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The time of the formation and destruction of the Meso-Cenozoic peneplanation surface in East Sayan

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Abstract

The history of the peneplain in East Sayan was studied using apatite fission-track analysis (AFTA). This method is suitable for determining the formation time of the erosional surface and estimating its denudation rate. The largest known relic of the peneplanation surface in this area is the Oka Plateau, separated from the Kropotkin Ridge by the Oka–Zhombolok fault. The AFTA shows that the peneplain on the Oka Plateau formed in the Late Jurassic–Early Cretaceous. This peneplain is much younger than the erosional surfaces that persist today in the Tien Shan, Gobi Altai, and Mongolian Altai (Early Jurassic). However, it is older than the peneplain on the Chulyshman Plateau, Altai (Late Cretaceous), suggesting asynchronous formation of the ancient peneplain in Central Asia. The similar exhumation histories of samples from the Oka Plateau and Kropotkin Ridge indicate that these morphotectonic structures developed from Jurassic to late Miocene as a single block, which underwent continuous slow denudation at an average rate of 0.0175 mm/yr. Active tectonic processes in the Late Miocene caused the destruction of the peneplanation surface and its partial uplifting to different altitudes. The rate of Pliocene–Quaternary vertical movements along the Oka–Zhombolok fault is roughly estimated at 0.046–0.080 mm/yr, which is several times higher than the denudation rate in this area. During the Pliocene–Quaternary, the Oka Plateau has not undergone any significant morphologic changes owing to its intermediate position between the summit plain and datum surface of East Sayan and to its partial shielding by basaltic lavas.

Keywords: topography evolution; apatite fission-track analysis; age of peneplanation surface; denudation rate

Introduction

Studying the evolution of the Meso-Cenozoic peneplain is important for solution of the problem of topography evolution in Central Asia. In the second half of the 20th century, large-scale studies of ancient peneplanation surfaces and the formation mechanisms of denudation topography were conducted. The relative age of this topography was determined from correlative sediments and lithofacies analysis of sedimentary strata (Florensov, 1973; Gerasimov and Sidorenko, 1974; Ivanovskii, 2011; Lopatin and Timofeev, 1971; Milyaeva, 1971; Timofeev, 1976, 1979; Timofeev and Chichagov, 1976). As a result of recent thermochronological studies (De Grave et al., 2007, 2008, 2011a,b; Glorie et al., 2012; Jolivet et al., 2001, 2007, 2011; Sobel et al., 2006; Vassallo et al., 2007b), the studies of topographic evolution progressed to the next level and the Jurassic age was determined by absolute geochronology for a large peneplanation area in Central Asia. Relics of a peneplanation surface persist today on a vast area from northern Tibet to southern Siberia. This surface was affected by Tertiary tectonic faults associated with the Indo-Asian collision. Its individual parts are summit plateaus elevated to 4000 m (e.g., the Ikh Bogd Ridge in the Gobi Altai, Baatar in the Mongolian Altai) (Fig. 1). This surface has persisted in Central Asia for almost 150 Myr owing to an unusual combination of a long period of tectonic quiescence and relatively dry climate during the Mesozoic and Cenozoic (Jolivet et al., 2007). The peneplain in the Tien Shan, Gobi Altai, and Mongolian Altai began to develop in the Early Jurassic (De Grave et al., 2007, 2011a,b; Glorie et al., 2011; Jolivet et al., 2007, 2010; Vassallo et al., 2007b). The peneplain on the Chulyshman Plateau (Altai) was assigned to the Cretaceous (Fig. 1) (De Grave et al., 2008). Track analysis permitted reconstructing a three-stage exhumation history of this plateau. It is determined by the Late Jurassic–Early

