Tectonic Evolution of the SE West Siberian Basin (Russia): Evidence from Apatite Fission Track Thermochronology of Its Exposed Crystalline Basement

Evgeny V. Vetrov 1,*, Johan De Grave 2, Natalia I. Vetrova 1, Fedor I. Zhimulev 1, Simon Nachtergaele 2, Gerben Van Ranst 3 and Polina I. Mikhailova 4

1 Sobolev Institute of Geology and Mineralogy SB RAS, 630082 Novosibirsk, Russia; pisareva.nataly@gmail.com (N.I.V.); zhimulev@igm.nsc.ru (F.I.Z.)
2 Department of Geology, Mineralogy and Petrology Research Unit, Ghent University, 9000 Gent, Belgium; johan.degrave@ugent.be (J.D.G.); simon.nachtergaele@ugent.be (S.N.)
3 Environment Unit, Antea Group Belgium, 2600 Antwerpen, Belgium; gerben.vanranst@ugent.be
4 Siberian Research Institute of Geology, Geophysics and Mineral Resources, 630091 Novosibirsk, Russia; polin_ka_91@mail.ru

* Correspondence: vetrov@igm.nsc.ru

Abstract: The West Siberian Basin (WSB) is one of the largest intracratonic Meso-Cenozoic basins in the world. Its evolution has been studied over the recent decades; however, some fundamental questions regarding the tectonic evolution of the WSB remain unresolved or unconfirmed by analytical data. A complete understanding of the evolution of the WSB during the Mesozoic and Cenozoic eras requires insights into the cooling history of the basement rocks as determined by low-temperature thermochronometry. We presented an apatite fission track (AFT) thermochronology study on the exposed parts of the WSB basement in order to distinguish tectonic activation episodes in an absolute timeframe. AFT dating of thirteen basement samples mainly yielded Cretaceous cooling ages and mean track lengths varied between 12.8 and 14.5 µm. Thermal history modeling based on the AFT data demonstrates several Mesozoic and Cenozoic intracontinental tectonic reactivation episodes affected the WSB basement. We interpreted the episodes of tectonic activity accompanied by the WSB basement exhumation as a far-field effect from tectonic processes acting on the southern and eastern boundaries of Eurasia during the Mesozoic–Cenozoic eras.

Keywords: West Siberian Basin; apatite fission track thermochronology; thermo–tectonic evolution; exhumation; subsidence

1. Introduction

It is thought that the tectonic evolution of intracratonic basins is to a large extent controlled by geodynamic processes in the lithospheric mantle [1–3]. Uplift events such as doming can, for example, be associated with mantle plume activity and the propagation of the plume material to the Earth’s surface. The direct influence of horizontal tectonic forces on the evolution of such basins is traditionally excluded, since they are located far away at the boundaries of tectonic plates. At the same time, some episodes of tectonic uplift are difficult to explain in terms of geodynamic processes in the lithospheric mantle, especially when there is no other geological evidence of mantle plume activity.

The West Siberian Basin (WSB) is one of the largest intracratonic basins of our planet (Figure 1). It is located on the Eurasian plate between the East European Craton to the West and the Siberian Craton to the East [4]. The basement of the WSB is covered by up to 12 km of Mesozoic–Cenozoic sediments that register the basin’s tectonic history. The sedimentary record has been vastly studied by drilling and seismic surveys [4,5]. Extensive borehole and seismic information and its elaborate interpretations permit constraining the tectonic vertical motions within the WSB using backstripping analysis in 2D [6]. Vibe
coworkers [6] have reconstructed the tectonic subsidence history of the WSB and discussed the mechanism for intraplate vertical motions.

Therefore, despite the extensive study of the sedimentary fill of the WSB, its tectonic evolution requires complementary independent data including quantitative estimations of vertical tectonic movements. The crystalline rocks from the WSB basement, as well as the overlying Mesozoic–Cenozoic sediments, contain a record of the tectonic processes that controlled the long-term evolution of the basin. One of the sensitive methods available for elucidating such record over timescales of millions of years is apatite fission track (AFT) thermochronology. A temperature range for AFT annealing is established between ~60–120 °C [10]. According to a geothermal gradient of 20–25 °C/km, which is typical for an intracratonic setting, this low-temperature range would correspond to a depth of 2.5 to

Figure 1. (a) Geographic map of Eurasia showing position and topography of the West Siberian Basin (WSB) (b). Tectonic map of the southeastern WSB showing position of the exposed basement segments and locations of the boreholes that give insight to stratigraphy of the southeastern WSB. (c) Geological position of the Ob and Novosibirsk massif (after [7,8]) and (d) geological position of the Kalman massif (after [7,9]) with indication of sample locations. Depth of “n” km means depth of the massif root according to geophysical data [7].
6 km (upper crust). Such temperature sensitivity is able to cover intraplate low-amplitude tectonic movements. We carried out AFT analyses and thermal modeling on the exposed granitic massifs (Ob, Novosibirsk, and Kalman) of the WSB basement to better unravel tectonic events within the WSB that influence its stratigraphic evolution and to reconstruct the thermo-tectonic evolution of the southeastern WSB basement.

2. Geological Setting

2.1. Paleozoic Basement of the West Siberian Basin

The WSB basement was formed as a result of collisional events between the Baltica, Siberian, and Kazakhstan paleocontinents [11,12], or the Russian Platform, the East Siberian Platform, and the Kipchak Arc complex [13,14] during the Middle–Late Paleozoic. The final amalgamation of the WSB basement was accompanied by mantle plume activity and during Permian–Triassic times, the WSB basement was affected by rift structures [8,14–16]. In the early phases (~250 Ma ago) it was associated with the formation of a vast province of rift basalts and Siberian flood basalts on the Siberian craton [3]. The majority of the West Siberian rifts evolved and became extinct in a continental setting. The plume arrival is suggested to have led to a Permian–Triassic uplift event, followed by WSB basement subsidence as rift structures evolved [16].

Small segments of the WSB basement are exposed in its southeastern realm within the Kolyvan Tomsk Fold Zone (KTFZ) and Northern Charysh–Talitsk Fold Zone (CTFZ) [4,6]. In this sense, these segments can be considered as the northwestern part of the Central Asian Orogenic Belt (CAOB) [17–19]. The NE-oriented KTFZ is predominantly composed of sedimentary and volcanic rocks of Middle Devonian to Mississippian age intruded by granitic and mafic rocks of Permian–Triassic age. The formation and evolution of the KTFZ are controlled by a thrust fault system. The formation of these faults is associated with tectonic deformation due to the collisional events between the Baltica, Siberian, and Kazakhstan paleocontinents [11,12] during the Middle–Late Paleozoic and Early Mesozoic.

The post-Jurassic reactivation of the faults is confirmed by the thrust of the Middle–Late Paleozoic KTFZ rocks onto Jurassic deposits along the Tomsk fault (Figure 1b). The NW-oriented CTFZ includes mainly Cambrian to Devonian sediments hosting granitoids of Devonian and Permian ages. The evolution of the CTFZ is controlled by the Charysh right-lateral strike-slip fault due to the aforementioned collision events during the Paleozoic and Mesozoic (Figure 1b) [7]. From the available geological data, there is no indication of any post-collisional reactivation of this fault.

