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RETROSPECTIVE ANALYSIS OF VERTICAL MOVEMENTS AND MAJOR EARTHQUAKES IN THE CAUCASUS (1925–2023)

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Abstract

This study presents a retrospective analysis of vertical crustal movements in the Caucasus for the period 1925–2023, based on geodetic leveling, GNSS observations, and satellite interferometry (InSAR). Spatial–temporal patterns of surface uplift and subsidence, reflecting the development of orogenic processes in the region, were identified through mapping. It is established that the central part of the Caucasus has been characterized by stable uplift (up to 10–12 mm/year) throughout the entire period, whereas peripheral zones demonstrate subsidence of varying intensity. A comparative analysis of seismicity revealed a correlation between anomalous vertical deformations and the foci of strong earthquakes, confirming their possible role as indicators of seismic hazard. Particular attention is given to the correlation of vertical tectonic movement phases with major seismic events of the 20th–21st centuries, including earthquakes in Armenia, Dagestan, Georgia, as well as adjacent areas of Turkey and Iran. The results emphasize the need for integrated monitoring using modern geodetic and remote sensing techniques to assess seismic risk in the Caucasus.

Keywords: Caucasus, vertical crustal movements, orogenic processes, geodetic leveling, GNSS, InSAR, seismicity, seismic hazard, geodynamics, tectonic deformation.

QAFQAZIN ŞAQULİ HƏRƏKƏTLƏRİNİN VƏ İRİ ZƏLZƏLƏLƏRİN RETROSPEKTİV TƏHLİLİ (1925–2023)

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Xülasə

Təqdim olunan işdə 1925–2023-cü illər dövrü üzrə Qafqazda Yer qabığının şaquli hərəkətlərinin geodezik nivelirləmə, GNSS müşahidələri və peyk interferometriyası (InSAR) məlumatları əsasında retrospektiv təhlili aparılmışdır. Tərtib edilmiş xəritələr əsasında regionda orogen proseslərin inkişafını əks etdirən yer səthinin qalxma və çökməsinin məkan-zaman qanunauyğunluqları müəyyən edilmişdir. Müəyyən olunmuşdur ki, Qafqazın mərkəzi hissəsi bütün dövr ərzində davamlı qalxma ilə (ildə 10–12 mm-ə qədər) səciyyələnir, periferiya zonaları isə müxtəlif intensivlikli çökmə nümayiş etdirir. Seysmikliyin müqayisəli təhlili anomal şaquli deformasiyaların güclü zəlzələlərin ocaqları ilə əlaqəsini aşkar etmişdir ki, bu da onların seysmik təhlükənin mümkün indikatorları kimi rolunu təsdiqləyir. Xüsusi diqqət XX–XXI əsrlərdə baş vermiş iri seysmik hadisələr, o cümlədən Dağıstan, Azərbaycan və Gürcüstanda, eləcə də Türkiyə və İranın qonşu ərazilərində baş vermiş zəlzələlər ilə şaquli tektonik hərəkətlərin fazalarının müqayisəsinə yönəldilmişdir. Alınmış nəticələr Qafqazda seysmik riskin qiymətləndirilməsi üçün müasir geodezik və məsafədən zondlama metodlarından istifadə etməklə kompleks monitorinqin vacibliyini vurğulayır.

Açar sözlər: Qafqaz, Yer qabığının şaquli hərəkətləri, orogen proseslər, geodezik nivelirləmə, GNSS, InSAR, seysmiklik, seysmik təhlükə, geodinamika, tektonik deformasiyalar.

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РЕТРОСПЕКТИВНЫЙ АНАЛИЗ ВЕРТИКАЛЬНЫХ ДВИЖЕНИЙ И КРУПНЫХ ЗЕМЛЕТРЯСЕНИЙ КАВКАЗА (1925–2023 ГГ.)

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Аннотация

В работе представлен ретроспективный анализ вертикальных движений земной коры Кавказа за период 1925–2023 гг. по данным геодезического нивелирования, GNSS-наблюдений и спутниковой интерферометрии (InSAR). На основе построенных карт выделены пространственно-временные закономерности поднятия и опускания земной поверхности, отражающие развитие орогенических процессов в регионе. Установлено, что центральная часть Кавказа на протяжении всего периода характеризуется устойчивым поднятием (до 10–12 мм/год), в то время как периферийные зоны демонстрируют опускание различной интенсивности. Сравнительный анализ сейсмичности выявил связь аномальных вертикальных деформаций с очагами сильных землетрясений, что подтверждает их возможную роль в качестве индикаторов сейсмической опасности. Особое внимание уделено сопоставлению фаз вертикальных тектонических движений с крупными сейсмическими событиями XX–XXI вв., включая землетрясения в Дагестане, Азербайджане, Грузии, а также на сопредельных территориях Турции и Ирана. Полученные результаты подчеркивают необходимость комплексного мониторинга с использованием современных геодезических и дистанционных методов для оценки сейсмического риска на Кавказе.

Ключевые слова: Кавказ, вертикальные движения земной коры, орогенические процессы, геодезическое нивелирование, GNSS, InSAR, сейсмичность, сейсмическая опасность, геодинамика, тектонические деформации.