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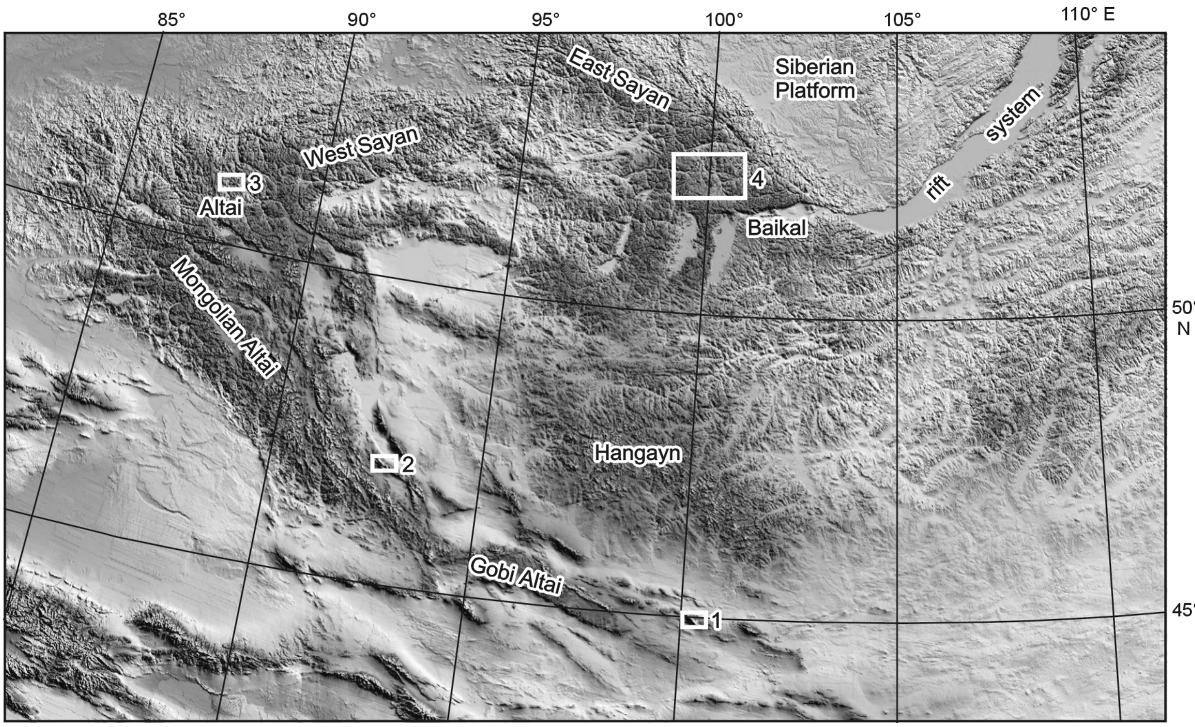

Fig. 1. Digital elevation model for northern Central Asia. White rectangles indicate dated large relics of a Meso-Cenozoic peneplain and the study area: 1, Ikh Bogd Plateau (195 ± 21 and 196 ± 7 Ma (Jolivet et al., 2007)); 2, Baatar Plateau (192 ± 7 Ma (Jolivet et al., 2007)); 3, Chulyshman Plateau (beginning of formation, 70–100 Ma (De Grave et al., 2008)); 4, Oka Plateau.

Cretaceous tectonic activity in the region (probably related to shear tectonics, identified in (Metelkin et al., 2012) with the compression and deformation regime in the Altai–Sayan area in the Mesozoic); Late Cretaceous–Early Neogene stabilization; and Late Cenozoic reactivation.

Relics of a peneplanation surface were distinguished in the Siberian Platform as pediplains and valley surfaces (Timofeev, 1976, 1979) and in the mountains bordering it in the south. The original smoothed topography in the mountain border was reworked in the Cenozoic by orogeny and basin formation on the southwestern flank of the Baikal Rift System (Florensov, 1964; Lamakin, 1960). The largest relic of a peneplanation surface in the southern border of the Siberian Platform is the Oka Plateau (Fig. 1), located at an altitude of 2000–2500 m in East Sayan, between the summit plain and datum surface of the ridge. The formation mechanism of peneplanation surfaces is disputable (Lopatin and Timofeev, 1971; Timofeev, 1979; Timofeev and Chichagov, 1976), and we cannot assess horizontal (peneplain) or lateral (pediplain) planation on the Oka Plateau. This is a subject for special geomorphological studies, which is outside the scope of the present paper. Therefore, calling the Oka Plateau a relic of an ancient peneplain, we use this term in its original meaning ("an undulating denudation peneplain which appeared in a dissected territory" (Timofeev, 1979)). Like other researchers (Grossval'd, 1965; Obruchev, 1953), we use the term "peneplain" for the Oka Plateau, not claiming to know the peneplanation mechanisms in the area. The study is aimed at dating the peneplanation surface near the Oka Plateau to find out whether it belongs to the Jurassic peneplanation region in Central Asia or is a relic of a more local peneplanation surface, which formed near the southern boundary of the Siberian Platform later on.

The work is based on apatite fission-track analysis, which makes it possible to determine the age of the peneplanation surface and to estimate its denudation rate.

Topography evolution in East Sayan

According to thermochronological studies (De Grave and Van den haute, 2002; De Grave et al., 2003, 2007, 2008, 2011a,b; Jolivet et al., 2007), the Altai–Sayan mountain area is the northernmost region in Central Asia whose topography is associated with the remote effect of the Indo-Asian collision. Compression and shear compression are typically observed in most of the regions of Central Asia north of the collision front. Their propagation is reflected in the orogeny which formed mountain systems from Himalayas to Altai (Buslov et al., 2007, 2008; De Grave and Van den haute, 2002; De Grave et al., 2003, 2007, 2008, 2011a,b; Jolivet et al., 1999, 2001, 2007; Vassallo et al., 2007b). The East Sayan is located along the southwestern boundary of the Siberian Platform and makes up the northeastern termination of the Altai–Sayan mountain area (Fig. 1).

