Geotectonics, Vol. 36, No. 2, 2002, pp. 109–123. Translated from Geotektonika, No. 2, 2002, pp. 27–42.

Seismotectonics and Contemporary Caspian Sea Level Oscillations

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Received March 19, 2001

Abstract—Relationships between Caspian Sea level oscillations and the seismicity in the Middle and South Caspian sea region and their coastal areas during the last 160 years are discussed. The sea level oscillations in a confined sea basin, 70% of which is occupied by uncompensated Pliocene–Quaternary depressions filled with thick sediments, are compared in time with the variations in the total seismic energy liberated in the focal zones within the principal neotectonic structural features. It is demonstrated that the events of sea level decline coincided with the periods of higher seismic activity in the western portion of the Middle Caspian Basin (the Derbent Trough), in the Lower Kura Basin, and in the eastern frame of the South Caspian Basin (the Gorgan Trough), and that the events of sea level rise coincided with an increase in seismic energy emission in the region of the western and southern shelves of the South Caspian depression, in its southern and western mountain surroundings, the Apsheron bridge, and in the margin of the Kara Bogaz High contiguous with the bridge eastern part. The earthquake parameters (hypocenter distribution, depth, and focal mechanisms, as well as the amount of emitted energy) are considered as indicators of the activity and trends of deformation processes in the Earth's crust and in the subcrustal layer of the recent Caspian region structures. An increase in the tectonic deformation rate gives rise, on the one hand, to a further subsidence of individual basins and to the deepening of the sea floor and, on the other hand, to the transverse shortening and growth of local anticlines. In addition, this intensifies the dehydration of deep sedimentary layers and fluid transfer.

INTRODUCTION

High-frequency oscillations of the Caspian Sea level have been recorded by hydrometric stations since the end of the 1930s [17, 23, 24, 32]. Prior to 1930, the sea level oscillated within a range of –26.6 to –25.6 m in a period of nearly a hundred years (Fig. 1). The oscillation intervals lasted a few years, reaching at times a duration of 10 years. A continuous sea level decline to –27.9 m occurred in the 1930s–1940s. The sea level continued declining slowly to a level of –28.8 m with intermittent oscillations up to 0.4 m high from 1941 though 1976. The direction of the movement changed dramatically in 1978: an intense, though variable, rise of the sea level began, which resulted in a sea level of –27.05 m by the end of 1992 and –26.5 m by the end of 1997. This means that the sea level nearly reached the value recorded at the beginning of the century. Some drop in the sea level was recorded in 1998 [32], although it remains unclear, so far, whether it marked a change in the general trend or a partial fluctuation, because a 0.05-m rise of the sea level was recorded in 1999.

The impact of the high-frequency variations on the coast and on the functioning of coastal installations is an environmental problem. Therefore, the Caspian Sea water balance, controlled by climatic conditions and water withdrawal from the influent rivers, primarily from the Volga River, for irrigation and other industrial needs, was analyzed for a solution [7, 9, 15–17, 41]. Simultaneously with the analysis of the water balance fluctuations, the potential effects of present-day geodynamic processes, on the sea level revealed by geodetically recorded seacoast tectonic motions [23, 24] and by fluctuations in groundwater dynamics [22], were demonstrated.

We examined, within the framework of the problem discussed, the relationship between the sea level fluctuations and the deformation processes in active neotectonic structural features of the region expressed in the seismicity variations. These are the epicenter distribution in time and space, seismic foci depths, the amount of emitted energy, and the earthquake focal mechanisms. The seismicity was analyzed using a data sample for the period 1835–1990 from a Specialized Earthquake Catalogue for North Eurasia [31] compiled at the Schmidt Joint Institute of Physics of the Earth, Russian Academy of Sciences, and the Catalog Earthquakes in Iran [48]. The data were supplemented by those found on the Internet from the NEIC Catalogue up to the year 1999. These data samples, when combined contained 1200 events. A total release of seismic energy was computed by years in order to compare the seismicity with the Caspian Sea level oscillations. In doing so, the well known Rautian's equation $\log e(J) = 4 + 1.8M$ was used. The fact that this formula overestimates the amounts of energy of the strongest earthquakes was

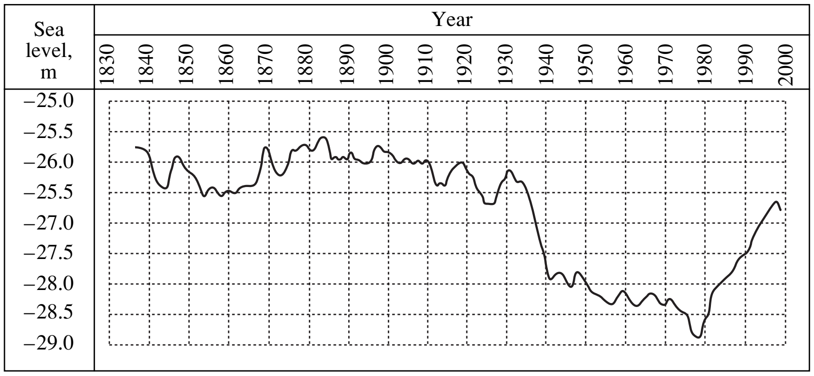

Fig. 1. Caspian Sea level oscillations from 1838 through 1998 [23, 24, 32].

insignificant in our case, because relative, instead of absolute, values of the released energy were important. The seismicity variations for the Caspian region, as a whole, did not point to any unique correlation with the sea level oscillations. Therefore, average seismic energy values were computed for individual seismotectonic provinces that differ in the Earth's crustal structure, in the sense and intensity of neotectonic movements, and in the seismicity. Variations in the region's mode of deformation were also examined using data on the focal mechanisms of earthquakes for the last 45 years. The results of their comparison with the sea level oscillations were interpreted on the assumption that the seismic energy released makes up but a portion of the energy of tectonic processes and does not give a complete idea of their deformation effect.

SEISMOTECTONIC PROVINCES OF THE CASPIAN REGION

The seismotectonic provinces listed below were mapped using the following criteria: the Earth's crustal structure [4, 19, 30], specific features of the neotectonic (Pliocene–Quaternary) evolution [2, 18, 22, 25, 28, 44], the pattern and kinematics of active faults [33, 35], as well as the distribution of the earthquake focal zones and the dynamics of their activation during the time interval reviewed. Although our criteria contain kinematic information for different periods of time, they are genetically related and determine the specific features of the contemporary tectonic evolution and its seismic manifestations. Earthquake focal zones, usually confined to the boundaries of neotectonic structures, are most important elements in seismotectonic zoning. They are marked by high gradients of the deep-seated structural parameters and by contrasting direction and scopes of neotectonic movements.

The North Caspian region has not been examined, owing to its nearly total lack of earthquakes and sluggish other neotectonic manifestations. The study area of the Middle and South Caspian region and its frame, delineated by the coordinates of 36.5–44° N and 47.5–54.5° E with a slight widening in the southeast (Fig. 2), includes portions of the epi-Paleozoic Scythian–Turanian plate, more or less reworked by the subsequent Alpine tectonics, and the Alpine structures proper. The former include the Middle Caspian region and the adjacent coasts, as well as the eastern part of the South Caspian Basin (provinces I, II, and VII), while the latter include the western and southern parts of the South Caspian Basin and its framing (provinces III–VI). Late Cenozoic tectonic movements had produced a system of contrast neotectonic structural features, to the boundaries of which the earthquake focal zones are confined.

Province I is a contrasting combination of mountains at the Daghestan Wedge eastern margin and of the Southeastern Caucasus with the Derbent trough in the west of the Middle Caspian region.[1] They originated simultaneously in the Pliocene–Quaternary, and their formation was accompanied by the reworking of the epi-Paleozoic Earth's crust in both structural features (Fig. 3, *1* and *2*). The maximum thickness of sediments in the Derbent trough is >14 km, while the thickness of the Pliocene–Quaternary sediments is >5 km. It should be noted that the most intense subsidence commenced only at the end of the Pliocene and is continuing at the present time, remaining uncompensated by sediment accumulation [22]. The main earthquake focal zone including events of up to $M_s = 6.3$ with hypocenter depths of up to 110 km extends along the southwestern slope of the Derbent trough.

A large portion of province II, embracing the eastern part of the Middle Caspian and its coast, is slightly deformed by recent movements. The Kara Bogaz arch, with its very thin sedimentary cover and a thin crust, was mapped in the east of the South Caspian region (Fig. 3, *3*). R.G. Garetskii [8] reported a positive gravity anomaly there and assumed that the arch had been formed due to density decrease in the upper mantle. The North Balkhan and South Balkhan fault zones, with the Greater Balkhan ramp between them, were mapped in the southern margin of the province. There,

[1] See Fig. 4 for all geographical and geological names mentioned in the text.