Introduction

The study of vertical movements of the Earth's surface using geodetic methods has a long history. The greatest attention has been paid to seismically active regions, where the effort to understand the mechanisms of destructive earthquakes is combined with the goal of ensuring safety. Since the 1970s–1980s, particular interest has been focused on the relationship between crustal deformations and seismic activity, including the search for short-term precursors of strong earthquakes [31, 32]. In this context, geodynamic observatories have been established in several regions to provide regular monitoring of deformations, which has allowed the identification of characteristic changes in the behavior of the Earth's surface before, during, and after earthquakes.

The most studied deformations are vertical movements preceding major seismic events. In the 1960s–1970s, large-scale uplifts of the Earth's surface covering hundreds of square kilometers were recorded, which were interpreted as precursors to strong earthquakes. Such anomalies were observed prior to the 1964 Niigata earthquake in Japan (M = 7.4) [30]. Similar cases have also been documented in Costa Rica (1991) [30], Alaska (1964), Chile (1960), and other regions.

Cases of anomalous uplift have also been recorded in Southern California. In this region, the persistent uplift of mountain structures (1–2 mm/year) is associated with compression along the San Andreas Fault zone and is confirmed by GPS and InSAR data [30].

With the introduction of InSAR, remote monitoring of vertical deformations has become possible. The combination of InSAR and GNSS allows for increased accuracy in displacement measurements and is widely used in Europe and other regions.

Thus, crustal uplift serves as an important indicator of tectonic processes and a potential precursor of strong earthquakes. High-precision geometric leveling, which forms the basis of height reference systems in various countries, has been actively used to determine vertical movements of the Earth's crust.

Vertical Movements of the Caucasus Crust Based on Leveling, GNSS, and InSAR Data (1925–2023)

To date, it can be stated that the geotectonic evolution of the Caucasus remains insufficiently studied. There is no consensus on the course of geological processes in this region. Vertical movements of the Earth's crust in the Caucasus have been documented on several maps based on repeated precise leveling data. Works [8, 30] provide detailed descriptions and maps of vertical movements for the period 1925–1992.

The first map, the "Map of Contemporary Vertical Movements in Eastern Europe" was compiled using leveling data from 1925–1950. In 1968, a survey of new leveling lines spanning 3,200 km and covering 266 benchmarks was conducted, which for the first time recorded intense uplift of the Greater Caucasus using geodetic data. The second map, the "Map of Contemporary Crustal Vertical Movements" covers several European countries and the USSR. The Caucasus data in both versions of this map are consistent and are based on leveling data from 1951–1975. The third map, the "Map of Vertical Movements of the Caspian Region Surface" was constructed using leveling results from 1975–1992. The average interval between survey cycles was approximately 30 years. The accuracy of vertical movement estimates ranged from 0.2 to 2.6 mm/year [7].

Observations of vertical and horizontal surface movements in the Caucasus using InSAR began around the early 2000s, following the availability of satellite data with sufficient spatial and temporal resolution. Considering GNSS station data from the Institute of Geology and Geophysics of the Ministry of Education of Azerbaijan for the period 1998–2014, as well as data [28, 29] from GNSS stations of the Republican Center of the Seismological Service [7] and maps based on InSAR observations [6], a map of vertical movements in the Caucasus for the period 1998–2023 was compiled.

The maps of vertical movements of the Caucasus for different periods—1925–1950, 1951–1975, 1975–1992, and 1998–2023—are presented below. These maps, shown as color gradients, depict the rate of vertical displacement in millimeters per year (mm/year), where blue indicates subsidence and red indicates uplift. As shown in Fig.18, uplift is evident in the Greater Caucasus during the periods 1925–1950, 1975–1992, and 1998–2023.

During 1951–1975, uplift was observed in the Lesser Caucasus. It should be noted that, across all studied geophysical fields, the Eastern Caucasus differs from the Western Caucasus. In 1925–1950, the central part of the Caucasus, particularly along the Main Caucasus Ridge, exhibited significant uplift at rates of 5–10 mm/year, reaching peaks of up to 12 mm/year in active zones concentrated within a 100–150 km wide north–south strip. Peripheral areas, especially near the Black Sea, showed subsidence at rates of -1 to -3 mm/year, reaching -5 mm/year in coastal zones, reflecting the initial phase of compressional tectonic activity caused by plate collision.

Subsequently, during 1951–1975, the intensity of central uplift decreased to 3–7 mm/year, with peaks up to 8 mm/year, while subsiding zones expanded near the Caspian and Black Seas, where rates reached -1 to -5 mm/year, with maxima up to -6 mm/year in sedimentary basins, possibly due to sedimentary loading or changes in the tectonic regime.

In 1975–1992, uplift in the central region intensified again to 5–10 mm/year, with local maxima of 12–15 mm/year along the Main Caucasus Ridge, whereas subsidence was confined to the southwestern and northeastern corners of the region, with rates of -1 to -3 mm/year, reaching -4 mm/year along the coasts, possibly related to seismic activity or renewed crustal deformation.

