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MODERN SURFACE DEFORMATIONS OF THE TERRITORY OF KAZAKHSTAN BASED ON GPS DATA

GPS ДЕРЕКТЕРІ НЕГІЗІНДЕ ҚАЗАҚСТАН АУМАҒЫ ЖЕР БЕТІНІҢ ҚАЗІРГІ ЗАМАНҒЫ ДЕФОРМАЦИЯЛАРЫ

СОВРЕМЕННЫЕ ДЕФОРМАЦИИ ЗЕМНОЙ ПОВЕРХНОСТИ ТЕРРИТОРИИ КАЗАХСТАНА ПО ДАННЫМ GPS

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keywords:

crust movement; tectonic
plates; deformation; GPS
data; vector field.

ABSTRACT

The paper presents a new dataset from reference GNSS stations intended for differential topographic surveying. The processing results provided acceptable outcomes for studying tectonic movements, and if certain conditions regarding antenna stabilization and long-term observations without re-locating the stations to new positions are met, such data can also be used for geodynamic monitoring. The results showed that the main movements of the Earth's surface in Kazakhstan occur along the northern border of the Tien Shan and in the eastern part of the country in a zone covering all mountain ranges, including the Altai. The data correlate well with the terrain as well as with historical and contemporary seismicity. In the rest of Kazakhstan, movements are almost imperceptible, with speeds not exceeding 0.5–0.6 mm/year. For the first time, a deformation field for the territory of Kazakhstan has been calculated using the triangulation overlay method, which has increased resolution in detecting heterogeneities in the deformation velocity field, particularly the zones of localization and the boundaries between areas with different deformation velocities. The limitations of the method are also demonstrated.

Түйінді сөздер:

жер қыртысының
қозғалысы; тектоникалық
плиталар; деформация;
GPS деректері;
векторлық өріс.

ТҮЙІНДЕМЕ

Мақалада дифференциалдық топографиялық-геодезиялық түсірілімдерді орындауға арналған тірек GNSS станцияларынан алынған жаңа деректер жиынтығы ұсынылған. Деректерді өңдеу нәтижелері тектоникалық қозғалыстарды зерттеу үшін қолайлы дәлдікті көрсетті. Антенналардың орнықтылығын қамтамасыз ету және станцияларды жаңа орындарға көшірмей ұзақ мерзімді үздіксіз бақылаулар жүргізу шарттары сақталған жағдайда, мұндай деректерді геодинамикалық мониторинг жүргізу үшін де пайдалануға болады.



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Алынған нәтижелер Қазақстан аумағындағы жер бетінің негізгі қозғалыстары Тянь-Шаньның солтүстік шекарасы бойында, сондай-ақ елдің шығыс бөлігінде, Алтайды қоса алғанда барлық тау жүйелерін қамтитын аймақта шоғырланғанын көрсетті. Алынған деректер жер бедерінің ерекшеліктерімен, сондай-ақ тарихи және қазіргі заманғы сейсмикалық белсенділікпен жақсы үйлеседі. Қазақстанның қалған аумағында жер бетінің қозғалыстары іс жүзінде байқалмайды және олардың жылдамдығы 0,5–0,6 мм/жылдан аспайды. Қазақстан аумағы үшін алғаш рет триангуляциялық торды қабаттастыру әдісі қолданылып, деформациялар өрісі есептелді. Бұл деформация жылдамдықтары өрісіндегі біртектіліктерді, атап айтқанда олардың шоғырлану аймақтарын және деформация жылдамдықтары әртүрлі учаскелер арасындағы шекараларды анықтаудың кеңістіктік ажыратымдылығын арттыруға мүмкіндік берді. Сонымен қатар аталған әдістің шектеулері де көрсетілді.

Ключевые слова:

движения земной коры;
тектонические плиты;
деформации; данные GPS;
векторное поле.

АННОТАЦИЯ

В статье представлен новый набор данных, полученных на опорных ГНСС-станциях, предназначенных для выполнения дифференциальных топографо-геодезических съемок. Результаты обработки показали приемлемую точность для исследования тектонических движений. При соблюдении определенных условий, связанных со стабильностью установки антенн и проведением длительных непрерывных наблюдений без переноса станций на новые позиции, такие данные также могут использоваться для геодинамического мониторинга.

Полученные результаты показали, что основные движения земной поверхности на территории Казахстана сосредоточены вдоль северной границы Тянь-Шаня, а также в восточной части страны — в зоне, охватывающей все горные системы, включая Алтай. Полученные данные хорошо согласуются как с особенностями рельефа местности, так и с исторической и современной сейсмичностью. На остальной территории Казахстана движения земной поверхности практически не выражены, а их скорости не превышают 0,5–0,6 мм/год.

Впервые для территории Казахстана рассчитано поле деформаций с использованием метода наложения триангуляционной сети, что позволило повысить пространственную разрешающую способность при выявлении неоднородностей поля скоростей деформаций, в частности зон их локализации и границ между участками с различными скоростями деформаций. Также продемонстрированы ограничения данного метода.

INTRODUCTION

Global patterns of both vertical and horizontal movements in the Earth's crust are the result of the combined influence of plate motions and glacial isostatic adjustments. At the regional and local levels, these movements are additionally influenced by factors such as flexure from eustatic or sedimentary loading, volcanic deformation, or human-induced changes (Orogeny & St, 2005; Stewart, 2004). Studying crustal movements at the regional and local levels is crucial for a comprehensive understanding of Earth's dynamic processes and their impact on the environment (Attia, Hegazy & El-Hameed, 2012), and GNSS technologies, with their high sensitivity over large areas and their ability to provide acceptable accuracy in determining velocity parameters, have become highly sought after for studying these movements. (Abdrakhmatov et al., 1996; Ischuk et al., 2013; Mohadjer et al., 2010; Reigber et al., 2001; Zubovich et al., 2010).

These studies provide insights into the geological forces shaping landscapes, influencing seismic activity, and contributing to the formation of natural resources (Adebiyet et al., 2022; Petricca, Bignami & Doglioni, 2021). They are important for land-use planning, infrastructure development, and help improve the resilience of communities in regions prone to tectonic activity. Moreover, the study of crustal movements advances various scientific fields, including geophysics, geology, and environmental science, contributing to a broader understanding of Earth's complex and interconnected systems (Famin et al., 2008; Kuneš, 2012).