The studied granite massifs of the KTFZ (Ob and Novosibirsk) are of Permian–Triassic age based on data from several geochronological systems. Ar-Ar dating of biotite from the Ob massif granitoids yielded 254.5 ± 2.4 and 249.7 ± 2.0 Ma [20], while zircon U-Pb ages were 260.7 ± 1.6 and 248.8 ± 0.4 Ma [8]. The Novosibirsk massif has a hornblende Ar-Ar age of 243.7 ± 2.1 Ma, a microcline Ar-Ar age of 249.1 ± 0.7 Ma [20], and zircon U-Pb ages ranging between 258.3 ± 0.6 and 249.2 ± 0.6 Ma [8]. The age of the Kalman massif of the CTFZ is based on U-Pb dating of zircon (258.3 ± 2.3 Ma) [7]. Geological and geophysical data for the granitic massifs (Ob, Novosibirsk, and Kalman) show that they have experienced various denudation events leading to different exhumation history of these massifs. According to geophysical data, the depth of the Novosibirsk intrusion root resides at 2 km only, while the Ob massif depth varies from 4 to 8 km and the depth of the Kalman massif reaches 6–12 km [7]. Thus, studying the massifs with different exhumation histories potentially allows evaluation of not only the tectonic history of the WSB basement, but also considers the potential to reveal differential denudation histories within a single area during the same time interval.
2.2. Mesozoic Tectonic Evolution of the Southeastern West Siberian Basin

After the assembling of the WSB basement during the Permian–Triassic, its geodynamic evolution has been dominated by intracontinental tectonics [21–23]. The WSB records Mesozoic–Cenozoic tectonic events since the Early Jurassic (Figure 2).

WSB subsidence started in the Jurassic following the Permian–Triassic plume-induced uplift event and even continued until the Cenozoic [6]. In the Early–Middle Jurassic, alluvial-plains and lacustrine sediments were deposited in the vast territory of the WSB, while grayish coal-bearing molasses (Glushin Formation) accumulated in isolated depressions [24], marking reactivation of the different parts of the basement. An Early Jurassic (179 Ma) AFT age obtained for the KTFZ granitoid basement confirms this exhumation episode within the study area [25].

During the Middle–Late Jurassic, the WSB represents a marine basin where bituminous clays and silts (Tatar and Georgiev Formations) were deposited in its southeastern part. In the Late Jurassic, the tectonic subsidence of the Southeastern WSB is estimated to have reached ~250 m [6]. At the beginning of the early Cretaceous (Berriasian), the subsequent accumulation of finely dispersed clay material enriched in organic matter (Kulomzin Formation) with clear signs of shallowing of the marine basin can be observed. This is followed by a regression in the Valanginian. Sandy to clayey sediments representing shallow marine and lagoon deposits [26] accumulated during this period (Tarsk Formation) and up to the Hauterivian–Barremian (Kiyalin Formation). In the Early–Late Cretaceous, the WSB area developed into a lacustrine and alluvial plain setting with continental coal-bearing deposits (Pokur Formation). Results of a backstripping analysis [6] estimate the tectonic subsidence of the southeastern WSB during Aptian and Late Albian-Cenomanian as up to 200 m. The Turonian–Maastrichtian period is characterized by slow tectonic subsidence >200 m. During this time, thick strata of marine clays and sands accumulated (Kuznetsov, Ipatov, Slavgorod, and Gankin Formations).
Figure 2. Schematic stratigraphic column of the Mesozoic and Cenozoic sediments of the Southeastern West Siberian Basin with indication of climatic conditions (climate oscillation curve after [27]). Absolute ages of stage boundaries shown are according to [28].
2.3. Cenozoic Tectonic Evolution of the Southeastern West Siberian Basin

During the Paleocene to Eocene, the WSB represents a vast marine basin with a transgressive maximum in the Middle Eocene [29]. During this time, predominantly clayey sediments (Talits, Lulinvor, and Tavdin Formations) were formed in the Southeastern WSB. The KTFZ area was tectonically stable in this period and a peneplain surface was formed at elevations between 250–500 m [30]. We suggested the planar surfaces were formed on sea level or even below during stable sea level period. This period of peneplanation was widespread and affected the entire CAOB to the south of the WSB [22,25,31,32].

In the Oligocene, renewed tectonic activity led to the fragmentation of the peneplain surface and initiation of the modern relief [7,30]. During the Early Oligocene, the marine WSB transformed into a huge lake-swamp plain where the deposits of Atlym and Novomikhailov formations accumulated under a moderately warm climate [33]. In the Late Oligocene, further progressive WSB subsidence led to the formation of a huge lake [30] in which the Zhurav Formation sediments accumulated in shallow water conditions. The lake basin eventually evolved into a series of enclosed swamp reservoirs in the Early Miocene. Lacustrine and swamp sediments represented by gray and brownish coal-bearing clays, and silts with interlayers of sand and brown coal (Abrosimov Formation) were formed. From the Late Burdigalian to the beginning of the Serravalian, the WSB was characterized by alluvial plain sediments (Beshcheul Formation) that were deposited in valley-like depressions with recycling of the underlying sediments. In the Middle Neogene, the humid conditions (Abrosimov and Beshcheul Formations) changed to a semi-arid environment (Tavolzhan and Pavlodar Formations) (Figure 2).

Since the Late Pliocene, sedimentation in the WSB was limited to various large depressions where coarse clastic material was accumulated, while Southeastern WSB areas were exposed to intensive erosion indicating a neotectonic phase affecting the WSB basement [34].

3. Apatite Fission Track Thermochronology: Samples and Analytical Methodology

In this study, we collected thirteen fresh outcropping Permian–Triassic granitic rocks (Novosibirsk and Ob massifs from KTFZ and Kalman massif from CTFZ) mainly from quarries. Two samples (syenogranite 1-1 and monzogranite 31-1) were sampled from the Ob massif at an elevation of 50 m, seven samples (syenogranites 676, 686, 708 and monzogranites 712, 670, 671-4, 664-4) were taken from the Novosibirsk massif at elevations between 50 and 175 m, and four samples (granites 1502-2, 1524, 1564 and granodiorite 727) were collected from the Kalman massif at elevations between 51 and 268 m. Table 1 presents the location and lithology for each sample. Apatite separation was conducted by a standard procedure of crushing, panning, heavy liquid, and magnetic separation techniques at the laboratory of the Siberian Research Institute of Geology, Geophysics and Mineral Resources (Novosibirsk, Russia). For each sample, at least 20 apatite grains with the fewest number of inclusions and micro-fractures were handpicked and embedded in epoxy, polished, and etched in a 5.5-M HNO₃ solution for 20 s at 21 °C. AFT analyses were performed at Ghent University (Ghent, Belgium) using the external detector method with thermal neutron irradiation [35–38]. Apatite mounts were covered with a muscovite external detector and irradiated with thermal neutrons at the Belgian Reactor 1 in the Belgian Nuclear Research Center (Mol, Belgium). Induced tracks were covered by thermal neutron irradiation in the muscovite external detector were etched in 40% HF for 40 min at 20 °C.

