



Article Studying the Depth Structure of the Kyrgyz Tien Shan by Using the Seismic Tomography and Magnetotelluric Sounding Methods

Irina Medved ^{1,2,*}, Elena Bataleva ³ and Michael Buslov ¹

- ¹ Institute of Geology and Mineralogy SB RAS, Koptyug Ave., 3, 630090 Novosibirsk, Russia; buslov@igm.nsc.ru
- ² Institute of Petroleum Geology and Geophysics SB RAS, Koptyug Ave., 3, 630090 Novosibirsk, Russia
- ³ Research Station of the Russian Academy of Sciences in Bishkek, Bishkek 720049, Kyrgyzstan; bataleva@gdirc.ru
- * Correspondence: zabelirina@yandex.ru or ZabelinaIV@ipgg.sbras.ru; Tel.: +7-952-9224-967

Abstract: This paper presents new results of detailed seismic tomography (ST) on the deep structure beneath the Middle Tien Shan to a depth of 60 km. For a better understanding of the detected heterogeneities, the obtained velocity models were compared with the results of magnetotelluric sounding (MTS) along the Kekemeren and Naryn profiles, running parallel to the 74 and 76 meridians, respectively. We found that in the study region the velocity characteristics and geoelectric properties correlate with each other. The high-velocity high-resistivity anomalies correspond to the parts of the Tarim and Kazakhstan-Junggar plates submerged under the Tien Shan. We revealed that the structure of the Middle Tien Shan crust is conditioned by the presence of the Central Tien Shan microcontinent. It manifests itself as two anomalies lying one below the other: the lower low-velocity low-resistivity anomaly, and the upper high-velocity high-resistivity anomaly. The fault zones, limiting the Central Tien Shan microcontinent, appear as low-velocity low-resistivity anomalies. The obtained features indicate the fluid saturation of the fault zones. According to the revealed features of the Central Tien Shan geological structure, it is assumed that the lower-crustal low-velocity layer can play a significant role in the delamination of the mantle part of the submerged plates.

Keywords: seismic tomography; lithosphere; electrical conductivity; magnetotelluric studies; geodynamics; Tien Shan

1. Introduction

The Tien Shan is characterized by a contemporary intercontinental orogeny (Figure 1) and is unique for examining present-day geodynamics. This mountain system comprises the east–west trending ranges detached by parallel intermountain basins. The western part of the Tien Shan is largely located in the Kyrgyz Republic, the eastern part being located in China. For this reason, the Tien Shan has been drawing the attention of the international scientific community for a long period of time [1–4]. One of the major scientific challenges is the investigation of its lithospheric structure. The surface and upper crust of the Central Tien Shan have been scrutinized by seismic tomography (ST) and magnetotelluric sounding (MTS), which are regarded as the most informative methods for the problem addressed. The profiles are shown in Figure 1.

Seismic tomography. Over the past few decades, a lot of work has been done to study the depth structure of the crust and upper mantle of the Tien Shan by seismic methods. In particular, these include deep seismic sounding (DSS), the common depth point seismic reflection method (CDP), wave attenuation, receiver function method and local and regional ST.



Citation: Medved, I.; Bataleva, E.; Buslov, M. Studying the Depth Structure of the Kyrgyz Tien Shan by Using the Seismic Tomography and Magnetotelluric Sounding Methods. *Geosciences* **2021**, *11*, 122. https:// doi.org/10.3390/geosciences11030122

Academic Editors: Jesus Martinez-Frias and Edoardo Del Pezzo

Received: 7 January 2021 Accepted: 2 March 2021 Published: 8 March 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/).



Figure 1. Locations of the geophysical profiles in the study region. The seismic tomography (ST) profiles 1, 2, 3, 4 are highlighted in black, and the magnetotelluric sounding (MTS) profiles are in pink: 1—Kekemeren, 3—Naryn. Main fault structures: TF—Talas–Fergana Fault, NL—Nikolaev Line Fault, AI—At–Bashy–Inylchek Fault, KK—Kyrgyz–Kungei Fault, NTF—North Tarim Fault.

To explore the region on a global scale, such deep seismic methods as teleseismic or regional tomography prevail, as far as they contribute to the study of the upper mantle structure in more detail. Teleseismic surveys based on data from the global network have been carried out independently in many works [5–10]. All of them revealed similar patterns: (1) a slope of the high-velocity anomaly (Kazakhstan–Junggar plate) in the north under the Tien Shan, and (2) a slope of the other anomaly (Tarim plate) in the south below the Tien Shan, as well as (3) a reduced-velocity anomaly beneath the collision zone, which may indicate a partial absence of the lithospheric mantle.

In order to investigate the crust and upper mantle to a depth of 100 km beneath the Kyrgyz Tien Shan, researchers have applied the methods of attenuation, receiver function, DSS, CDP and local tomography. For instance, in [11] it is revealed that the average thickness of the Tien Shan crust is about 55–65 km. The maximum Moho depth is evidenced in the Central Tien Shan [11–14]. The DSS and receiver function surveys showed that the thickness of the Tien Shan crust is greater than that of the nearby Kazakhstan–Junggar and Tarim plates [15,16].

Studies along the MANAS profile (middle Asian active seismic profiling), which diagonally intersects the Tien Shan territory and only in the south runs perpendicular to the boundary between the Central Tien Shan and Tarim and coincides with the Naryn

profile (MTS), were carried out by means of the CDP and earthquake converted-wave methods, along with teleseismic tomography. This made it possible to scrutinize the crust and upper mantle of the Tien Shan to a depth of 80 km. As a result, a boundary is distinguished in the CDP section, which submerges from the edge of the Tarim plate under the Tien Shan [12]. There are also distinctions between the layers in terms of seismic velocities, density and viscosity [12,17,18]. A decrease in the velocities can be caused by the decompaction of the host rocks and also by partial melting at depths of more than 25 km [13,19,20]. As follows from the seismological data, a reduction in the velocities under the Chatkal Ridge is seen in the depth interval 23–29 km, whereas under the Alai ridge it is within 10–21 km. According to the DSS data, the reduced velocities below the Gissar Ridge are at depths of 27–32 km, and the corresponding interval for the Fergana Depression is 38–44 km [21]. The CDP velocities along the MANAS profile are decreased at depths of 10–18 km. In the Tarim crust, the reduced-velocity layer has a minimum thickness and lies at a depth of 25–30 km [12]. In the Tien Shan, within this layer and below it, many heterogeneities characterizing the upper crust disappear from the geophysical fields.

Electromagnetic methods. Being a research priority, the depth structure of the Central Tien Shan lithosphere has been examined with electromagnetic methods by the Research Station of the Russian Academy of Sciences in Bishkek for the last 40 years [22–31]. The most vivid example of such research is a set of geological and geophysical surveys carried out under international collaboration at the Naryn profile (76° E), which comprised magnetotelluric and magnetovariational sounding. The magnetotelluric and other geophysical studies in the Central Tien Shan are generalized in [27,28,30,32,33].

Variations of the physical properties in the crust and upper mantle are evident as geophysical field anomalies. A constant attention of geophysicists is drawn by the interrelation of electrical conductivity and seismic velocity changes in the geoenvironment. The results obtained by [32] showed a relatively good correlation between the low-velocity and high-conductivity areas, which points at the fluid nature of the measured anomalies. We, in turn, conducted our research to get a more complete idea about the depth structure, texture and composition of the Central Tien Shan lithosphere. This was achieved by juxtaposing such physical properties of the Tien Shan lithosphere as electric conductivity and velocity characteristics, with the aid of new data and geophysical models.

2. Geological Environment and Geodynamic Model of the Tien Shan Formation

The Tien Shan is part of the Central Asian Orogenic System, which was formed as a result of the "domino" principle of long-distance transmission of deformations from the Indo-Eurasian collision through the rigid structures of the Precambrian continental blocks located amid the Paleozoic–Mesozoic folded zones [34–37]. As a consequence of the compression, the folded zones were evolving into mountain systems, and the Precambrian continental blocks served as the basement for the formation of the Cenozoic basins (Tarim, Tajik, Junggar, Issyk–Kul, etc.). The Indian continent, after a long-lasting slide along the boundary with Eurasia, collided with it at the end of the Eocene. Subsequently, over a period of about 35 million years, this continent was pressed into Eurasia for a distance of more than 900 km along the Earth's surface and up to 1500 km in depth. Its frontal part is now located under the Tarim [10]. The stress transfer from the Indian continent was facilitated by the subsidence and partial rotation of the rigid Precambrian blocks: the Tarim continent, Aktau-Junggar, Tuva-Mongolian and other microcontinents. This process, in turn, was fostered by the presence of mantle plumes that formed mantle lenses to a depth of 100 km under the Pamir, Eastern and Central Tarim, Tien Shan, Dzungaria and, especially, under the Sayan, Khangai and Baikal regions [34,36,38]. According to fission-track dating, active uplifts began 25–30 Ma in the Himalayas and Tibet, 16–19 Ma in the Tien Shan, about 5 Ma in the Altai and about 3 Ma in the Baikal region. The active phase occurred in the entire Central Asian Orogenic Belt approximately 3 Ma. In this regard, high mountains came into existence throughout Central Asia almost simultaneously. The peak of growth of the mountain systems over the past 3 million years is especially clearly recognized on

the basis of the apatite fission-track dating and the presence of formed molasses in the intermountain basins [37,39–51]. The Tien Shan is situated on the way of stress transfer from the Tarim plate subsidence [34–36].

