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EVOLUTION OF "NARYN" GEOELECTRIC CROSS-SECTIONS AND COMPARISON WITH EARTHQUAKE DISTRIBUTION IN HISTORICAL PERSPECTIVE

Abstract

The "NARYN" geoelectric model, which runs along the 76° E meridian through the Central Tien Shan from the Kazakh Shield to the Tarim Platform, is one of the longest cross-sections in continental Asia. This paper provides a historical overview of geoelectric models based on magnetotelluric (MT) soundings from 1999–2000 and 2005. Two inversion models constructed from these data using different algorithms are presented: the discrete-smoothed NARYN-RLM model and the piecewise continuous NARYN-INV2D model. A local earthquake catalog for 1980–2022 is considered. Hypocenter distributions from four regional and global seismic catalogs are superimposed on a reference cross-section to re-examine the previously identified relationship between crustal conductivity and earthquake depth distribution. It is noted that weak seismicity is mainly concentrated above the upper boundary of the middle and lower crustal conductor, while the strongest events are grouped in resistive, consolidated blocks of the earth's crust or at their contacts with conductive zones.

Key words: Tien Shan, magnetotelluric sounding, geoelectric cross-section, seismicity.

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Introduction

Intracontinental orogens such the Tien Shan is under our consideration. Situated more than 1500 km north of the Himalayan front, it has nevertheless absorbed a substantial fraction of India–Eurasia convergence since the Cenozoic reactivation of its Paleozoic Caledonian–Hercynian basement [1]. Deep electromagnetic sounding, sensitive to fluids, partial melt, graphite and other conductive phases that mark crustal weaknesses invisible to seismic velocity alone, has therefore been used for three decades to image the lithosphere beneath the Kyrgyz and Central Tien Shan and to relate its structure to present-day deformation and seismic hazard. Magnetotelluric (MT) and magnetovariational (MV) sounding, measured to recover the electrical resistivity structure of the crust and upper mantle.

The "NARYN" profile, running along the 76° E meridian for roughly 500 km across the Central Tien Shan from the Kazakh Shield to the Tarim platform, is one of the longest-running deep magnetotelluric cross-section in intracontinental Asia (Figure 1). Instrumental control on this seismicity is provided by several overlapping catalogues: KNET, operated jointly by the Research Station of the Russian Academy of Sciences in Bishkek (RS RAS) and the Institute of Seismology of the National Academy of Sciences of the Kyrgyz Republic (NAS KR); KRNET, operated by the Institute of Seismology, NAS KR; CAIAG, compiled by the Central Asian Institute for Applied Geosciences in Bishkek; and the global National Earthquake Information Center (NEIC) catalogue of the United States Geological Survey (USGS). Each of these has a different completeness threshold, spatial coverage and operating interval.