Measuring track densities, confined track lengths, and the kinetic parameter $D_{par}$ were performed using a Nikon Eclipse Ni-E microscope system with a Nikon DS-Ri2 camera (Nikon, Tokyo, Japan), and Nikon NIS Elements Advanced Research software, supplemented with the TRACKflow system [39]. Results of AFT analyses can be found in Table 2. Some of analyzed apatite grains contained zircon microinclusions, which produced local haloes of high spontaneous track numbers. Accordingly, a reduced number of grains (5 to 12) could be counted only, however, with more than 1000 spontaneous tracks for each
sample. AFT ages were calculated as conventional mean zeta-ages \( \bar{\zeta} \) [40]. AFT zeta-ages were calculated based on an overall weighted mean \( \bar{\zeta} \)-value of 281.6 ± 5.1 a-cm\(^2\), based on Durango [41] and Fish Canyon Tuff [42] age standards with ages of 31.4 ± 0.7 and 28.476 ± 0.064 Ma, respectively, and IRMM-540 dosimeter glasses. Confined track lengths and angles to the crystallographic c-axis were measured using a 100× plan apochromat glass objective and an optical 1250× magnification. Mean track length (MTL) values were calculated based on both horizontal and inclined (corrected for dip angle) confined tracks with the TRACKflow system [39] using the precise z-readout of the microscope of the track’s endpoints and a correction for the optical media transitions. The values of the kinetic parameter \( D_{\text{par}} \) (etch pit diameter parallel to the crystallographic c-axis) [43] were measured using automated and manual measurement to estimate AFT annealing behavior.

| No. | Sample | Lithology       | Latitude       | Longitude       | Altitude | Location          |
|-----|--------|-----------------|----------------|-----------------|----------|-------------------|
| 1   | 1-1    | syenogranite    | 55°41′49″ N    | 83°36′53″ E     | 84       | Near the village Baturino |
| 2   | 31-1   | monzogranite    | 55°28′30″ N    | 83°16′16″ E     | 86       | Near the village Dubrovino |

| No. | Sample | Lithology       | Latitude       | Longitude       | Altitude | Location          |
|-----|--------|-----------------|----------------|-----------------|----------|-------------------|
| 3   | 664-4  | monzogranite    | 55°07′42″ N    | 82°54′28″ E     | 132      | Mochischensky quarry |
| 4   | 712    | monzogranite    | 55°02′12″ N    | 82°56′57″ E     | 127      | Kamensky quarry   |
| 5   | 676    | syenogranite    | 55°06′27″ N    | 83°03′15″ E     | 176      | Near the village Kamensky |
| 6   | 686    | syenogranite    | 54°58′53″ N    | 82°56′51″ E     | 93       | Near the Novosibirsk River Station |
| 7   | 708    | syenogranite    | 55°03′45″ N    | 82°48′50″ E     | 91       | Near the village Priob |
| 8   | 670    | monzogranite    | 54°58′58″ N    | 82°59′53″ E     | 76       | Borok quarry |
| 9   | 671-4  | monzogranite    | 54°58′40″ N    | 82°59′46″ E     | 51       | Borok quarry |

| No. | Sample | Lithology       | Latitude       | Longitude       | Altitude | Location          |
|-----|--------|-----------------|----------------|-----------------|----------|-------------------|
| 10  | 1502-2 | granite         | 52°09′58″ N    | 82°59′46″ E     | 51       | Near the village Kalmanka |
| 11  | 1524   | granite         | 52°08′12″ N    | 83°23′43″ E     | 176      | Near the village Kalmanka |
| 12  | 1564   | granite         | 52°05′05″ N    | 83°26′07″ E     | 159      | Near the village Kalmanka |
| 13  | 727    | granodiorite    | 52°08′02″ N    | 83°33′34″ E     | 268      | Near the village Kalmanka |

Obtained AFT data such as track densities, confined track lengths, and \( D_{\text{par}} \) were used to produce AFT thermal history models using the QTQt software (version 5.4.6, Rennes, France) [44], the annealing equations of [45], and the Monte Carlo Markov Chain search method for inverse modeling. Thermal history modeling was performed on each sample (with the exception of sample 712 with insufficient measurements of confined track lengths) and on multiple samples for individual massifs. At least \( 10^3 \) iterations were performed in a fixed time-temperature frame ranging from 140 to 20 ± 20 °C and from 250 ± 10 Ma (granitoid massif emplacement) until present day. Additional constraints (20 ± 20 °C for 25 ± 10 Ma for the Novosibirsk and Ob massifs and 20 ± 20 °C for 15 ± 10 Ma for the Kalman massif) have been introduced due to geological data that evidence the granitic massifs to have been exposed to the surface during the Oligocene–Miocene. Thermal histories for individual samples and combining models for massifs are presented in an identical time-temperature scale in Figure 3 and Figure 5. Maximum likelihood models showing the time-temperature path with the highest probability are represented by red paths. Maximum posterior models with the maximum posterior probability are shown as khaki paths. The expected t-T models (black paths) are an average of all accepted models weighted to their posterior probability [44]. Detailing input parameters used for thermal histories modeling are given in the supplementary materials.
Table 2. Apatite fission track results: n is the number of analyzed grains; \( \rho_s \), \( \rho_i \) (in \( 10^6 \) tracks/cm\(^2\)), and \( \rho_d \) (in \( 10^5 \) tracks/cm\(^2\)) are the densities of spontaneous tracks in apatites, induced tracks in micas, and induced tracks in the dosimeter micas. \( N_i \), \( N_s \), and \( N_d \) are the numbers of spontaneous tracks in apatite, induced tracks in micas, and induced tracks in the dosimeter micas. \( \mu \) (in \( 10^3 \) tracks/cm\(^2\)), \( \sigma \) (in \( 10^3 \) tracks/cm\(^2\)), and \( \rho \) (in \( 10^5 \) tracks/cm\(^2\)) are the densities of spontaneous tracks in apatites, induced tracks in micas, and induced tracks in the dosimeter micas. \( P(\chi^2) \) is the probability that the dated grains have a constant \( \rho_s/\rho_i \)-ratio. AFT ages (in Ma) are presented as AFT zeta-ages. \( l_m \) is the number of measured horizontal confined tracks.

| Sample | n   | \( \rho_s \) (\( \pm 1\sigma \)) | \( N_s \) | \( \rho_i \) (\( \pm 1\sigma \)) | \( N_i \) | \( \rho_d \) (\( \pm 1\sigma \)) | \( N_d \) | \( \mu/\rho_i \) | \( P(\chi^2) \) | \( l_m \) | \( n_i \) | \( \sigma \) | \( D_{par} \) |
|--------|-----|-------------------------------|--------|-------------------------------|--------|-------------------------------|--------|----------------|----------------|--------|--------|--------|----------|
| Ob massif |     |                               |        |                               |        |                               |        |                |                |        |        |        |          |
| 1-1    | 12  | 7.982 (0.227)                 | 1233   | 6.946 (0.212)                 | 1073   | 5.478 (0.120)                 | 2096   | 1.13 ± 0.05     | 0.98       | 86.8 ± 4.4 | 13.5 | 40      | 1.5    | 2.1 ± 0.3 |
| 31-1   | 10  | 10.080 (0.298)                | 1143   | 7.549 (0.258)                 | 856    | 5.265 (0.116)                 | 2153   | 1.35 ± 0.06     | 0.64       | 101.4 ± 5.4 | 14.5 | 100     | 1.0    | 2.5 ± 0.4 |
| Novosibirsk massif |     |                               |        |                               |        |                               |        |                |                |        |        |        |          |
| 664-4  | 7   | 9.635 (0.262)                 | 1355   | 7.943 (0.238)                 | 1187   | 5.402 (0.117)                 | 2148   | 1.19 ± 0.05     | 0.52       | 90.1 ± 4.4 | 13.1 | 84      | 1.6    | 2.6 ± 0.4 |
| 670    | 7   | 8.009 (0.238)                 | 1135   | 7.903 (0.236)                 | 1120   | 5.409 (0.117)                 | 2143   | 1.04 ± 0.04     | 0.61       | 78.4 ± 4.0 | 12.8 | 40      | 1.3    | 2.3 ± 0.3 |
| 671-4  | 7   | 22.979 (0.435)                | 2787   | 14.990 (0.352)                | 1813   | 5.417 (0.117)                 | 2138   | 1.53 ± 0.05     | 0.98       | 115.6 ± 4.8 | 12.9 | 75      | 1.2    | 2.5 ± 0.4 |
| 676    | 8   | 14.962 (0.312)                | 2303   | 9.082 (0.243)                 | 1398   | 5.494 (0.120)                 | 2084   | 1.67 ± 0.06     | 0.57       | 127.8 ± 5.7 | 13.1 | 91      | 1.3    | 2.3 ± 0.3 |
| 686    | 6   | 12.604 (0.277)                | 2073   | 6.731 (0.202)                 | 1107   | 5.438 (0.118)                 | 2123   | 1.87 ± 0.07     | 0.82       | 141.3 ± 6.6 | 13.3 | 94      | 1.3    | 2.3 ± 0.4 |
| 708    | 6   | 13.800 (0.363)                | 1446   | 7.091 (0.260)                 | 743    | 5.471 (0.119)                 | 2100   | 1.94 ± 0.09     | 1.00       | 148.0 ± 7.9 | 13.3 | 73      | 1.2    | 2.4 ± 0.4 |
| 712    | 12  | 4.496 (0.138)                 | 1054   | 2.397 (0.101)                 | 562    | 5.431 (0.118)                 | 2128   | 1.87 ± 0.10     | 0.85       | 141.5 ± 8.3 | 13.8 | 26      | 1.3    | 2.6 ± 0.4 |
| Kalman massif |     |                               |        |                               |        |                               |        |                |                |        |        |        |          |
| 1502-2 | 9   | 6.085 (0.180)                 | 1140   | 6.491 (0.186)                 | 1216   | 5.501 (0.121)                 | 2080   | 0.94 ± 0.04     | 0.77       | 71.3 ± 3.6 | 14.0 | 42      | 1.6    | 2.4 ± 0.5 |
| 1524   | 10  | 9.319 (0.233)                 | 1595   | 9.518 (0.236)                 | 1629   | 5.509 (0.121)                 | 2074   | 0.98 ± 0.03     | 0.60       | 72.1 ± 3.3 | 13.5 | 57      | 1.4    | 2.4 ± 0.4 |
| 1564   | 5   | 12.745 (0.320)                | 1582   | 12.245 (0.327)                | 1644   | 5.517 (0.121)                 | 2068   | 0.96 ± 0.03     | 0.51       | 74.0 ± 3.4 | 13.8 | 70      | 1.3    | 2.5 ± 0.4 |
| 727    | 8   | 7.966 (0.234)                 | 1159   | 7.450 (0.226)                 | 1084   | 5.423 (0.117)                 | 2133   | 1.07 ± 0.05     | 0.78       | 80.5 ± 4.1 | 13.8 | 40      | 1.1    | 2.4 ± 0.4 |