The uplifting of East Sayan had an arch-block character and was accompanied by the renewal of ancient faults, formation of intermountain basins, and effusion of basaltic lavas. Two-stage orogeny in East Sayan was repeatedly pointed out (Ivanov and Demonterova, 2009; Rasskazov et al., 2000; Strelkov and Vdovin, 1969; Vdovin, 1976). In the earlier publications (Strelkov and Vdovin, 1969; Vdovin, 1976), it was stated that the first stage in the Cenozoic orogeny began in the Oligocene. In the Neogene, there was a period of tectonic quiescence and stabilization, which had ended by the late Pliocene. From then on, active orogeny entered its second stage, which has lasted throughout the Quaternary and given rise to the main features of recent topography. In later geochronological studies of volcanic and sedimentary rocks (Ivanov and Demonterova, 2009; Rasskazov et al., 2000), absolute dating was used to reconstruct the main orogenic stages in East Sayan. According to these data, the first stage of extensive uplifting falls on 22–15 Ma. It was accompanied by slight erosional dissection with subsequent effusion of basaltic lavas, which shielded the Early Miocene paleotopography. The second stage, characterized by the rapid uplifting of individual mountain ranges, began at 8.7 (Rasskazov et al., 2000) or ca. 5 Ma (Ivanov and Demonterova, 2009). It was associated with the transformation of the drainage network, deformations of the peneplanation surface, and volcanic eruptions. The tectonic movements were accompanied by intensified erosional dissection and formation of the recent river system.

In spite of the active orogeny, areas with ancient denudation topography, almost unchanged by the subsequent processes, are found in some parts of East Sayan. They occur most extensively (400 km^2) on the Oka Plateau (Fig. 2). The peneplanation surface here is a gently undulating plain, slightly dissected by river valleys and partly overlain by basaltic lavas. According to (Ufimtsev et al., 2007), the main topographic features of the Oka Plateau are the presence of steps of different heights and a difference in morphologic landscapes in the southwestern (plateau landscapes alone) and northeastern (more differentiated topography) parts. The age of the erosional surface is traditionally considered Cretaceous–Paleogene (Medvedev, 1970; Milyaeva, 1971), though no absolute dating of the peneplain has been specially carried out in this area. In the previous paper (Jolivet et al., 2011), apatite fission-track thermochronology, tectonic analysis, and morphological study of Neogene lava flows were used to reconstruct the pre-Oligocene morphology of East Sayan. According to our data, it was a constantly rejuvenating vast erosional surface. The track-analysis data characterizing the peneplain age and the reconstructed Meso-Cenozoic tectonic history are given below.

Track analysis

In the 1960s, a new method for determination of the age of minerals was proposed and developed successfully. It was based on calculations of the density of tracks from the spontaneous fission of the U nuclei accumulating in the mineral through its geologic history (Fleischer et al., 1975; Price and Walker, 1963; Shukolyukov et al., 1965; Solov'ev and Bogdanov, 2000). Track analysis today is a standard geochronological method, which is common practice in the world, including the quantitative estimate of the uplifting rate and age of topography (Jolivet et al., 1999, 2001, 2007, 2009, 2011; Ritz et al., 2003; Roger et al., 2003; Sobel et al., 2001; Vassallo et al., 2007b). The method makes it possible to reconstruct the thermal history of bedrock in the partial-annealing zone between 60 ± 10 °C and 110 ± 10 °C (at a depth of 2–4 km, with the standard geothermal gradient 30 °C/km). The track ages of apatite from terrigenous and igneous rocks are used to estimate the time during which the rocks were brought to near-surface levels.

Samples for the track analysis were taken from apatite-bearing bedrocks on the Oka Plateau (sample S07-3, granite) and on the southern slope of the Kropotkin Ridge (S07-5, -7, -8, -11, -12) along the scarp of the Oka–Zhombolok fault (Table 1, Fig. 2). Note that samples S07-5, -7, and -8 (granites) were taken along a 350-m-long vertical profile, and sample S07-11 (two-mica paragneiss) was taken lower than,