The Tien Shan originates from the Turkestan Ocean closure in the Paleozoic [52–55]. The ultimate closure of the Turkestan Ocean basin was completed in the Permian, during the collision of the Tarim and Tien Shan with the Kazakhstan–Junggar plate [56–58].

The Northern Tien Shan is a reactivated part of the Kazakhstan–Junggar plate, which is a considerable early Paleozoic thrust-and-fold belt spanning from North Kazakhstan to the Chinese Central Tien Shan through South Kazakhstan and North Kyrgyzstan. It contains the Precambrian microcontinental pieces (Aktau–Junggar microcontinent), Early Paleozoic ophiolites and high-grade metamorphic rocks, which were fused together in the Cambrian and Early Ordovician and afterwards overlain by the Ordovician and Middle Paleozoic continental arcs [2,59,60]. Intense granitoid magmatism was taking place there in the Late Ordovician and Early Silurian [61]. Between the Silurian and Carboniferous, the Northern Tien Shan was a stable continental block with terrestrial facies [62].

The Middle Tien Shan is the most contrasting in its parameters, due to the existence of the Central Tien Shan (Issyk–Kul) microcontinent. The microcontinent is made up of Paleoproterozoic highly metamorphosed rocks overlapped by Neoproterozoic and Paleozoic rock—volcanogenic–sedimentary and sedimentary [50,61–65]. During the Ordovician–Silurian, granitites were immensely intruding the Central Tien Shan (Issyk–Kul) microcontinent [57,66–68]. In the Middle and Late Paleozoic, the southern passive margin of the Kazakhstan continent covered this microcontinent. In the Early Silurian, Late Silurian to Middle Devonian and Pennsylvanian, a low-lifetime arc developed in the southwest of the Central Tien Shan. In the Jurassic–Cenozoic, huge sedimentary basins were concentrated in the Central Tien Shan (Issyk–Kul) microcontinent.

The Southern Tien Shan is known to be the Late Paleozoic thrust-and-fold belt with ophiolitic and high-pressure rocks. It occurred from the convergence and collision of the Kazakhstan–Junggar plate with the Central Tien Shan (Issyk–Kul) microcontinent of the time in the north and the Tarim plate in the south [62,69,70]. The activated collision with the Tarim also resulted in the disappearance of the continental volcanic arc, uplifting, folding and termination of marine sedimentation in the Southern and Middle Tien Shan. In the Early Permian, it was succeeded by intruding granite plutons, which indicates the main collisional stage [62,71].

Thus, the Tien Shan comprises three geodynamic units differing drastically in their composition and age (Figures 1 and 2): the Late Paleozoic accretionary complex of the Kazakhstan–Junggar plate in the Northern Tien Shan, the Precambrian Central Tien Shan (Issyk–Kul) microcontinent with the Lower Paleozoic island arc complexes in the Middle Tien Shan, partially including the Upper Paleozoic cover and the Middle–Late Paleozoic accretionary complex in the Southern Tien Shan. The boundary between the Kazakhstan–Junggar plate and the Central Tien Shan (Issyk–Kul) microcontinent is the Kyrgyz–Kungei fault zone, and the southern confine of the microcontinent is the Nikolaev Line fault zone. The accretionary complexes of the Southern Tien Shan are thrust over the cover of the Tarim continent through the North Tarim Fault. The three specified geodynamic units of the Tien Shan and Tarim continent are clearly distinguishable in the geophysical fields.



Figure 2. Simplified geological map of the Paleozoic Tien Shan from [60]. 1—Mesozoic–Cenozoic cover; 2–3—North-Eastern Tien Shan: 2—active margin volcanic belt and collision-related molasse (Upper Carboniferous to Lower Permian), 3—accreted arc terranes (volcanic rocks and associated formations) (Devonian–Upper Carboniferous, locally Silurian); 4—Northern Tien Shan: island arc Lower Paleozoic complexes, partly with the Upper Paleozoic cover; 5,6—Middle Tien Shan: 5—Chatkal–Kurama accretionary terrane (before the Devonian) and volcanic–plutonic belt of the Kazakhstan active margin, 6—Syr Darya and Talas passive margin sediments (Neoproterozoic to Carboniferous); 7–10—Southern Tien Shan: 7—Erben–Kymyshtala accreted arc and possible forearc complex (Devonian), 8—active margin and rift formations of the Karakum–Tajik continent (Carboniferous), 9—Bukantau–Kokshaal collisional fold-thrust belt: accreted arc and ophiolites, passive margin sediments of the Kyzylkum–Alai and other microcontinents (mainly Silurian to Carboniferous), 10—turbidites and molasses of the syn-collisional foreland basin in the Tarim and Turkestan–Alai; 11—deformed sedimentary cover of the Tarim; 12—Precambrian basement; 13—main faults and thrusts.

3. Seismic Tomography Studies

Data. The dataset was composed of three parts. The first part was provided by the Institute of Seismology of the National Academy of Sciences of the Kyrgyz Republic and contained 11,163 rays (6175 rays of P waves and 4988 rays of S waves). Approximately 260 seismic stations recorded 435 earthquakes during one year. This data was used in [10]. The second part contained 10 seismic stations of KNET telemetric network, which was working on the time period from 1999 to 2014 and recorded ~5000 events in Kyrgyzstan and surrounding areas. This dataset mainly covered the northern and central parts of Kyrgyzstan. This subset was used in [14]. The third subset is comprised of data from ISC catalogs, which encompass rays from more than 8000 earthquakes recorded in the study region from 1965 to 2017.

Therefore, 113,028 seismic rays were used in the research, of which 63,721 were Pand 49,307 were S-rays from more than 14,000 earthquakes registered by 418 stations in Kyrgyzstan and neighboring regions. The observation network and distribution of the earthquakes are shown in Figure 3.

Three-dimensional velocity models were obtained by means of the LOTOS nonlinear algorithm for passive seismic tomography (Local Tomography Software [72]), which is freely available on the Internet. Previously, the algorithm was successfully applied by the co-authors to study diverse collision zones [10,14,73,74].



Figure 3. Observation network: earthquakes (red dots), stations (blue triangles) and rays (gray lines).

Method. Before getting down to the inversion, we preliminarily determined the optimal 1D reference model. The P- and S-wave velocities were chosen at certain levels, between which the velocity variations were linear. The 1D models from the previous studies of Tien Shan region such as [10,75], two models from [76] were compared. Moreover, new reference models, similar to the ones listed above, were made up. To find the optimal reference model, we identified the source locations for several 1D velocity models in the first iteration and created tables with misfits and data amounts for all the models. As the optimal reference model, we chose the one with the smallest misfit and the largest number of peaks and events. Its parameters are shown in Table 1.

Depth, km	Vp, km/s	Vs, km/s
-4	3.5	2.78
6	5.7	3.35
21	6.2	3.5
65	6.9	3.8
120	7.8	4.2

The LOTOS algorithm implies several successive steps. Before the tomographic inversion, the dataset was obtained after applying two criteria. The first was discarded data with fewer than a total of 8 P and S picks per event. Then at the stage of determining the preliminary source locations in the initial 1D velocity model, the data with residuals exceeding 1 s were removed. The first step of the algorithm consists in a preliminary localization of earthquakes in a 1D velocity model with the use of the stable grid-search

method, which allows a solution to be found even in the absence of a priori information on the source coordinates. In the second step, the sources are localized in a 3D model. At this step, the gradient optimization method is employed, which provides fast enough computations of the most likely source location. The travel times are calculated through the 3D ray tracer based on the principle of least time (Fermat principle), as in the code proposed by [77]. In the third step, a parametrization grid is constructed in the first iteration to describe 3D distributions of the velocity anomalies. To avoid artifacts associated with the grid geometry, the inversion is performed on four grids with different orientations (0, 22, 45, 66 degrees), providing the optimal azimuthal coverage. After inverting on all four grids, the

for the source parameters, P- and S-wave anomaly distributions and station corrections. The matrix inversion was conducted with the LSQR algorithm [78]. Its stability was regulated by amplitude damping and flattening, which minimize discrepancies between the solutions in neighboring nodes. The LOTOS code makes it possible to regularize amplitudes of the anomalies and adjust smoothing in both the vertical and horizontal direction. The optimal values of the smoothing factors along with the weighting factors for the station and source corrections were specified after several numerical simulations.

results are averaged into a unified model. The algorithm provides simultaneous inversion

Seismic Tomography Results

As the inversion result, we obtained 3D tomographic models of the P- and S-velocity anomalies, which were presented in four horizontal sections (Figure 4) and four vertical (Figure 5). Translucent shaded areas in Figures 4 and 5 cover parts of the study area with poor resolution. The three vertical sections 300 km long were built along the meridians 74°, 75° and 76°, partially overlapping the MTS Kekemeren (74°) and Naryn (76°) profiles. The fourth profile, which was 500 km long, was constructed across the aforementioned sections. The positions of the seismic tomography profiles and their intersections with the MTS profiles are shown in Figure 1.



Figure 4. P- and S-velocity anomalies in the horizontal sections.



Figure 5. P- and S-velocity anomalies in the vertical sections.

Model validation. Before interpreting the results, it is necessary to understand which of the anomalies are reliable and which should not be trusted, due to the peculiarities of the observation network resolution.

One of the arguments in favor of the reliability of seismic tomography results are similar structures of the P- and S-velocity anomalies. In our case, the P- and S-anomalies had very similar configurations, which may indicate the credibility of the inversion results. It should be realized that this rule holds for large objects such as tectonic blocks, faults and large sedimentary basins. Small anomalies that do not correlate with each other may be artifacts.

To check the resolution of the model, we carried out a number of synthetic tests such as the test with even-numbered and odd-numbered sources and the checkerboard test with different sizes of specified anomalies.