Figure 3. Cont.
Figure 3. AFT thermal history modeling results produced by the QTQt software [44] and track length distributions for individual samples from the Ob, Novosibirsk, and Kalman massifs. Thermal history models are presented in a fixed time-temperature interval of 0–140 °C and 200–0 Ma. The color scale indicates high probability for red and yellow, but low probabilities for blue colors. The central black curve and its surrounding envelope display the expected time-temperature (t-T) model and the 95% probability range interval. The red line indicates the maximum likelihood model while the khaki line shows the maximum posterior model. For each sample observed (O) and predicted (P) data for AFT ages, the mean track length (MTL) and the fit (blue line) of the track length distribution are displayed. The legend for the geological maps is the same as shown in Figure 1.
4. Results and Interpretation

4.1. Apatite Fission-Track Data

In total, thirteen AFT ages were reported as conventional zeta ages for samples from the WSB basement. The resulting ages were mainly Cretaceous and ranged from 148 to 71 Ma. Two samples (1-1 and 31-1) from the Ob massif exhibited Early–Late Cretaceous (86.8 ± 4.4 and 101.4 ± 5.4, respectively) AFT ages. Mean track lengths (MTL) ranged from 13.5–14.5 μm (with standard deviations between 1.5 and 1.0 μm, Table 2). They commonly exhibit narrow to slightly negatively skewed track length distributions (Figure 3). Such length data propose moderate thermal shortening, suggesting a relatively rapid transit through the apatite partial annealing zone (APAZ, temperature range of 120–60 °C). Analyzed samples from the Ob massif have apatite grains with relatively high values of D_{par}, i.e., 2.1 and 2.5 μm (standard deviations 0.3 and 0.4 μm), which indicate higher apatite resistance to annealing [46,47].

The AFT ages obtained for the Novosibirsk massif can be divided into three groups: (1) Late Jurassic–Early Cretaceous; (2) early Cretaceous, and (3) early–Late Cretaceous. Samples 686, 708, and 712 yielded Late Jurassic–Early Cretaceous AFT ages (141.3 ± 6.6, 148 ± 7.9, and 141.5 ± 8.3 Ma, respectively) while samples 671-4 and 676 resulted in Early Cretaceous AFT ages (115.6 ± 4.8 and 127.8 ± 5.7 Ma) and samples 664-4 and 670 revealed Early–Late Cretaceous AFT ages (90.1 ± 4.4 and 78.4 ± 4 Ma). The length-frequency distributions for all samples show broader asymmetrical histograms with lower MTL values between 12.9 and 13.8 μm (standard deviations between 1.2 and 1.6 μm) (Figure 3, Table 2). This indicated somewhat prolonged residence in the APAZ causing thermal track shortening. The analyzed apatite grains from the Novosibirsk massif samples had relatively high values of D_{par} between 2.3 and 2.6 μm (standard deviations 0.3 and 0.4 μm).

Samples from the Kalman massif reveal Late Cretaceous AFT ages in a narrow range from 71.3 ± 3.6 to 80.5 ± 4.1 Ma. The length-frequency distributions for the Kalman samples exhibited broader asymmetrical histograms with relatively high MTL values between 13.5 and 14.0 μm (standard deviations between 1.1 and 1.4 μm) (Figure 3, Table 2). As for the Ob massif samples, the measured confined apatite fission tracks from the Kalman massif samples evidenced moderate signs of thermal track shortening. These samples also had apatite grains with relatively high D_{par} values 2.4 and 2.5 μm (standard deviations 0.4 and 0.5 μm).

In order to identify periods of tectonic reactivation, the MTL values for each sample were plotted against their corresponding age (Figure 4). This so-called “boomerang plot” [48,49] demonstrates that the basement has likely experienced multiple tectonic events. For the Novosibirsk massif, only a “half boomerang” segment is displayed, indicating signs of an exhumed fossil APAZ with a Late Jurassic–Early Cretaceous exhumation event (old AFT age and long MTL values) with a tail of mixed signature (shortening within the APAZ) with Late Cretaceous AFT ages and shorter MTL values. We assumed that the Novosibirsk massif rocks with Late Cretaceous AFT ages were affected by a prolonged residence in the APAZ and represent an uplifted/exhumed APAZ. Therefore, in this case, Late Cretaceous AFT ages have no direct geological meaning, but postdate the actual event. Only two AFT ages were obtained for the Ob massif, i.e., 101 and 86 Ma with MTL values of 14.5 and 13.5 μm, respectively. We speculated that the Early Cretaceous AFT age with the MTL value of 14.5 μm dated the exhumation event, while the Late Cretaceous AFT age with shorter lengths showed an age value mixed with a younger event. In the case of the Kalman massif, a “half boomerang” segment was characterized by slightly increasing AFT ages (from 71 to 81 Ma) with decreasing MTL values (from 14.0 to 13.5 μm). This may indicate that the granitic rocks of the Kalman massif have recorded a relatively young (Late Cretaceous) exhumation event after a prolonged residence in the APAZ or in even deeper zones of the upper crust, which led to significant annealing of the signatures of an older (e.g., Early Cretaceous) exhumation event.
4.2. Inverse Thermal History Modeling

Twelve thermal history models for individual samples (Figure 3) and three multiple sample models for the Ob, Novosibirsk, and Kalman massifs (Figure 5) are presented. A low numbers of grains per analyzed sample could lead to weakly constrained individual thermal history models. Hence, a combination of individual models was used to better constrain the thermal history of the granitic massifs. Samples from each massif were taken from almost the same altitude and had similar $D_{\text{par}}$ (therefore eventually composition) and MTL values. This allowed us to generate common thermal models for these massifs. We used the expected t-T paths (black lines on the models) as guidelines for the interpretation of the thermal histories.