Therefore, scientists around the world are deeply involved in the systematic study and long-term measurement of crustal movements. Through focused research and continuous monitoring, they aim to understand the dynamic processes shaping the Earth's crust. This collaborative international endeavor provides valuable insights into tectonic activity, helping us better understand geological phenomena and contributing to advances in geophysics and Earth sciences (Watts, 2015). Below, we will review some of the latest studies from different parts of the world.

The study conducted by Mahrus et al. (Mahrous et al., 2022) focused on the Nile Delta, the oldest delta in the Mediterranean basin, which holds strategic importance for Egypt. Addressing issues such as sea level rise, subsidence due to reduced sediment inflow from the Aswan Dam, and the impact of oil and gas activities, the research aimed to monitor crustal deformation from 2013 to 2020. Using data from 14 permanent GNSS stations, the study revealed heterogeneous movements with an average local horizontal velocity of 2.5 mm per year, indicating relatively low speeds. Distinct geodynamic behavior was observed on the eastern and western sides, linked to structural features. Vertical velocities showed significant subsidence, ranging from -0.11 mm per year in Helwan to -9.1 mm in Mansoura, providing valuable insights into the dynamic changes in this critical landscape.

Giambiagi et al. (Giambiagi et al., 2022) investigate the mechanisms of orogenic growth in the Central Andes, an important example of mountain formation in subduction zones. The study focuses on the Southern Central Andes (from 22° to 35° S latitude), analyzing changes in the Cenozoic uplift and tectonic shortening-thickening history. By constructing continental cross-sections guided by a new thermomechanical model, the research aims to align kinematic models of crustal deformation with geological constraints in this subduction-related orogen. Their 2D geodynamic model suggests that zones of low strength in the upper and middle levels of the crust function as sequential décollements, concentrating orogenic deformation and seismicity. The orogen undergoes transitional stages of crustal thickening, explaining variations in shortening and crustal thickness from north to south and providing valuable insights into the complex dynamics of mountain-building processes.

In the northeastern Tibetan Plateau, known for tectonic collisions and frequent large earthquakes, the study (Li, Gao & Jin, 2023) combines Global Navigation Satellite System (GNSS) observations with S-wave splitting analysis of seismic data. GNSS reveals strong heterogeneous tectonic deformation, while S-wave splitting studies provide parameters of seismic anisotropy, indicating deformation in the upper crustal environment. By comparing the primary directions of compressional deformation from GNSS with the fast polarization directions of S-waves, the study analyzes surface and upper crustal deformation. While they are generally consistent, local tectonic regions show significant differences, revealing diverse deformation mechanisms. This integration of GNSS data and seismic anisotropy improves the understanding of depth-varying characteristics during crustal deformation, providing insights into the three-dimensional processes of the Earth's crust and their underlying dynamic mechanisms.

Niwa et al. (Niwa et al., 2019) address the lack of data on millennial-scale crustal movements along the Sanriku coast, which are crucial for understanding subduction zone deformation during megathrust earthquake cycles. Focusing on the northern Sanriku coast,

where comparable data were lacking following the 2011 Tohoku-Oki earthquake, the study utilizes a well-dated Holocene sedimentary record on the Omoto Plain. Environmental changes driven by sea-level fluctuations reveal distinct phases: barrier and tidal delta formation (10,000–9,000 cal. BP), estuarine conditions (9,000–8,000 cal. BP), and a regressive delta followed by a fluvial environment after 8,000 cal. BP. Unlike the central Sanriku coast, the Omoto Plain shows no evidence of mid-Holocene subsidence, which aligns with less coseismic subsidence during the 2011 earthquake. These findings highlight the need to separately evaluate the northern and central-southern Sanriku coast when assessing regional crustal deformation related to subduction.

In China (Yu et al., 2019) over 260 continuous stations and 2,000 campaign stations from the Crustal Movement Observation Network of China (CMONOC) project, covering the period from 1998 to 2018, were processed using Bernese Global Navigation Satellite System (GNSS) software. The resulting time series of coordinates, referenced to ITRF2014, facilitated the assessment of coseismic deformation after removing outliers. The study provides the most recent, comprehensive, and accurate modern horizontal velocity field relative to the stable Eurasian Plate. It shows intensified tectonic movement in Western China, particularly on the Tibetan Plateau, with velocities of 18–32 mm/year, sharply decreasing from south to north. Northern and Southern China exhibit consistent movement from east to southeast at 4–10 mm/year, while the northeastern region of China shows the lowest velocity at 2–4 mm/year, slightly higher along coastal areas. Dense GNSS observations provide valuable information on contemporary crustal movements and tectonic deformation characteristics, expanding our understanding of the kinematics and dynamics of the region.

Studies of contemporary surface movements in Kazakhstan have been conducted previously, yielding vectors of surface velocity for the country, but a deformation velocity field was not computed. In this work, we aimed to address this. There are various methods for calculating surface deformations, with the Shen method (Sagiya, Miyazaki & Tada, 2000; Shen, Jackson & Ge, 1996) being the most well-known. In this study, we applied a different approach – the method of triangulation overlays (Zubovich & Mukhamediev, 2010). Since the movement velocities obtained from previously published data are minor for most of Kazakhstan and lack significant gradients, this provides a favorable opportunity to test the capabilities and limitations of this method for computing the deformation field.

TECTONIC FEATURES AND SEISMICITY OF THE STUDY AREA

Being the 9th largest country in the world, Kazakhstan requires significant attention to its crustal movements due to its vast geological expanse and complexity. Located at the crossroads of Europe and Asia, with most of its land in Asia and a smaller portion in Eastern Europe (between 55°30' N and 40°35' N, and 46°30' E and 87°20' E), Kazakhstan's geological landscape is diverse. The western region borders the East European Platform, while the southwestern part is adorned with the fold mountains of the Alpine belt, and the remaining space is framed by orogenic and epigercynian plates of the Ural-Mongolian system. Over 300 million years, Kazakhstan's geological history, spanning from the Precambrian era to the end of the Paleozoic, has witnessed significant movements of the continental crust, leading to the formation of various tectonic systems and distinct geostructural areas. These include orogens characterized by significant uplift and frequent strong earthquakes, and platforms representing areas with relatively weak recent tectonic movements. The Caspian Depression, containing the PZ-KZ plate complex, is a remnant of an ancient paleoplatform, while the Turan Plate of MZ-KZ age is part of a more recently formed platform. Notably, the Kazakh Shield stands out as a distinctive feature in the structural forms of the newly formed platform (Samygin & Kheraskova, 2019; Soloviev et al., 2020).