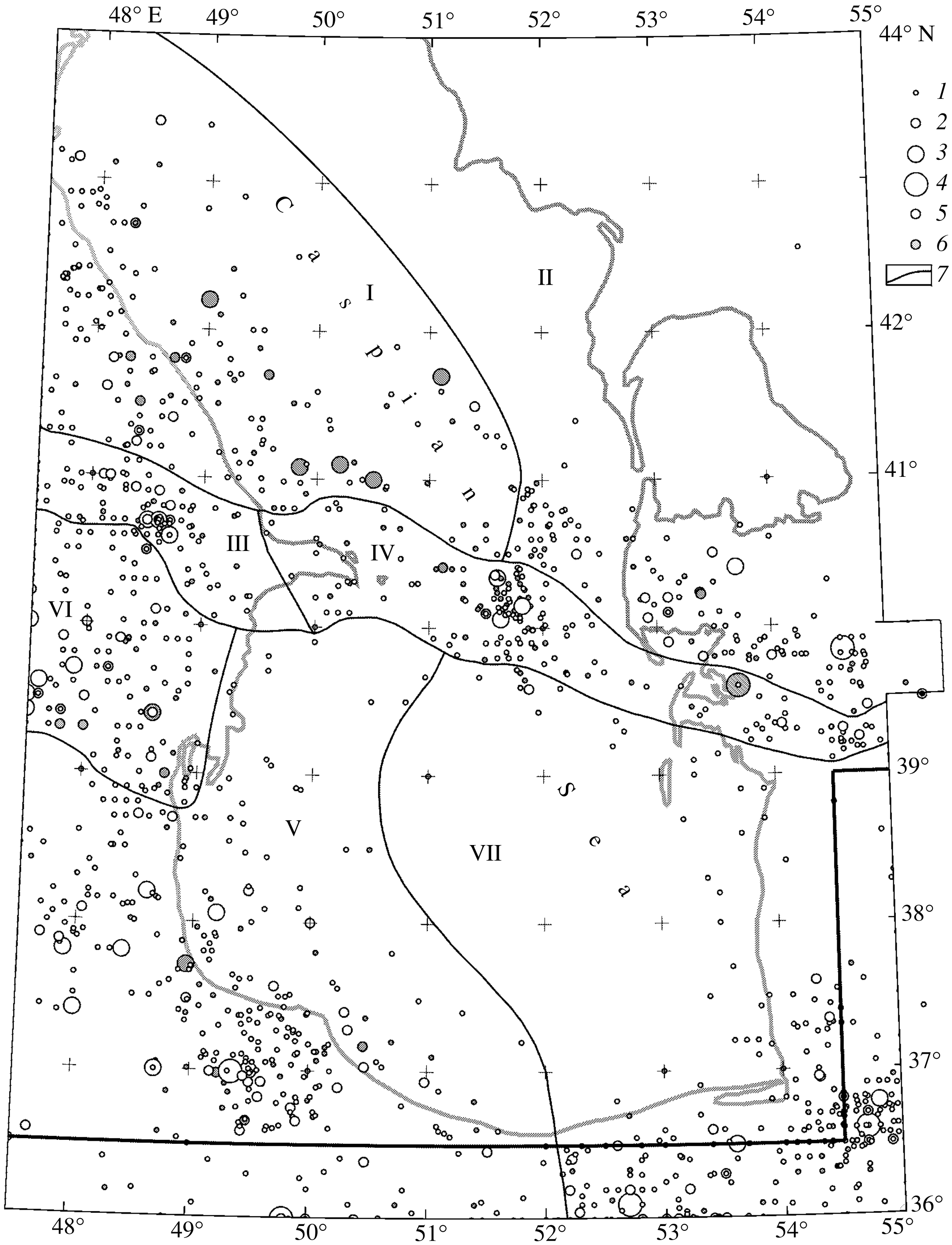

Fig. 2. Seismotectonic provinces I–VII and earthquake epicenters in the Caspian region: (*1–4*): earthquake magnitudes M_s: (*1*) <5; (*2*) 5–5.9; (*3*) 6–6.9; (*4*) ≥7; (*5* and *6*) hypocenter depth: (*5*) ≤33 km; (*6*) >33 km; (*7*) province boundary.

in the transition zone between the Kara Bogaz arch and the Western Turkmenian depression, the sedimentary thickness and the properties of the Earth's crust change most dramatically [1, 21]. The Krasnovodsk–Greater Balkhan earthquake zone, with its three clusters of earthquake epicenters, is located in this tectonically contrasting region. Large earthquakes, such as the Kazandzhik event in 1946 (M_s = 7) and the Greater Balkhan earthquake of December 6, 2000 (M_s = 7.4), were confined to the eastern cluster.

In province VII, the crystalline crust in the Western Turkmenian depression, similar to the crust of the Turanian plate, wedges gradually westward to measure 15–20 km under the eastern part of the southern Caspian

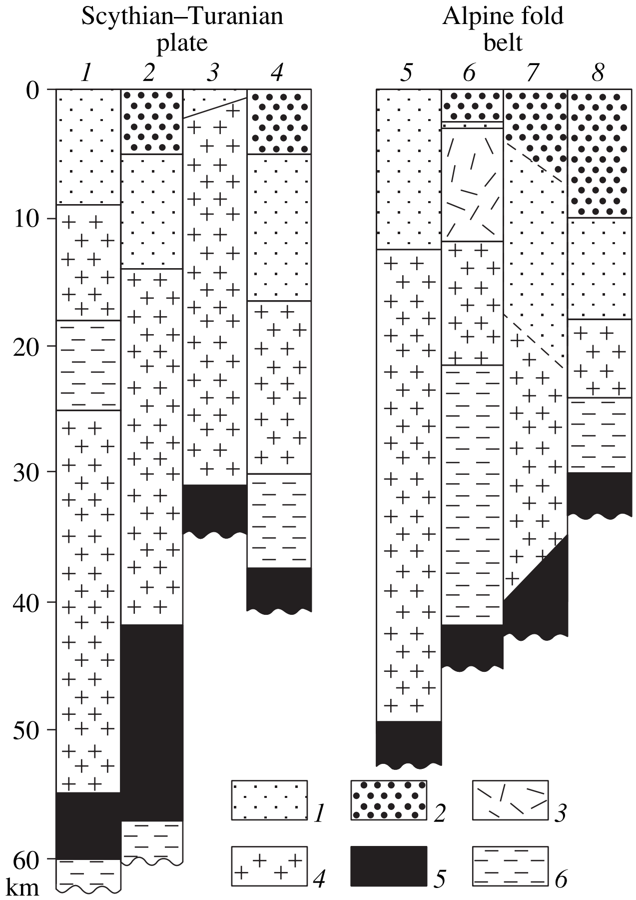

Fig. 3. Schematic deep vertical sections of Caspian provinces: (*1*) sedimentary cover or its pre-Pliocene section; (*2*) Pliocene–Quaternary sediments; (*3*) Jurassic–Earth Cretaceous volcanic complex; (*4*) crystalline crust; (*5*) upper mantle; (*6*) low-velocity layers in the crust and mantle. Numbers above the vertical sections: (*1* and *2*) province I: (*1*) coastal part of the East Caucasus [19]; (*2*) Derbent trough [2, 19, 22]; (*3*) province II, Kara Bogaz arch [8]; (*4*) province VII, South Caspian east coast [2, 4, 22, 30]; (*5*) province III, Southern slope of the Greater Caucasus [19]; (*6*) province VI, Lower Kura depression [19]; (*7*) province IV, Apsheron bridge [2, 10, 22]; (*8*) province V, western part of the South Caspian region [4].

region (Fig. 3, *4*). The sedimentary cover there has a moderate thickness and is, relatively poorly deformed. It grows thicker southward, where the sediments fill the Gorgan foredeep in front of the Late Cenozoic Ala Dagh and East Elburz ranges, where transverse shortening coexists with left-lateral strike-slip displacements. Most of the earthquakes of this province, including several events with $M_s > 6$, are confined precisely to the region of the tectonic contrast between the foredeep and the ranges.