The expected t-T models for samples from the Ob massif (1-1 and 31-1) showed Cretaceous–Paleogene (115–45 Ma) slow cooling and Cretaceous (115–90 Ma) rapid cooling, respectively, followed by a stable thermal regime without visible oscillations. Multiple sample modeling of the Ob massif (Figure 5) combined the thermal history models of the individual samples and demonstrated two stages: (1) Early–Late Cretaceous (~105–90 Ma) rapid cooling and (2) Late Cretaceous to recent (~90–0 Ma) thermal stability (30–35 °C). During the Early–Late Cretaceous stage, the Ob massif rocks were cooled to below 60 °C within 15 myr. After the Early–Late Cretaceous rapid cooling, tectonic stability occurred in the Late Cretaceous and continued until recently.

The thermal history models for the individual samples from the Novosibirsk massif revealed differing cooling histories. Some of them (for instance, samples 676, 671-4, 664-4 and 670) revealed a three-stage thermal history: (1) Jurassic–Cretaceous moderate cooling; (2) Cretaceous–Neogene stability; and (3) Neogene to recent cooling. Other models (e.g., samples 708 and 686) were characterized by a two-stage thermal history: (1) Jurassic–Cretaceous moderate cooling and (2) Cretaceous-to-recent rather slow cooling from 50 to 30 °C (Figure 3). The multiple sample thermal history model combines all samples into a single thermal history model for the Novosibirsk massif and shows three steps: (1) Early Cretaceous (~140–130 Ma) fast cooling, followed by (2) an Early Cretaceous–Miocene (130–15 Ma) period of thermal stability, and (3) Late Neogene (last 15 Ma) slow cooling.
Figure 5. AFT thermal history model results for the Ob, Novosibirsk, and Kalman massifs produced by the QTQt software [44] combining n samples. Thermal history models are presented in a fixed time-temperature interval of 0–140 °C and 200–0 Ma. The color scale indicates high probability for red and yellow, and the blue colors indicate low probability values (see the caption of Figure 3 for further clarification).

The individual thermal history models generated for all samples from the Kalman massif were characterized by moderate cooling with fluctuating rates during the last 100 myr (Figure 3). Multiple sample modeling for the Kalman massif combined the thermal history models of four individual samples and revealed two similar stages: (1) Late Cretaceous (85–80 Ma) rapid cooling and (2) Late Cretaceous-to-recent (80–0 Ma) monotonous slow cooling.

5. Discussion

We discuss here the results of our thermochronological study on the Novosibirsk, Ob, and Kalman massifs in the context of the Mesozoic–Cenozoic tectonic evolution and associated cooling of the WSB basement, its denudation, and sediment accumulation. AFT ages obtained in this study fit with observations that are widespread for the CAOB area to the south of the WSB (Figure 6). Cretaceous AFT ages are typical for fault zones
in Tuva [50,51], Khakassia [52], Altay [25,53–57], Gobi Altay [58], the East Sayan [59,60], Kazakhstan [61,62], Beishan [63], and Tien Shan [32,38,64–67].

5. Discussion

We discuss here the results of our thermochronological study on the Novosibirsk, Ob, and Kalman massifs in the context of the Mesozoic–Cenozoic tectonic evolution and associated cooling of the WSB basement, its denudation, and sediment accumulation. AFT ages obtained in this study fit with observations that are widespread for the CAOB area to the south of the WSB (Figure 6). Cretaceous AFT ages are typical for fault zones in Tuva [50,51], Khakassia [52], Altay [25,53,54,55,56,57], Gobi Altay [58], the East Sayan [59,60], Kazakhstan [61,62], Beishan [63], and Tien Shan [32,38,64–67].

Figure 6. Schematic tectonic map with Cretaceous AFT ages (in black) and a Late Neogene cooling pulse (in red) based on AFT age ranges, apatite U-Th-He dating (the apatite He system with a closure temperature range between ~45–75 °C [68] is more sensitive to near-surface processes than the AFT system), and thermal modeling in the Central Asia Orogenic Belt area to the south of the West Siberian Basin. Strike-slip faults are lines with lateral direction of movement shown by the arrows. Extensional structures are shown by striped lines. ISZ—Irtysh shear zone, TFF—Talas–Fergana fault, ES—East Sayan fault, BRZ—Baikal rift zone, TV—Tuva, Kh—Khakassia.

5.1. The Novosibirsk Massif

The multiple sample thermal history model for the Novosibirsk massif reveals a two-stage cooling from 120 °C to present ambient temperatures during the last 140 myr. The thermal history models as well as the AFT ages for the Novosibirsk massif indicate an Early Cretaceous fast cooling episode. This episode can be explained by basement denudation and exhumation as a response to fault-reactivation and/or marine base-level drop. As shown in Figure 7, the Novosibirsk massif cooled across the APAZ during 140–130 Ma, which generally coincides with the WSB marine regression with its peak in the Valanginian. This suggests that some influence of erosional base-level drop may have added to the total denudation of the Novosibirsk massif. However, eustatic changes in the range of 50 m would have a minor influence when cooling the Novosibirsk massif from ~120 to 60 °C.
Figure 7. Correlation of the multiple sample thermal history models (expected t-T trends) of the Ob (orange line), Novosibirsk (grey line), and Kalman (green line) massifs (below) with Mesozoic and Cenozoic tectonic events (red, atop), main sedimentation stages in the West Siberian Basin (blue, bottom), and mean paleo-water depth (above). Global eustatic level from different studies [69–72] after [6].

The denudation of the Novosibirsk massif most likely occurred as a result of the fault reactivation and associated tectonic uplift. Using a geothermal gradient of 20–25 °C/km, denudation rates of the Novosibirsk massif rocks during the Early Cretaceous stage were estimated as ~240–300 m/Myr, but again geothermal gradients may have been enhanced by fast cooling and thus derived denudation rates lower. Early Cretaceous cooling is consistent with the results of backstripping modeling, where irregular tectonic uplift of the Southeastern WSB is shown (Figure 8) and the total amplitude during ~150–110 Ma is estimated at 400 m [6]. The tectonic uplift could be caused by far-field effects from (1) the Mongol–Okhotsk ocean closure and ensuing convergence between Siberia and Amuria [73,74] and (2) the joining of the Lhasa block to the southern margin of the Eurasia [75–77] (Figure 8).
After Early Cretaceous fast cooling, an Early Cretaceous–Miocene (~130–15 Ma) episode of tectonic stability is clearly recognized in the thermal history model for the Novosibirsk massif. During this period, the WSB developed from a lacustrine and alluvial plain to a marine basin. A peneplain surface was formed within the uplifted areas. The multiple sample thermal history model for the Novosibirsk massif shows an expected t-T path with an increase in temperature in the Neogene that allows interpreting this as a possible reheating episode. In some individual thermal history models the reheating event is more clearly pronounced, but modeling artefacts could nevertheless be at play here [45]. As the reheating episode is recognized at temperatures <60 °C, it is not well constrained by the AFT data.