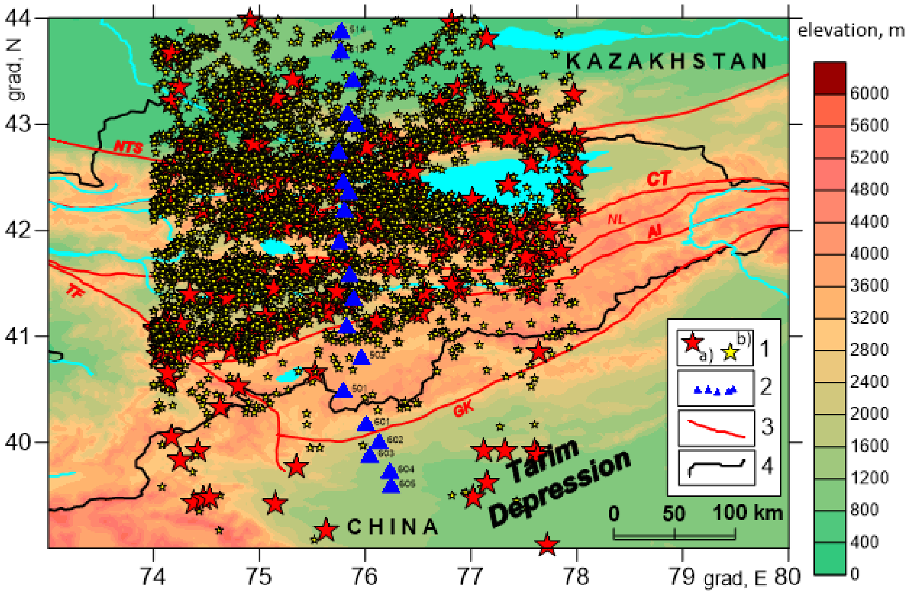

Figure 1 – Location map of magnetotelluric sounding points along the "NARYN" profile (76°E) 1 – earthquakes epicenters: a – strong (K>10), b – small- and moderate-size earthquakes (6<K<10); 2 – MT sounding sites; 3 – major faults: NTS – Northern Tien Shan, CT – Central Terskey, NL – Nikolaev Line, AI – Atbashi-Inylchek, GK – Hissar-Kokshaal; 4 – state border of Kyrgyzstan. The time span is selected between 2000 and 2025 for the present study, from local and global catalogues.

Materials and methods

RS RAS in 2005, carried out 23 wideband (0.003–1448 s) paired-synchronous MT soundings using Phoenix MTU-5 stations. This survey effectively quadrupled the spatial density of long-period control across the "NARYN" depression relative to the 1999–2000 LIMS coverage alone [2]. The "NARYN" geoelectric cross-section is the product of field MT and MV investigations, which were interpreted as different geoelectric models, because of the step-change in resolution of the new updated inversion algorithms.

The geoelectric model is built upon inversion algorithm applied with MT data of the "NARYN" profile line, from 42 points (1990s), and additional 19 long-period and 23 broadband infill points (from 1999–2005 records). It is this accumulated and interpreted separately upon new techniques, which are renovated though decades.

The first-generation model: NARYN-RLM

The earliest two-dimensional geoelectric cross-section spanning the Kyrgyz Tien Shan segment of the transect was obtained by Bielinski et al. [2], within a discrete, smoothed-structure inversion scheme (the NARYN-RLM model). This model provided the first regional image of lithospheric heterogeneity beneath the Kyrgyz Tien Shan, identifying deep conductive zones associated with major fault systems and a candidate asthenospheric conductor, and established the broad architecture that was subsequently refined by the sequential-inversion approach described below.

The second-generation model: NARYN-INV2D

The current reference cross-section NARYN-INV2D (Figure 2) was built using the piecewise-continuous (block) inversion code INV2D, developed in [3–5], which implements a sequence of partial inversions treating different field characteristics in turn, beginning with geomagnetic transfer functions and proceeding, with stepwise fixing of well-resolved conductivity blocks, through phase and full-impedance data, followed by a robust cell-by-cell averaging of the resulting ensemble of partial-inversion models. Various aspects of the construction of the NARYN-INV2D model, and of its subsequent geological–geophysical interpretation, have been described in a series of publications [4, 5]. Later on this model was recalculated in [6] (Figure 3).

The two models agree on the overall crust architecture, a fragmentary shallow (8–10 km) upper-crustal conductor, a steep conductive zone rooted beneath the Naryn depression, a lower-crustal conductive layer and a candidate asthenospheric conductor, which lends confidence to the persistence of these features across independent inversion strategies and partly independent datasets. However, NARYN-INV2D achieves markedly higher along-profile resolution.

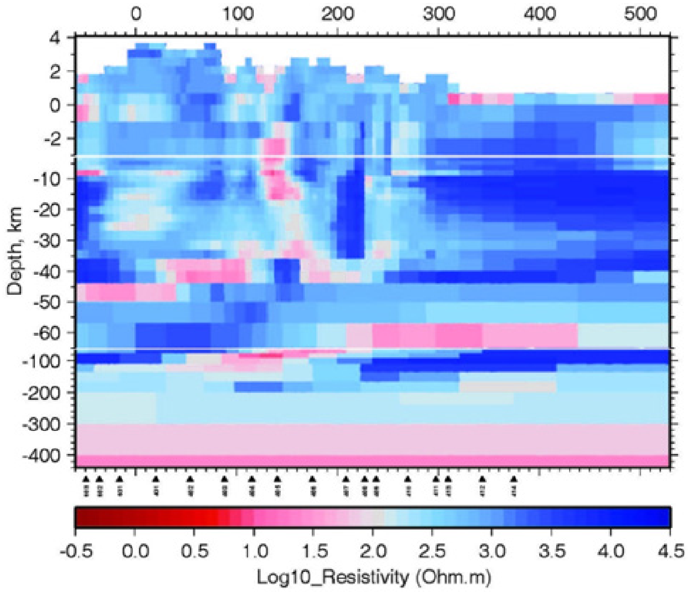

Figure 2 – The NARYN-INV2D geoelectric cross-section
of the Central Tien Shan, obtained by robust averaging
of a set of minimally regularised inversions