When conducting the test with even/odd-numbered sources, inversion results for two independent data groups are juxtaposed, which makes it possible to estimate how random noise and data errors affect the result. All data are divided into two equal groups with even-numbered and odd-numbered sources. Full inversion is performed for these groups, using the same parameters and algorithms as for the complete dataset. The results of the test with even and odd events for our case are depicted in Figure 6. It can be seen that all the large anomalies were distinguished quite confidently in both models, which indicates their reliability. The smaller anomalies characterized by differences were probably artifacts and were not considered in the interpretation.



Figure 6. Test with even and odd events in the horizontal sections. The depth is 30 km.

Figure 7 illustrates the results of the traditional seismic tomography checkerboard test aimed at assessing the spatial resolution of the observation system and, accordingly, the model. In the synthetic test, positive and negative various-size anomalies with an amplitude of 5% were set: 30×30 km, 50×50 km and 80×80 km. The inversion of the synthetic checkerboard model was performed with the same observation system that was used for the field data inversion.



Figure 7. Checkerboard test with the anomalies 30×30 , 30×30 , 50×50 and 80×80 km.

The data catalogue utilized in this investigation contained more P-wave arrival times than for S-waves. Correspondingly, the resolution of the model with P-velocity anomalies was higher than that of the S-velocity model. As seen in Figure 3, the highest ray density was evidenced in the central and northern parts of Kyrgyzstan, which was due to the location of the greater part of the KNET seismic station network. Respectively, the resolution of the model in this part was the highest. As follows from the checkerboard test, the anomalies with a lateral size from 30 km were well reconstructed to a depth of 10-20 km in the northern part of Kyrgyzstan, while at depths of 30 and 40 km, anomaly amplitude attenuation and blurring took place. The checkerboard anomalies with a lateral size of 50 km were reliably evaluated throughout the study area up to a depth of 40 km.

To check the depth resolution of the observation network, we carried out a synthetic test for vertical sections with realistic anomalies. Figure 8 gives the results for two synthetic models along profile 1. In the first model (vertical sections on the left in Figure 8), a sandwich structure was defined, which was an alternation of anomalies (from top to bottom): a high-velocity near-surface anomaly with an amplitude of 8% and a thickness of 5 km, a low-velocity anomaly with an amplitude of 8% and a thickness of 10 km at a depth of ~20 km and a tilted southward high-velocity anomaly with an amplitude of 10% at a depth of ~40 km. The second model contained only two layers: a high-velocity layer with a thickness of 15 km and an amplitude of 5%, underlain by a low-velocity layer with a thickness of 5 km and an amplitude of 9%.

The simulation results showed that up to a depth of 30 km, the blurring of the rays was not significant. Accordingly, it is certain that the near-surface anomaly had approximately the same size that we saw in the models obtained, that is, ~15–20 km. Consistent with the synthetic model 2 in Figure 8 (on the right), we found that the ray configuration "blurred" the anomalies deeper than 30 km. For instance, the low-velocity thin 5 km layer set at a depth of 30 km was reconstructed as a large low-velocity anomaly with a thickness of at least 40 km. By using the model 1, it was discovered that under the low-velocity anomaly, there was a high-velocity structure tilting beneath the Middle Tien Shan from the north to south. This conclusion is in agreement with the existing hypotheses on the immersion of the Kazakhstan–Junggar plate under the Tien Shan. It also followed from model 1 that



the low-velocity block was no more than 15–20 km thick, since at a larger thickness the anomaly was blurred to depth. In addition, the low-velocity anomaly was found to lie subhorizontally at a depth of \sim 20 km.

Figure 8. Two synthetic tests with the realistic anomalies set for the vertical Section 1, the same as in Figure 5. Above: parameters of the synthetic models, in the middle and below: reconstruction results for the P- and S-velocity anomalies.

Description of the seismic tomography results. Taking into account the analysis of all the test results, it is possible to draw conclusions and interpret the velocity anomalies in the model obtained from the field data.

In the horizontal sections of the model (Figure 4), there is a clearly visible high-velocity anomaly in the northern part of the study area in Kazakhstan. This anomaly, most likely, characterizes the structure of the consolidated block of the Kazakhstan-Junggar plate. The authors came to a similar conclusion in [10,14]. Additionally, according to the horizontal sections, at a depth of 20 km beneath the Northern Tien Shan there is a large low-velocity anomaly with dimensions of ~150 km from the north to south and 220 km from the west to east up to the Issyk-Kul basin. This anomaly is also traced in the vertical sections (Figure 5) at a depth of 20 km, its thickness being ~15-20 km. Moreover, the sections demonstrate that above the anomaly under consideration, there is a near-surface high-velocity anomaly ~20 km thick. This anomaly is observed in all four presented vertical sections and has a maximum size of ~150 km from the north to south and ~300 km from the west to east. In the vertical sections 1 and 2 (Figure 5), the considered near-surface high-velocity anomaly is isolated by two small near-surface low-velocity anomalies from the north and south. The horizontal section in Figure 5 shows that these anomalies are located at the northern and southern boundaries of the Issyk-Kul microcontinent. The northern low-velocity anomaly is highly blurred due to the insufficient data density, which is confirmed by the simulation results in Figure 8.

At depths exceeding 30 km, the northern parts of the vertical sections 1-3 are characterized by a high-velocity anomaly with a downward trend from the north to south.

One might assume that this anomaly is associated with the plunging Tarim continent, whose marginal part can be traced under the Southern Tien Shan. In the southern parts of the vertical sections 1–3, as noted above, there is a high-velocity anomaly confined to the submerging Kazakhstan–Junggar plate.

The interpretation is presented further in more detail after a comprehensive analysis of the MTS and ST results.

4. Magnetotelluric Studies

Since the mid-1980s, MTS has been carried out along the Kekemeren and Naryn geotraverses, intersecting the Middle Tien Shan along 74° and 76° E, respectively, which is across the strike of the main structures. In Figure 1, the positions of these profiles are schematically drawn in pink. The main aim of the MT soundings is to study the junction zone of the Tarim and the Tien Shan and the depth structure of the intramontane and intermontane troughs, and to clarify the nature of the crustal electrical conductivity. To date, a sufficiently large volume of the field research results has been accumulated, along with the constructed geoelectric and velocity models of the depth structure of the Tien Shan [12,24,27,28,36,79–83]. In our article, we consider the MTS results along the Naryn and Kekemeren profiles, described in [24,82] and [27,82,84,85], respectively.

4.1. Magnetotelluric Data and Method

The MTS method differs from other electrical prospecting methods in its greater depth, environmental friendliness, low cost of surveys and portability of the equipment employed. This is because MTS implies using the natural electromagnetic field of the earth as a source and, therefore, there is no need for high-power generating units. At the same time, the method has the most developed apparatus for data analysis and interpretation, including the case of complex 3D inhomogeneous media. The disadvantage of MTS is its high sensitivity to various kinds of interference, which is overcome by means of unconventional approaches to data processing, for example, the remote reference.

Different MTS modifications involve the electromagnetic field registration in the range from 0.01 to 20,000 s. At each point, five components (Ex, Ey, Hx, Hy, Hz) of the magnetotelluric field are recorded. The electric field components in the mountainous conditions of the Tien Shan were measured with a five-electrode cross-shaped installation consisting of electric dipoles 50 m long. Special non-polarizable electrodes developed by the Research Station of the Russian Academy of Sciences in Bishkek (Kyrgyzstan) were used for grounding. The magnetic field components were registered via inductive sensors. Taking into consideration the presence of sublatitudinal geological structures of the Tien Shan, the electric and magnetic field sensors were oriented along the geographic meridian and perpendicular to it (azimuths 0° and 90°, respectively), i.e., along and across the main strike directions of the geological structures.

Software based on the correlation method was applied to process the data from the Phoenix MTU-5A station. It calculated the cross-correlation functions of all the field components. Next, the Fourier transform was carried out, which resulted in computing the power spectra in a wide frequency range, which were then converted into the impedance tensor components. Interpretation included data analysis for the purpose of suppressing the influence of near-surface heterogeneities in order to determine the dimension of the interpretation model. A solution of the inverse problem was sought by the fitting method in the class of 2D geoelectric models [85].

4.2. The Naryn Profile

The Naryn profile (76°), given in Figure 9a, occupies a central position among the series of regional magnetotelluric and magnetovariational profiles of the Tien Shan and is the longest one—it extends from Lake Balkhash (Kazakhstan) in the north to Kashgar city (China) in the south. The results of the field data inversion and interpretation were published in [12,23,27,33,80,86,87]. The main data set for simulation included 42 soundings

performed by the TIS-2 (observation points 182–144) and MT-PIK (observation points 435–441) stations. The inversion results and their analysis are presented in [23,27], where the key features of the depth geoelectric structure of the crust in the study area are given. In our work, we used the model [82] supplemented by the data from 14 deep MTS sites. The observations at each sounding point were taken for 3–4 weeks with a step of 20–30 km along the profile, which enabled a stable geoelectric model to be obtained to a depth of 140 km. In order to improve the field data quality, 2 points of synchronous observations were organized, which made it possible to process the sounding results through the remote reference technique. At each sounding point, also conducted were the detailed shallow investigations with the MT-24 system. Thus, the combined sounding range was 0.003–16.000 s. The obtained data array was complemented with the observation points 601–605 in China, where the measurements were performed with the Phoenix (Canada) equipment (16–16.000 s).



Figure 9. (a) Geoelectric section along the MTS Naryn profile [80]; (b) geoelectric section along the MTS Kekemeren profile [82]. Lines at Naryn profile indicate faults.