Province VI (Lower Kura depression) is similar to province VII (Fig. 3, *6*) in terms of its crustal thickness and the structure of its crystalline portion [19]. The depression is filled with Pliocene–Quaternary sediments attaining a thickness of 3 km and overlying the rocks of the para-Tethys southern slope in the north and the structures of the Lesser Caucasus–Talysh arc in the south. The Saatly deep hole (8 km) drilled in the south of the province penetrated a 2.5-kilometer succession of Upper Miocene and Quaternary deposits transgressively overlying the Upper Cretaceous carbonate rocks, which are underlain at a depth of 3 km by Early Cretaceous–Jurassic island-arc volcanics (a branch of the Somkheti–Kafan zone?). Small earthquakes are numerous throughout the province, although the principal focal zone, where larger events and all deep-focus (lower crust) earthquakes occurred, is confined to an active fault zone (Fig. 4) at the boundary between the depression and the Talysh arc [34].

Province V encompasses the western and southern parts of the South Caspian region, the Talysh arc, and a portion of the Western Elburz Range and is characterized by the most complex and contrasting Late Cenozoic movements. The western part of the South Caspian region is a deep uncompensated depression with the crystalline portion of its Earth crust as thin as 8–10 km (Fig. 3, *8*). As much as 20 km of sediments accumulated there [4, 22]. At least half of them fall into the Pliocene–Quaternary time span, while the thickness of merely Upper Pliocene–Quaternary rocks locally exceeds 6 km. The present-day water depth is as much as 1 km. The sedimentary cover in the depression is pressed into late anticlines and shows evidence of clay diapirism and mud volcanism. Steep faults separate it from the less subsided Lower Kura depression. The faults are expressed on the surface as younger normal faults extending along the coastline (Fig. 4).

The modern structural style of the WNW–ESE-trending Western Elburz includes Pliocene–Quaternary folds and young reverse faults and thrusts conjugated with longitudinal left-lateral strike-slip displacements [34, 45]. The Elburz abuts the eastern flank of the Talysh arc in the west, in Ardebil, where reverse faults and other manifestations of transverse shortening are combined with evidence of young longitudinal right-lateral strike-slip displacement. In spite of the above-mentioned kinematic difference between them the western Elburz and the Talysh arc are similar in terms of their structural–formational characteristics and their role in the modern structural pattern forming the mountainous frame of the South Caspian depression. Most of the large earthquakes that occurred in the province were confined to the boundary zone between the inclusive part of the shelf and the coastal zone. Shorter focal zones are associated with the Ardebil and Elburz active faults. The Rudbar earthquake of 1990 was the strongest among them ($M_s = 7.4$).

Provinces III and IV are the high-gradient zones restricted to the boundaries of the large recent structures. The contrast at the boundary between zone III (Southern slope of the Greater Caucasus) and zone I was predetermined by the deposition of deeper sea Late Mesozoic, Paleogene, and Early Miocene sediments,

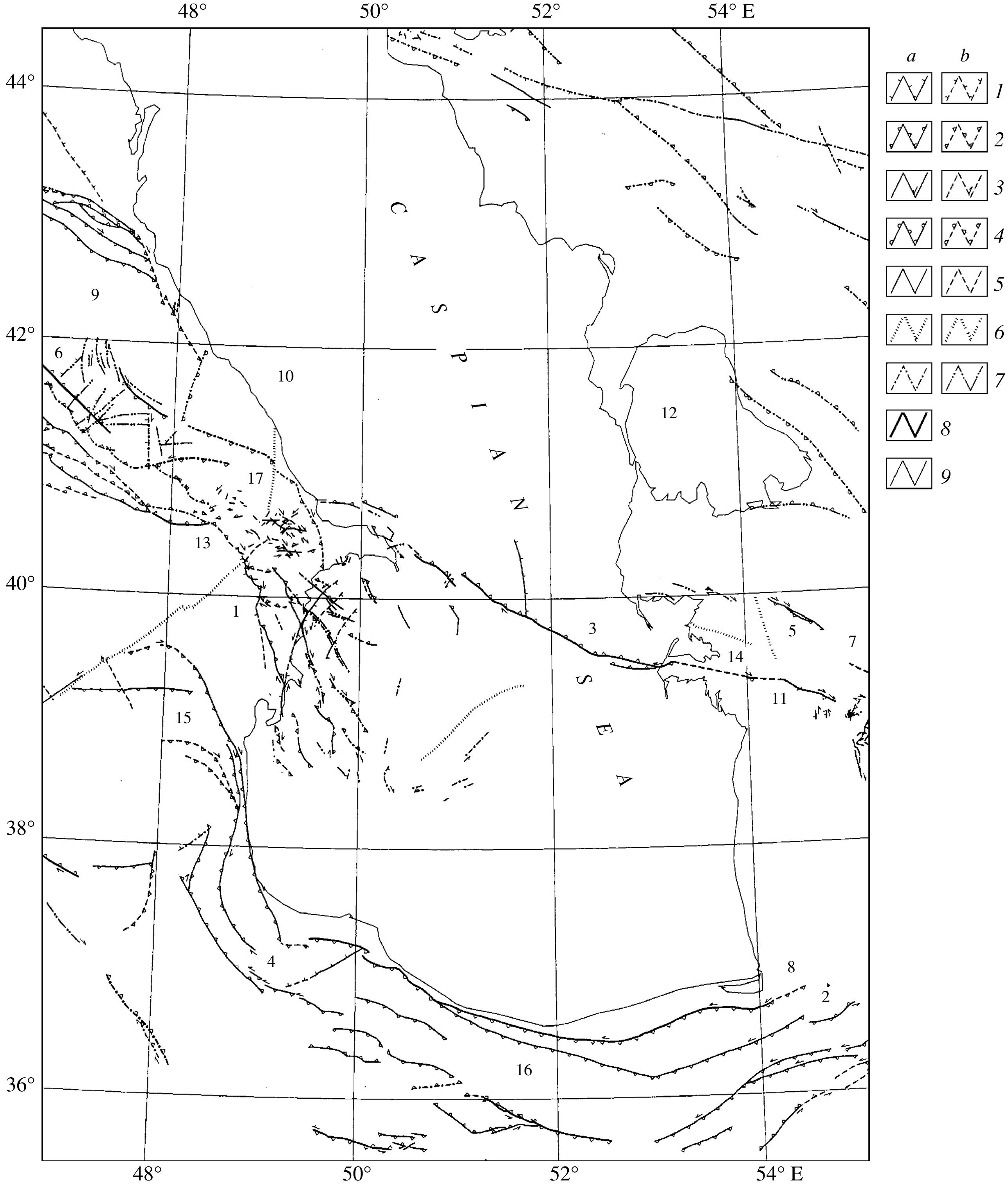

Fig. 4. Map of Caspian active faults: (*1–6*) faults with the last recorded activity in Late Pleistocene or Holocene, including historical time (left, proved; right, inferred): (*1*) normal fault; (*2*) overthrust or reverse fault; (*3*) strike-slip fault; (*4*) flexure; (*5*) fault with unknown type of displacement; (*6*) deep–seated fault expressed on the surface by indirect evidence; (*7*) faults with last recorded activity in the Middle Pleistocene: (*a*) proved; (*b*) inferred (subdivided into types similar to *1–5*); (*8* and *9*) average displacement rates along the faults, mm/year: (*8*) ≥1; (*9*) < 1. Numbers in the map: (1) Adjichai fault; (2) Ala Dagh; (3) Apsheron bridge; (4) Ardebil; (5) Greater Balkhan (ramp); (6) Main Caucasus thrust; (7) Main Copet Dagh fault; (8) Gorgan trough; (9) Daghestan wedge; (10) Derbent trough; (11) Isak–Cheleken zone; (12) Kara Bogaz Gol (gulf); (13) Kara Mariam anticline; (14) Kelkor trough; (15) Talysh arc; (16) Elburz; (17) South East Caucasus.

which accumulated on the relatively thin crust of the para-Tethys. This contrast was intensified in Late Cenozoic due to its boundary position between the Caucasus and the Lower Kura depression, which was expressed in the formation of southward vergent folds and thrusts that resulted in the growth of the Earth's crust thickness [19] (Fig. 3, *5*). The folds become less elongated closer to the South Caspian region and extend farther into the sea area along the active reverse faults and right-lateral reverse strike-slip faults. The Late Quaternary tectonic activity was most significant in the Kara Mariam Ridge and in the Adjichai (Sal'yan–Lengibiz) fault zone, where the average rate of Late Quaternary movements attained a value of 1 mm/year [25, 33]. Small earthquakes were distributed throughout the zone, although the Shemakha earthquake (1902) was the largest event (M_s = 6.9).