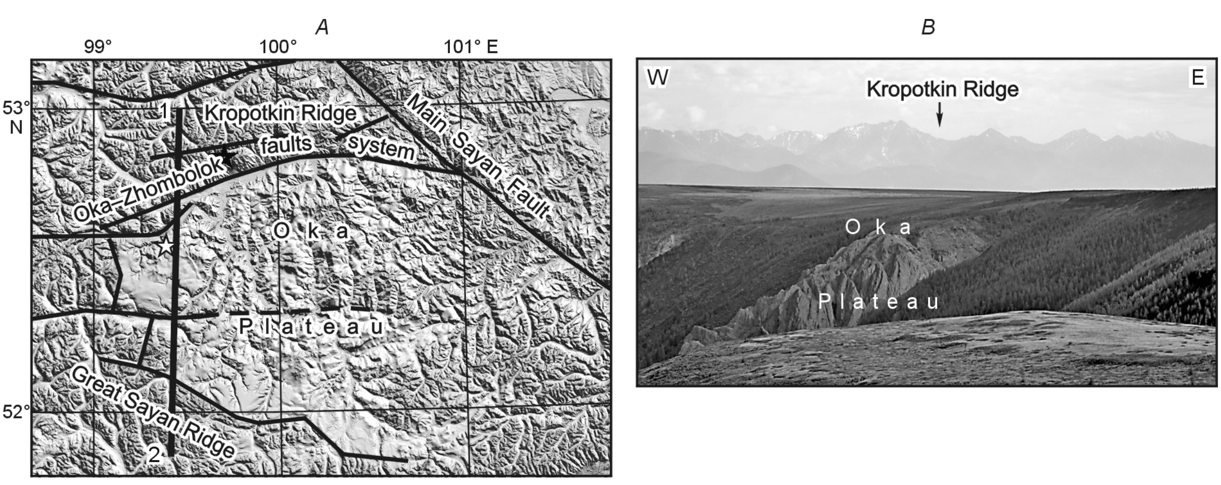

Fig. 2. Digital elevation model for the Oka Plateau and surrounding ridges (*A*); photograph of the Oka Plateau (*B*). *A*, Black lines show the main faults, and stars indicate the sampling sites on the Oka Plateau and on the southern slope of the Kropotkin Ridge. 1–2, profile.

Table 1. Apatite track analysis

Sample	Rock	Sampling-site coordinates, N; E	Altitude, m	N	$\rho_d \times 10^4$/cm^2	$\rho_s \times 10^4$/cm^2	$\rho_i \times 10^4$/cm^2	[U], ppm	$P(\chi^2)$, %	D_{par}, μm	MTL ± 1σ, μm	Std, μm	FT age ± 2σ, Ma
S07-3	Granite	52°35′14.7″; 99°25′29.3″	2009	25	142.6 (10533)	41.39 (601)	83.2 (1208)	7	71	1.0	13.1 ± 0.1	1.71	123.5 ± 9.6
S07-5	Granite	52°49′52.0″; 99°43′42.3″	2348	14	139.7 (10533)	42.74 (106)	121.77 (302)	12	75	2.8	12.8 ± 0.1	2.00	85.6 ± 10.9
S07-7	Granite	52°48′51.3″; 99°44′34.6″	2113	28	130.9 (10533)	31.43 (182)	83.59 (484)	8	83	1.7	13.3 ± 0.1	1.93	85.9 ± 9.0
S07-8	Granite	52°48′45.2″; 99°44′47.1″	2034	25	129.5 (10533)	54.82 (358)	145.48 (950)	14	48	1.2	12.7 ± 0.1	2.10	85.2 ± 7.4
S07-11	Paragneiss	52°46′50.0″; 99°41′11.3″	1735	12	138.2 (10533)	242.53 (747)	505.52 (1557)	44	5	1.0	12.5 ± 0.1	1.83	114.6 ± 9.5
S07-12	Granite	52°45′29.1″; 99°39′10.7″	1464	20	135.3 (10533)	87.64 (546)	260.03 (1620)	23	55	1.0	12.9 ± 0.1	1.72	79.6 ± 6.2

Note. *N*, Number of analyzed crystals; ρ_d, density of induced tracks which could be obtained in every sample if its U content were equivalent to that in the CN5 dosimeter glass; ρ_s, ρ_i, densities of spontaneous and induced tracks, respectively (the total number of calculated tracks is given in parentheses after the ρ_d, ρ_s, and ρ_i values); [U], calculated U content; $P(\chi^2)$, probability of a constant ρ_s/ρ_i ratio in the dated crystals; D_{par}, average diameters of the etched intersection of the tracks with the surface of the analyzed apatite crystal; MTL, average measured track length; Std, standard deviation in the track length measurements; FT age, apatite fission-track age, calculated by the TRACKKEY software (Dunkl, 2002).

and to the west of, the previous profile, close to the Oka–Zhombolok fault. Sample S07-12 (granite) was obtained in immediate proximity to the Oka–Zhombolok fault, at the scarp bottom but within the Kropotkin Ridge block. The rocks were sampled away from the numerous basalt flows present in the area to avoid the thermal effect of volcanism on the studied samples. The analyses were carried out in the Géosciences Rennes laboratory (UMR CNRS 6118), France. The procedures of determination of the apatite track age and thermal-history modeling are described in detail in (Jolivet et al., 2011) and briefly presented below.

The apatite samples were etched in 6.5% HNO_3 (1.6 M) at 20 °C for 45 s to detect tracks from the spontaneous fission of U nuclei (Seward et al., 2000). They were preliminarily irradiated by a neutron flux at a rate of 1.0×10^{16} neutrons/cm^2 (Oregon State University, United States). Mica, used as an external detector, was etched in 40% HF for 40 min at 20 °C to detect induced tracks. Age was calculated by the method recommended by the Fission Track Working Group, IUGS Subcommission on Geochronology (Hurford, 1990). The tracks were calculated manually by the Autoscan software under a Zeiss M1 microscope at 1250× magnification and dry objectives. All the ages are central, and the errors are estimated at 2σ (Galbraith, 2005; Galbraith and Laslett, 1993) (Table 1).