In the modern period, 1993–2023, the data show the most pronounced movements: extensive central uplift at rates of 6–8 mm/year, with peaks up to 10 mm/year in a 50–100 km wide band, and scattered subsidence at rates of -1 to -5 mm/year, reaching -7 mm/year in sedimentary basins near the Caspian Sea, indicating ongoing compression and orogenesis.

Relationship Between Vertical Movements and Major Earthquakes in the Caucasus: A Retrospective Analysis (1925–2023)

Based on the above, maps of vertical movements in the Caucasus were compiled for the periods 1925–1950, 1951–1975, 1975–1992, and 1998–2023 [7, 30] (Fig. 1). Seismicity data were taken from [3, 17–27].

The persistent uplift along the Main Caucasus Ridge reflects compressional tectonics resulting from plate collisions, while variations in the intensity and spatial distribution of movements may be related to seismic activity and changes in the tectonic regime. From 1925 to 2023, the amplitude and spatial variability of movements increased, which may be attributed to accelerated tectonic processes or improved measurement accuracy.

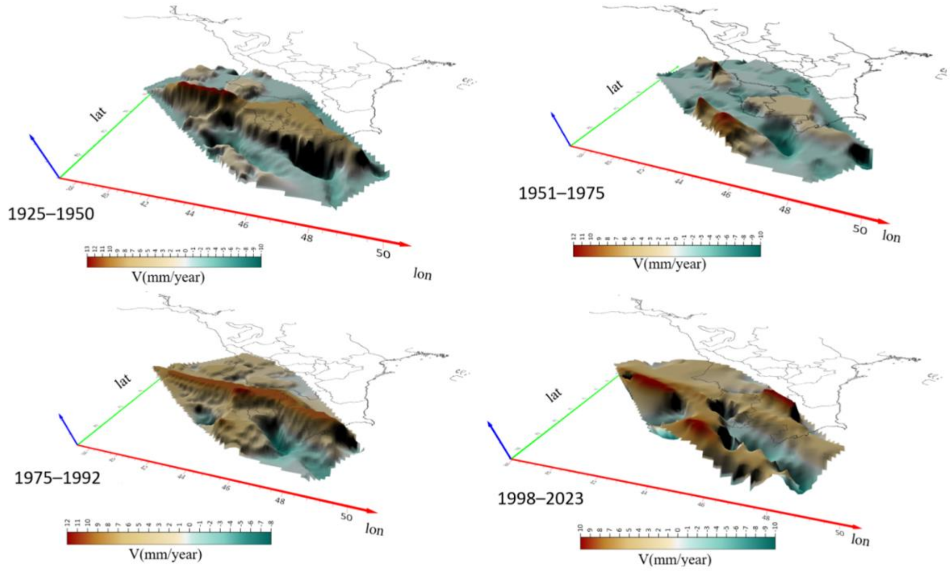

Figure 1. Maps of vertical movements in the Caucasus for the periods 1925–1950, 1951–1975, 1975–1992 [8, 30], and 1998–2023

The Absheron Peninsula also exhibits subsidence, which can be explained by hydrocarbon extraction in the region. The maps demonstrate a consistent trend of central uplift associated with orogenesis, and peripheral subsidence reflecting the interaction of tectonic and isostatic factors.

An interesting observation indicating a real connection between anomalous uplift of the Earth's surface in various regions of the world and strong earthquakes is that these earthquakes often occur within or near zones of anomalous uplift, particularly in areas with high gradients of transition from subsidence to uplift. At the same time, there are areas of anomalous uplift that have not yet experienced earthquakes (or where earthquakes have not yet occurred). One such area is the Stavropol Uplift, isolated from the Greater Caucasus uplift and located on a tectonic platform. Notably, a strong earthquake with a magnitude of approximately 6.0 occurred in this region in 1921. These circumstances suggest that the area should be considered seismically hazardous.

During the considered time interval, catastrophic earthquakes were repeatedly recorded across the Caucasus. To establish a possible relationship between major seismic events and phases of vertical tectonic movements in the region, diagrams were constructed showing the correlation between the Caucasus topography, the magnitude of vertical displacements, and the distribution of earthquakes across different time periods. Profiles were made across the Caucasus along the southwest–northeast direction (Fig. 2).

