al., 2002). During a first Late Pliocene–Pleistocene phase, SSW–NNE shortening predominated, accommodated by roughly E–W and NW–SE directed thrust faults within the main ranges. During Late Quaternary a probably local eastward rotation of the stress field facilitated horizontal sinistral strike–slip motion along the main E–W structures such as the Oka-Jombolok fault. This new tectonic setting induced clockwise rotation of small tectonic blocks between the major strike–slip faults as well as transpressive movements along SE termination of the Main Sayan Fault as shown by Chipizubov et al. (1994).

The tectonic model proposed in this study does explain the deformation and structure of the South East Sayan area. However it does not explain the widespread and long-lasting volcanism that affects a large part of Mongolia and SE Siberia. It has been clearly demonstrated that these magmas are generated by a thermal anomaly inside the asthenospheric mantle and most probably in its upper level (e.g. Zorin et al., 2006; Barry et al., 2007; Kulakov, 2008; Ivanov and Demonterova, in press). Volcanism is not only associated with the large extensional structures. For example there is no evidence of volcanism inside the central Baikal Rift where extension is maximum. The occurrence of a positive thermal anomaly within the mantle thus does not appear to be the driving mechanism of the tectonic activity within the upper crust. We cannot exclude that such an anomaly has some effects on the deformation of the crust but they are either of a much lower magnitude compared to the effects of the far-field tectonic forces or they correspond to much larger wave-lengths deformation.

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