Thermal history was modeled by the QTQt software (Gallagher et al., 2009) with multikinetic annealing (Ketcham et al., 2007), regarding parameter D_{par} (diameter of the etched intersection of the tracks with the surface of the apatite crystal). The measurements were taken at 2000X magnification. Every D_{par} value (Table 1) was averaged from 50–100 measurements.

The U fission tracks spread in all directions in apatite crystals. However, for reliable measurement of their lengths, we measured only horizontal tracks, which were parallel to the sample surface and contained entirely in the crystal (i.e., not breaking the surface and, therefore, partially uncut). The measurements were taken in reflected light at 1250× magnification (dry objective) by hand in Autoscan. Histograms for the track length distribution are shown in Fig. 3.

Track dating (Table 1) shows the Cretaceous age of the samples (85–123 Ma). The large average track lengths (MTL, from 12.5 ± 0.1 to 13.3 ± 0.1 μm) and their uniform distribution (Table 1, Fig. 3) indicate a one-stage exhumation history (Galbraith and Laslett, 1993).

Thermal modeling of track-analysis data yielded a more complete temperature-time history of the Oka Plateau and Kropotkin Ridge (Fig. 4). The model for the thermal history of the samples shows their cooling dynamics, which reflects the exhumation rate during a certain period. In this case, all the samples cooled slowly and monotonously in the partial-annealing zone (PAZ). The Oka Plateau sample (S07-3) entered the PAZ in the Early Jurassic (190 Ma) and left it in the Late Cretaceous (90 Ma). The samples from the Kropotkin Ridge, which belong to a single block (S07-5, -7, -8, -12), entered the PAZ in the Late Jurassic–early Cretaceous (135, 150, 155, and 145 Ma, respectively) and left it in the late Cretaceous–early Paleogene (50, 65, 60, and 55 Ma, respectively). With the mean cooling line obtained from track modeling for sample S07-3 (Oka Plateau) (the sample cooled from 120 to 20 °C for 190 Myr) and the average geothermal gradient 30 °C/km, the average exhumation rate between 190 and 0 Ma is estimated at 0.0175 mm/yr.

Discussion

The exhumation rate is the rate at which the rocks are brought to the surface from greater depths. Exhumation occurs