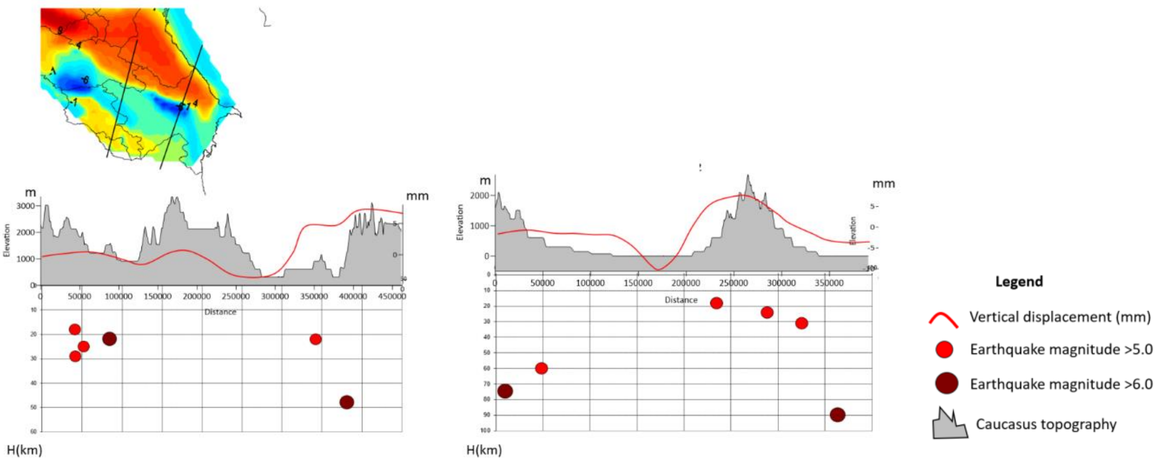

Figure 2. Diagrams showing the relationship between the Caucasus topography, vertical displacements, and the distribution of earthquakes for the period 1925–1950

It is assumed that increased rates of modern horizontal and vertical movements in seismically active regions reflect the interseismic phase of the seismic cycle, during which accumulated elastic stresses are redistributed and partially released. Conversely, a slowdown of these movements may indicate the accumulation of deformation energy and, consequently, an increased seismic hazard. The spatial distribution of major earthquake hypocenters generally supports this interpretation: their epicenters, with few exceptions, are located near the boundaries of preceding tectonic uplifts.

In the first profile (1925–1950) along the Nakhchivan–Dagestan direction, a minor uplift of 1 mm/yr is observed in the Lesser Caucasus and an uplift of up to 7 mm/yr in the Greater Caucasus, which is consistent with the regional topography (Fig. 3). During this period, six earthquakes with magnitudes of M = 5.5–6.6 were recorded. The strongest events include the earthquake on 22 February 1934 with M = 5.8, on 29 June 1948 with M = 6.4 (depth 48 km), and on 27 April 1931 with M = 6.6 (depth 15 km). The earthquake on 27 April in the Syunik region (Armenia) caused a very large number of casualties (2,890 people) and injuries, with extensive damage to buildings and infrastructure near the epicenter. This was the 8th most destructive earthquake ever recorded in Armenia and the 5th most destructive earthquake in the world in 1931. Additionally, the Zagatala earthquakes on 2 September 1936 (M = 5.3, $I_0 = 6$) and 29 June 1948 (M = 6.1, $I_0 = 7$) were significant events.

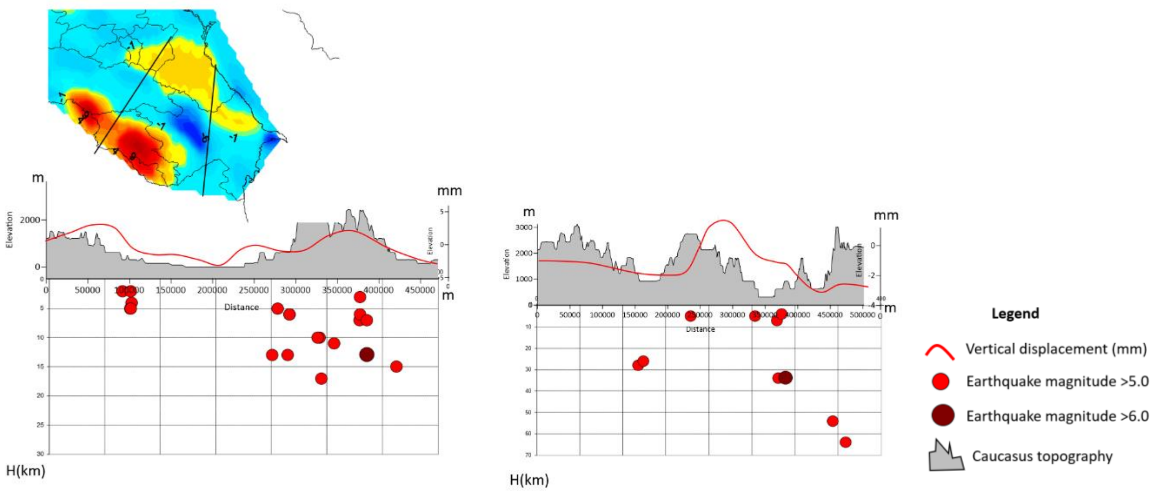

Figure 3. Diagrams showing the relationship between the Caucasus topography, vertical displacements, and the distribution of earthquakes for the period 1951–1975

In the second profile along the Iran–Caspian Sea direction, subsidence of the Kurin Basin of up to 10 mm/yr and uplift of the Greater Caucasus up to 6 mm/yr are observed. This uplift was accompanied by earthquakes with magnitudes of M = 5.5–6.9. On 19 February 1924 at 06:59 GMT, a strong earthquake of magnitude 6.0 occurred in northern Iran in the Ardabil region, with the epicenter 21 km from Jalilabad. On 9 April 1935, a major Caspian earthquake with M = 6.6 (depth 90 km) occurred. Furthermore, on 9 October 1931, 5 July 1931, and 30 August 1948, three earthquakes with M = 5.5–5.6 took place in the Shamakhi and Guba districts.