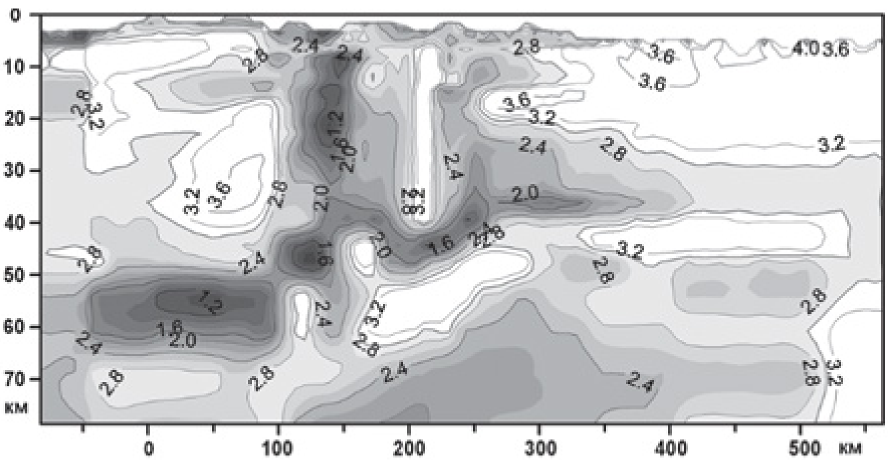

Figure 3 – The NARYN geoelectric cross-section
of the Central Tien Shan after Rybin and Kostyuk [6]

Results

The area studied straddles the South Tien Shan and North Tien Shan seismoactive zones[8]. Analysis of seismicity along the “NARYN” geoelectric model and its comparison with the seismicity were published before [7, 8] and proved some relationship. Here we use the regional catalogues (KNET, KRNET, CAIAG) for 1980–2022 restricted to the square 39°–44° N, 75°–77° E (Figures 4, 5).

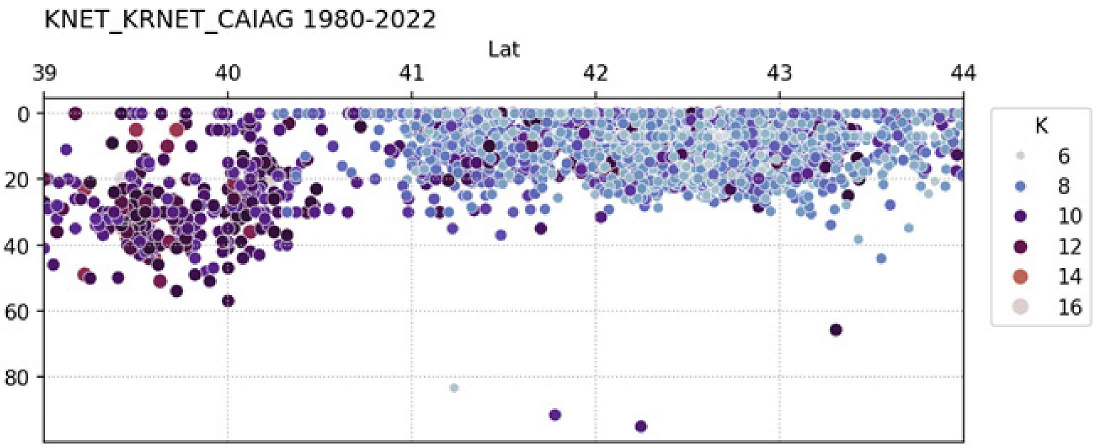

Figure 4 – Depth distribution of earthquake hypocenters with energy class K > 6 for 1980–2022, from the KNET, KRNET and CAIAG catalogues, in a 76±1° E corridor across latitude