A detailed analysis of the depth geoelectric model indicated significant electrical conductivity variations not only in the crust, but also in the upper mantle. The upper part of the crust, confined below by the crustal conductive layer, has a block structure complicated by numerous faults. The deep-seated fault structures of various lengths present in the geoelectric model (with blurred geoelectric boundaries) correlated well with geological objects, for example, in [88]. In terms of geoelectrics, the most complex depth structure was observed in the Naryn Depression, limited in the north by the most important tectonic element of the Tien Shan—the Nikolaev Line fault zone, separating the Northern and Middle Tien Shan. The conductivity anomalies, possibly associated with graphitized shales confined to the Nikolaev Line, were evidenced at points 504 and 505 (Figure 9a). The suture zone formations, which include the Nikolaev Line fault zone, were characterized by the presence of such rocks as graphitic shales, which have increased electrical conductivity. Subvertical conductive structures were characteristic of the upper and middle crust; at

certain depths, they flatten out and often take the form of listric faults. The largest of them are limited to the central part of the profile and concentrated in the Naryn Depression and under the Kyrgyz Range. In the lower part of the crust, the crustal conductive layer is strongly pronounced, its resistivity decreasing from the north to south from 350–300 ohm to 5–20 ohm.

4.3. The Kekemeren Profile

The Kekemeren profile (74°). The immediate task of the geophysical surveys at the Kekemeren profile consisted of identifying and tracing the differentiation of physical properties and local inhomogeneities in the crustal structure. In our research, we considered a part of the Kekemeren profile—from the observation point 828 to 571. One of the newest models obtained from the profile [84] is shown in Figure 9b. This is the MTS model under the points 828–842 in the central part of the Kekemeren profile, with a length of approximately 200 km. The corresponding data set comprised the results of 14 long-period soundings (sounding periods 0.1–3.000 s) measured by the Phoenix MTU-5 station. The 2D inversion results of the highest-quality data from 22 wide-range soundings obtained with the TIS-2 equipment (sounding periods 0.1–1.600 s) along the entire regional profile over 400 km in length are presented in [27].

The model [84] revealed a number of anomalous zones under the sounding points 833–835 and 840–842, characterized by increased conductivity. As in the case of the Naryn profile, these anomalies were confined to the fault zones. Additionally, in the lower crust under the Kekemeren profile there was a clearly manifested high-conductivity saddle-shape layer. Varying from several ohm to 100 ohm, the resistivity of this structure corresponded to both the subvertical zones of increased electrical conductivity associated with faults and crustal conductive layers. Abnormally high electrical conductivity values under the point 835 and near 842 can be associated with graphitized formations, for instance, graphite-containing shales, the resistivity of which can range from several ohm to a fraction of an ohm.

5. Comparison of the MTS and Seismic Tomography Results

Let us consider the acquired geophysical models and the feasibility of their application to determine the features of the depth structure of the Tien Shan and surrounding territories.

Figure 10a,b shows a comparison of the results obtained for the Naryn (76°) and Kekemeren (74°) profiles by MTS (black-and-white models) and ST (color models). For the ease of comparison, the models were drawn to the same scale. The models in Figure 10a,b indicate that the same anomalies were observed along both the Kekemeren and Naryn profiles. The profiles have a submeridional strike and run parallel to each other; therefore, the observed velocity inhomogeneities referred to the same geological objects.

Figure 11a gives the result of superposing the main ST anomalies (highlighted in color) on the MTS anomalies from the Kekemeren profile (black-and-white). Among the observed heterogeneities obtained using both methods, four main similar structures could be distinguished:

- (1) In the ST models, there was a discernable high-velocity near-surface anomaly (Figure 10 a,b) corresponding to the MTS anomaly with the electrical resistivity $\rho \approx 10^2$ ohm. In Figure 11a, this anomaly is in light-blue color.
- (2) Subsequent to the tomographic inversion results, a low-velocity anomaly with a thickness of ~20 km was distinguished at a depth of ~20 km (Figure 10b). In the MTS models, this anomaly was present as a highly conductive saddle-shaped layer with the resistivity $\rho \approx 10$ –100 ohm and a thickness of ~15–20 km. In Figure 11a, this anomaly is shown in red.
- (3) The locations of the low-velocity near-surface seismic anomalies in the northern and southern parts of the vertical profiles coincided with those of the anomalously conductive subvertical structures ($\rho \approx 0.1$ ohm) found according to the MTS results

beneath the points 835 and 842. In Figure 11a, these anomalies are highlighted in yellow.

- (4) At a depth of ~40 km in the southern part of the Kekemeren profile, there was a high-velocity ST anomaly, which coincided with the MTS anomaly having $\rho >> 10^3$ ohm. In Figure 11a, this anomaly is marked in blue.
- (5) In the northern part of the Naryn profile (Figure 10a) under the observation point 510 (Kyrgyz Range) in the 30 km depth, an anomaly with $\rho > 10^3$ ohm was distinct, which coincided with the high-velocity anomaly. Both anomalies have the same shape and plunging trend from the north to south. In Figure 11a, this anomaly is in blue color.



Figure 10. Comparison of the MTS (black-and-white models) and ST (color models) results at the Naryn (**a**) and Kekemeren (**b**) profiles.





In the example of the Kekemeren profile (Figure 11a) it is apparent that the structures obtained by the results of the two independent geophysical methods were, in general, similar. However, there were some differences:

- (1) The near-surface anomaly with $\rho \approx 10^3$ ohm, as follows from the geoelectric model, occurred to a depth of about 30 km, while the seismic velocity anomaly (light-blue in Figure 11a) had a thickness of only ~15–20 km and lay subhorizontally.
- (2) The derived from the MTS results lower-crustal low-resistivity anomaly with a thickness of ~20 km had a saddle-like shape, whereas the seismic velocity anomaly was subhorizontal (red anomaly in Figure 11a).

The validity of comparing the anomalies of electrical conductivity and elastic properties in the lithosphere is primarily due to their common nature and relies on the features of the rheological state of the environment. The good agreement between quantitative geoelectric and seismic estimates of volumetric porosity for the conductive and low-velocity layers of the crust is a strong argument in favor of the fluid concept of crustal conductivity.

The differences in the considered models can be associated with insufficient resolution of one or both. The accuracy of solving the inverse problem depends on the density of the seismic network and the uniformity of the location of stations, which is extremely difficult to do in the mountainous conditions of the Tien Shan. Therefore, there may be inconsistencies when comparing models in those areas where there is a large step between magnetotelluric soundings or a sparse seismic network. Differences in geophysical models may also be due to the methods considering different physical properties of rocks. In particular, the presence of a fluid component in microcracks and pores will show low-resistivity but low-velocity anomalies.

Thus, the near-surface anomalies with low seismic velocities and high electrical conductivity in the northern and southern parts of the presented Kekemeren section are most likely associated with the fault zones. In accordance with the locations of the tectonic units shown in Figure 1, we may deduce that the northern anomaly under the point 842 is confined to the foothills of the Tien Shan from the side of the Kazakhstan-Junggar plate, where the Kyrgyz–Kungei fault passes. At the same time, the southern low-velocity anomaly (point 835) is associated with the Nikolaev Line fault zone, dividing the Middle and Southern Tien Shan. Drawing from the geological data [88,89], the Southern Tien Shan is characterized by the prevailing thrust faults with a sublatitudinal orientation and S-N dipping trend. In the Northern Tien Shan, thrust faults tend to dip in the N–S direction, which indicates a predominance of the compression mechanism in the region. Therefore, the observed low-velocity anomalies are likely to be attributed to the large fault zones detaching the Middle Tien Shan. Anomalies of increased conductivity, obtained from MTS data, are often confined to zones of dynamic influence of faults, since such areas are characterized by a high fluid saturation. This is exactly what we have in the case under discussion.

The lower-crustal low-velocity ST anomaly located at a depth of ~20 km coincides with the highly conductive saddle-shaped MTS anomaly ($\rho \approx 10$ –100 ohm). The MTS models clearly demonstrate the relationship of this anomaly with the near-surface highly conductive anomalies associated with the fault zones. The horizontal ST section (Figure 5) indicates that the boundaries of this anomaly coincide with those of the Central Tien Shan (Issyk–Kul) microcontinent. We assume that the anomaly corresponds to the Precambrian mica-bearing granite–gneisses and metamorphic rocks, which are characterized by a strong fracturing and high fluid saturation. Such rocks build up the lower part of the microcontinent. Numerous laboratory studies have shown that the high electrical conductivity of the lower crust can be explained by the P–T conditions existing there, which leads to the release of the chemically bound water. Its volume can reach only 1% of the total volume of the substance; however, the electrical conductivity of the rock increases by several orders of magnitude. According to [27], the bound water content reaches its maximum at depths of 20–30 km.

Concerning the lower-crustal anomaly, note that the differences in its shape in the MTS and ST sections are due to the peculiarities of the methods, as well as the mineral compositions of the rocks in the lower crust. For instance, the volumetric content of graphite matter of even about 1% can cause a decrease in the resistivity of the rocks by several orders of magnitude. At the same time, this will not affect the results of ST.

The near-surface subhorizontal high-velocity anomaly is located above the lowercrustal anomaly and is detached in the north and south by the fault zones confined to the Middle Tien Shan boundaries. The upper part of the Precambrian microcontinent is associated with basic rocks of the Early Paleozoic volcanic–plutonic association, which are characterized by high density values [60]. Thus, the observed seismic anomaly coinciding with the electrical resistivity anomaly $\rho >> 10^2$ ohm is most likely to be related to the presence of a large number of intrusive bodies in the upper crust. Conventionally, an object with a resistivity of several tens of ohms is considered to be a good conductor. In the present case, such resistivity results from a large number of microcracks in the upper crust [27], which the ST method appears not to be sensitive to.