The Apsheron Bridge (province IV) is located above a flexure–fault zone in the basement separating the Middle Caspian region with its epi-Paleozoic continental crust from the South Caspian depression. The bridge consists of rootless Late Pliocene–Quaternary synsedimentary uplifts arranged en echelon or into a line extending eastward into the Isak–Cheleken anticlinal zone. The bridge is limited in the north by the deep and narrow North Apsheron trough, which joins the Derbent trough in the west and extends as the Kelkor trough into Turkmenistan. The contrast structure of the province confined to a deep-seated tectonic step is accentuated further by an en-echelon zone of active faults extending along it (Fig. 4), which is continued en echelon-like by the Main Copet Dagh fault in the east and by the extension of the Main Caucasus thrust in the west. The kinematics of these faults change within the Caspian region. These are reverse faults in the South-Eastern Caucasus, according to M.L. Kopp [18], display a left-lateral displacement whereas right-lateral strike-slip displacements, considerably larger than the reverse faults, were recorded in the Turkmeni portion of the system [28, 33, 35]. Against the background of a great number of small earthquakes in province IV, the strongest event in the whole region was the Krasnovodsk earthquake which took place in 1895 (M_s = 7.9 with a hypocenter depth of 55 km), whose extensive focal zone was located in the east of the province. In addition, the Central Caspian focal region produced earthquakes in 1986 and 1989 with $M_s \geq 6$. Their hypocenters were located either below or at the base of the Earth's crust.

To sum up, the largest earthquake foci of all provinces reviewed are confined to the neotectonically contrast regions, which indicates contemporary differential movements. In provinces I, VI, and VII, seismicity is concentrated in the slopes of the Derbent and Gorgan troughs and the Lower Kura depression, which suggests their still continuing subsidence. Conversely, in provinces II, IV, and V, seismicity is confined to the slopes of the mountain ranges (the coastal region of the Elburz and Talysh, the Apsheron Bridge, and the southern part of the Kara Bogaz arch), emphasizing their continuous rise. These differences proved to be valuable when estimating the relationships between the Caspian Sea level fluctuations and the seismicity variations in different provinces.

CASPIAN REGION SEISMICITY AND CASPIAN SEA LEVEL OSCILLATIONS

The main contribution to the amount of released seismic energy was made by the largest earthquakes, most of which occurred in the focal regions located along the western and southern margins of the South Caspian depression and its mountainous frame. A total of 6 earthquakes with $M_s \geq 7$, 7 earthquakes with M_s = 6.5–6.9, and 20 events with M_s = 6.0–6.4 have been recorded in the region (limited by 36° N in the south and by 55° E in the southeast: Fig. 2). A sea level rise (or, more seldom, a slowdown of its lowering) was recorded after every earthquake with $M_s \geq 6.5$; it was only after the Buiin Zara earthquake of 1962 (the most remote event from the Caspian Sea) such a rise lagged behind the seismic event by approximately a year. A sea level rise by 30 cm followed the Krasnovodsk earthquake of 1895 with M_s = 7.9, a rise by 20 cm followed the Kazandzhik earthquake of 1946 (M_s = 7.0), and a rise by 10 cm followed the Gorgan event of 1890 (M_s = 7.2). A sea level rise by 8 cm occurred a few months after the Shemakha earthquake with M_s = 6.9 in 1902, and the Rudbar earthquake of 1990 (M_s = 7.4) in the western Elburz was followed by the acceleration of the sea level rise.

Thus, all earthquakes having $M_s \geq 6.5$ and characterized by small areas of focal and structural-influence zones were followed by a rise of the sea level. A 100 percent coincidence of sea level rise with seismic events of M_s = 6.0–6.4 and, consequently, with smaller focal areas were recorded only for the earthquakes whose epicenters were located either in the sea or close to the coast. This correlation was recorder only for 60% of the earthquakes which occurred farther from the sea.

This effect of the largest earthquakes, which was reported by other investigators of the Caspian region [36, 42, 43], can be regarded as the result of a residual seismic deformation (density decrease) on the sea floor, possibly, aggravated by the rapid inflow of underground water into the sea basin. This deformation effect was confirmed by repeated geodetic measurements carried out in regions of large earthquakes, as well as by the computations that were based on their results [27]. A sea level rise by 8–30 cm observed after earthquakes with magnitudes of 7 is comparable with the deformational effect of the 1988 Spitak earthquake in Armenia (M_s = 7), where the northern limb of the seismogenic fault rose, according to the results of a repeated geodetic survey, by dozens of centimeters over an area of 1000 km^2 [6]. If the region of such a deformation had been located on the Caspian Sea floor, it would have resulted in a rise of the sea water level by 8–10 cm.

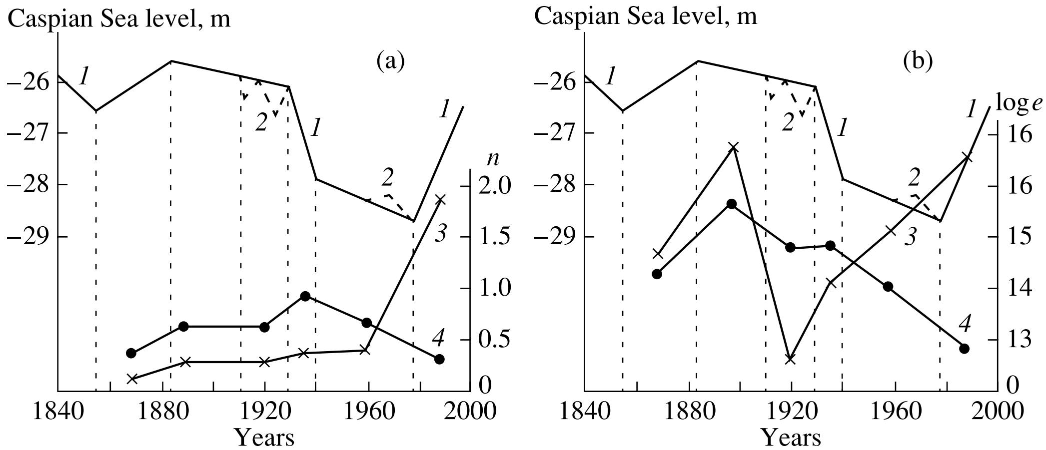

Fig. 5. Correlation between the periods of the Caspian Sea level changes and the number of earthquakes with $M_s \geq 4.9$ (a) and the annual average seismic energy released during these periods (b): Lines in the plots: (*1*) generalized line of the Caspian Sea level changes by stages; (*2*) most significant sea level fluctuations; (*3* and *4*): number of earthquakes (*n*) and average annual amounts of released seismic energy (log*e*, J) during every stage: (*3*) in provinces II, IV, and V; (*4*) in provinces I, III, VI, and VII.

Somewhat weaker earthquakes have smaller focal areas and, consequently, have an essentially weaker effect on the sea level. For example, the focal area of the earthquake that occurred in the Apsheron bridge on March 6, 1986 (M_s = 6.3), was only 410 km^2 [10]. Thus, the direct effect of large earthquakes could result only in relatively small-amplitude and short-lived sea level changes.

However, earthquakes and the amount of seismic energy released by them are but a partial expression of the deformational effect resulting from the contemporary tectonic processes. This is most evident in the so-called “soft” earthquakes [20, 35] that represent a peak acceleration of the creep, i.e., a protracted and directional displacement, whose amplitude significantly exceeds the seismic displacement. This is also true of common “rigid” earthquakes. The contribution of seismogenic motions to tectonic movements varies in different regions depending on their geological structure. It exceeds 50% in northern and central Iran with its thick consolidated crust [46]. This value is true for the eastern coast of the Caspian Sea, i.e., for provinces II and, partly, VII. The computed contribution is less than 10% in deep sedimentary basins, such as the Mesopotamian trough and the Outer Zagros [46], to which the Derbent trough and the South Caspian depression are similar in terms of a number of indications. This contribution is probably lower in the lower crustal and upper mantle layers. The contribution of tectonic movements to the shape of a sea basin and, consequently, to the Caspian Sea level can be viewed as considerably more significant if the above relationships are taken into account.

With due account for the data available in the literature [11], we determined the number of earthquakes with $M_s \geq 4.9$ in each province for 7 stages of the sea level changes (excluding the minor oscillations) to estimating the relationship between the sea level fluctuations and the seismicity variations in the adjacent provinces. These stages are as follows: a sea level decline until 1853, a sea level rise in 1854–1883, a practically stable position in 1884–1910, considerable fluctuations against the background of a slow decline between in 1911 and 1929, a continuous rapid decline in 1930–1940, fluctuations against the background of a weak decline 1941–1977, and a continuous rapid rise in 1978–1997. The provinces were united into two groups on the basis of their variation trends in the number of earthquakes (Fig. 5a). The maximum annual number of earthquakes in provinces I, III, VI, and VII coincided with sea level declines in 1930–1940, whereas most of the earthquakes occurred during the periods of it sea level rise in the 1978–1997 period in provinces IV, V, and II. This difference called for the use of a more stringent index of a province’s seismicity level.