For the Late Neogene (from ~15 Ma onwards), renewed cooling associated with denudation and exhumation is suggested by the Novosibirsk massif thermal history model. The Late Neogene episode of rapid cooling is known in the entire CAOB to the south of the WSB (Figure 6) and supported by (1) thermal modeling [36,52,54]; (2) AFT ages of ~17–10 Ma [38,62]; and (3) apatite U-Th-He ages of ~15–5 Ma [65]. In our study area, geological data recorded (1) the general uplift of the WSB basement in the Early Miocene [30]; (2) intensive erosion of the Pliocene deposits in the southeastern part of the basin; and (3) coarse clastic sedimentation in the northern WSB since the Late Pliocene [6,34]. Although the Late Neogene cooling episode in the thermal history models may point to a modeling artifact [45], this cooling episode was however consistent with regional geological evidence and may date a real Late Neogene event.

The Late Neogene cooling episode of the Novosibirsk massif could be related to a structural reorganization within the CAOB edifice due to ongoing India–Eurasia colli-
The Neogene basement cooling is possibly emphasized by a change in climate as well. In the Late Miocene, the temperate climate changed to more arid and cooler conditions as reflected by the sediment accumulation in the WSB (Figure 2). Additionally, an influence of global sea level fluctuations on the denudational history of the WSB cannot be ruled out. As shown in Figure 7, the episodes of rapid cooling in the Cenozoic generally coincide with a global drop in sea level.

5.2. The Ob Massif

In turn, the multiple sample thermal history model for the Ob massif revealed two-stage cooling during the last ~105 myr. The thermal history models and AFT ages for the Ob massif indicated a Late Cretaceous (~105–90 Ma) rapid cooling episode. This Late Cretaceous episode could be explained by fast denudation as a response to fault reactivation. Assuming a geothermal gradient of 20–25 °C/km, a denudation rate was estimated as ~160–200 m/myr, but fast cooling may have increased the geothermal gradient for some time. The origin of this fault reactivation is not clear; however, it seems to have occurred simultaneously with the initiation of extensional tectonics due to the Late Cretaceous collapse of the supposed Mongol–Okhotsk orogen that formed during Siberia–Amuria collision (Figure 7). A ~105–90 Ma cooling event was detected in several adjacent areas to the WSB (e.g., along the East Gobi fault zone [58] and along the Baikal rift zone [23]), suggesting that fault reactivations related with extensional tectonics were prevalent throughout most of northern Central Asia at that time [78]. This indicates that fast denudation and exhumation of the Ob massif could be caused by far-field effects from tectonic events in the eastern part of Eurasia. After the Late Cretaceous fast cooling, the cooling path in our thermal history model for the Ob massif showed only weak slopes during the Cenozoic (~90–0 Ma), suggesting the absence of tectonic activity.

It is noteworthy that the results of our AFT thermochronological study suggest a different Mesozoic–Cenozoic evolution of the Ob and Novosibirsk massifs that are located in the same KTFZ. On the one hand, the Early Cretaceous (~140–130 Ma) event is not preserved in the Ob massif due to the possible removal of the corresponding AFT signal during Late Cretaceous (~105–90 Ma) tectonic reactivation. On the other hand, the difference in the evolution of the Ob and Novosibirsk massifs could be linked to the reactivation of the different fault structures that might be hidden below the post-Cretaceous sedimentary cover of the WSB.

5.3. The Kalman Massif

The thermal histories and AFT ages for the Kalman massif reveal a Late Cretaceous (~85–80 Ma) rapid cooling episode that can be explained by fast denudation as a result of fault reactivation. During the Late Cretaceous stage, the rocks of the Kalman massifs were brought to ~60 °C and, when assuming a geothermal gradient of 20–25 °C/km, a denudation rate of ~480–600 m/myr was estimated. Geothermal gradients may have been distinctly higher after Late Cretaceous cooling; thus, true denudation rates may have been lower than estimated here. The tectonic evolution of the Kalman massif is controlled by the NW-oriented Charysh fault, which could have been reactivated during the Late Cretaceous and thereby caused fast denudation and exhumation. Similar AFT ages and thermal history models are known in CAOB areas (Figure 6) situated along important fault zones (e.g., the Teletskoye graben [35,36], the Irtysh shear zone [3], and the Kurai fault zone [35]) and hence bear witness to a widespread event of Middle–Late Cretaceous fault-reactivation. This fault reactivation event cannot easily be linked to distant compressional tectonic forces; however, it is coeval with the onset of the Karakoram–Pamir collision in the southern part of Eurasia [79]. During the Middle–Late Cretaceous, the Karakoram block collided with the Pamir and led to a reorganization of tectonic blocks within the CAOB and could have caused the reactivation of the Charysh fault and other fault zones (Figure 9c). If the Charysh fault is the only fault structure responsible for the exhumation of the Kalman
massif, then dip-slip movement should be expected along the Charysh fault during its Middle–Late Cretaceous reactivation.

After this episode, the thermal history model showed a near-horizontal t-T path reflecting a period of prolonged tectonic quiescence during the Late Cretaceous to recent times. The Late Neogene cooling, shown for the Novosibirsk massif, was not manifested in the thermal history model for the Kalman massif.

5.4. Implication for the Mesozoic–Cenozoic Tectonic Evolution of the WSB Basement

Thermal history modeling based on AFT data demonstrates the occurrence of several fast cooling episodes associated with the denudation and exhumation of the Southeastern WSB basement after its consolidation during the Permian–Triassic. The episodes of basement denudation and exhumation recognized in thermal history models for the Novosibirsk, Ob, and Kalman massifs are difficult to explain by mantle plume activity beneath the WSB basement as in the case of the Permian–Triassic uplift event, since no evidence of mantle plume activity exists in the study area during the Late Jurassic to recent. Kimberlites with an age of 140–170 Ma indicate plume activity during the Middle Jurassic–Early Cretaceous in the northeastern part of the Siberian Craton [80,81], but this plume activity did not affect the tectonic evolution of the WSB. Moreover, if the vertical motions were induced by convective stresses of mantle flow, then they would display a large regional effect and slowly change over time. Recent backstripping analysis shows episodic irregular vertical motions within the area of the WSB during this time [6]. We propose alternative causes for the cooling episodes of the WSB basinment during the Mesozoic–Cenozoic.

During the Late Jurassic–Early Cretaceous, the Mongol–Okhotsk ocean was closed along the Mongol–Okhotsk suture zone in a diachronous, scissor-like manner from central Mongolia to the Okhotsk sea [82] at the eastern margin of Eurasia (Figure 9b,c). It is suggested that almost simultaneously with the proposed Mongol–Okhotsk event, the Lhasa block collided with the Qiangtang block along the southern margin of Eurasia, i.e., during the Latest Jurassic–Early Cretaceous [83,84] (Figure 9b,c). The Lhasa–Qiangtang collision could have caused the Late Jurassic–Early Cretaceous exhumation in the Tian Shan and other inner regions of the CAOB [22,41,78]. Both of these tectonic events could have led to the denudation and exhumation of the WSB basement during the Early Cretaceous (~140–130 Ma); however, the contribution of each of them is difficult to evaluate, and the question remains if this effect would be propagated this far. The signals of these tectonic events were preserved in the Novosibirsk massif and are not found in the deep rooting Ob and Kalman massifs.

After rapid Mongol–Okhotsk ocean closure by the end of the Early Cretaceous, extensional tectonics have been recorded [83,84]. Possibly this is related to a gravitational collapse of the enigmatic Mongol–Okhotsk orogeny [74]. Tectonic activity might have triggered reactivation of fault systems further inland, causing fast exhumation of the Ob massif during the Late Cretaceous. Slightly later, in the Middle–Late Cretaceous–Early Paleogene, the Karakoram block drifted northwards and collided with the Pamir at the southern Eurasian margin [79]. The stress-field induced by the Karakoram–Pamir collision propagated to the north of Eurasia and could have reorganized the tectonic blocks within the CAOB and the WSB and reactivated fault structures such as the Charysh fault, leading to exhumation of the Kalman massif during this period.