Two high-velocity anomalies are also of great interest. One of them, coinciding with the highly resistive feature ($\rho > 10^3$ ohm) observed below the points 509–511, is clearly manifested in the ST model in the northern part of the Naryn profile (Figure 10a). The second high-velocity ST anomaly, located at a depth of 40 km in the southern part of the Kekemeren profile (Figure 10b), is also prominent as the resistivity anomaly ($\rho > 10^3$ ohm) under the points 832–836. According to the evidenced geophysical properties, we suppose these structures to belong to continental blocks. The first anomaly, located to the north

of the Kyrgyz–Kungei fault, most likely refers to the submerged part of the Kazakhstan– Junggar plate. The second one, situated underneath the Southern Tien Shan, is connected with the submerged part of the Tarim plate. In Figure 11a, these anomalies are shown in blue.

We created the interpretation scheme of the depth structure in the study region (Figure 11b). This figure to the depth of 60 km is based on the detailed analysis of the ST and MTS models. The image of the mantle part of lithosphere was based on result of regional tomography from [10].

It should be noted that the structure of this region characterized by three differentaged multifold segments is pronounced in the distributions of the geophysical anomalies presented in this work. Among the clearly recognizable main geological objects are the Precambrian Central Tien Shan (Issyk-Kul) microcontinent and the overlying Early Paleozoic volcanic-plutonic complex in the Middle Tien Shan, together with the Tarim and Kazakhstan–Junggar plates submerged under the Tien Shan. The submerged parts of the Kazakhstan-Junggar and Tarim plates involve increased seismic velocities in the ST models and high-resistivity anomalies present in the MTS models. The Middle Tien Shan, represented by the Precambrian Central Tien Shan (Issyk-Kul) microcontinent, manifests itself in the form of two anomalies, each ~20 km thick: low-velocity high-resistivity at the surface, and high-velocity low-resistivity at a depth of ~30 km. It is dictated by the complex heterogeneous structure of the crust, in which there are volcanic-plutonic bodies at the surface and a fragmented fluid-saturated lower layer consisting of the Precambrian granite-gneisses at the depth. The zones of collision of the Kazakhstan-Junggar and Tarim plates with the Tien Shan are expressed in the geophysical models as low-velocity ST and high-conductivity MTS anomalies, which undoubtedly indicates a high content of sedimentary rocks and the presence of fluid-saturated fault structures. Presumably, the fluid saturation of the lower-crustal highly conductive layer occurs along these faults detaching the Precambrian microcontinent.

6. Discussion

The structural features of the crust under the Tien Shan highlighted in the previous section are of key importance for the global depth geodynamics of the region, which has been studied mainly by the teleseismic and mathematical simulation methods. Subsequent to the teleseismic results [5-10], there is a low-velocity anomaly in the upper mantle under the Kyrgyz Tien Shan. It is attributed to the absence of the mantle part of the lithosphere, which can also be called the opening of the lithospheric window. The reason for the opening, according to the above-listed works, is the immersion of the mantle part of the lithosphere (delamination) of the Tarim and Kazakhstan-Junggar plates, whose traces were also evidenced in these investigations. The question of what caused the delamination under the Tien Shan collision zone remains open. There is a hypothesis for the occurrence of the delamination process due to the eclogitization in the lower crust [90–92]; every 10% of the formed eclogites lead to an increase in the density of the lower crust material by about 1%, which may lead to instability in the crust. The heavy material of the lower crust becomes a trigger for the immersion of the mantle part of the lithosphere into the mantle. However, the formation of eclogites is possible only under certain P-T conditions achieved in case where the lower weakly heated crust sinks to a depth of less than 50 km in the presence of fluid [90,91]. In addition to the formation of eclogites, the delamination process can be boosted by the acceleration of shortening [93,94], as well as the presence of fluid in the lower crust [95]. The higher the compression rate, the faster the phase transitions in the thickened crust evolve, leading to acceleration of the delamination process.

Some knowledge about the depth structure of the Middle Tien Shan crust testifies in favor of the "eclogite" nature of delamination. For example, according to the results of many investigations applying the receiver function and CDP methods, the Moho depth beneath the Middle Tien Shan is maximal and amounts to 55–65 km [11–14]. Moreover, in this research we witnessed the lower-crustal low-velocity high-conductivity layer apparently

having a high fluid saturation. As described above, the appearance of fluid in the lower crust could have occurred in consequence of deep faults at the boundaries of the Middle Tien Shan, which have a trend of subsiding under the latter. In addition, as described in [27], the P–T conditions at a depth of 20–30 km lead to the release of the chemically bound water. The Moho depth over 55 km and the presence of fluid are essential for the formation of eclogites.

As for the compression speed, GPS data denote that the present-day collision processes in the Kyrgyz Tien Shan have a rate of 1–1.5 cm/year [96]. However, it is exceedingly difficult to assess at what rate the convergence took place 20 Ma, when the Tarim plate began to plunge under the Tien Shan. As long as the Tarim plate submerged beneath the Southern Tien Shan by more than 200 km [10], we can assume that since the collision (~20 Ma), the Tarim plate has been moving at an average rate of 1 cm/year. As it follows from the mathematical simulation of collision processes [97], in order for delamination to occur, the convergence rate should be at least 0.6–1 cm/year. Thus, the estimated speed of the Tarim plate is sufficient for the delamination process to take place. Nevertheless, so as to understand exactly how the separation and immersion of the mantle part of the lithosphere occurred, it is necessary to perform a thorough mathematical simulation of the process, taking into account all key parameters.

At the moment, all the facts testify in favor of the "eclogite" nature of delamination under the Kyrgyz Tien Shan. Therefore, we suppose that the presence of the fluid-saturated layer in the crust of the Central Tien Shan (Issyk–Kul) microcontinent could play a critical part in the delamination of the mantle part of the lithosphere, which led to the opening of the lithospheric window.

7. Conclusions

In the presented research, we obtained new seismic tomography results beneath the Middle Tien Shan. For a deeper understanding of the observed structures, the obtained velocity models were compared with the results of magnetotelluric soundings along the Kekemeren and Naryn profiles, crossing the Tien Shan in the sublatitudinal direction. When analyzing the results acquired by the two methods, we revealed that the velocity characteristics and geoelectric properties correlate with each other: the structures with high electrical conductivity in the geoelectric sections coincide with the low-velocity objects in the seismic tomography models, and vice versa, the areas with low electrical conductivity are consistent with the high-velocity structures.

By juxtaposing the resistivity models and seismic tomography models, the following features were identified:

- (1) Parts of the Tarim and Kazakhstan–Junggar plates submerged under the Tien Shan are distinguished as high-velocity anomalies with resistivity $\rho \approx 10-100$ ohm.
- (2) The Nikolaev Line and Kyrgyz–Kungei fault zones, confining the Precambrian Central Tien Shan (Issyk–Kul) microcontinent, are discerned in the models in the form of low-velocity high-resistivity ($\rho > 10^3$ ohm) anomalies tending to submerge under the Central Tien Shan. The obtained features of the depth structure indicate the fluid saturation of the fault zones.
- (3) The structure of the Middle Tien Shan crust is conditioned by the presence of the Precambrian Central Tien Shan (Issyk–Kul) microcontinent, which is differentiated in the geophysical models as two anomalies lying one below the other, each having a thickness of ~20 km: the upper high-velocity anomaly with resistivity $\rho >> 10^2$ ohm, and the lower low-velocity high-conductivity anomaly with $\rho \approx 10-100$ ohm, with the exception of individual sections where $\rho \approx 0.1$ ohm.
- (4) The geophysical features of the upper anomaly in the Issyk–Kul block are likely to have resulted from the presence of the Late Ordovician and Early Silurian volcanic– plutonic intrusive bodies.

(5) The geophysical characteristics of the lower anomaly in the Issyk–Kul block are most likely to be associated with the presence of ancient granite–gneisses, which, as indicated in [27], are fluid-saturated.

In general, the structure of the study area, observed by means of magnetotelluric sounding and seismic tomography, corresponds to the main geological segments—the Tarim and Kazakhstan–Junggar plates, which plunge under the complex heterogeneous structure of the Middle Tien Shan. Consistent with the revealed features of the Middle Tien Shan geological structure, we assume that the lower-crustal low-velocity layer can make a big difference in the delamination of the mantle part of the submerged plates.

Author Contributions: I.M. obtained seismic tomography models and contributed to interpretation of the seismic tomography results; E.B. provided magnetotelluric sounding results and interpretation; M.B. provided the geodynamic model of the study region. All authors participated in discussions of the results and contributed in writing the manuscript and preparing figures. All authors have read and agreed to the published version of the manuscript.

Funding: The research was carried out with funding from the Russian Foundation for Basic Research under the scientific project No. 19-35-60002, and as part of the state assignments for IGM SB RAS (No. 0330-2016-0014), IPGG SB RAS (No. 0331-2019-0010) and RS RAS (No. AAAA-A19-119020190063-2).

Data Availability Statement: The full directory of LOTOS code with data corresponding to this study is available at https://zenodo.org/record/3992699#.YEcXiNwRVPY (accessed on 4 January 2021).