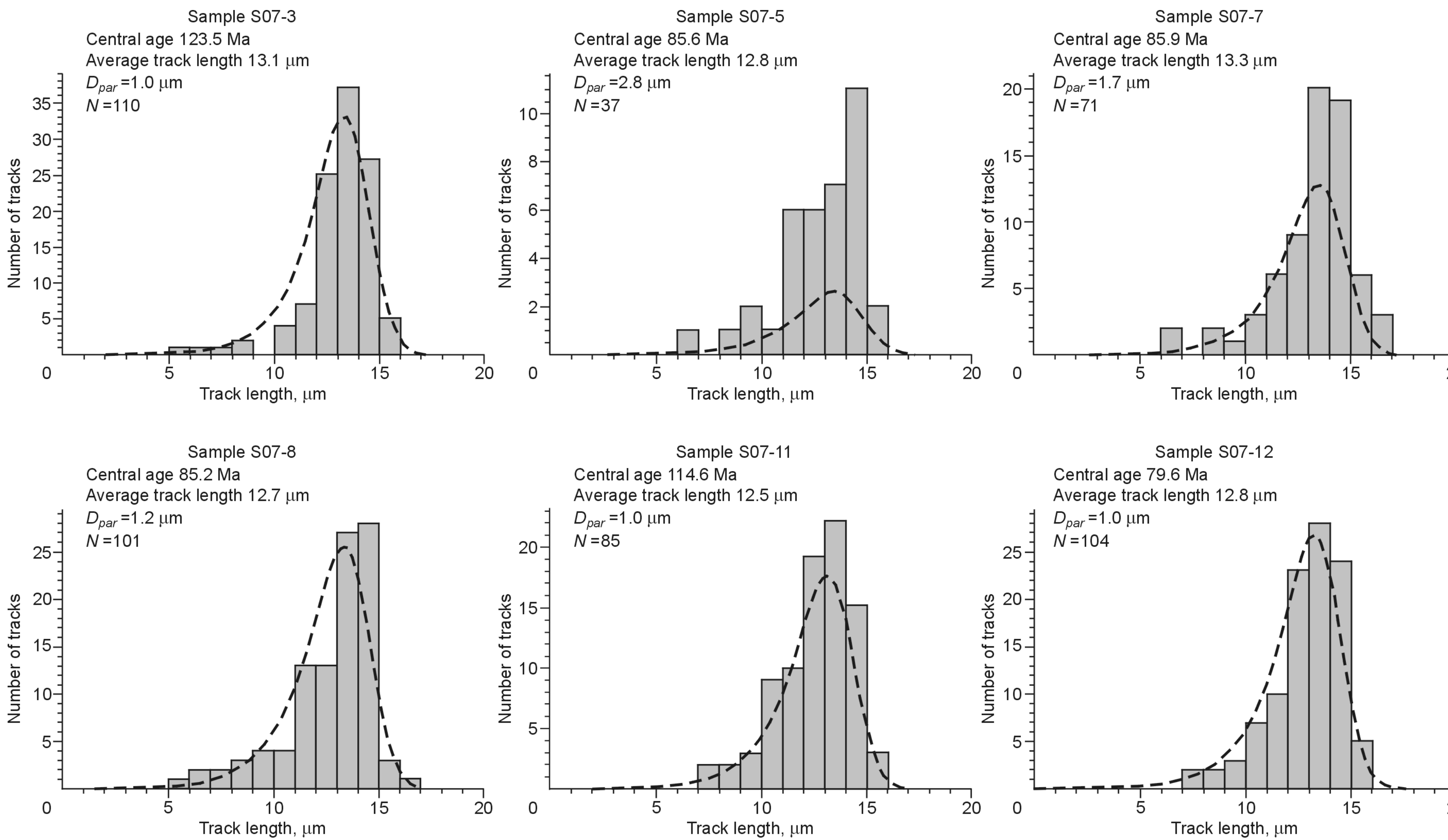

Fig. 3. Histograms of the track length distribution for samples from the Oka Plateau (S07-3) and Kropotkin Ridge (S07-5, -7, -8, -11, -12). *N*, Number of measured track lengths. Histograms correspond to the measurement data, and the dashed line to the calculated data.

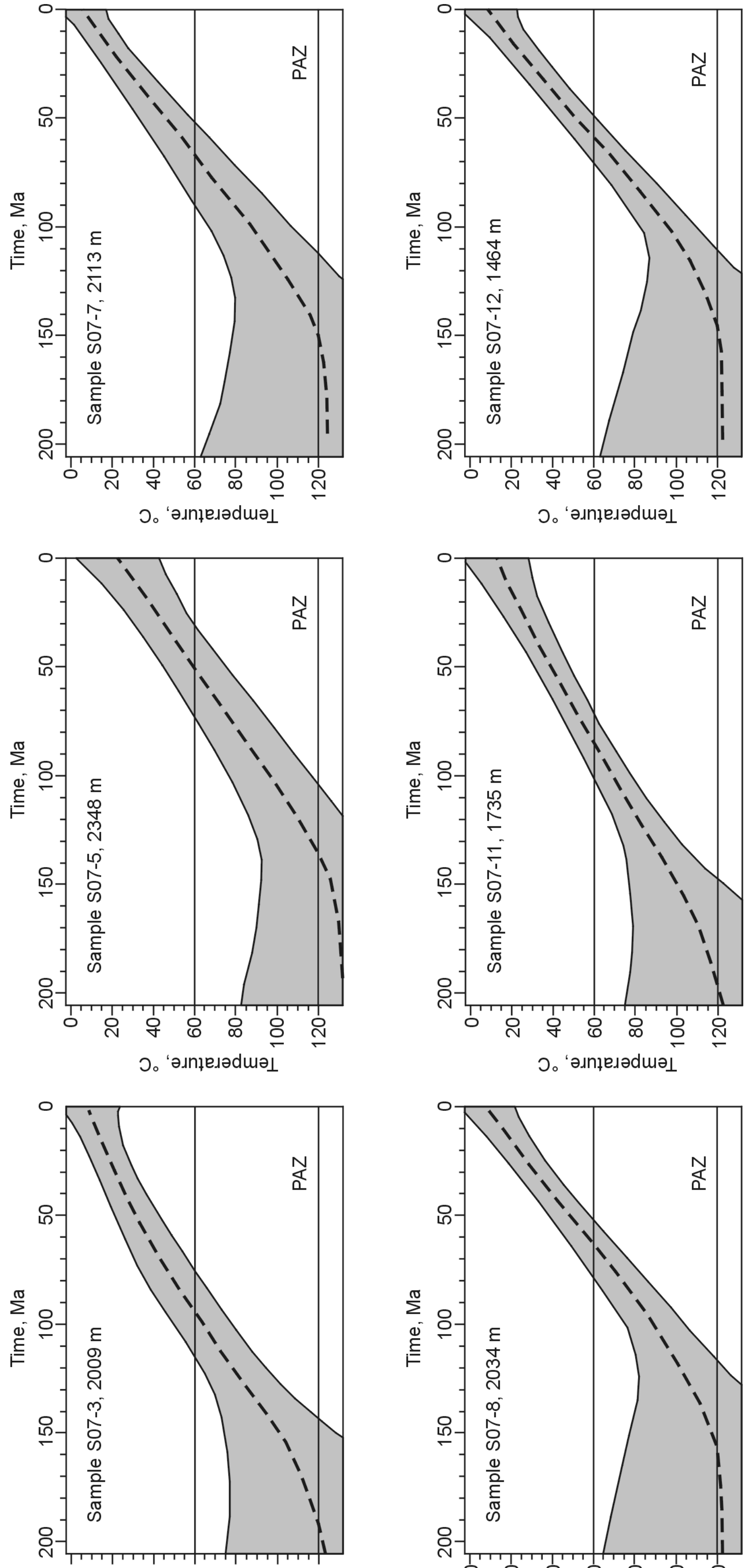

Fig. 4. Thermal modeling for samples from the Oka Plateau (S07-3) and Kropotkin Ridge (S07-5, -7, -8, -11, -12). Gray color shows the area of thermal history for each sample with 95% certainty (Gallagher et al., 2009). Dashed line on the models corresponds to the average of all the measured values. Horizontal lines mark the boundaries of the partial-annealing zone.