The amount of specific seismic energy (seismic power), i.e., the average amount of energy released by the earthquakes per annum, was adopted as such an index. The seismic power values were determined in every province for the above-mentioned periods of Caspian Sea level changes. The maximum seismic energy was recorded for the period of 1884–1910, i.e., a period of the stable highest sea level. The provinces were separated into two groups by the peculiarities of their further activation. One group included the Derbent, Lower Kura, and Gorgan depressions and the zone of the Southern slope of the Greater Caucasus (provinces I, III, VI, and VII), while the south of the Kara Bogaz arch, the Apsheron bridge, the Talysh–Elburz coast, and the adjoining part of the South Caspian Sea area made up the second group (provinces II, IV, and V). Figure 5b shows that the seismic power in the provinces in group II declined greatly (log$e$ = 12.6) during the time of short-period sea level oscillations,

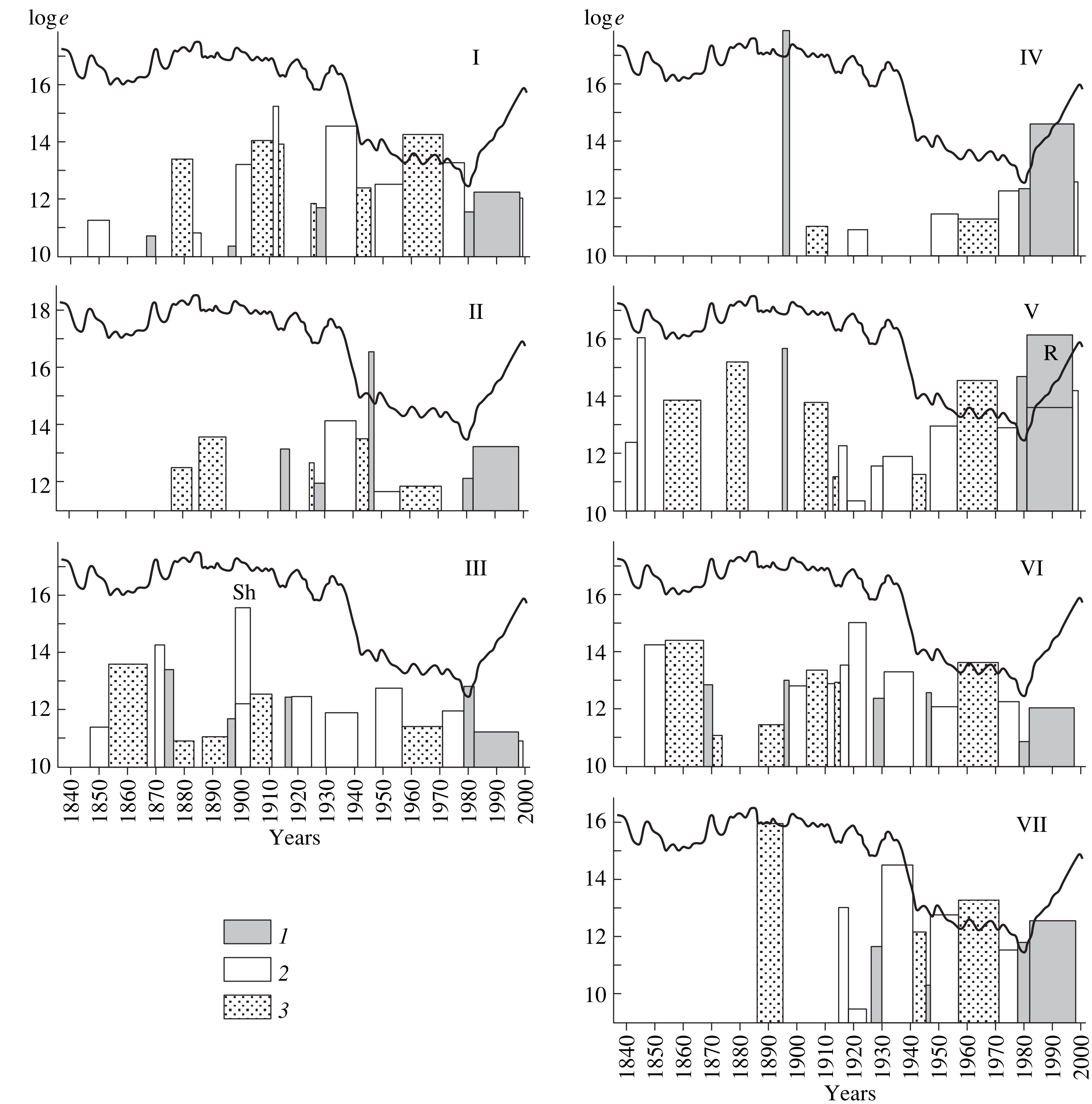

Fig. 6. Correlation between the Caspian Sea level oscillation curve and the average annual amounts of seismic energy released in provinces I–VII during the phases of the sea level rise, decline, and static position: (*1–3*) phases of sea level oscillations: (*1*) rise; (*2*) decline; (*3*) static position; I–VII are seismotectonic provinces. The letters designate the earthquakes with the largest contribution: K for Krasnovodsk earthquake of 1895; R for the Rudbar earthquake of 1990, and Sh for the Shemakha earthquake of 1902.

which occurred against the background of a slight sea level decline and was considerably lower than in group I provinces ($\log e = 14.8$). These values were closer during the period of a continuous sea level decline by 1.8 m (1930–1940) due to a seismic power growth in group II provinces ($\log e = 14.1$). In 1941–1977, when small sea level oscillations occurred against the background of its slowed down decline, the seismic power in group I provinces declined ($\log e = 14$), while that in group II provinces increased ($\log e = 15.1$). This reflects a decline of seismic activity in the Derbent, Lower Kura, and Gorgan focal zones and the activation of the western and southern coasts of the South Caspian depression and, later, the Apsheron bridge. This tendency persisted also during the subsequent period of a steady Caspian Sea level rise (1978–1997), and the logarithms of the specific seismic energy released in the provinces of the two groups were 12.9 and 16.5, respectively. The behavior of the provinces where only a small fraction of the deformational effect of tectonic processes manifests itself in seismicity, i.e., the Derbent trough and the frame of the South Caspian depression, is particularly important for the province discrimination above.

Since the periods of sea level changes, except for those of 1930–1940 and 1978–1997, included also events of reversed-sign sea level oscillations, a more detailed correlation was performed between these events and the amounts of released seismic energy. For this purpose, the whole time period reviewed was subdivided into phases of different durations but with the same mode of Caspian Sea level changes, i.e., its rise and decline at rates of >0.05 mm/year or slight lower rate oscillations about some stable position. Specific seismic energy was computed for every phase (Fig. 6). It was found that its highest values in provinces I, III, and VI fell into the phases of sea level decline. A peak in seismic energy release in province VII, coincident with the Gorgan earthquake (stable sea level), is particularly remarkable; if we discard its effect, then the highest specific energy values are also concomitant with the phases of sea level decline. A different pattern was observed in provinces IV, V, and II, where the specific energy values were usually higher during the phases of sea level rise than during the phases of sea level decline. This is particularly vivid in province IV (regardless of whether we do or do not take into consideration the effect of the Krasnovodsk earthquake), where the seismicity was increasing during a phase of an especially high rise in 1978–1989.

The above-mentioned differences in the seismic behavior of the provinces that basically coincide with those revealed by comparing the seismicity with the sea level changes, are visually demonstrated in the bar charts of the mean specific seismic energy released in the provinces during all phases of sea level rise (36 years), decline (60 years), and static position (58 years) (Fig. 7). Provinces I, III, VI, and VII are characterized by the predominance of seismic energy release during the phases of Caspian Sea level decline, while a maximum of seismic energy release in provinces II, IV, and V occurred during the phases of sea level rise.

Similar relationships were found when analyzing the distribution of only deep-focus earthquakes (with their foci located deeper than 33 km), which were related to tectonic processes in lower crustal and upper mantle layers. Inaccuracy in estimating the earthquake focal depths and the specific physical properties of rocks at these depths, where only a minor portion of the tectonic energy had been in seismicity, did not allow us to determine the deep-focus seismicity evolution in time using the number and energy of the earthquakes. Therefore, only changes in the ratios between the number of events in different provinces could be used. Note that as many as 116 out of the 180 deep-focus earthquakes recorded occurred in 1978–1998, which is at least partly accounted for by the improved techniques of earthquake recording and parametrization.