Conflicts of Interest: The authors declare no conflict of interest

References

- 1. Avouac, J.P.; Tapponnier, P.; Bai, M.; You, H.; Wang, G. Active thrusting and folding along the Northern Tien Shan, and Late Cenozoic rotation of the Tarim relative to Dzungaria and Kazakhstan. J. Geophys. Res. Solid Earth 1993, 98, 6755–6804. [CrossRef]
- Windley, B.F.; Alexeiev, D.; Xiao, W.J.; Kroner, A.; Badarch, G. Tectonic models for accretion of the Central Asian Orogenic Belt. J. Geol. Soc. 2007, 164, 31–47. [CrossRef]
- Gao, J.; Klemd, R.; Qian, Q.; Zhang, X.; Li, J.L.; Jiang, T.; Yang, Y.Q. The collision between the Yili and Tarim blocks of the Southwestern Altaids: Geochemical and age constraints of a leucogranite dike crosscutting the HP–LT metamorphic belt in the Chinese Tianshan Orogen. *Tectonophysics* 2011, 499, 118–131. [CrossRef]
- He, C.; Santosh, M.; Chen, X.; Li, X. Crustal growth and tectonic evolution of the Tianshan orogenic belt NW China: A receiver function analysis. J. Geodyn. 2014, 75, 41–52. [CrossRef]
- 5. Lei, J.; Zhao, D. Teleseismic P-wave tomography and the upper mantle structure of the central Tien Shan orogenic belt. *Phys. Earth Planet. Inter.* **2007**, *162*, 165–185. [CrossRef]
- 6. Xu, Y.; Liu, F.; Liu, J.; Chen, H. Crust and upper mantle structure beneath western China from P wave travel time tomography. *J. Geophys. Res. Solid Earth* **2002**, 107, ESE-4. [CrossRef]
- Xu, L.; Rondenay, S.; Van der Hilst, R.D. Structure of the crust beneath the southeastern Tibetan Plateau from teleseismic receiver functions. *Phys. Earth Planet. Inter.* 2007, 165, 176–193. [CrossRef]
- 8. Zhiwei, L.; Roecker, S.; Zhihai, L.; Bin, W.; Haitao, W.; Schelochkov, G.; Bragin, V. Tomographic image of the crust and upper mantle beneath the western Tien Shan from the MANAS broadband deployment: Possible evidence for lithospheric delamination. *Tectonophysics* **2009**, *477*, 49–57. [CrossRef]
- 9. Koulakov, I.Y. High-frequency P and S velocity anomalies in the upper mantle beneath Asia from inversion of worldwide traveltime data. *J. Geophys. Res. Solid Earth* **2011**, *116*. [CrossRef]
- 10. Zabelina, I.V.; Koulakov, I.Y.; Buslov, M.M. Deep mechanisms in the Kyrgyz Tien Shan orogen (from results of seismic tomography). *Russ. Geol. Geophys.* **2013**, *54*, 695–706. [CrossRef]
- 11. Vinnik, L.; Reigber, C.; Aleshin, I.; Kosarev, G.; Kaban, M.; Oreshin, S.; Roecker, S. Receiver function tomography of the central Tien Shan. *Earth Planet. Sci. Lett.* 2004, 225, 131–146. [CrossRef]
- Makarov, V.I.; Alekseev, D.V.; Batalev, V.Y.; Bataleva, E.A.; Belyaev, I.V.; Bragin, V.D.; Dergunov, N.; Efimova, N.; Leonov, M.; Munirova, L.; et al. Underthrusting of Tarim beneath the Tien Shan and deep structure of their junction zone: Main results of seismic experiment along MANAS Profile Kashgar-Song-Köl. *Geotectonics* 2010, 44, 102–126. [CrossRef]
- 13. Laverov, N.P. Present-Day Geodynamics of the Intracontinental Collisional Orogeny; Nauchnyi Mir: Moscow, Russia, 2005; pp. 1–400. (In Russian)
- Sychev, I.V.; Koulakov, I.; Sycheva, N.A.; Koptev, A.; Medved, I.; El Khrepy, S.; Al-Arifi, N. Collisional processes in the crust of the northern Tien Shan inferred from velocity and attenuation tomography studies. *J. Geophys. Res. Solid Earth* 2018, 123, 1752–1769. [CrossRef]

- 15. Chen, H.; Kosarev, G.; Roecker, S. Shear wave velocity structure at depths 0–410 km determined by the teleseismic broadband P-wavefroms in northern Pakistan and Kirghizstan. *EOS Trans. AGU* **1994**, *75*, 464.
- 16. Bump, H.A.; Sheehan, A.F. Crustal thickness variations across the northern Tien Shan from teleseismic receiver functions. *Geophys. Res. Lett.* **1998**, *25*, 1055–1058. [CrossRef]
- 17. Peive, A.V. Tectonic Stratification of the Lithosphere of the Latest Mobile Zones; Nauka: Moscow, Russia, 1982; Volume 115. (In Russian)
- 18. Bragin, V.D.; Dergunov, N.; Efimova, N.; Leonov, M.; Munirova, L.; Pavlenkin, A.; Shchelochkov, G. Tarim sinking under the Tien Shan and the deep structure of the zone of their articulation: The main results of seismic studies on the MANAS profile. *Geotectonics* **2010**, *2*, 23–42. (In Russian)
- 19. Gubin, I.E. The Tien Shan Lithosphere; Nauka: Moscow, Russia, 1986. (In Russian)
- 20. Nikolaevsky, V.N. Mechanics of Porous & Fractured-Fissured Media; Nedra: Moscow, Russia, 1984; Volume 232. (In Russian)
- 21. Krasnopevtseva, G.V. *Geologic-Geophysical Features of Low Velocity Layers in the Earth's Crust;* All-Union Scientific Research Institute of Mineral Resources Economics: Helsinki, Finland, 1978; Volume 30.
- 22. Batalev, V.Y.; Berdichevsky, M.N.; Golland, M.L.; Golubtsova, N.S.; Kuznetsov, V.A. Interpretation of the deep magnetotelluric soundings in the BChu basin. *Izv. Phys. Solid Earth* **1989**, *9*, 42–45.
- 23. Batalev, V.Y.; Volykhin, A.M.; Rybin, A.K.; Trapeznikov, Y.A.; Finyakin, V.V. The structure of the crust in the Eastern Kyrgyz Tien Shan from MTS data. In *Reflection of Geodynamic Processes in Geophysical Fields*; Nauka: Moscow, Russia, 1993; pp. 96–113. (In Russian)
- 24. Batalev, V.Y.; Bataleva, E.A.; Matyukov, V.E.; Rybin, A.K.; Egorova, V.V. The lithospheric structure of the Central and Southern Tien Shan: MTS data correlated with petrology and laboratory studies of lower-crust and upper-mantle xenoliths. *Russ. Geol Geophys.* **2011**, *52*, 1592–1599. [CrossRef]
- 25. Batalev, V.Y. Petrological interpretation of the magnetotelluric data of the depth zone of the Tarim and Tian Shan junction. *Dokl. Earth Sci.* **2011**, *438*, 588–592. (In Russian) [CrossRef]
- 26. Batalev, V.Y.; Bataleva, E.A.; Matyukov, V.E.; Rybin, A.K. Deep structure of the western area of Talas-Fergana fault because of magnetotelluric soundings. *Lithosphere* **2013**, *4*, 136–145. (In Russian)
- 27. Trapeznikov, Y.A.; Andreeva, E.V.; Batal Kissinev, V.Y.; Berdichevsky, M.N.; Vanyan, L.L.; Volykhin, A.M.; Golubtsova, N.S.; Rybin, A.K. Magnetotelluric soundings in the Kyrgyz Tien Shan. *Izv. Phys. Solid Earth* **1997**, *33*, 1–17.
- Rybin, A.K.; Batalev, V.Y.; Il'ichev, P.V.; Shchelochkov, G.G. Magnetotelluric and magnetovariational soundings of the Kyrgyz Tien Shan. *Russ. Geol. Geophys.* 2001, 42, 1485–1492.
- 29. Rybin, A.K.; Batalev, V.Y.; Bataleva, E.A.; Matyukov, V.E.; Spichak, V.V. Array magnetotelluric soundings in the active seismic area of northern Tian Shan. *Russ. Geol. Geophys.* **2008**, *49*, 337–349. [CrossRef]
- Bragin, V.D.; Batalev, V.Y.; Zubovich, A.V.; Lobanchenko, A.N.; Rybin, A.K.; Trapeznikov, Y.A.; Shchelochkov, G.G. Signature of neotectonic movements in the geoelectric structure of the crust in and seismicity distribution in the central Tian Shan. *Russ. Geol. Geophys.* 2001, 42, 1527–1537.
- 31. Bataleva, E.A.; Buslov, M.M.; Rybin, A.K.; Batalev, V.Y.; Safronov, I.V. Crustal conductor associated with the Talas-Fergana fault and deep structure of the southwestern Tien Shan: Geodynamic implications. *Russ. Geol. Geophys.* 2006, *9*, 1036–1042.
- 32. Kissin, I.G.; Ruzaikin, A.I. Relations between seismically active and electrically conductive crustal zones in the Kyrgyz Tien Shan. *Izv. Phys. Solid Earth* **1997**, *33*, 18–25.
- 33. Rybin, A.K. Deep Structure and Recent Geodynamics of the Central Tien Shan by Magnetotelluric Research Results; Nauchnyi Mir: Moscow, Russia, 2011; p. 272. (In Russian)
- 34. Dobretsov, N.L.; Buslov, M.M.; Delvaux, D.; Berzin, N.A.; Ermikov, V.D. Meso-and Cenozoic tectonics of the Central Asian mountain belt: Effects of lithospheric plate interaction and mantle plume. *Int. Geol. Rev.* **1996**, *38*, 430–466. [CrossRef]
- 35. Buslov, M.M.; De Grave, J.; Bataleva, E.A. Cenozoic tectonics and geodynamic evolution of the Tien Shan mountain belt as response to India-Eurasia convergence. *Himal. J. Sci.* **2004**, *2*, 106–107. [CrossRef]
- 36. Buslov, M.M.; De Grave, J.; Bataleva, E.A.V.; Batalev, V.Y. Cenozoic tectonic and geodynamic evolution of the Kyrgyz Tien Shan Mountains: A review of geological, thermochronological and geophysical data. *J. Asian Earth Sci.* **2007**, *29*, 205–214. [CrossRef]
- 37. De Grave, J.; Buslov, M.M.; Van den Haute, P. Distant effects of India—Eurasia convergence and Mesozoic intracontinental deformation in Central Asia: Constraints from apatite fission-track thermochronology. *J. Asian Earth Sci.* 2007, 29, 188–204. [CrossRef]
- Dobretsov, N.L.; Buslov, M.M.; Vasilevsky, A.N. Geodynamic Complexes and Structures of Transbaikalia: Record in Gravity Data. *Russ. Geol. Geophys.* 2019, 60, 254–266.
- 39. Buslov, M.M. Geodynamic nature of the Baikal Rift Zone and its sedimentary filling in the Cretaceous–Cenozoic: The effect of the far-range impact of the Mongolo-Okhotsk and Indo-Eurasian collisions. *Russ. Geol. Geophys.* **2012**, *53*, 955–962. [CrossRef]
- 40. De Grave, J.; Buslov, M.M.; Van den Haute, P. Intracontinental deformation in central Asia: Distant effects of India–Eurasia convergence revealed by apatite fission-track thermochronology. *Himal. J. Sci.* 2004, 2, 121–122. [CrossRef]
- 41. De Grave, J.; Buslov, M.; Van den Haute, P.; Metcalf, J.; Batalev, V. From Palaeozoic Eurasian assembly to ongoing Indian indentation: Multi-chronometry of the northern Kyrgyz Tien Shan batholith. *J. Asian Earth Sci.* **2006**, *26*, 133.
- 42. De Grave, J.; Buslov, M.M.; Van den Haute, P.; Dehandschutter, B. Meso-Cenozoic evolution of Mountain range—Intramontane basin systems in the southern Siberian Altai Mountains by apatite fission–track thermochronology. J. Asian Earth Sci. 2007, 29, 2–9.