The orogens of the Northern Tien Shan, Dzungaria, Tarbagatai, and the western part of the Altai in southeastern Kazakhstan outline the northern boundary of the deformed lithosphere, which resulted from the collision of India and Eurasia that began about 60 million years ago. Over the past 25 years, GPS measurements have contributed to a comprehensive study of global deformation processes in the Indian-Eurasian plate collision zone. This research covers various regions such as the Pamirs, the Tibetan Plateau, the Tien Shan, the Himalayas of Nepal, the subduction zone of the western Pacific, and the monitoring of velocity fields in Central and Eastern Asia (Wang & Barbot, 2023).

More detailed studies of recent geodynamic movements in Central Asia and adjacent territories can be found in the works of G. Zheng, S. Mohajer, H. Wang, M. Hao, V.I. Ulomov, V.K. Kuchay, G.M. Steblov, M.G. Kogan, Y.A. Trapeznikov, F.N. Iudakhin, K.E. Abdrakhmatov, V.I. Makarov, A.V. Zubovich, S.I. Kuzikov, K.N. Abdullabekova, D.Kh. Yakubova, A.R. Yarmukhamedov, L.A. Khamidov, Z.F. Shukurov, A.K. Kurskeeva, Zh.Sh. Zhantayeva, A.V. Timusha, Yu.G. Shcherbyna, E.N. Nusipov, and other specialists from various global scientific centers ("Geology and Geophysics 2001 Number 10", 2001; Abdrakhmatov et al., 1996; Abdrakhmatov et al., 2001; DeMets, Gordon & Argus, 2010; England & Molnar, 2005; Grebby et al., 2019; Hao, Li & Zhuang, 2019; Kamza et al., 2018; Simkin et al., 1994; Vilayev, Zhantayev & Bibosinov, 2017; Zubovich et al., 2010).

According to studies, the kinematics of the Central Asia region are primarily influenced by the interaction of the Indian Plate in the southeast and the Arabian Plate in the extreme southwest of Kazakhstan with the Eurasian Plate. This complex tectonic interaction plays a crucial role in shaping the geological dynamics of the region. The collision and convergence of these plates contribute significantly to the deformation processes observed in Central Asia. Understanding these interactions is vital for revealing the geodynamic complexities and seismic activity in this tectonically active area (Simkin et al., 1994). The most active region over the past 125 years has been the Northern Tien Shan, where some of the strongest earthquakes occurred (Belozorskoye 1885, M6.9; Vernensky 1887, M7.3; Chilik 1889, M8.3; Kemin 1911, M8.2; Kemin-Chui 1938, M6.9; Janalash-Tüp 1978, M6.8; Baysorun 1990, M6.3). In the Tarbagatai-Altai region, significant events are associated with the Zaisan zone (1857, M6.4; 1990, M6.8); in the Karatau area, with the Kyzylkum zone (1929, M6.4; 1968, M5.1) and the Chatkal-Kuramin zone (Tashkent 1868 and 1886, M6.5; 1966, M5.2) and the Pskem zone (1937, M6.5). Isolated earthquakes with magnitudes of M4.5-5.0 have occurred in the Northern and Eastern Caspian region, Central Kazakhstan, and Northern Balkhash (Figure 1).

Figure 1 also shows seismicity with magnitudes $M \geq 5.0$ over the past 30 years. According to the USGS catalog, there have been only 18 such earthquakes in Kazakhstan and its immediate vicinity, of which only 2 were greater than magnitude 6 (6.0 and 6.1). Out of the 18 events, two earthquakes occurred in central and northeastern Kazakhstan: one on the Kazakh Shield with M5.0 and one south of Uralsk with M5.1. Another event with M5.1, not directly related to the mountains, occurred on the border with Uzbekistan southwest of Shymkent. The remaining earthquakes occurred in mountainous regions: 4 within the Saur-Tarbagatai zone, 3 in the Dzungarian Alatau, and the rest in the Tien Shan.

A detailed analysis of GPS measurements in the Northern Tien Shan region shows a maximum annual crustal compression rate of 20 ± 2 mm. This rate constitutes a significant portion, nearly two-thirds, of the total convergence observed between India and Eurasia. As one moves north, the deformation rates in the Dzungarian Alatau and Tarbagatai gradually decrease to 2-3 mm/year. In the southwestern part of Kazakhstan, influenced by the Arabian Plate, the displacement rates range from 1 to 3 mm/year. This nuanced understanding of regional crustal movements provides valuable information on the dynamic interaction of tectonic forces shaping the geological landscape (Abdrakhmatov et al., 1996; Yerzhankyzy et al., 2018).

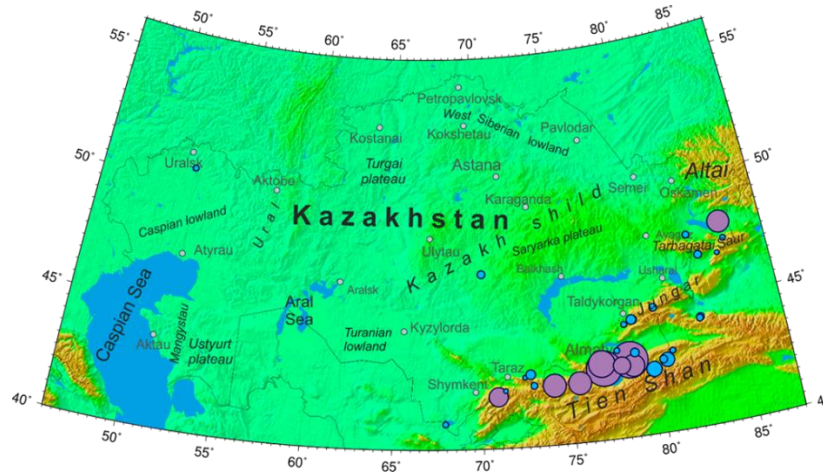


Figure 1. Topographic map of Kazakhstan with seismicity.