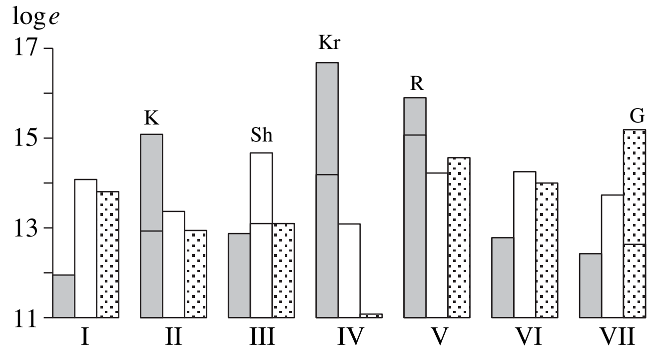

Fig. 7. Average annual amounts of seismic energy released in provinces I–VII during all phases of the Caspian Sea level rise, decline, and static position. (See Fig. 6 for explanations.) Earthquakes with the largest contribution: G—Gorgan of 1890; K—Kazandzhik of 1946; Kr—Krasnovodsk of 1895; R—Rudbar of 1990; Sh—Shamakha of 1902.

Our analysis revealed that most of the earthquakes that had occurred in the crust–mantle transition zone characterized the activity of the deeper portions of the same foci that accounted for the upper crustal seismicity. The largest Krasnovodsk earthquake of 1895 with its hypocenter at a depth of 55 km had a drastic effect on the distribution of deep-focus earthquakes. A period of seismic quiescence began in the east of the region, and the first deep-focus earthquake occurred after this period in the Krasnovodsk area only in 1970. Until 1978, the seismic activity was relatively growing in the western Caspian provinces, particularly in the Derbent trough, and the deep-focus seismicity in the east of the region remained at a minimum. All events during that period coincided with period of sea level decline or static position. For example, five deep-focus earthquakes occurred in the Derbent trough between 1902 and 1914 with M_s = 5.3–6.4 and 2 earthquakes in the Lower Kura depression (in 1910, M_s = 5.7 and in 1924, M_s = 6.4). The decline of the Caspian Sea level in 1930–1940 was marked by two large earthquakes (M_s = 6.2–6.3) on both sides of the Derbent trough. Subsequently, deep-focus earthquakes occurred also in the foci of the Talysh–Elburz zone against the background of the slower decline or static position of the Caspian Sea level, although the strongest events of 1961, 1963, and 1968 (M_s = 5.4–6.2) were confined, as previously, to the Derbent trough.

A dramatic change in the deep-focus seismicity during the stage of the sea level rise in 1978–1997 was marked by a great decrease in the number of earthquakes in the Derbent and Lower Kura focal zones and in the zone of the Caucasus Southern slope and by the increase in their number in the eastern part of the Southern Caspian Sea and its mountainous framing (up to 12% of the total number of events) and, particularly, in the Apsheron bridge (up to 23%). The relative number of events somewhat decreased in the Talysh–Elburz focal zone, and, conversely, the proportion of earth-

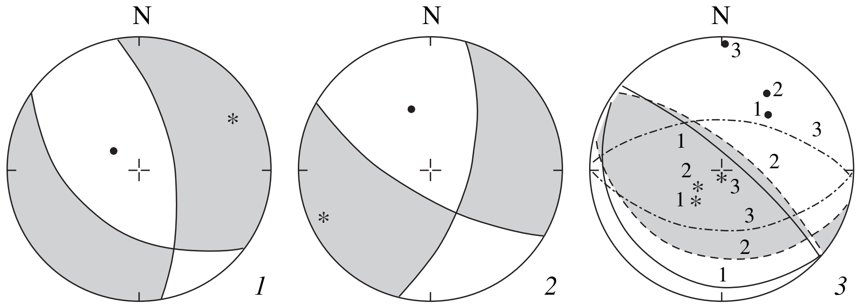

Fig. 8. Earthquake focal mechanisms: (*1*) Kazandzhik (04.11.1946); (*2*) Rudbar (20.06.1990); (*3*) Caspian (1 of 06.03.1986; 2 of 16.09.1989; 3 of 17.09.1989). See Fig. 9 for explanations.

quakes increased in the deep-sea depression proper (17% of the total number of earthquakes) and on the coast (23%). All deep-focus earthquakes that occurred in the province in 1978–1981, when the sea level rise was particularly fast, happened precisely in these areas. Most of the deep-focus earthquakes of province VII occurred in the Ala Dagh piedmont. But the most dramatic changes took place in the Apsheron bridge where the Central Caspian focal zone renewed its activity. Two fifths of the total number of deep-focus earthquakes in the region occurred there and in the adjacent part of province II. Hence, the redistribution in the activity of the deep-seated seismic foci coincided with the reversal in the sign of the Caspian Sea level oscillations, which proves that the latter are relate to deep-seated tectonic processes.

ANALYSIS OF EARTHQUAKE FOCAL MECHANISMS

A sample from earthquake catalogues [5, 26] included data on 128 events and covered a period between 1961 and 1991, except for the Kazandzhik earthquake of 1946 and the largest earthquake of 1957 in Elburz. This limited the possibilities of earthquake comparison with sea level oscillations. Therefore, we analyzed only two periods of time: the year of 1967, when oscillations of variable sign gave place to a decline and, 1978, when a long period of sea level rise commenced. Moreover, we had to unite many separate provinces into three superprovinces, viz.: the Middle Caspian area (where most of our determinations were made for province I), the Apsheron bridge (province IV), and the South Caspian area (provinces V, VI, and VII, with most of the determinations of focal mechanisms having been made in province V).

We used a conventional procedure [13, 29] to determine the spatial orientation of compression (shortening, *P*) and extension (lengthening, *T*) regions using the whole set of earthquakes in a superprovince for a chosen time interval. The closely oriented (up to 10°) *P* and *T* axes were mutually excluded. Since we considered a seismic event to be part of a tectonic deformation, we did not use any weighing coefficients for earthquakes of different magnitudes. Yet, differences in their contributions to the total deformation were partly allowed for, since the procedure of the mutual exclusion was applied only to earthquakes with $M_s < 6$.

The mechanisms of four Middle Caspian earthquakes were determined for the time interval prior to 1968. These were the Kazandzhik earthquake of 1946 and the three large events of 1961–1966 in the Derbent trough. The first one had a near-vertical orientation of the *T* axis and a nearly horizontal northeastern orientation of the *P* axis, which is wan accord with a thrust-type displacement (Fig. 8, *1*). Three other events had a near-vertical orientation of the *P* axis and variable, although nearly horizontal orientations of the *T* axis. The *P* axes in most of the 10 earthquakes, which occurred in the Middle Caspian area in 1968–1977, were inclined or nearly horizontal and oriented NNW–SSE (σ_3 plunged toward NNW at an angle of 14°), while all *T* axes, except for one, were grouped into a belt trending WSW–ENE. This belt included also a few *P* axes, although there was a region of near-vertical *T* axes orientation where *P* axes were absent; this situation was opposite to that which had existed before 1968 (Fig. 9, *1*). Most of the *P* axes for the 14 earthquakes of 1978–1991 preserved their previous orientation (σ_3 plunged toward SSE at an angle of 28°), while all *T* axes, with an exception of one, grouped into a belt trending WSW–ENE. Yet, contrary to the previous epoch, this belt did not contain a region of near-vertical orientation completely devoid of *P* axes (Fig. 9, *2*).

We determined the mechanisms of four South Caspian earthquakes for the period of 1957–1968. The *T* axes of three events were oriented almost vertically, while the *P* axes formed a belt around them (Fig. 9, *3*). In 1969–1977 (8 events), the region of the *T* axes acquired a more horizontal pattern with a NNE–SSW orientation (σ_1 plunged NNE at an angle of 20°), while the belt of the *P* axes was oriented WNW–ESE (Fig. 9, *4*). Later, a dramatic change took place. The *P* axes in most of the 17 earthquakes (without the Rudbar earthquake of 1990 and its aftershocks) were oriented WSW–ENE, while the *T* axes grouped in a belt between them, and a near-vertical region of overwhelming preponderance of *T* axes was discernible (Fig. 9, *5*). The solution for the Rudbar earthquake mechanism [26] was found to fit this pattern (Fig. 8, *2*). One of the borders of its sectors, trending WNW and indicating a left-lateral reversed strike-slip displacement, was found to be similar in its orientation to a seismogenic fault, which resulted from the earthquake and was accompanied by the same displacement. The earthquake mechanism solution suggested by M. Berberyan [45] displayed an even closer similarity with is fault.