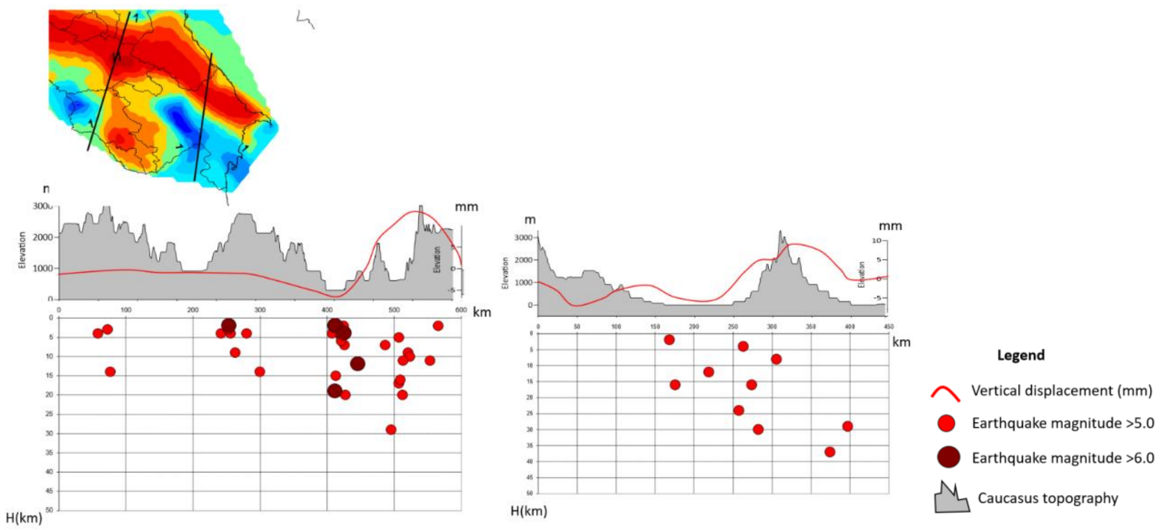

Figure 4. Diagrams showing the relationship between the Caucasus topography, vertical displacements, and the distribution of earthquakes for the period 1976–1992

As noted above, the second period (1951–1975) is characterized by active vertical uplift of the Lesser Caucasus. Along the Armenia–Dagestan profile, an elevation of up to 5 mm/yr is observed, followed by subsidence of the Kura Basin up to 2 mm/yr and uplift of the Greater Caucasus up to 3 mm/yr. This period is marked by high seismic activity at depths ranging from 2 to 16 km. In Armenia, earthquakes with M = 5.5 at depths of 2–5 km were recorded in 1962 and 1968. On the territory of the Greater Caucasus, 13 earthquakes with magnitudes of M = 5.5–6.7 were registered. The most significant event was the earthquake on 14 May 1970 in Dagestan, with a magnitude of M = 6.7 and an intensity of 9. The epicenter was located 30 km northwest of Makhachkala. The earthquake destroyed 22 settlements, killed 31 people, and left about 45,000 homeless. This event became the largest seismic event in the Caucasus in the 20th century after the 1902 Shamakhi earthquake.

Along the second profile, Iran–Makhachkala, the southern slope of the Greater Caucasus shows an uplift of 2 mm/yr, while the Tersk-Caspian depression subsides by 2 mm/yr. During this period, 8 earthquakes with magnitudes of M = 5.2–6.6 occurred along this profile, the strongest being the Caspian earthquake on 19 September 1961, with M = 6.6 and a depth of 64 km.

Along the profile-oriented Armenia–Grozny (1976–1992), tectonic movements are observed as subsidence of the Kura Basin at a rate of up to 5 mm/yr and uplift within the Greater Caucasus reaching 9 mm/yr (Fig. 4).

This region is characterized by heightened seismic activity, with three focal zones identified, showing a gradual increase in focal depths toward the northeast. The most active zone is associated with the Main Caucasus thrust.

During the analyzed period along this profile, seven earthquakes with magnitudes M = 6.0–6.9 and more than 25 earthquakes with magnitudes M = 5.6–5.9 were recorded. Among them, the most significant events include: on 24 November 1976, an earthquake with a magnitude of M = 6.9 occurred on the border of Iran and Turkey, with a focal depth of approximately 10 km. Within the