Finally, India collided with Eurasia as a consequence of the closure of the Neotethys Ocean in the Early Cenozoic, leading to tectonic signals within a vast zone of orogens in southern Eurasia [85–87] (Figure 9d–f). This large-scale collision initiated a renewed episode of reactivation of the areas north of the Southern Eurasian margin and could have led to another exhumation episode of the WSB basement as shown above in the thermal history models for the Novosibirsk massif.
Minerals 2021, 11, x FOR PEER REVIEW 19 of 24

Figure 9. Simplified paleo-tectonic maps (after [73,88,89]) illustrating the position of the various continental blocks and oceanic plates from the Late Permian–Early Triassic to the Miocene (a–f).

6. Conclusions
This study presents apatite fission track (AFT) results for granitic rocks from the exposed basement of the Southeastern West Siberian Basin (WSB). The obtained results allowed us to put further constraints on the Mesozoic–Cenozoic tectonic evolution of the WSB. The following conclusions could be drawn:

1. The granitic massifs of the exposed segments of the WSB basement exhibit differing cooling histories, implying differential basement denudation and exhumation patterns as shown by our AFT data;
2. AFT ages and thermal history models of the Novosibirsk granitic massif displayed an Early Cretaceous (~140–130 Ma) period of rapid cooling associated with basement exhumation and denudation. This denudation episode can be interpreted as a result of fault reactivation due to the convergence between Siberia and Amuria and/or the Lhasa–Qiangtang collision;
3. AFT data obtained for the Ob massif show a distinct Late Cretaceous (~105–90 Ma) fast cooling period associated with exhumation and denudation of the WSB basement. This event could be caused by fault reactivation due to a far-field effect from the gravitational collapse of the Mongol–Okhotsk orogeny after final collision between Siberia and Amuria;
4. Similar AFT ages and thermal history models of the Kalman massif reveal a Late Cretaceous (~85–80 Ma) rapid cooling period indicating basement exhumation and denudation as a result of reactivation of the Charysh fault and could be related to Karakoram–Pamir convergence along the southern Eurasia margin;

5. Thermal history models for all granitic massifs show, that the WSB basement experienced temporary thermal stagnation during much of the Cretaceous and the Cenozoic. This period of tectonic stability is evidenced by the development of the marine basin and the occurrence of peneplanation surfaces within uplifted areas of the WSB basement;

6. A final Neogene rapid cooling episode of the WSB basement registered in the Novosibirsk massif started at ~15 Ma and brought the rocks to surface temperatures at their present outcrop position. This event might be linked to continuous indentation of the Indian plate into Eurasia.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/min11060604/s1, File: parameters used for thermal histories modeling.

Author Contributions: Conceptualization, E.V.V.; formal analysis, S.N. and P.I.M.; funding acquisition, E.V.V. and J.D.G.; investigation, E.V.V., N.I.V. and F.I.Z.; methodology, J.D.G., S.N. and G.V.R.; project administration, E.V.V.; resources, J.D.G.; software, G.V.R.; supervision, E.V.V.; visualization, N.I.V.; writing—original draft, E.V.V.; writing—review and editing, J.D.G. and N.I.V. All authors have read and agreed to the published version of the manuscript.

Funding: The study was carried out with a grant from the Russian Science Foundation (project No. 19-77-00033). Natalia Vetrova was funded by a grant 19-45-543001 from the Russian Foundation for Basic Research and Government of the Novosibirsk Region. Fedor Zhimulev was funded by a state assignment of IGM SB RAS. Simon Nachtergaele was funded by a Ph.D. fellowship of the Research Foundation Flanders (FWO).

Acknowledgments: We also wish to express our appreciation to the UGent Russia Platform for assistance and travel funds. The academic editors (Alexandre Kounov and Meinert Rahn) and three anonymous reviewers are thanked for their constructive comments all of which greatly improved this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Ju, Y.; Wang, G.; Li, S.; Sun, Y.; Suo, Y.; Somerville, I.; Li, W.; He, B.; Zheng, M.; Yu, K. Geodynamic mechanism and classification of basins in the Earth system. Gondwana Res. 2020, in press. [CrossRef]
2. Allen, P.A.; Armitage, J.J. Cratonic Basins. In Tectonics of Sedimentary Basins: Recent Advances; Busby, C., Pérez, A.A., Eds.; John Wiley & Sons, Ltd.: West Sussex, UK, 2011; pp. 602–620.
3. Nikishin, A.M.; Ziegler, P.A.; Abbott, D.; Brunet, M.-F.; Cloetingh, S. Permo-Triassic intraplate magmatism and mangle dynamics. Tectonophysics 2002, 351, 3–39. [CrossRef]
4. Vyssotski, A.; Vyssotski, V.; Nezhdanov, A. Evolution of the West Siberian Basin. Mar. Pet. Geol. 2006, 23, 93–126. [CrossRef]
5. Kontorovich, A.E.; Nesterov, I.I.; Salmanov, F.K.; Surkov, V.S.; Trofimuk, A.A.; Ervye, Y. Geology of Oil and Gas of West Siberia; Nedra: Moscow, Russia, 1975; p. 679. (In Russian)
6. Vibe, Yu.; Bunge, H.-P.; Clark, S.R. Anomalous subsidence history of the West Siberian Basin as an indicator for episodes of mantle induced dynamic topography. Gondwana Res. 2018, 53, 99–109. [CrossRef]
7. Babin, G.A.; Chernyh, A.I.; Golovina, A.G.; Zhigalov, S.V.; Dolgushin, S.S.; Vetrov, E.V.; Korableva, T.V.; Bodina, N.A.; Svetlova, N.A.; Fedoseev, G.S.; et al. Explanation Note to the State Geological Map of Russian Federation, Scale 1:1 000 000 (Third Generation) Atai-Sayan Series, Sheet N-44 (Novosibirsk); Russian Geological Research Institute: Sankt Petersburg, Russia, 2015; p. 181. (In Russian)
8. Vetrov, E.V.; De Grave, J.; Kotler, P.D.; Kruk, N.N.; Zhigalov, S.V.; Babin, G.A.; Fedoseev, G.S.; Vetrov, N.I. Evolution of the Kolyvan-Tomsk granitoid magmatism (Central Siberia): Insights into the tectonic transition from post-collision to intraplate settings in the northwestern part of the Central Asian Orogenic Belt. Gondwana Res. 2021, 93, 26–47. [CrossRef]
9. Gusev, N.I.; Vovshin, Y.E.; Kruglova, A.A. Explanation Note to the State Geological Map of Russian Federation, Scale 1:1 000 000 (Third Generation) Atai-Sayan Series, Sheet M-44 (Rubtsovsk); Russian Geological Research Institute: Sankt Petersburg, Russia, 2015; p. 320. (In Russian)
10. Wagner, G.A.; Van den haute, P. Fission Track-Dating; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1992; p. 285.
37. De Grave, J.; Glorie, S.; Buslov, M.M.; Izmer, A.; Fournier-Carrie, A.; Elburg, M.; Bataliev, V.Y.; Vanhaeke, F.; Van den haute, P. The thermo-tectonic history of the Song-Kul Plateau, Kyrgyz Tien Shan: Constraints byapatite and titanite thermo-chronometry and zircon U/Pb dating. *Gondwana Res.* 2011, 20, 745–763. [CrossRef]

38. Glorie, S.; De Grave, J.; Buslov, M.; Elburg, M.; Stockli, D.; Gerdes, A.; Van den Haute, P. Multi-method chronometric constraints on the evolution of the Northern Kyrgyz Tien Shan granitoids (Central Asian Orogenic Belt): From emplacement to exhumation. *J. Asian Earth Sci.* 2010, 38, 131–146. [CrossRef]