- 43. De Grave, J.; Buslov, M.M.; Van den Haute, P.; Dehandschutter, B.; Delvaux, D. Meso-Cenozoic evolution of Mountain Range— Intramontane basin systems in the Southern Siberian Altai Mountains by apatite fission-track thermochronology. In *Trust Belts and Foreland Basins: From Fold Kinematics Hydrocarbon Systems*; Springer: Berlin/Heidelberg, Germany, 2007; Volume 24, pp. 457–490.
- 44. De Grave, J.; Van den Haute, P.; Buslov, M.M.; Dehandschutter, B.; Glorie, S. Apatite fission-track thermochronology applied to the Chulysman Plateau, Siberian Altai Region. *Radiat. Meas.* **2008**, *43*, 38–42. [CrossRef]
- 45. De Grave, J.; Glorie, S.; Buslov, M.M.; Izmer, A.; Fournier-Carrie, A.; Elburg, M.; Batalev, V.Y.; Vanhaeke, F.; Van den Haute, P. The thermo-tectonic history of the Song-Kul Plateau, Kyrgyz Tien Shan: Constraints by apatite and titanite thermo-chronometry and zircon U/Pb dating. *Gondwana Res.* 2011, 20, 745–763. [CrossRef]
- 46. De Grave, J.; Glorie, S.; Zhimulev, F.I.; Buslov, M.M.; Elburg, M.; Vanhaecke, F.; Van den Haute, P. Emplacement and exhumation of the Kuznetsk-Alatau basement (Siberia): Implications for the tectonic evolution of the Central Asian Orogenic Belt and sediment supply to the Kuznetsk, Minusa and West Siberian Basins. *Terra Nova* 2011, 23, 248–256. [CrossRef]
- 47. De Grave, J.; Glorie, S.; Ryabinin, A.; Zhimulev, F.I.; Buslov, M.M.; Izmer, A.; Elburg, M.A.; Vanhaecke, F. Late Palaeozoic and Meso-Cenozoic tectonic evolution of the southern Kyrgyz Tien Shan: Constraints from multimethod thermochronology in the Trans-Alai, Turkestan-Alai segment and the southeastern Ferghana Basin. *J. Asian Earth Sci.* **2012**, *44*, 149–168. [CrossRef]
- 48. De Grave, J.; Glorie, S.; Buslov, M.M.; Stockli, D.F.; Mcwilliams, M.O.; Batalev, V.Y.; Van den Haute, P. Thermo-tectonic history of the Issyk-Kul basement (Kyrgyz Northern Tien Shan, Central Asia). *Gondwana Res.* 2013, 23, 998–1020. [CrossRef]
- Glorie, S.; De Grave, J.; Buslov, M.M.; Elburg, M.A.; Stockli, D.F.; Gerdes, A.; Van den Haute, P. Multimethod 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]
- Glorie, S.; De Grave, J.; Buslov, M.M.; Zhimulev, F.I.; Stockli, D.F.; Batalev, V.Y.; Izmer, A.; Van den Haute, P.; Vanhaecke, F.; Elburg, M.A. Thermotectonic history of the Kyrgyz South Tien Shan (Atbashi-Inylchek) suture zone: The role of inherited structures during deformation-propagation. *Tectonics* 2011, *30*, 6016. [CrossRef]
- Glorie, S.; De Grave, J.; Buslov, M.M.; Zhimulev, F.I.; Elburg, M.A.; Van den Haute, P. Structural control on Meso-Cenozoic tectonic reactivation and denudation in the Siberian Altai: Insights from multi-method thermochronometry. *Tectonophysics* 2012, 544–545, 75–92. [CrossRef]
- 52. Allen, M.B.; Windley, B.F.; Zhang, C. Palaeozoic collisional tectonics and magmatism of the Chinese Tien Shan, Central Asia. *Tectonophysics* **1993**, *220*, 89–115. [CrossRef]
- 53. Jun, G.; Maosong, L.; Xuchang, X.; Yaoqing, T.; Guoqi, H. Paleozoic tectonic evolution of the Tienshan Orogen, northwestern China. *Tectonophysics* **1998**, *287*, 213–231. [CrossRef]
- 54. Chen, C.; Lu, H.; Jia, D.; Cai, D.; Wu, S. Closing history of the southern Tianshan oceanic basin, western China: An oblique collisional orogeny. *Tectonophysics* **1999**, *302*, 23–40. [CrossRef]
- 55. Brookfield, M.E. Geological development and Phanerozoic crustal accretion in the western segment of the southern Tien Shan (Kyrgyzstan, Uzbekistan and Tajikistan). *Tectonophysics* **2000**, *328*, 1–14. [CrossRef]
- 56. Laurent-Charvet, S.; Charvet, J.; Shu, L.; Ma, R.; Lu, H. Palaeozoic late collisional strike-slip deformations in Tianshan and Altay, Eastern Xinjiang, NW China. *Terra Nova* **2002**, *14*, 249–256. [CrossRef]
- 57. Van der Voo, R.; Levashova, N.M.; Skrinnik, L.I.; Kara, T.V.; Bazhenov, M.L. Late orogenic, large-scale rotations in the Tien Shan and adjacent mobile belts in Kyrgyzstan and Kazakhstan. *Tectonophysics* **2006**, *426*, 335–360. [CrossRef]
- 58. Yang, T.N.; Wang, Y.; Li, J.Y.; Sun, G.H. Vertical and horizontal strain partitioning of the central Tianshan (NW China): Evidence from structures and 40Ar/39Ar geochronology. *J. Struct. Geol.* 2007, *29*, 1605–1621. [CrossRef]
- 59. Alexeiev, D.; Cook, H.E.; Djenchuraeva, A.V.; Mikolaichuk, A.V. The stratigraphic, sedimentological and structural evolution of the southern margin of the Kazakhstan continent in the Tien Shan Range during the Devonian to Permian. *Geol. Soc. Lond. Spec. Publ.* **2017**, *427*, 231–269. [CrossRef]
- 60. Biske, Y.S.; Seltmann, R. Paleozoic Tian-Shan as a transitional region between the Rheic and Urals-Turkestan oceans. *Gondwana Res.* **2010**, *17*, 602–613. [CrossRef]
- 61. Bakirov, A.B.; Maksumova, R.A. Geology and evolution of the Tien Shan lithosphere. Russian Geol. Geofiz. 2001, 42, 1435–1443.
- 62. Maksumova, R.A.; Jenchuraeva, A.V.; Berezansky, A.V. Major tectonic units and evolution of the Tien Shan orogen. In *Paleozoic Geodynamics and Gold Deposits in the Kyrgyz Tien Shan, Proceedings of the IGCP 373 Field Conference, IAGOD Guidebook Series 9, London, UK, 16–25 August 2001*; Seltmann, S., Jenchuraeva, R., Eds.; Natural History Museum: London, UK, 2001; pp. 17–20.
- 63. Buslov, M.M.; Klerkx, J.; Abdrakhmatov, K.; Delvaux, D.; Batalev, V.Y.; Kuchai, O.A.; Dehandschutter, B.; Muraliev, A. Recent strike-slip deformation of the northern Tien Shan. In *Intraplate Strike-Slip Deformation Belts*; Storti, F., Holdsworth, R.E., Salvini, F., Eds.; Geological Society, Special Publications: London, UK, 2003; Volume 210, pp. 53–64.
- 64. Wang, B.; Chen, Y.; Zhan, S.; Shu, L.; Faure, M.; Cluzel, D.; Charvet, J.; Laurent-Charvet, S. Primary Carboniferous and Permian paleomagnetic results from the Yili block (NW China) and their implications on the geodynamic evolution of Chinese Tianshan belt. *Earth Planet. Sci. Lett.* **2007**, *263*, 288–308. [CrossRef]
- 65. Wang, B.; Shu, L.S.; Cluzel, D.; Faure, M.; Charvet, J. Geochemical constraints on Carboniferous volcanic rocks of the Yili block (Xinjiang, NW China): Implications for the tectonic evolution of western Tianshan. J. Asian Earth Sci. 2007, 29, 148–159. [CrossRef]
- 66. Solomovich, L.I.; Trifonov, B.A. Postcollisional granites in the South Tien Shan Variscan collisional belt, Kyrgyzstan. J. Asian Earth Sci. 2002, 21, 7–21. [CrossRef]