Greater Caucasus, on 29 April 1991, the destructive Racha earthquake occurred with Mw = 7.0, accompanied by two aftershocks exceeding Mw = 6.0. In the western part of this event's focal zone, strong earthquakes with magnitudes M = 6.0–6.4 had previously occurred in 1905, 1963, and 2009 [11]. Particular attention is given to the catastrophic Spitak earthquake on 7 December 1988 (Mw = 6.8), which claimed over 25,000 lives. It should be noted that from 1964 to 1983, the epicentral region experienced increased seismic activity, predominantly in a sub-meridional direction. The strongest earthquake during this period occurred in 1978 with M = 5.3. Maximum seismotectonic deformation values were recorded between 1977 and 1983, during which seven seismic events with magnitudes M = 4.5–5.3 were registered. The focal zone of the 1988 Spitak earthquake, reaching an intensity of up to 10 at the epicenter and located in northwestern Armenia, is associated with major fault systems: Abul-Samsar, Pambak-Sevan, and Transcaucasian [1]. This area remains one of the most seismically active zones in the Caucasus. On 15 June 1991, near the city of Bakuriani (Georgia), a significant earthquake occurred, destroying eight villages with a magnitude of M = 6.3. The tremors were felt along the Black Sea coast. Along the Iran–Caspian Sea profile, vertical movements of the southern slope of the Greater Caucasus reached up to 10 mm/yr. Eleven earthquakes with magnitudes M = 5–5.5 were recorded, mainly in the Shamakhi region. The most significant earthquake occurred on 29 November 1981 (M = 5.5), and on 15 October 1993 at 22:37 northwest of Ismailli, an earthquake with M = 5 occurred.

The fourth period was characterized by uplift in both the Lesser and Greater Caucasus (Fig. 5).

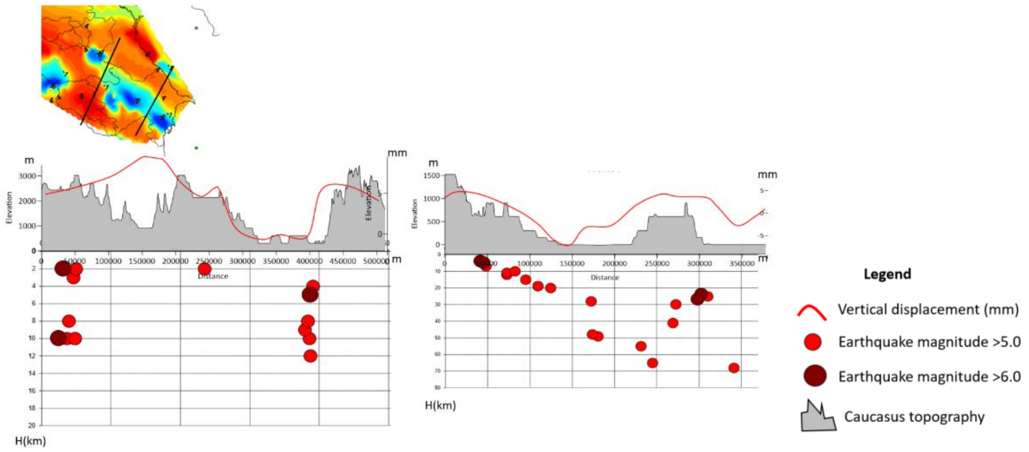

Figure 5. Diagrams showing the relationship between the Caucasus topography, vertical displacements, and the distribution of earthquakes for the period 1998–2023

During the period 1998–2023, along the first profile, the rate of vertical uplift in the Lesser Caucasus reached up to 8 mm/yr, and in the Greater Caucasus — up to 6 mm/yr. One of the most significant seismic events in the region was the earthquake on 11 August 2012, which occurred at 15:53 local time, 60 km northeast of Tabriz. The main shock had a magnitude of M = 6.4, with the epicenter located in Ahar Shahrestan, approximately 20 km southwest of the city of the same name, and a hypocenter depth of 9.9 km. Eleven minutes later, an aftershock of M = 6.3 occurred, with its epicenter 12 km southwest of the main shock.

Earlier, on 23 October 2011, a destructive earthquake of Ms=7.3 occurred in Van Province, southeastern Turkey, near the Iranian border, causing 604 fatalities and injuring 2,068 people. At the Georgia–Armenia border in the Javakheti Highlands near Lake Paravani, two earthquakes were recorded: on 9 February 1997 (MLH = 4.5, I_0 = 5–6) and 14 January 1999 (MS = 4.3, I_0 = 6–7). The region had also experienced previous seismic activity, including an event on 29 June 1967 with intensity 6.

On 27 November 1997, at 17:34 in the Sagarejo District of eastern Georgia, the Hashmi earthquake occurred (MW = 5.3, I_0 = 7). In Tbilisi, on 25 April 2002, one of the strongest post-1900 earthquakes struck (KR = 12.2, Imax = 7–8), characterized by a shallow focus (h = 5 km) and predominantly southeast-oriented extensional stresses. The Oni earthquakes on 6 February 2006 (04:08) and 7 September 2009 (22:41), occurring in the Racha area along the middle Rioni River on the southern slope of the Greater Caucasus, reached M = 6.2 and were associated with the northern branch of the focal zone of the 29 April 1991 Racha earthquake (M = 7.0, I_0 = 7–8).

On 7 June 2017, at 18:25, a M = 5.1 earthquake occurred in the Kura Depression, Georgia. Along the Armenia–Turkey border in July 2004, several seismic events occurred: 1 July (M = 4.8, h = 25 km, I_0 = 6–7) and 30 July (M = 4.2, h = 10 km, I_0 = 6). The epicentral area is bounded by ridges and mountain massifs, including the Tsakhkunatsky Ridge, Mount Aragats (4000 m), Arailer (2500 m), Gegham Ridge, Greater and Lesser Ararat (5165 m and 3925 m), and the Agryadak Ridge. Earthquake foci in the Iğdır–Doğubayazıt region are related to the Ararat deep fault, as well as the Spitak–Ararat and Sevan–Ararat faults. On 5 February 2021, an earthquake of M = 5.5 occurred in Armenia.