The strongest historical earthquakes are marked in purple. Blue circles represent seismic events with magnitudes $M \geq 5.0$ over the past 30 years

Note – compiled by the authors

DESCRIPTION OF GPS NETWORK AND DATA PROCESSING

Description of the GPS observation network. Phase-1: Initial measurements to study the geodynamic state of the Earth's crust in Kazakhstan based on GPS data began in 1992 with the implementation of international projects aimed at establishing a measurement network in the Kyrgyz and Kazakh Tien Shan regions (Zubovich et al., 2001; Zubovich et al., 2010). Scientists from the Institute of Seismology of Kyrgyzstan, the Institute of Seismology of Kazakhstan, and the Institute of Astronomy of Uzbekistan, together with geodetic service staff, established the initial 40 points in these countries. By 2004, the total number of GPS measurement points in Central Asia had exceeded 400 (Abdrakhmatov et al., 1996). Measurements were conducted through annual or biennial campaigns. The observations from 1992-1994 were exploratory and episodic and were not included in the final velocity-field calculation because they were obtained during the early stage of GPS network deployment, with a less complete satellite constellation, early-generation equipment, and non-uniform observation sessions that did not consistently provide continuous daily records. To maintain temporal and quality homogeneity, only quality-controlled Phase-1 campaign data from 1995 onward were used for the velocity solutions analyzed in this study.

Phase-2: In 2005, the "Ionosphere Institute" and the "Seismology Institute" initiated joint efforts to develop the Kazakh segment of the network. They established 10 GPS stations for continuous monitoring in the seismically hazardous region of Southeastern Kazakhstan. These GPS stations are strategically located in 9-point seismic zones in the Zailiyskiy Alatau range and the seismic transition zone of the Kazakh Shield. The permanent stations are integrated with the seismic network of the Almaty region.

Phase-3: The third phase of GPS research began in 2015 through collaboration between "Kazakhstan Gharysh Sapary," "Leica Geosystems Kazakhstan," and "GEOTRONICS LLP." This phase involved the establishment of a high-precision satellite navigation system (HSNS), consisting of 137 GPS stations. The continuous GPS monitoring initiative covers approximately 80% of Kazakhstan's territory, with stations strategically located in major cities and several oil fields.

Thus, the domestic GPS data used in this study comprise three observation phases with different observation regimes: Phase-1 campaign data from 1995-2004, Phase-2 continuous observations from 10 permanent stations for 2005-2020, and Phase-3 continuous HSNS observations from 137 stations for 2015-2020. Raw observations were sampled at 30-second intervals where

available, while daily solutions were used for the continuous networks. The earlier 1992-1994 Phase-1 measurements are retained only in the historical description of network development and were excluded from the final velocity-field estimation for the reasons given above.

Besides the data from the Kazakh continuous station network, data from surrounding regional and Eurasian reference stations, part of the International GPS Service (IGS), were also used. These data are available at <https://cddis.nasa.gov> and <http://garner.ucsd.edu>.

After station-by-station quality assessment, the merged velocity catalogue used in the subsequent analysis included solutions from 350 Phase-1 campaign stations (1995-2004), all 10 Phase-2 permanent stations (2005-2020), 137 Phase-3 HSNS stations (2015-2020), and the IGS reference stations used for reference-frame stabilization. The Phase-2 stations were therefore not excluded from the analysis; their omission from the previous summary sentence was a textual oversight. The combined catalogue was subsequently subjected to an additional spatial and quality selection before constructing the deformation-field triangulation, as described below.

Processing of GPS Data. The initial GPS data were processed using the GAMIT/GLOBK software from the Massachusetts Institute of Technology (Heering, King & McClusky, 2010; Herring, King & McClusky, 2006). The calculations were performed in the stable reference frame ITRF2014_COMB_EURA, created using the combine_ITRF2014.sh tool by Mike Floyd on March 29, 2020. To stabilize the reference frame, a set of a priori IGS stations distributed around the perimeter of Kazakhstan was used. It is important to note that the processing algorithm accounts for atmospheric and tropospheric delays of the satellite signal, ocean loading models, Earth rotation parameters, precession and nutation of the poles, as well as orbits, time zones, coordinates of each satellite, mechanical parameters of the receiving antenna, and other factors see (Heering, King & McClusky, 2010; Herring, King & McClusky, 2006).

The mean and median errors of the velocity-component estimates for the regional HSNS, local Almaty seismic-zone, Phase-1 campaign, and GNSS reference-station solutions are summarized in Table 1.

Table 1. Mean and median errors of velocity component calculation by different GPS stations

Error type	Trend component	HSNS	Seismic zone	GPS data from (Zubovich et al., 2010)	GNSS
		mm/year	mm/year	mm/year	mm/year
Mean value	SN	0.648	0.344	0.464	0.225
	WE	0.739	0.355	7.205	0.254
	Up	2.542	1.320	-	0.935
Median value	SN	0.395	0.290	0.600	0.095
	WE	0.455	0.290	6.000	0.140
	Up	1.670	1.200	-	0.425

Note – compiled by the authors

Table 1 shows that the mean errors of the HSNS velocity estimates are higher, not lower, than those of the GNSS reference-station solutions. The HSNS/GNSS ratios are 2.88 for SN (0.648/0.225), 2.91 for WE (0.739/0.254), and 2.72 for Up (2.542/0.935). Thus, the mean HSNS velocity errors are approximately 2.7-2.9 times larger. This difference is consistent with the characteristics of the HSNS network: many antennas are installed on buildings to ensure open-sky visibility for differential positioning, but long-term building motion and monument

instability can degrade the accuracy of geodynamic velocity estimates. For the Almaty seismic-zone stations, the mean errors are 0.344 mm/year (SN), 0.355 mm/year (WE), and 1.320 mm/year (Up). As expected for GNSS positioning, the vertical component is less precise than the horizontal components. Campaign-style solutions are additionally sensitive to the temporal distribution, duration, and repeatability of observation sessions. Therefore, the values in Table 1 should be interpreted as error characteristics of different observation networks and monummentation/observation regimes rather than as evidence of higher geodynamic accuracy for HSNS.

The second stage involved processing the data with the Gired program, which is similar to Globk but processes each day separately to obtain time series of station positions in three components (east, north, and up). It should be noted that in such processing, the reference system defined by the stabilization stations may also vary each day. At this stage, as stabilization stations, we additionally used those observation points measured from 2015 to 2020, even if they had been relocated during this period.

Velocity calculations for station movements were performed using time series data processed by the tsfit program, which is part of the Gamit/Globk package. This program calculated and removed seasonal annual and semi-annual variations before determining the station velocity vectors. The velocity field across Kazakhstan is shown in Figure 2.