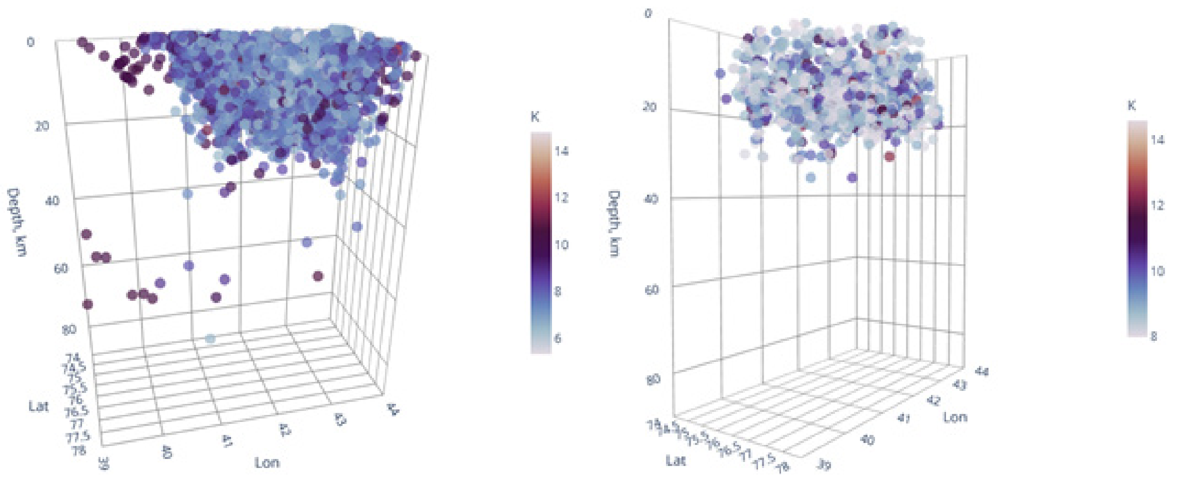

Figure 5 – Depth distribution of earthquake hypocenters with energy class K > 6 for 1980–2022, from the KNET (left) and KRNET (right) seismic networks

As part of the present study, a dedicated compilation of local earthquakes not present in the NEIC/USGS or other global catalogues was undertaken for the area 39°–44°N, 76±2°E, and combined with the global NEIC catalogue for 2025 and with fresh KNET/KRNET data for 2024–2025 (Figure 6). A depth-versus-latitude projection of hypocentres along the 76±1° E corridor for 2024–2025 (Figure 4) shows the same first-order pattern already known from the 1980–2022 window (Figure 5): near-continuous shallow (0–20 km) seismicity punctuated by discrete clusters of stronger events (K ≥ 10) tied to the Hissar–Kokshaal, Atbashi–Inylchek, Nikolaev Line and Central Terskey faults. The corresponding epicenter map (Figure 1) confirms that this clustering is not an artefact of a single network: KNET, KRNET and NEIC epicenters for 2024–2025 are co-located along the same fault-bounded corridors identified in the earlier, longer-duration catalogues. The newly compiled 2024–2025 data reproduce the same association (Figure 6): strong events (K ≥ 10, red stars) cluster tightly around the Atbashi–Inylchek and Central Terskey faults, while the background of weaker seismicity (6 ≤ K < 10, yellow symbols) is more broadly and continuously distributed across the corridor.