In the Chechen Republic, increased seismic activity was also observed. On 11 October 2008, at 09:06, the Kurchaloy earthquake occurred (Mw = 5.8, I_0 = 7–8), felt over a wide area including neighboring regions of Russia, Georgia, and northern parts of Armenia and Azerbaijan. On 12 December 2020, the Chernogorsk earthquake (Mw = 4.8, I_0 = 5–6) was recorded in Chechnya.

In Azerbaijan, seismic activity increased, particularly in the northwest. Notable events include: 8 February 2004 — Shaki earthquake (MPVA = 5.1, h = 8–14 km), 7 May 2012 — two Zaqatala earthquakes (M = 5.6 and 5.7; Mw = 5.6 and 5.3, I_0 = 7), 14 October 2012 — Balakan earthquake (M = 5.6), and 29 June 2014 — M = 5.3 event in the Zagatala and Balakan area. Subsequent shocks occurred on 29 September and 4 October (M = 5.5 and 5.0) in the Vandam structure. On the border with Dagestan, earthquakes were recorded on 3 May 2017 (M = 5.2) and 5 June 2018 (M = 5.5).

Along the second profile, vertical uplift of both the Lesser and Greater Caucasus reached 5 mm/yr. Along the southwest–northeast-oriented profile, the increasing focal depth of earthquakes indicates the subduction of the Kura Depression beneath the Greater Caucasus. In central Azerbaijan, in Agdash, a Mw = 5.4 earthquake with intensity I_0 = 7 occurred on 4 June 1999.

On 21 March 2000, a M = 4.3 earthquake (I_0 = 6) was recorded near Lake Sarysu (Saatly District), felt in several cities. On 4 September 2015, a M = 5.9 earthquake (I_0 = 7, depth = 16 km) occurred in Oghuz District, accompanied by two foreshocks and 92 aftershocks. On 1 August 2016, a M = 5.6 earthquake occurred in Imishli District, and on 11 May 2017 in Saatly — M = 5.4. On 15 November 2017, at the junction of the Lesser Caucasus and Kura Depression, a notable earthquake of M = 5.7 also occurred [17].

In the Talysh Zone, the strongest earthquake occurred on 9 July 1998 in the Lerik District (Mw = 6.0, I_0 = 7). It was accompanied by intense aftershock activity — within the first five hours, 67 aftershocks were recorded, and the overall aftershock field extended along the Talysh Fault. A secondary event in the same area occurred on 11 July 2007, with a magnitude of Mw = 5.2 and intensity I_0 = 6. In 2024, seismic activity resumed in the region: on 11 May, an earthquake of M = 5.3 occurred in Lankaran, followed by another event of M = 5.0 on 28 June.

The Caspian Zone also exhibits high seismicity. Among the most powerful events were two earthquakes on 25 November 2000, occurring one minute apart (Mw = 6.8 and 6.5), with a maximum intensity of I_0 = 8 in the epicentral area. They were felt almost throughout the country, generating 165 aftershocks, 36 of which were felt in Baku. On 10 January 2014, a M = 5.0 offshore earthquake occurred in the northern sector of the Azerbaijani Caspian, followed on 10 February by the stronger

Hadjigabul earthquake (M = 5.7) [20]. In 2023, additional earthquakes with magnitudes of M = 5.6 were recorded in the central Caspian Sea on 4 July and 7 December.

In Ismayilli District, a M = 5.3 (Mw = 5.1) earthquake occurred on 7 October 2012 with intensity I_0 = 5–6. Seismic activity resumed on 5 February 2019, with a foreshock of M = 4.4 followed by the main shock of M = 5.2 [19]. In Shamakhi District, a notable earthquake of ML = 5.1 occurred on 20 November 2021. Two moderate earthquakes in 2007 should also be noted: 23 August in Aghsu District (M = 4.0) and 19 September in Terter District (M = 4.5), both with maximum intensity I_0 = 5.

Discussion of Results

Thus, vertical movements indicate the ongoing tectonic growth of the Caucasus Mountains, reflecting the region's active neotectonic evolution. A spatial correlation has been established between zones of intense vertical uplift and areas of strong seismic activity. Epicenters of major earthquakes are generally located along boundaries between uplift and subsidence zones, particularly within the Main Caucasian Thrust. This supports the concept of deformation accumulation during the interseismic phase, followed by its release as earthquakes.

A key factor controlling both historical and contemporary tectonic movements in the Caucasus is the progressive motion of the Arabian lithospheric plate, driven by Alpine orogeny [5,16]. However, the energy sources and primary causes of this process remain subjects of scientific debate, as no unified, widely accepted concept satisfactorily explains its nature. In addition to the Arabian Plate motion, several studies note a counteracting, though less intense, convergence of the southern sector of the East European Platform. The combination of these processes generates meridional compression and sub-latitudinal extension of the crust, as confirmed by GNSS observations.