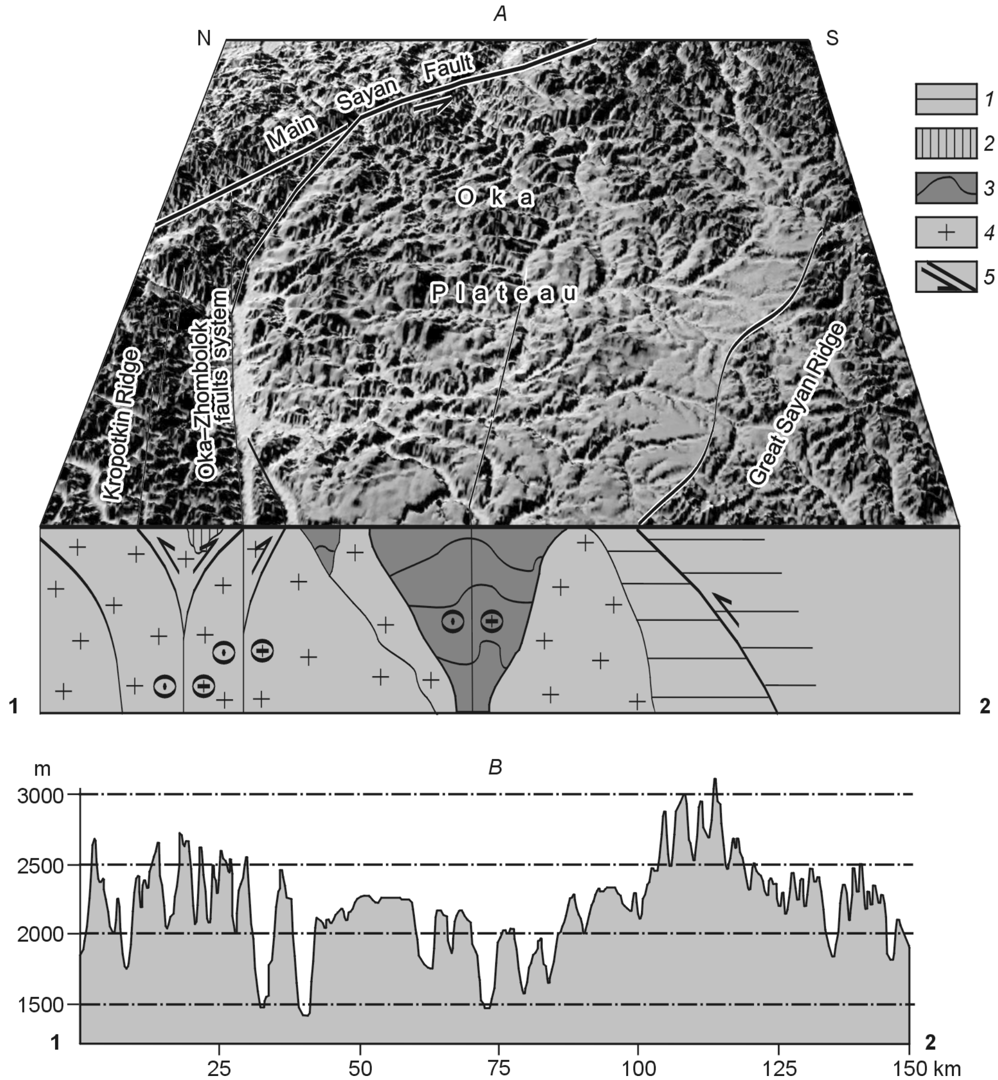

Fig. 5. Generalized tectonic sketch map of mountain range formation at the boundary with the Oka Plateau during the Neogene–Quaternary tectonic movements (cross-section along profile 1–2, Fig. 2) (*A*); topographic profile along the cross-section (*B*). *1–3*, sediments: *1*, Cambrian; *2*, Lower Paleozoic; *3*, Proterozoic; *4*, Paleozoic granitoids; *5*, active faults.

owing to both tectonic and denudation processes. In our case, the samples from the Oka Plateau and Kropotkin Ridge have identical thermal histories, suggesting the lack of interblock vertical movements between these structures in the Late Mesozoic–Early Cenozoic. This fact, along with the low calculated rate, suggests that the exhumation rate corresponds to the denudation rate of these morphotectonic structures.