We determined the focal mechanism of only one earthquake that had occurred in the Apsheron bridge area before 1978. Our generalization of 30 focal mechanism solutions for 1978–1990 revealed a peculiar pattern (Fig. 9, *6*), where the *P*axes were either vertical or inclined generally toward the west (σ_3 plunged eastward at an angle of 50°), while the *T* axes plunged generally toward the east (σ_1 dipped SSW at an angle of 40°). The intermediate σ_2 axis was found to be nearly horizontal. This orientation of seismotectonic deformation axes is favorable for the formation of steep faults with vertical displacements and for the horizontal decollement of crustal and upper mantle rocks. Our focal mechanism solutions for the three very large earthquakes of 1986 and 1989 in the Apsheron bridge (Fig. 8, *3*) showed that the axes of their orientation fitted this pattern, although the trend of the steep boundary between the sectors was closer to an E–W (WNW) orientation and suggested a predominantly vertical displacement.

To conclude, the mode of deformation of the region was different in its different parts and during the time intervals which were characterized by their specific patterns of sea level changes. The most important changes occurred in 1977–1978 when a decline of the Caspian Sea level was replaced by a long rise. These changes were especially significant in the South Caspian area where the orientations of the compression and extension axes changed by nearly 90°, while only some deviations of the σ_1 and σ_3 axes from the vertical and horizontal patterns, respectively, took place in the Middle Caspian. These changes were clearly expressed also in the integral effect of all earthquake focal mechanisms determined in the region. The integral extension was oriented roughly E–W before 1977 and can be regarded as uniaxial, while the compression can be viewed as circular, since it was oriented either vertically or roughly N–S (Fig. 9, *7*). After 1977, the extension changed to nearly vertical, remaining at the same time uniaxial, while the circular compression was characterized by a gentle inclination of the axes, which trend in various, although more often in southwesterly directions (Fig. 9, *8*). The tectonic interpretation of these changes is discussed below.

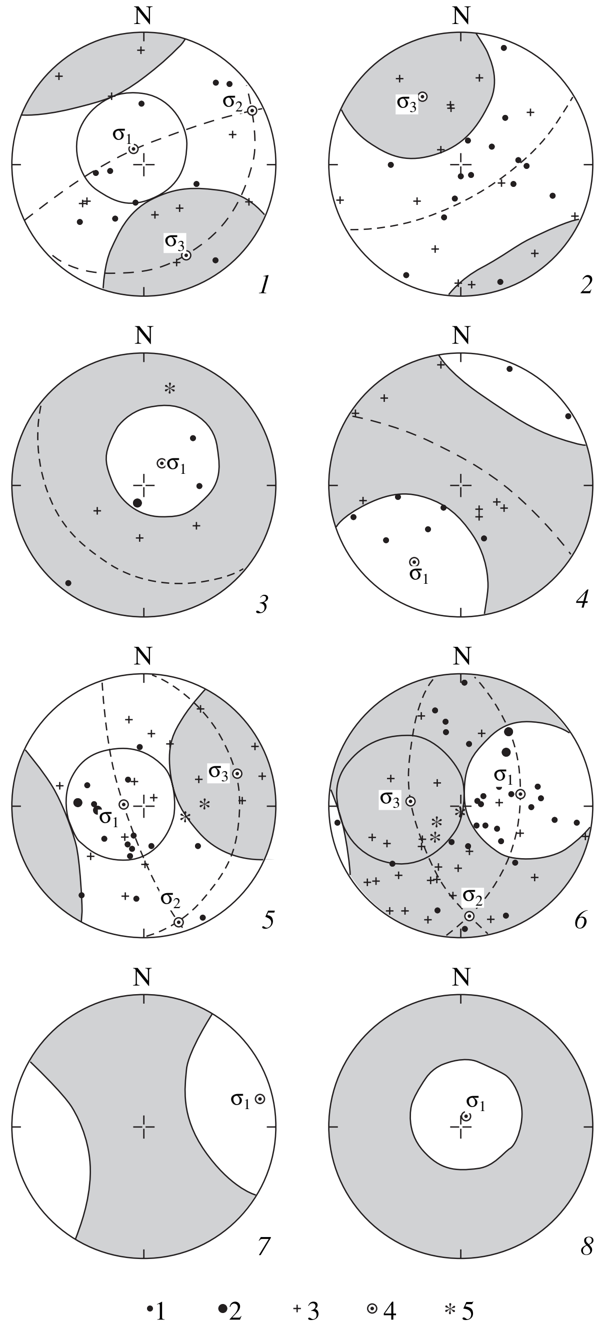

Fig. 9. Seismotectonic characteristics of the Caspian region individual areas in various time intervals: (*1* and *2*) Middle Caspian: (*1*) in 1968–1977; (*2*) in 1978–1991; (*3–5*) South Caspian: (*3*) in 1957–1968; (*4*) in 1969–1977; (*5*) in 1978–1990 (without the Rudbar earthquake of 1990 and its aftershocks); (*6*) Apsheron bridge, 1980–1991; (*7* and *8*) the whole region: (*7*) 1946–1977; (*8*) 1978–1991; (1 and 2) *T* axes of earthquakes: (1) with $M_s < 6$; (2) with $M_s \geq 6$; (3 and 4) *P* axes of earthquakes: (3) with $M_s < 6$; (4) with $M_s \geq 6$; (5) computed attitude of the principal deformation axes σ_1, σ_2, and σ_3.

INTERPRETATION AND DISCUSSION OF THE RESULTS

The results of this study demonstrate that the seismic reactivation of the focal zones located within the subsiding structural elements (provinces I, III, VI, and VII) was followed by a decline of the Caspian Sea level; the reactivation of the coastal slopes of the mountains (provinces IV, V, and partly, II), by a sea level rise. This relationship, expressed in changes of crustal and upper mantle seismicity, suggests an effect of contemporary tectonic processes, partly reflected in the seismicity, on changes in the shape of the sea basin and, as a consequence, in its water level. In this respect, the antiphase seismic activity in the Derbent trough (province I) and in the framing of the South Caspian depression (provinces IV and V) is of particular interest, because the size of the tectonic deformations there can be many times greater than the magnitude of their seismic effects.

A tectonic interpretation of the deep-focus earthquakes, which were most numerous under the Apsheron bridge (up to 70 km deep) and the Derbent trough (up to 110 km), is particularly important for estimating the deformational effects on the basin volume. Some geoscientists [36] suggested a potential subduction of the South Caspian thin crust under the continental "Scythian–Turanian" lithosphere of the Middle Caspian. This assumption is supported by the specific features of the focal mechanisms of the Apsheron earthquakes, suggesting a possibility of the nearly horizontal decollement (Fig. 9, *6*) and deepening of the focali depths north of the bridge. The bridge proper can be regarded in this interpretation as the result of the piling of the detached sediments in front of the northern plate.

Admitting the threshold formation as the result of the compressing detached sedimentary cover, it should be noted that the mantle seismicity was not recorded over the whole of the Middle Caspian area but was confined only to the Derbent trough. This suggests that its deep-focus earthquakes were related, at least partly, to an interaction between the trough and the adjacent mountains. These structures make up a dynamic pair similar to that consisting of the South Caspian depression with the structures that frame it, viz., the Elburz and Talysh, on the one side, and the Apsheron bridge rising above the Middle Caspian tectonic step, on the other. These structural features are currently under conditions of a collision-induced compression, which is indicated both by the morphology of modern dislocations in the framing of both depressions [18, 25, 34, and 45] and by the present-day deformations detected by GPS measurements [40, 47]. It is noteworthy that the contemporary compression deformations are more intense in the South Caspian frame, where the mountains thrust over the conjugated basins during high compression phases, which results in the basin's transverse shortening, its volume decrease and, hence, in the sea level rise. Seismicity intensifications in the South Caspian frame reflect these phases. Moreover, the compression was accompanied by the growth of submarine anticlines, which also contributed to the sea level rise. The subsidence of the negative structures, such as the Derbent and other troughs, accelerated during low compression phases, which was reflected in the growth of their focal-zone seismicity, resulting in the sea level decline.