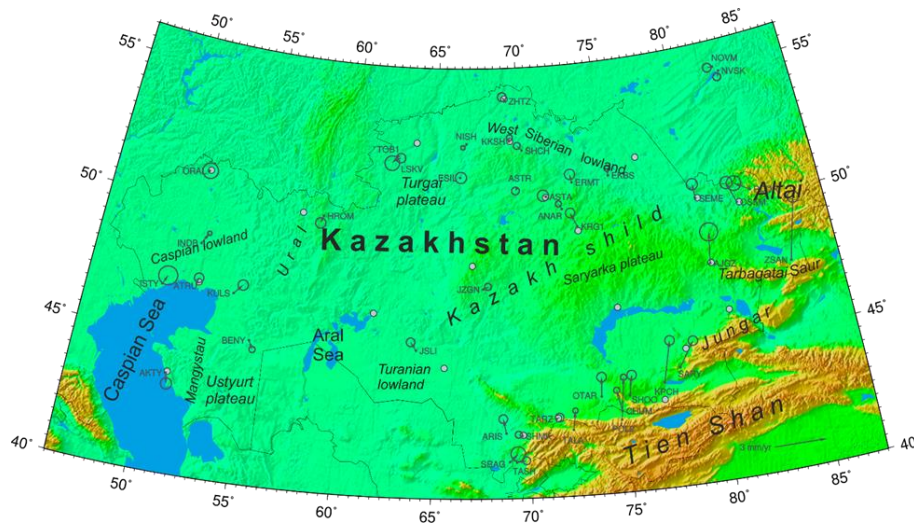


Figure 2. Field of velocity vectors of GPS stations of the territory of Kazakhstan
Note – compiled by the authors

To analyze the distribution of crustal velocity in the plane, the kriging method was used for interpolation on a regular 20x20 km grid, employing the GIS software SURFER 13. The displacement fields are presented through three orthogonal components: south-north (SN), west-east (WE), and vertical (Up) components, as well as the magnitude of the absolute horizontal displacement in the ITRF2014_COMB_EURA coordinate system.

To analyze the distribution of the velocity vector field in the context of crustal movements, operations of divergence and curl can be used.

$$\text{div}V = \frac{1}{2} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right); \text{rot}V = \frac{1}{2} \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \quad (1)$$

Where u and v are the velocity components in the SN and WE directions. The divergence and curl of the velocity field provide valuable information about the behavior and characteristics of the field. The divergence of a vector field serves as an indicator of whether a specific point in space acts as a source or sink of the field flow and can be formally interpreted as highlighting

areas of potential compression or expansion in all directions. Positive divergence values indicate a source point of the field, negative values indicate a sink, and zero values suggest a balance between sources and sinks or their compensation. To identify rotational horizontal movements of individual crustal blocks, characterized as rotational shear deformations, we applied a procedure involving the differentiation of the initial horizontal velocity field combined with the calculation of the normalized curl. The curl of the velocity field shows both the magnitude and direction of rotation for individual blocks at each point. Positive curl values are physically interpreted as counterclockwise rotation, causing the Earth's surface to rise. Conversely, negative values indicate clockwise rotation of the block, resulting in a lowering of the geological environment.

Calculation of the deformation field. There are several ways to represent surface movements. One commonly used method is to represent movements as velocity vectors on a two-dimensional plane, which visually show the magnitude and direction of the velocity of points on the Earth's surface. However, since velocity depends on the chosen reference frame, changing the reference frame can drastically alter the direction and magnitude of the vectors. Additionally, if the velocity of the area under study relative to the reference frame is significantly greater than the displacements within the study area, these internal deformations are difficult to discern. Another representation is displaying velocities as profiles along a specific direction. This approach is independent of the reference frame, but its main drawback is that the profile is one-dimensional and only shows changes in velocity along the line of the profile. In contrast to the first two methods, the deformation velocity field is independent of the reference frame and is two-dimensional, making it an important complement to the representation of relative movements on the Earth's surface.

In this study, the deformation velocity field was calculated using the method of triangulation overlays (Zubovich & Mukhamediev, 2010). The principle is as follows: to determine the six parameters of planar deformation (maximum shortening rate, maximum elongation, maximum shear rate, rotation rate, and two displacement components), three non-collinear GPS/GNSS observation points with their velocity vectors are required and can be represented as the vertices of a virtual triangle. Before triangulation, the Phase-1/Phase-3 source pool (487 station solutions: 350 Phase-1 and 137 Phase-3) was screened together with the Phase-2 and IGS solutions included in the merged velocity catalogue. Sites with duplicate or near-coincident coordinates, insufficiently long observation series, or elevated noise in the velocity estimates were excluded. To avoid excessive local clustering and to obtain a stable, spatially representative geometry, the base Delaunay network was constructed from approximately 60-70 of the most reliable key stations, selected to provide relatively uniform coverage of Kazakhstan and its surrounding frame. The Delaunay triangulation of this reduced reference set, implemented using Generic Mapping Tools (Wessel et al., 2019), produced 101 initial triangles (Figure 3a). Therefore, the 101 triangles do not represent a triangulation of all 487 Phase-1/Phase-3 stations.

In the next stage, each pair of adjacent triangles forming a quadrilateral was divided by the alternative diagonal, and the overlay procedure was repeated for five iterations. This generated 4062 overlapping triangles. Geometrically ill-conditioned configurations with excessively sharp angles (tangent of the angle < 0.2) and triangles strongly affected by high velocity errors at their vertices were rejected during quality control. After filtering, 3108 overlapping triangles remained for the deformation calculations (Figure 3b). The subsequent grid-point selection by triangle area and stability criteria is described below.

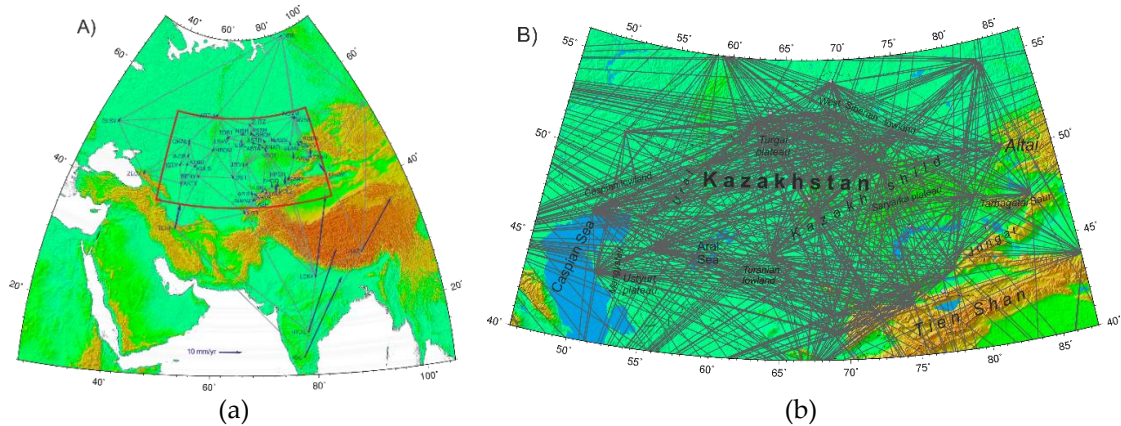


Figure 3. (a) Base Delaunay triangulation constructed from the reduced set of quality-controlled key GPS/GNSS stations selected for deformation analysis (101 initial triangles). The red contour delineates the study area shown in panel (b); (b) superimposed triangles generated after five iterations of alternative-diagonal subdivision and subsequent quality filtering

Note – compiled by the authors

As a result, excluding the boundary areas of the study region, each point within it was covered by multiple triangles. In Figure 4, it can be seen that in the center of the network, the number of overlapping triangles reaches 200 or more.