- 67. Konopelko, D.; Biske, G.; Seltmann, R.; Eklund, O.; Belyatsky, B. Hercynian post-collisional Atype granites of the Kokshaal Range, Southern Tien Shan, Kyrgyzstan. *Lithosphere* **2007**, *97*, 140–160.
- Kröner, A.; Hegner, E.; Lehmann, B.; Heinhorst, J.; Wingat, M.T.D.; Liu, D.Y.; Ermelov, P. Palaeozoic arc magmatism in the Central Asian Orogenic Belt of Kazakhstan: SHRIMP zircon ages and whole-rock Nd isotopic systematics. *J. Asian Earth Sci.* 2008, 32, 118–130. [CrossRef]
- 69. Burtman, V.S. The structural geology of the Variscan Tien Shan. Am. J. Sci. 1975, 275, 157–186.
- 70. Biske, Y.S. Paleozoic Structure and History of Southern Tian-Shan; Leningrad University: Leningrad, Russia, 1996; p. 187.
- 71. Seltmann, R.; Konopelko, D.; Biske, G.; Divaev, F.; Sergeev, S. Hercynian postcollisional magmatism in the context of Paleozoic magmatic evolution of the Tien Shan orogenic belt. *J. Asian Earth Sci.* 2011, 42, 821–838. [CrossRef]
- 72. Koulakov, I. LOTOS code for local earthquake tomographic inversion. Benchmarks for testing tomographic algorithms. *Bull. Seismol. Soc. Am.* **2009**, *99*, 194–214. [CrossRef]
- 73. Zabelina, I.; Ruppert, N.A.; Freymueller, J.T. Velocity structure of the Saint Elias, Alaska, Region from local earthquake tomography. *Bull. Seismol. Soc. Am.* 2014, 104, 2597–2603. [CrossRef]
- 74. Zabelina, I.; Koulakov, I.; Amanatashvili, I.; El Khrepy, S.; Al-Arifi, N. Seismic structure of the crust and uppermost mantle beneath Caucasus based on regional earthquake tomography. *J. Asian Earth Sci.* **2016**, *119*, 87–99. [CrossRef]
- 75. Ghose, S.; Hamburger, M.W.; Virieux, J. Three-dimensional velocity structure and earthquake locations beneath the northern Tien Shan of Kyrgyzstan, central Asia. *J. Geophys. Res. Solid Earth* **1998**, *103*, 2725–2748. [CrossRef]
- 76. Roecker, S.W.; Sabitova, T.M.; Vinnik, L.P.; Burmakov, Y.A.; Golvanov, M.I.; Mamatkanova, R.; Munirova, L. Three-dimensional elastic wave velocity structure of the western and central Tien Shan. *J. Geophys. Res. Solid Earth* **1993**, *98*, 15779–15795. [CrossRef]
- 77. Um, J.; Thurber, C.A. Fast algorithm for two-point seismic ray tracing. Bull. Seismol. Soc. Am. 1987, 77, 972–986.
- 78. Van der Sluis, A.; Van der Vorst, H.A. *Seismic Tomography*; Nolet, G., Ed.; Springer: Dordrecht, The Netherlands, 1987; pp. 49–83. ISBN 978-90-277-2583-7.
- 79. Roecker, S. Constraints on the crust and upper mantle of the Kyrgyz Tien Shan from the preliminary analysis of GHENGIS broadband seismic data. *Russ. Geol. Geophys.* **2001**, *42*, 1554–1565.
- Rybin, A.K.; Batalev, V.Y.; Bataleva, E.A.; Makarov, V.I.; Safronov, I.V. Structure of the Earth crust by magnitotelluric soundings. In Recent Geodynamics of Intracontinental Areas of Collision Mountain Building (Central Asia); Nauchny Mir: Moscow, Russia, 2005; pp. 79–96.
- Rybin, A.K.; Bataleva, E.A.; Morozov, Y.A.; Leonov, M.G.; Batalev, V.Y.; Matyukov, V.E.; Nelin, V.O. Specific features in the deep structure of the Naryn Basin–Baibichetoo Ridge–Atbashi Basin System: Evidence from the complex of geological and geophysical data. Dokl. Earth Sci. 2018, 479, 499–502. [CrossRef]
- Bielinski, R.A.; Park, S.K.; Rybin, A.; Batalev, V.; Jun, S.; Sears, C. Lithospheric heterogeneity in the Kyrgyz Tien Shan imaged by magnetotelluric studies. *Geophys. Res. Lett.* 2003, 30, 15. [CrossRef]
- Bataleva, E.A.; Przhiyalgovskii, E.S.; Batalev, V.Y.; Lavrushina, E.V.; Leonov, M.G.; Matyukov, V.E.; Rybin, A.K. New data on the deep structure of the South Kochkor zone of concentrated deformation. *Dokl. Earth Sci.* 2017, 475, 930–934. (In Russian) [CrossRef]
- Zabinyakova, O.; Rybin, A. The Deep Distribution of Longitudinal Electrical Conductivity in the Earth's Crust (Central Tien Shan). Int. J. Civ. Eng. Technol. 2019, 10, 398–404.
- 85. Berdichevsky, M.N.; Dmitriev, V.I.; Novikov, D.B.; Pastutsan, V.V. *Analysis and Interpretation of Magnetotelluric Data*; Dialog: Moscow, Russia, 1997; pp. 1–161. (In Russian)
- Berdichevsky, M.N.; Sokolova, E.Y.; Varentsov, I.M.; Rybin, A.K.; Baglaenko, N.V.; Batalev, V.Y.; Golubtsova, N.; Matyukov, V.; Pushkarev, P.Y. Geoelectric section of the Central Tien Shan: Analysis of magnetotelluric and magnetovariational responses along the Naryn geotraverse. *Izv. Phys. Solid Earth* 2010, *46*, 679–697. [CrossRef]
- 87. Bataleva, E.A.; Batalev, V.Y.; Rybin, A.K. Interrelation of conductivity, seismic velocities and the seismicity for Central Tien Shan lithosphere. *Lithosphere* 2015, *5*, 81–89.
- 88. Thompson, S.C.; Weldon, R.J.; Rubin, C.M.; Abdrakhmatov, K.; Molnar, P.; Berger, G.W. Late Quaternary slip rates across the central Tien Shan, Kyrgyzstan, Central Asia. *J. Geophys. Res.* 2002, *107*, 1–32. [CrossRef]
- 89. Makarov, V.I. The Newest Tectonic Structure of the Tien Shan; Nauka: Moscow, Russia, 1977; Volume 169. (In Russian)
- 90. Austrheim, H. The granulite-eclogite facies transition: A comparison of experimental work and a natural occurrence in the Bergen Arcs, western Norway. *Lithosphere* **1990**, 25, 163–169. [CrossRef]
- 91. Bird, P. Formation of the Rocky Mountains, western United States: A continuum computer model. *Science* **1988**, 239, 1501–1507. [CrossRef] [PubMed]
- 92. Leech, M.L. Arrested orogenic development: Eclogitization, delamination, and tectonic collapse. *Earth Planet. Sci. Lett.* **2001**, *185*, 149–159. [CrossRef]
- 93. Houseman, G.A.; McKenzie, D.P.; Molnar, P. Convective instability of a thickened boundary layer and its relevance for the thermal evolution of continental convergent belts. *J. Geophys. Res. Solid Earth* **1981**, *86*, 6115–6132. [CrossRef]
- 94. McKenzie, D.; O'nions, R.K. Mantle reservoirs and ocean island basalts. *Nature* 1983, 301, 229. [CrossRef]
- 95. Kiselev, A.; Gordienko, I.; Lashkevich, V. Petrological aspects of gravitational instability of tectonically thickened lithosphere. *Tikhookean. Geol.* **2004**, *23*, 20–29. (In Russian)

- 96. Zubovich, A.V.; Trapeznikov, Y.A.; Bragin, V.D.; Mosienko, O.I.; Shchelochkov, G.G.; Rybin, A.K.; Batalev, V.Y. Deformation field, earth's crust deep structure, and spatial seismicity distribution in the Tien Shan. *Russ. Geol. Geophys.* **2001**, *42*, 1634–1640.
- 97. Ueda, K.; Gerya, T.V.; Burg, J.P. Delamination in collisional orogens: Thermomechanical modeling. *J. Geophys. Res. Solid Earth* **2012**, 117. [CrossRef]