The thermal modeling of the oldest sample from the Oka Plateau (S07-3) showed that the tectonic processes in the area have been steady since at least the Early Jurassic (since the entrance into the PAZ, 190 Ma) and the existing topography has undergone slow denudation. The determination of "the age" of the peneplanation surface (i.e., the time when the surface already had low, poorly broken relief) is possible in the case of joint consideration of the thermal models for all the samples (Fig. 4). This is the moment when the mean cooling lines for all the samples in the PAZ become identical. This is because there is no more differentiated topography above the samples and, from this moment on, they have eroded at the same rate. Thus, the peneplanation surface is dated at 150–140 Ma from the thermal modeling. The ongoing denudation favored the continuous rejuvenation of the formed surface later on.

Differentiated movements of the blocks relative to each other have begun during the latest (Neogene–Quaternary) stage in the tectonic movements, when the Kropotkin Ridge was uplifted with respect to the Oka Plateau along the Oka–Zhombolok fault zone (Arzhannikova et al., 2011). A large contribution was made by strike-slip movements along near-E–W faults, which had sinistral kinematics and a reversed-fault component in the area of northeastward compression (Fig. 5*A*). The latest stage of neotectonic movements in the Sayan Mts., which has been accompanied by the uplifting of individual mountain ranges, is not detected in the thermal-history models for our samples. This is due to the low rate of the Neogene–Quaternary vertical movements of the Kropotkin

Ridge relative to the Oka Plateau. The difference between the altitudes of two blocks should be no less than 2000 m, so that the samples which have left the PAZ during the Pliocene–Quaternary could reach the surface. In our case, however, the average altitude difference is 400 m (Fig. 5*B*). This means that the samples containing information about the Neogene–Quaternary rates of the vertical movements along the Oka–Zhombolok fault have not been exposed yet.

However, the rate of the Neogene–Quaternary movements along the Oka–Zhombolok fault can be estimated from the amplitude of the uplifting of the Kropotkin Ridge relative to the Oka Plateau (400 m) and the starting time of the latest stage in the uplifting of individual mountain ranges, though such an estimate is very rough. The latest stage began at 8.7 (Rasskazov et al., 2000) or ca. 5 Ma (Ivanov and Demonterova, 2009). Thus, the approximate average rate of the vertical movements along the Oka–Zhombolok fault over this period might be 0.046–0.080 mm/yr, which is at least twice higher than the long-term denudation rate of the Sayan Mts.

The Late Pleistocene–Holocene denudation rate of the Oka Plateau calculated using the cosmogenic-isotope analysis of ^{10}Be (Jolivet et al., 2011) is close to that calculated by the track method and ranges from 0.012 to 0.020 mm/yr. The low denudation rate of the Oka Plateau during the latest stage might be due to its intermediate position between the summit plain and datum surface of the Sayan Mts. and to its partial shielding by basaltic lavas.

Our previous studies (Jolivet et al., 2007; Vassallo et al., 2007a,b) south of East Sayan, in the Gobi Altai, revealed several stages of active orogeny. The high exhumation rate in this area is typical of the Early Jurassic and Pliocene–Quaternary. These two periods are separated by a long stage of steady tectonic movements. Cosmogenic ^{10}Be dating of terraces was used to calculate the rate of vertical tectonic movements in the Ikh Bogd Ridge (Gobi Altai) in the Late Pleistocene–Holocene (0.1 mm/yr) (Vassallo et al., 2007a). This value is an order of magnitude higher than the rates for East Sayan, suggesting a northward decrease in the intensity of the orogenic process at the latest stage.

Conclusions

According to track analysis, the peneplain on the Oka Plateau formed in the Late Jurassic–Early Cretaceous. This peneplain is much younger than the erosional surfaces that persist today in the Tien Shan, Gobi Altai, and Mongolian Altai (Early Jurassic (De Grave et al., 2007, 2011a,b; Glorie et al., 2011; Jolivet et al., 2007, 2010; Vassallo et al., 2007b)). However, it is older than that on the Chulyshman Plateau, Altai (Late Cretaceous (De Grave et al., 2008)), thus indicating asynchronous formation of the ancient peneplain in Central Asia.

The similar exhumation histories of samples from the Oka Plateau and Kropotkin Ridge indicate that these morphotectonic structures developed from Jurassic to late Miocene as a single block, which underwent continuous slow denudation at an average rate of 0.0175 mm/yr.

Active tectonic processes in the Late Miocene caused the destruction of the peneplanation surface and its partial uplifting to different altitudes. The rate of Pliocene–Quaternary vertical movements along the Oka–Zhombolok fault is roughly estimated at 0.046–0.080 mm/yr, which is at least twice higher than the denudation rate. In general, the exhumation rates of the ridges in East Sayan are an order of magnitude lower than those in the Gobi Altai.

The low denudation rate during the Late Pleistocene–Holocene, calculated for the Oka Plateau, is due to the intermediate altitude of the plateau in the mountain-range borders, with the peneplain relics almost completely destroyed by erosion in the ridges. However, the plateau has been preserved between the mountains without significant morphologic changes in the Pliocene–Quaternary. This is also due to the partial shielding of its surface by Miocene basaltic lavas.

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