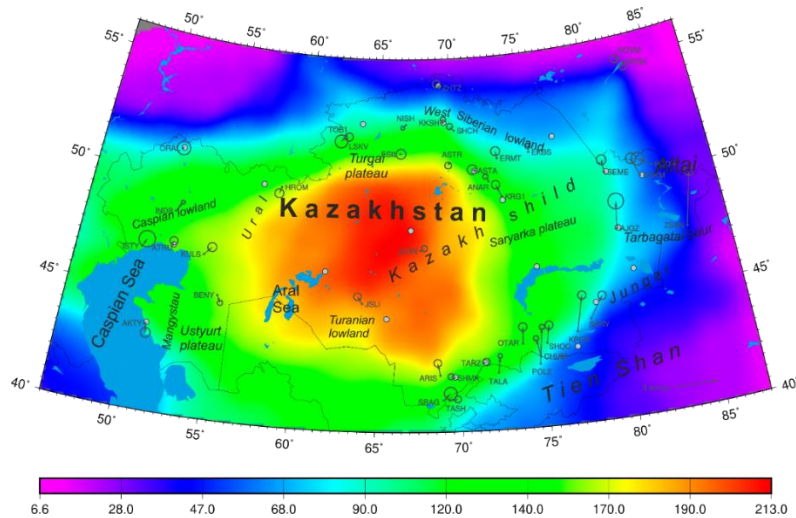


Figure 4. Map of the number of triangles covering each point of the regular grid

Note – compiled by the authors

Next, for each of the resulting triangles, the specified deformation parameters and the stability index (J) were calculated. The stability index (J) represents the deviation of the triangle's movement with the observed velocities at its vertices from the movement of the triangle as a rigid body (Zubovich & Mukhamediev, 2010). Therefore, the less internal deformation within the triangle, the smaller the stability index, and conversely, a high J value indicates significant deformation in the internal area, potentially due to an active fault passing through it.

By selecting from the many triangles covering a regular grid point those with the minimum J , weakly deformed areas of the Earth's surface can be outlined, thus localizing regions of increased deformation. It is evident that the magnitude of deformation depends not only on the

relative displacement between observation points but also on the distance between them. Consequently, in the triangulation overlay method, a portion of the triangles (up to one-third) covering each regular grid point and with the largest areas were excluded from the calculation. Additionally, triangles (up to one-third) with the highest error in velocity vectors at their vertices were also excluded.

RESULTS AND DISCUSSIONS

Field of velocity vectors of earth surface motion. In Figure 2, velocity vectors are presented on a scale of 3 mm/year. It can be seen that GPS observation points in most of Kazakhstan (the center, north, west, and southwest) exhibit very small magnitudes, mostly less than 0.5–0.6 mm/year. Those exceeding this value are still less than 1 mm/year and are chaotically directed, thus not forming any coherent structure on the Earth's surface. This is likely due to the unstable placement of antennas on high buildings, where broad coverage is required for differential corrections, and sub-millimeter precision is not crucial. The southeastern part of Kazakhstan and its eastern continuation differ significantly from the aforementioned tectonically quiet regions. Here, the surface velocities are as follows: 2.1 mm/year near the Kapchagai Reservoir (KPCH) north of Almaty, 3.6 mm/year south of Lake Zaysan (ZSAN), and 1.3 mm/year near the city of Ust-Kamenogorsk (OSKM). The latter station, located in the foothills of the Altai, has a small western component, unlike the Zaysan station where the velocity vector is directed to the north-northeast. Thus, the north-south shortening between the ZSAN and OSKM stations in eastern Kazakhstan, where earthquakes with magnitudes up to 6.8 occasionally occur, is 2.3 mm/year.

We compared the data from some stations with measurements from nearby points taken about 20 years ago during campaign mode (Zubovich et al., 2010) and transformed to the same reference system. Although the vectors are close in magnitude, some show slight differences in direction, indicating the presence of measurement errors.

An unclear zone is observed in the northern Caspian region and the Mangystau Peninsula. Here, the vectors fan out in different directions (ISTY: $V_x=0.23$, $V_y=0.52$; ATRU: $V_x=0.05$, $V_y=0.26$; KULS: $V_x=0.47$, $V_y=0.54$; BENY: $V_x=0.25$, $V_y=-0.49$; AKTY: $V_x=0.13$, $V_y=-0.60$ – all in mm/year), forming an area of extension. Although their values are small, the fact that these are not single vectors means the likelihood of simultaneous errors in adjacent measurement points is quite low.

Field of velocity vectors of earth surface motion. We applied the Method of Superimposed Triangulations to calculate the deformation velocity field based on the velocity vectors presented above for the territory of Kazakhstan. The calculation of deformations involves differential methods, so even small errors in the initial data can significantly affect the results. Hence, the velocity field of the Earth's surface in Kazakhstan, where relative velocities are very small and distances between measurement points are considerable, provides a good basis for testing the mentioned method.

The maps of the deformation-field components were visualized using a nonlinear, histogram-equalized color scale generated from the empirical cumulative distribution function (CDF) of the gridded deformation values. In this approach, the field values are ranked and mapped to evenly spaced positions in the color palette; consequently, the colors are distributed according to the data distribution rather than at equal numerical intervals. The transformation is applied only to visualization and does not modify the deformation values used in the calculations. The procedure follows the histogram-equalized color mapping implemented in the Generic Mapping Tools (GMT) `grd2cpt` module (Wessel et al., 2019; Generic Mapping Tools, 2026). This representation is useful for Kazakhstan because weak-deformation values occupy most of the regular grid, whereas high-deformation values are spatially localized; the CDF-based scale preserves visible detail within the low-amplitude background without suppressing the localized zones of higher deformation.