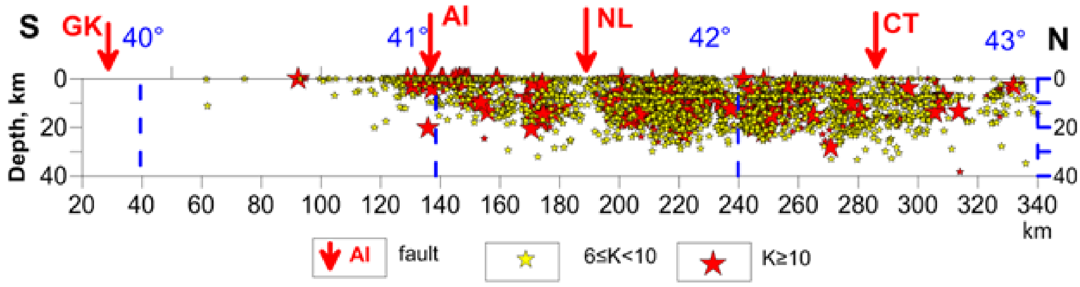

Figure 6 – Depth distribution of earthquake hypocenters along the 76±1°E meridian for 2024–2025 (updated local plus KNET/KRNET/NEIC compilation). Yellow symbols, 6 ≤ K < 10; red stars, K ≥ 10. Arrows mark the Hissar–Kokshaal (GK), Atbashi–Inylchek (AI), Nikolaev Line (NL) and Central Terskey (CT) faults

Superimposing the distribution of 'strong' hypocentres (energy class K ≥ 10) for 1980–2022 on the NARYN-INV2D section shows that the great majority of these events lie within high-resistivity, consolidated crustal blocks, or at the contacts between such blocks and the conductive zones. These contact zones, rather than the conductive zones themselves, are therefore interpreted as the segments of elevated seismic hazard in the vicinity of the geoelectric cross-section.

Taken together, three largely independent seismicity datasets spanning nearly six decades, the 1967–1999 completeness analysis, the 1980–2022 regional KNET/KRNET/CAIAG catalogues, and the newly compiled 2024–2025 data, converge on the same first-order conclusion. This convergence is regarded as the principal improvement offered by the present cross-section update: it establishes that the coupling between crustal conductivity structure and the depth and location of seismicity along the «NARYN» transect is a persistent, structurally controlled feature of the Central Tien Shan lithosphere, rather than an artefact of any one observational network, catalogue or epoch.

Discussion

The difference between inversion results for geoelectric cross-sections could be consequently explained. The magnetotelluric (MT) impedance tensor, formally the linear operator relating the horizontal electric and magnetic field spectra at the Earth's surface, is in practice never a single, unambiguously determined quantity: it is a statistical estimate whose value depends on the processing algorithm, the observation scheme, the time of acquisition and, in a deeper sense, on the mathematical class to which the underlying transfer function belongs. Varentsov [4, 5] frames this directly as a question of resolving power, arguing that the ability of natural-field electromagnetic methods to specifically resolve target features of the subsurface is fundamentally bounded by how reliably the transfer function itself can be recovered from noisy, finite-length records, rather than by the modelling or inversion algorithm alone. Zarochentsev [9], analysing the scatter of magnetotelluric errors as a function of time of day using the statistically processed MT data on the Baltic Shield, demonstrates that this variability is systematically modulated by diurnal changes in the natural source field and in cultural/industrial noise. Even when such statistical instabilities are controlled, a second, more fundamental layer of non-uniqueness remains: Zorin, Aleksanova, Yakovlev and Shimizu [10] prove that a given observed amplitude spectrum of the impedance is compatible in principle with infinitely many causal transfer functions differing in the location of their zeros in the lower half of the complex frequency plane, and that only one of them is minimum-phase; the presence of additional, non-minimum-phase zeros – caused by three-dimensional structures, anisotropy or coastal galvanic distortion – produces systematic violations of the dispersion (Kramers–Kronig/Hilbert) relations that are, without a dedicated causality check, indistinguishable from ordinary noise-induced bias. Taken together, these studies show that non-uniqueness enters the magnetotelluric impedance at several nested levels – statistical (estimator choice and violated error assumptions, Egbert and Booker [11]), temporal (diurnal and acquisition-scheme dependence [5, 9], directional (strike- and rotation-dependence [12, 13], theoretical (causal/minimum-phase indeterminacy [10] and mathematical (incorrect multidimensional inverse problem [14, 15]. None of these levels can be fully removed by a single processing step. Because two- and three-dimensional inversion algorithms treat the input apparent-resistivity and phase curves as if they were an unambiguous physical observation, any residual non-uniqueness that is not explicitly resolved before inversion does not vanish.

Conclusions

The updated seismicity, confirms and reinforces, using an essentially independent dataset, the previously reported relationship between the top of the crustal conductor and the depth ceiling of weak seismicity, and between the strongest (K ≥ 10) events and resistive crustal blocks or their contacts with conductive zones. These contact zones are identified as priority targets for seismic-hazard assessment along “NARYN” profile and, by extension, along comparable segments of the Central Tien Shan.