The northern protrusion of the Arabian Plate interacts with stable, consolidated areas of the oceanic lithosphere, resulting in redistribution of deformation: part of the strain is directed westward along the East Anatolian Fault, and part toward the northeast, toward the Lesser Caucasus. In this context, the system of strike-slip faults of the Lesser Caucasus arc, located in direct contact with the southern flank of the Greater Caucasus, plays a key role. Within this zone, the catastrophic Spitak earthquake of 1988 occurred.

Analysis of the morphostructural organization, kinematics of contemporary movements, and seismicity distribution in the Caucasus reveals characteristic geodynamic patterns associated with the interaction of rigid lithospheric blocks. Similar structural-geodynamic relationships are observed in other continental-type orogenic zones. In this context, it is instructive to compare the Caucasus region with the Pamir and Southern Tien Shan, where analogous morphostructural and tectonic features are recorded. A tectonic analogy emerges between two major geodynamic systems: Lesser Caucasus — intermontane depressions — Greater Caucasus and Pamir — intermontane depressions — Southern Tien Shan. Both structures demonstrate comparable morphotectonic configurations, including contrasting blocks in terms of geomechanical properties, separated by zones of active deformation represented by intermontane basins [1, 2].

The linear morphostructural organization of the Greater Caucasus and Southern Tien Shan is controlled by the predominance of rigid, mechanically consolidated lithospheric blocks that exhibit relatively plastic resistance to tectonic stresses. In contrast, the arcuate configuration of the Lesser Caucasus and the Pamir indicates the presence of more compliant and weakly consolidated blocks capable of significant intralithospheric deformation. This morphological distinction reflects fundamental contrasts in lithospheric mechanical behavior in response to compressive forces generated by tectonic plate collisions. In both cases, the central portion (intermontane depressions) constitutes a zone of active seismotectonic loading, concentrating contemporary vertical movements and deformations.

Despite alternative interpretations, a number of geophysical and geodynamic data support the hypothesis of a hidden subduction zone between the Lesser and Greater Caucasus [4, 9, 12]. First, seismic activity in the region demonstrates the presence of a dipping slab, manifested as a cluster of earthquake foci localized at depths up to 60 km with a distinct spatial orientation corresponding to the mid-segment of the subduction complex. Second, geodetic data and the pattern of contemporary vertical crustal movements [13, 14, 15] provide additional evidence. Specifically, geodetic and geophysical observations indicate prolonged subsidence of intermontane depressions such as the Kura and Rioni basins. These depressions exhibit persistently negative rates of vertical movement, consistent with a typical geodynamic subduction model, where a regional uplift is expected above the subducting plate due to mechanical underthrusting and material accumulation in the zone ahead of the subduction front.

Analysis of vertical movements in the southeastern Greater Caucasus shows gradual uplift and thrusting. Geophysical studies reveal a zone of reduced rock density between the Transcaucasian plate and the margin of the Scythian Platform, characterized by increased deformability [10, 18, 28]. This facilitates the underthrusting of the Transcaucasian crust beneath the northern block and is considered one of the factors contributing to the tectonic uplift of the Greater Caucasus. GNSS observations indicate a decrease in the absolute rates of contemporary vertical crustal movements from south to north.

Conclusions:

1. A retrospective analysis of vertical movements in the Caucasus for the period 1925–2023 reveals a stable pattern: the central parts of the Greater and Lesser Caucasus are characterized by continuous uplift, whereas peripheral zones and intermontane depressions, such as the Kura Basin, experience subsidence. These processes reflect the combined influence of tectonic and isostatic factors, as well as local anthropogenic impacts, for example, hydrocarbon extraction on the Absheron Peninsula.
2. Throughout the 20th and early 21st centuries, the central part of the Greater Caucasus has demonstrated sustained and intense uplift (up to 10–15 mm/year), whereas peripheral areas, particularly the Caspian and Black Sea coastal regions, are subsiding at rates of up to -7 mm/year. This reflects ongoing orogenesis and active tectonic plate collision.
3. Direct comparison of vertical displacement maps with epicenters of major earthquakes shows that most strong seismic events occur near the boundaries of anomalous uplift zones or in areas with a high gradient of transition from subsidence to uplift. This confirms the existence of a relationship between vertical tectonic activity and seismic processes.
4. Profile analyses along the Nakhchivan–Dagestan and Iran–Caspian Sea directions indicate that periods of accelerated vertical uplift coincide with interseismic phases of elastic stress redistribution, whereas a slowdown in vertical movements points to the accumulation of deformation energy and an increased likelihood of strong earthquakes.
5. Regional differences in the amplitude of vertical displacements reflect morphostructural and tectonic characteristics: the linear uplift of the Greater Caucasus is associated with rigid lithospheric blocks, while the arcuate structures of the Lesser Caucasus exhibit more plastic crustal behavior.
6. Seismic activity from 1925–2023, including catastrophic events (Spitak 1988, Racha 1991), confirms the high seismic hazard of certain zones in the Caucasus, such as the central part of the Greater Caucasus, the Kura Basin, the Talysh zone, and the Caspian region.

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