Maximum shortening velocity field. The field of maximum shortening rates E2 in the context of the ongoing collision between the Indian plate and Eurasia, which affects the southern and eastern regions of Kazakhstan, is of particular interest. Figure 5 clearly shows the correlation between areas of increased deformation and the topography. Significant deformations are observed in the Tian Shan mountain system, reaching up to -14×10^{-9} per year, and smaller ones in a strip in eastern Kazakhstan, including the mountain ranges of Junggar, Tarbagatai, and Altai. This may indicate ongoing processes of mountain building in these regions.

The remaining areas of Kazakhstan are tectonically stable. In these regions, there are virtually no deformations of the Earth's surface, which is also reflected in the topography. Small blue spots on the overall purple background are not the result of tectonic movements but are instead caused by errors in data from individual GPS observation points.

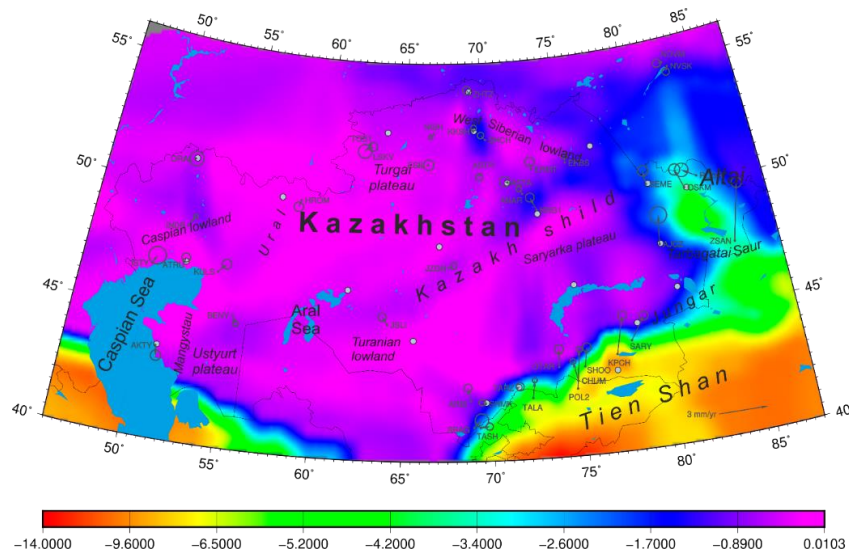


Figure 5. Velocity map of maximum shortening, E2

Note – compiled by the authors

An interesting area is observed in the southwest of Figure 5. Although there is no mountainous terrain here, the computed deformation rates are comparable to those in the Tian Shan. These are false deformations resulting from the sparse density of the GPS network. The deformation calculations included triangles whose vertices are far from Eurasia and exhibit high relative velocities with respect to it (see Figure 2).

Maximum elongation velocity field. The maximum elongation velocity field E1 (Figure 6) is more diverse compared to the maximum shortening velocity field, although it varies less, from 4.3 to -1.8×10^{-9} yr⁻¹. These are very small values bordering on errors. The purple color with negative values shows regions of all-round compression, which is unlikely to be real. From blue to blue - areas with deformation rates close to zero. Such - most of the surface of Kazakhstan. Tien-Shan and its surroundings stand out in red color. Indeed, due to strong meridional compression, the Earth's crust is being squeezed out to the sides, which can be seen in Figure 6. An interesting area of green color appeared from the western end of the Dzungarian ridge to the north and further to the north-west. It stood out due to a larger number of GPS observation points, so its reliability is higher and should be verified by other geophysical methods.

The stretching zone near the northern Caspian Sea and the Mangystau Peninsula, described at the end of Section 4.1, is also well manifested in the field of maximum elongation rates. The strain rate here averages $\sim 0.6 \times 10^{-9}$ yr⁻¹.

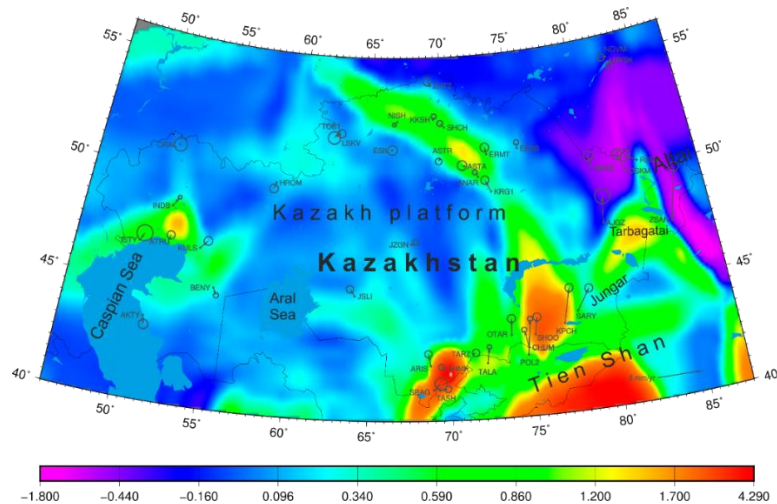


Figure 6. Velocity map of maximum elongation, E1

Note – compiled by the authors

Maximum shear velocity field.

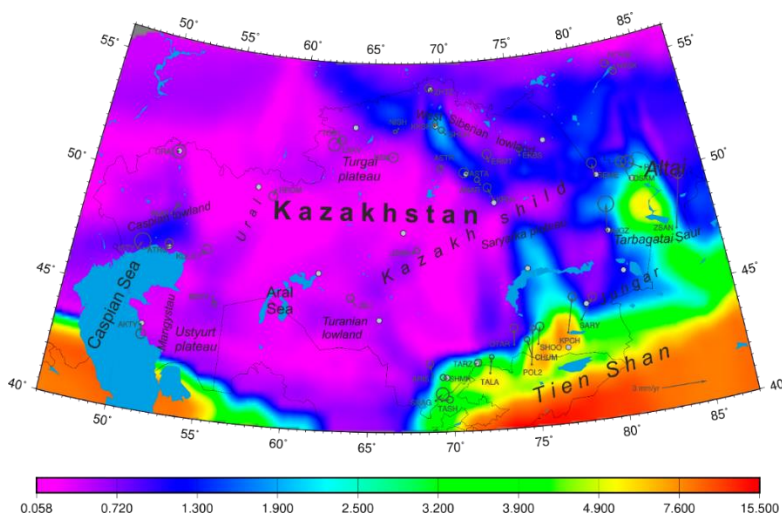


Figure 7. Maximum shear velocity map

Note – compiled by the authors

The shear component is more quiescent (Figure 7). Where the absolute values of E2 are greater than E1, the maximum shear velocity field is similar to the maximum shortening velocity field - these are the right and lower parts of the figures. Conversely, similar to the maximum extension rate field, though less distinctly, the same anomaly appears extending from the western end of the Dzungarian Range to the north and further northeast.