Three decades of progressively changing tools of digital inversion applied on magnetotelluric and magnetovariational observation along ”NARYN” geoelectric cross-section could provide more sharpener successive geoelectric cross-sections examined in this paper. The new iterations of geoelectric inversion could be attempt in new invented algorithms such as Inversio [16] or machine learning [17].

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НАРЫН ПРОФИЛІНІҢ ГЕОЭЛЕКТРЛІК МОДЕЛЬДЕРІНІҢ ЭВОЛЮЦИЯСЫ ЖӘНЕ ТАРИХИ ТҰРЫСТАҒЫ ЖЕР СІЛКІНІСТЕРІНІҢ ТАРАЛУЫМЕН САЛЫСТЫРУ

Аңдатпа

NARYN геоэлектрлік моделі Орталық Тянь-Шань арқылы 76° E меридианы бойымен Қазақ қалқанынан Тарим платформасына дейін созылып, құрлықтық Азиядағы ең ұзын көлденең қималардың бірі саналады. Бұл мақалада 1999–2000 және 2005 жылдардағы магнитотеллурлық (МТ) зондтауларға негізделген геоэлектрлік модельдерге тарихи шолу жасалған. Әртүрлі алгоритмдерді қолдана отырып, осы деректер негізінде құрылған екі инверсиялық модель ұсынылған: дискретті тегістелген NARYN-RLM моделі және бөліктік үздіксіз NARYN-INV2D моделі. 1980–2022 жж. арналған жергілікті жер сілкіністерінің каталогы қарастырылады. Жер қыртысының өткізгіштігі мен жер сілкіністері тереңдігінің таралуы арасындағы бұрын анықталған байланысты қайта қарау үшін төрт аймақтық және жаһандық сейсмикалық каталогтан алынған гипоцентрлік таралулар эталондық көлденең қимаға қабаттастырылған. Әлсіз сейсмикалықтың негізінен жер қыртысының ортаңғы және төменгі өткізгішінің жоғарғы шекарасынан жоғары шоғырланғаны, ал ең күшті оқиғалар жер қыртысының кедергілі, шоғырланған блоктарында немесе олардың өткізгіш аймақтармен жанасуында топтастырылғаны атап өтілген.

Түйін сөздер: Тянь-Шань, магнитотеллурлық зондтау, геоэлектрлік көлденең қима, сейсмикалық.

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ЭВОЛЮЦИЯ ГЕОЭЛЕКТРИЧЕСКИХ МОДЕЛЕЙ ПРОФИЛЯ NARYN И СРАВНЕНИЕ С РАСПРЕДЕЛЕНИЕМ ЗЕМЛЕТРЯСЕНИЙ В ИСТОРИЧЕСКОЙ ПЕРСПЕКТИВЕ

Аннотация

Геоэлектрическая модель NARYN, проходящая вдоль меридиана 76° в.д. через Центральный Тянь-Шань от Казахского щита до Таримской платформы, является одним из самых протяженных сечений во внутриконтинентальной Азии. В данной статье дан исторический обзор геоэлектрических моделей по данным магнитотеллурических (МТ) зондирований 1999–2000 гг. и 2005 г. Показаны две построенные на основе этих данных с помощью разных алгоритмов инверсии: дискретно-сглаженной модели NARYN-RLM и кусочно-непрерывной модели NARYN-INV2D. Рассматривается локальный каталог землетрясений за 1980–2022 гг. Распределения гипоцентров из четырех региональных и глобальных сейсмических каталогов наложены на эталонный поперечный разрез для повторной проверки ранее выявленной взаимосвязи между проводимостью земной коры и распределением землетрясений по глубине. Отмечается, что слабая сейсмичность в основном сосредоточена над верхней границей средне- и нижнекорового проводника, тогда как самые сильные события группируются в резистивных, консолидированных блоках земной коры или на их контактах с проводящими зонами.

Ключевые слова: Тянь-Шань, геоэлектрический разрез, магнитотеллурическое зондирование, сейсмичность.