39. Van Ranst, G.; Carlos Pedrosa-Saizes, A.P.; Novo, T.; Vermeesch, P.; De Grave, J. New insights from low-temperature thermochronology into the tectonic and geomorphologic evolution of the southeast Brazilian highlands and passive margin. *Geosci. Front.* 2020, 11, 303–324. [CrossRef]

40. Hurford, A.J.; Green, P.F. The zeta age calibration of fission-track dating. *Chem. Geol.* 1983, 41, 285–317. [CrossRef]

41. McDowell, F.W.; McIntosh, W.C.; Farley, K.A. A precise 40Ar/39Ar reference age for the Durango apatite (U-Th)/He and fission-track dating standard. *Chem. Geol.* 2005, 214, 249–263. [CrossRef]

42. Hurford, A.J.; Hammerschmidt, K. 40Ar/39Ar and K/Ar dating of the Bishop and Fish Canyon Tuffs: Calibration ages for fission-track dating standards. *Chem. Geol.* 1985, 58, 23–32. [CrossRef]

43. Donelick, R.A. Crystallographic orientation dependence of mean etchable fission track length in apatite: An empirical model and experimental observations. *Am. Mineral.* 1991, 76, 83–91.

44. Gallagher, K. Transdimensional inverse thermal history modeling for quantitative thermochronology. *J. Geophys. Res. Space Phys.* 2012, 2012, 1–16. [CrossRef]

45. Ketcham, R.A.; Carter, A.; Donelick, R.A.; Barbarand, J.; Hurford, A.J. Improved modeling of fission-track annealing in apatite. *Am. Mineral.* 2007, 92, 799–810. [CrossRef]

46. Carlson, W.D.; Donelick, R.A.; Ketcham, R.A. Variability of apatite fission-track annealing kinetics: I. Experimental results. *Am. Mineral.* 1999, 84, 1213–1223. [CrossRef]

47. De Grave, J.; Glorie, S.; Buslov, M.M.; Izmer, A.; Fournier-Carrie, A.; Elburg, M.; Bataliev, V.Y.; Vanhaeke, F.; Van den haute, P. The thermo-tectonic history of the Tuva region. *Tectonophysics* 2014, 621, 44–59. [CrossRef]

48. Vetrov, E.V.; De Grave, J.; Vetrova, N.I.; Nachtergaele, S.; Van Ranst, G.; Mikhailova, P.I. Tectonic history of the South Tannuul Fault Zone (Tuva Region of the Northern Central Asian Orogenic Belt, Russia): Constraints from multi-method geochronology. *Minerals* 2020, 10, 56. [CrossRef]

49. De Grave, J.; Glorie, S.; Zhimulev, F.I.; Glorie, S.; Buslov, M.M.; Van den haute, P. Emplacement and exhumation of the Kuznetsk-Altai basin (Siberia): Implications for the tectonic evolution of the Central Asian Orogenic Belt and sediment supply to the Kuznets, Minusa and West Siberian Basins. *Terra Nova* 2011, 23, 248–256. [CrossRef]

50. De Grave, J.; Van den haute, P.; Buslov, M.M.; Dehandschutter, B.; Glorie, S. Apatite fission track thermochronology applied to the Chulyshman Plateau, Siberian Altai Region. *Radiat. Meas.* 2008, 43, 38–42. [CrossRef]

51. Yuan, W.-M.; Carter, A.; Dong, J.-Q.; Bao, Z.; An, Y.; Guo, Z. Mesozoic-Tertiary exhumation history of the Altai Mountains, northern Xinjiang, China: New constraints from apatite fission track data. *Tectonophysics* 2006, 412, 183–193. [CrossRef]

52. Vetrov, E.V.; De Grave, J.; Vetrova, N.I.; Zhimulev, F.I.; Nachtergaele, S.; Van Ranst, G.; Mikhailova, P.I. Tectonic history of the Gurvan Bogd system (Gobi-Altay) by apatite fission track analysis. *Tectonophysics* 2012, 544–545, 75–92. [CrossRef]

53. De Grave, J.; Glorie, S.; Zhimulev, F.I.; Buslov, M.M.; Elburg, M.; Van den Haute, P. Structural control on Mesozoic-Cenozoic tectonic reactivation and denudation in the Siberian Altai: Insights from multimethod thermochronometry. *Tectonophysics* 2012, 544–545, 75–92. [CrossRef]

54. De Grave, J.; Glorie, S.; Zhimulev, F.I.; Buslov, M.M.; Elburg, M.; Van den Haute, P. Mesozoic-Cenozoic emplacement and Mesozoic-Cenozoic reactivation of the southern Kazakhstan granitoid basement. *Tectonophysics* 2013, 54, 685–694. [CrossRef]

55. De Pelsmaeker, E.; Jolivet, M.; De Grave, J.; Zhimulev, F.I.; Vetrov, E.V.; De Grave, J.; Glorie, S.; Buslov, M.M.; Vassallo, R.; Chauvet, A. The time of the formation and destruction of the Meso-Cenozoic peneplanation surface in East Sayan. *Russ. Geol. Geophys.* 2013, 54, 1075–1095. [CrossRef]

56. Vetrov, E.V.; De Grave, J.; Glorie, S.; Buslov, M.M.; Zhimulev, F.I.; Vassallo, R.; Chauvet, A. The time of the formation and destruction of the Meso-Cenozoic peneplanation surface in East Sayan. *Russ. Geol. Geophys.* 2013, 54, 685–694. [CrossRef]

57. Pullen, A.; Banaszynski, M.; Kapp, P.; Thomson, S.N.; Cai, F. A mid-cretaceous change from fast to slow exhumation of the western Chinese Altai mountains: A climate driven exhumation signal? *J. Asian Earth Sci.* 2020, 197, 104387. [CrossRef]

58. Vassallo, R.; Jolivet, M.; Bizet, J.-F.; Braucher, R.; Larroque, C.; Sue, C.; Todbile, M.; Javklanbold, D. Uplift age and rates of the Gurvan Bogd system (Gobi-Altay) by apatite fission track analysis. *Earth Planet. Sci. Lett.* 2007, 259, 333–346. [CrossRef]

59. Jolivet, M.; Arzhannikov, S.; Arzhannikova, A.; Chauvet, A.; Vassallo, R.; Braucher, R. Geomorphic Mesozoic and Cenozoic evolution in the Oka-Jombolok region (East Sayan ranges, Siberia). *J. Asian Earth Sci.* 2013, 62, 117–133. [CrossRef]

60. Arzhannikov, S.; Jolivet, M.; Arzhannikova, A.; Vassallo, R.; Chauvet, A. The time of the formation and destruction of the Meso-Cenozoic peneplanation surface in East Sayan. *Russ. Geol. Geophys.* 2013, 54, 685–694. [CrossRef]

61. De Pelsmaeker, E.; Glorie, S.; Buslov, M.M.; Zhimulev, F.; Poujol, M.; Korobkin, V.V.; Vanhaecke, F.; Vetrov, E.V.; De Grave, J. Late-Paleozoic emplacement and Mesozoic-Cenozoic reactivation of the southern Kazakhstan granitoid basement. *Tectonophysics* 2015, 662, 416–433. [CrossRef]

62. Glorie, S.; Otasevic, A.; Gillespie, J.; Jepson, G.; Danisik, M.; Zhimulev, F.I.; Gurevich, D.; Zhang, Z.; Song, D.; Xiao, W. Thermo-tectonic history of the Junggar Alatau within the Central Asian Orogenic Belt (SE Kazakhstan, NW China): Insights from integrated apatite U/Pb, fission track and (U-Th)/He thermochronology. *Geosci. Front.* 2019, 10, 2153–2166. [CrossRef]