Maximum elongation velocity field. Figure 8, showing the orientation and magnitudes of the principal axes of the strain tensor, illustrates the same patterns as the previous three figures. It reveals regions of maximum shortening in the southeastern Tien Shan and eastern Kazakhstan extending northward, including the Altai. In the southwest, there is a region of false deformations due to the sparse GPS network, which led to the inclusion of southern points with high velocities in the deformation calculations. The center, north, and west of Kazakhstan are tectonically stable, with only a few vectors deviating from the general trend, indicating that this deformation calculation method can be used to identify anomalous data.

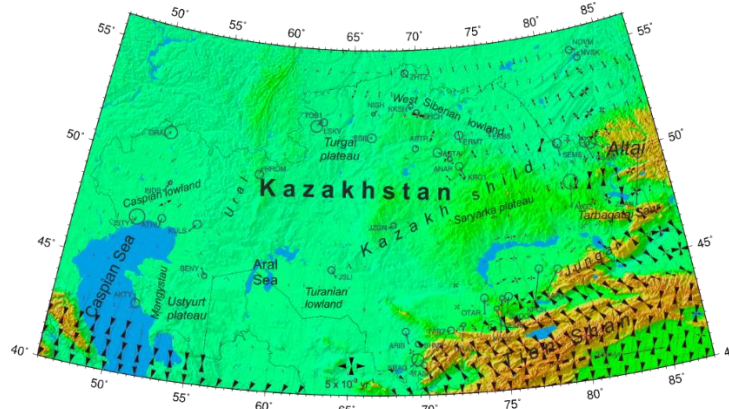


Figure 8. Schematic of the orientations of the maximum, E1, and minimum, E2, elongation velocities (diverging arrows represent elongation, converging arrows represent shortening). The length of the arrows is proportional to the absolute value of the corresponding strain rate.

The scale of the arrows is shown at the bottom of the figure above the caption 65°

Note – compiled by the authors

Rotational velocity field. Figure 9 illustrates the rotational velocity field of the grid points across Kazakhstan. Almost the entire surface of the country shows counterclockwise rotation, with the central part exhibiting low velocities around ~ 0.3 nanoradians per year, and the southeastern region displaying velocities ranging from 1 to 8 nanoradians per year or more. There are two notable spots: one is located to the west of Issyk-Kul, with a lower counterclockwise rotational speed, while the other is situated to the west of the Dzhungar Alatau and south of the Tarbagatai, where clockwise rotation is observed. The latter is likely unrealistic and may be attributed to the sparse data around the perimeter of the study area.

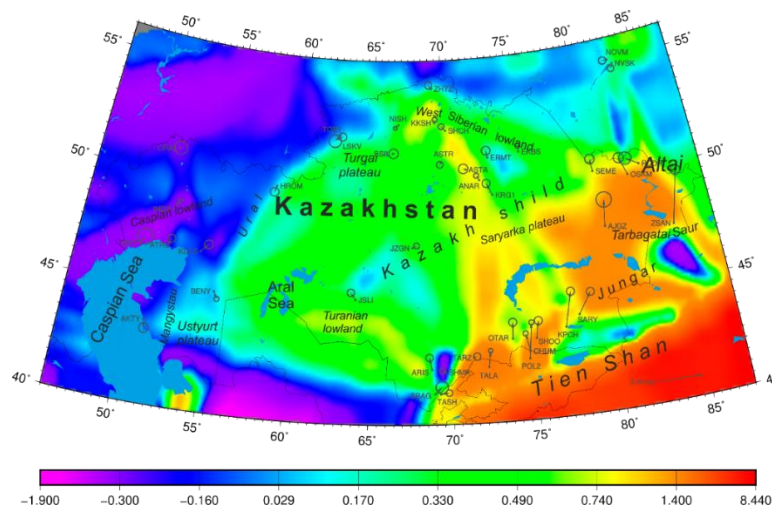


Figure 9. Map of rotation velocities. The scale under the figure is given in nanoradian/year values. Positive values indicate counterclockwise rotation

Note – compiled by the authors

CONCLUSIONS

The data from the reference GNSS stations, originally intended for differential topographic surveying in geodetic and cartographic work, have shown satisfactory results for use in geodynamical studies. Over time, the number of such stations in Kazakhstan may increase.

Therefore, if certain conditions for better stabilization of GNSS antenna installation points and cessation of station relocations are met, these stations can be used to monitor the dynamics of deformation field changes over time.

The results obtained in this study confirm previous findings about Kazakhstan's tectonics. Major surface movements occur along the northern boundary of the Tien Shan and in the eastern regions, encompassing the Dzungarian Alatau, Saur-Tarbagatai zone, and Altai mountain system, including the Zaysan depression. These data correlate well with both the topography and the historical and contemporary seismicity recorded in these areas. In the rest of Kazakhstan, movements are nearly negligible, with isolated vectors showing speeds up to 1 mm/year. However, these do not fit into the general trend and may be attributed to measurement errors or unstable behavior of GNSS antennas.

The deformation velocities calculated for Kazakhstan using the method of superimposed triangulations have shown good results under challenging initial conditions: sparse network and low speed gradients. They effectively highlight areas of increased deformation in the eastern and southeastern parts of the country. Furthermore, the method allows for the identification of data that do not conform to general tectonic movement trends, necessitating closer examination. On the other hand, the deformation calculations revealed some limitations of the method, such as the presence of deformation zones in the southwestern part of the study area where none should exist. The method is sensitive to the sparse number of GNSS stations around the perimeter and, consequently, the small number of superimposed triangles in those areas. Therefore, for better application of the method, it is essential to have observation points beyond the boundaries of the study area.

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DATA AVAILABILITY STATEMENT: Data are contained within the article. The data presented in this study are available from the corresponding author upon reasonable request.

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Сыдық Нұрмахамбет Қанатұлы – техника және технология магистрі, ғырыштық техника және технологиялар саласындағы PhD-докторант, «Ионосфера институты» ЖШС космостық және геоақпараттық технологиялар зертханасының меңгерушісі.

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