Secondary effects could accompany these deformational manifestations resulting from compression intensity changes. These were a density decrease in the focal zones of large earthquakes resulting in the above-mentioned spasmodic rises of the sea level and the possible sources of additional subsidence, which are indicated by two peculiarities in the deep-seated structure of the structural elements that had undergone the most intense sagging in the Pliocene–Quaternary period. First, a high-velocity layer has been located in the Derbent trough immediately below the Mohorovičič discontinuity, whose thickness increases from 5 to 16 km between the mountains and the trough axis [19]. This layer can be composed of eclogitic rocks, which is supported by the presence of a negative isostatic anomaly [3]. The presence of a larger negative isostatic anomaly under the South Caspian depression may suggest the existence, below the Moho discontinuity, of a layer composed of rocks heavier than those in the underlying mantle [3]. In E.V. Artyushkov's opinion [4], the layer may be composed of eclogite that had been formed from lower crustal rocks in the process of high-rate Pliocene–Quaternary subsidence. Second, the pre-Pliocene sedimentary cover of the East Caucasus, despite its tectonic stacking, is not thicker than that in the Derbent trough because of its erosion. In combination with the presence under the mountainous uplift of a low-velocity crustal layer, wedging out toward the trough, it may suggest an isostatic compensation due to transport of the eroded material into the trough. The occurrence of a low-velocity layer at the base of the Earth's crust in the South Caspian depression [30], which was recorded also in the sequence of the Lower Kura depression (in the vicinity of the Saatly settlement) [19], may be related to modern structural and material transformations. Both of these specific features suggest the processes that might have caused the decrease in the crustal thickness in the depressions and the additional subsidence of their surfaces.

The above reasoning stemming from the analysis of the present-day structure and seismicity of the provinces, was supported by the results of a study of the earthquake focal mechanisms. For example, the period of 1960–1978, when the highest seismicity was concentrated in the Derbent trough and in the troughs extending the South Caspian depression westward (Lower Kura depression) and eastward (Southeast Caspian and West Turkmenian depressions), was marked by a decrease in the transverse horizontal compression. The compression under the Derbent trough was vertical during the deep-focus earthquakes of 1961–1966, while the extension was nearly horizontal and variously oriented, which might have been caused by the eclogitization of the lower crustal layers and by the subsequent sinking of the heavy eclogitic rock masses. Compression changed to nearly horizontal there in 1968–1977 and was oriented along the trough axis, which resulted in the reactivation of longitudinal faults and, consequently, in subsidence. The extension axes in the

South Caspian depression were oriented across its generally northwest-trending structures, while the compression axes formed a west-northwest-trending belt, which also gave rise to normal-fault displacements that further deepened the depression. This resulted in the sea level decline.

Beginning from 1978, the σ_3 inclination in the Derbent trough increased, and the extension axes orientations became more diverse. This created originated favorable for the development of strike-slip faults, instead of longitudinal normal faults that hitherto had caused the trough deepening. The seismicity concentrated at the margins and frames of the South Caspian depression where the compression acquired an ENE–WSW orientation transverse to the collision trend, which facilitated a transverse shortening and caused the decrease of the sea basin volume and the rise of the sea level. The intensification of vertical movements in the Apsheron threshold, reconstructed from the *T* and *P* axes orientation in the earthquake foci, facilitated this rise (Fig. 9, *6*).

The differences in the stress-and-strain states in the South and Middle Caspian areas were controlled by the kinematics of the active fault zone separating them. A right-lateral strike-slip displacement predominated in the eastern, Kopet-Dagh region, while reverse-fault movements, possibly complemented by a left-lateral strike-slip displacement, were recorded in Southeast Caucasus. These differences in the character of the movements in the same fault zone resulted in that its southern limb was subject to a relative compression and shortening; the northern one, to extension and lengthening. This caused the deepening of the Middle Caspian area and the contraction of the South Caspian area, both processes accelerating during the phases of seismotectonic activity in these regions.

One more aspect of the relationships between seismicity and sea level oscillations is of interest. The maximum amount of seismic energy was released between 1884 and 1910. This burst of seismiotectonic activity did not significantly affect the sea level (possibly because of its universal character), but it forestalled its subsequent great oscillations. The seismicity intensification in the South Caspian area commenced before the beginning of the sea level rise in 1978 only accelerated throughout (Fig. 5). If this and other similar changes in the relationships between the seismicity parameters of the provinces do precede changes in the sea level oscillation mode, they can possibly be used as precursors of a sea level behavior. The development of a procedure for such a monitoring requires further studies.

The contemporary tectonic processes might have caused, in addition to a change in the sea basin shape, a change in the ground water flow. This is a different subject of study. Therefore, we will restrict our discussion to the most general and tentative ideas in respect to the transformation of sediments, predominantly clay, that accumulated in the basin. The clayey sediment contains up to 80% of water, most of which is contained in the pores, with less than 40% being physically or chemically bound [22]. The free water was squeezed out in the process of sedimentation under the load of the overlying sediments, and the porosity is as low from 8–10% at a depth of 1.5 km. The displacement of this water in a sea basin does not change its water level, while the water displaced from the sediments filling the terrestrial troughs adjoining the Caspian Sea increases water inflow and may affect the sea level. Seismicity intensification may accelerate ground water flow due to a vibration effect caused by earthquakes.

Another important effect is the role of the deep-seated clay transformation involving bound water. The leading role here belongs to the transformation of montmorillonite, a principal weathering-zone clay mineral, to hydromica occurring at a temperature of 100–140° and a high pressure supplemented by a tectonic stress [37]. The water released during this process makes as much as 10% of the initial rock weight. The released water gives rise to an abnormally high pore pressure, which may be reduced owing to water removal through reservoir beds or faults. N.A. Shilo [42, 43] called attention to the role of this factor in the Caspian Sea level oscillations. The South Caspian basin contains the bulk of the Caspian-region groundwater [22]. The high rate of its subsidence resulted in the low compaction of its clay and an incomplete displacement of groundwater, which created an abnormally high pore pressure even at a depth of 5–6 km. A zone of high density decline has been recorded at a depth of 7–12 km [12], which seems to be a zone of montmorillonite transformation in hydromica and of bound water liberation [38]. The water that can be liberated at this depth in the South Caspian area is of about 10^{20} g, a value commensurable with the Caspian Sea volume (about 0.75×10^{20} g). In abnormally high pore pressure zones, water concentrates in fluid chambers and is discharged in mud volcanoes within the basin itself or flows in reservoir rocks [39]. Newly formed fissures and preexisting channels, revived by strong earthquakes, are capable of discharging fluids from these fluid sources in a few months. The intensity of earthquake-induced fissure formation is controlled by the seismic foci depths and focal mechanisms rather than by earthquake energy. Hence, even events with $M_s = 5–6$ are capable of provoking hydrous eruptions, and as much as billions of cubic meters of water can be discharged to the surface during a period of high seismicity. P.P. Ivanchuk [14] estimated the water mass of a single mud-volcano eruption in the Akhtarma–Poshaly fold (Azerbaijan) to be 0.8×10^{16} g, which makes up a fifth of the water volume needed for a 0.1-meter average annual rise of the Caspian Sea level during the period of 1982–1997 [22].

Concluding this discussion of the tectonic effects on the Caspian Sea level oscillations, we should not neglect the effects of climate or of those caused by human withdrawal of water from rivers that flow into the sea. An estimation of the Caspian Sea water balance, based on the runoff and, less accurately, on evaporation measurements, explains many peculiarities in the sea level oscillations. However, the rapid and persistent sea level rise in 1978–1997 and some preceding variations have not been exhaustively explained. At the same time, these variations correlate, as shown above, with seismicity variations in the Caspian provinces. We assume that the impacts of the phenomena related to tectonic processes on the sea level were sufficiently high. However, an estimation of a quantitative ratio between them and the water-balance variations due to climatic changes is a matter for a future study.

CONCLUSION

Tectonic processes, partly reflected in seismicity, make a significant contribution to the contemporary Caspian Sea level oscillations. This manifests itself in sea level rises during large earthquakes and, more convincingly, in a correlation between the values of the total seismic energy released in individual seismotectonic provinces of the region and the sea level changes. The tectonic impacts produce an integral effect of interaction between the deformation processes causing changes in the sea basin volume (depression deepening or transverse shortening, and local anticline growths), possibly, supplemented by an intermittent water supply from the deep-seated layers of the sedimentary cover. This supply can be more significant in the deep and rapidly subsiding South Caspian depression, where it is enhanced by faults revived by earthquakes.

ACKNOWLEDGMENTS

We would like to thank A.I. Kozhurin, S.V. Oskolkova, and R.V. Trifonov for their help in processing the seismic data and in final presentation of the results. We are also grateful to M.P. Antipov, Yu.A. Volozh, V.I. Ulomov, and V.N. Kholodov for their valuable advice. Particular thanks are due to O.V. Soboleva and O.I. Gushchenko for their participation in the processing and interpretation of the earthquake focal mechanisms.

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