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Global Changes in the Seismic Regime and Water Surface Level of the Earth

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Abstract—Substantial changes in the seismic regime of the Earth during 1982–1993 are revealed on the basis of a new methodological approach to the study of the development of global seismogeodynamic processes. These changes are a more than threefold decrease in the recurrence rate of large earthquakes in the magnitude intervals $M = 8.5 \pm 0.2$, $M = 8.0 \pm 0.2$, $M = 7.5 \pm 0.2$, and $M = 7.0 \pm 0.2$ and a very intense activation of global seismicity after this relative seismic quiescence. Joint investigations of seismogeodynamic and hydrogeodynamic processes allowed us to reveal a certain synchronism between changes in the seismic regime of the Earth and the ocean water surface level. In this paper, we continue the search for a relation between changes in the regional seismicity and the level of closed water basins (with the Caspian Sea as an example), as well as investigations of the processes in individual seismic sources, in order to elaborate earthquake prediction methods. Hypotheses on the nature of the discovered phenomena are put forward, and structural phenomenological models are proposed. In particular, these correlated seismic and hydrologic phenomena are interpreted in terms of specific features of the seismogeodynamic regime in subduction zones on the periphery of the Pacific and Indian oceans.

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INTRODUCTION

Manifestations of global, regional, and local seismicity provide very important constraints on the present-day geodynamic development of the Earth. The role of water, covering about 70% of the surface of our planet and, together with gases, filling pores and cracks in rocks and minerals, is also very significant. The lithosphere contains nearly the same amount of water as the hydrosphere and atmosphere. The water-bearing crust extends to depths of 20–30 km. The same depth interval is characterized by the highest seismic activity. Consequently, groundwater and gases should be considered as constituents of the medium in which seismic processes develop.

Earth's water fractions of deep and surface origins permanently interact between themselves and with the atmosphere and lithosphere; however, their total amount remains virtually unchanged. For this reason, changes in the water surface level of oceans and other closed basins (for example, the Caspian Sea) serve as an indicator of changes in geophysical and geodynamic processes affecting the Earth's hydrosphere.

Movements and deformations of the crust and the entire lithosphere are, in a way, responsible for changes in the regime of surface water and groundwater (the level, temperature, chemical composition, recharge conditions, etc.) providing constraints on deep tectonic processes. On the other hand, water itself can initiate earthquakes, generating induced seismicity.

This paper continues the search for a relation between changes in regional seismicity and the level of a closed water basin (the Caspian Sea) [Ulomov et al., 1999; Ulomov, 2003], as well as our previous seismogeodynamic and hydrogeodynamic investigations of the processes in seismic sources, in order to elaborate earthquake prediction methods [Ulomov and Mavashev, 1967; Ulomov, 1971, 1974].

GLOBAL CHANGES IN THE SEISMIC REGIME OF THE EARTH

Seismic regimes of various regions and the Earth as a whole are usually represented as recurrence plots of earthquakes of various magnitudes and, studying the evolution of seismic processes with time, the number or energy of all earthquakes is often considered. Such an integral concept of the seismic regime smooths out natural features of the spatiotemporal development of the regime and its energy, thereby complicating their study.

The results obtained in this work are based on a new methodological approach to the study of the Earth's seismogeodynamic regime according to which the flow of seismic events is analyzed not integrally but in magnitude intervals reflecting the geodynamics of the hierarchical fault–block structure of the geological medium [Ulomov, 1987, 1993a, 1993b, 1998]. Sequences of

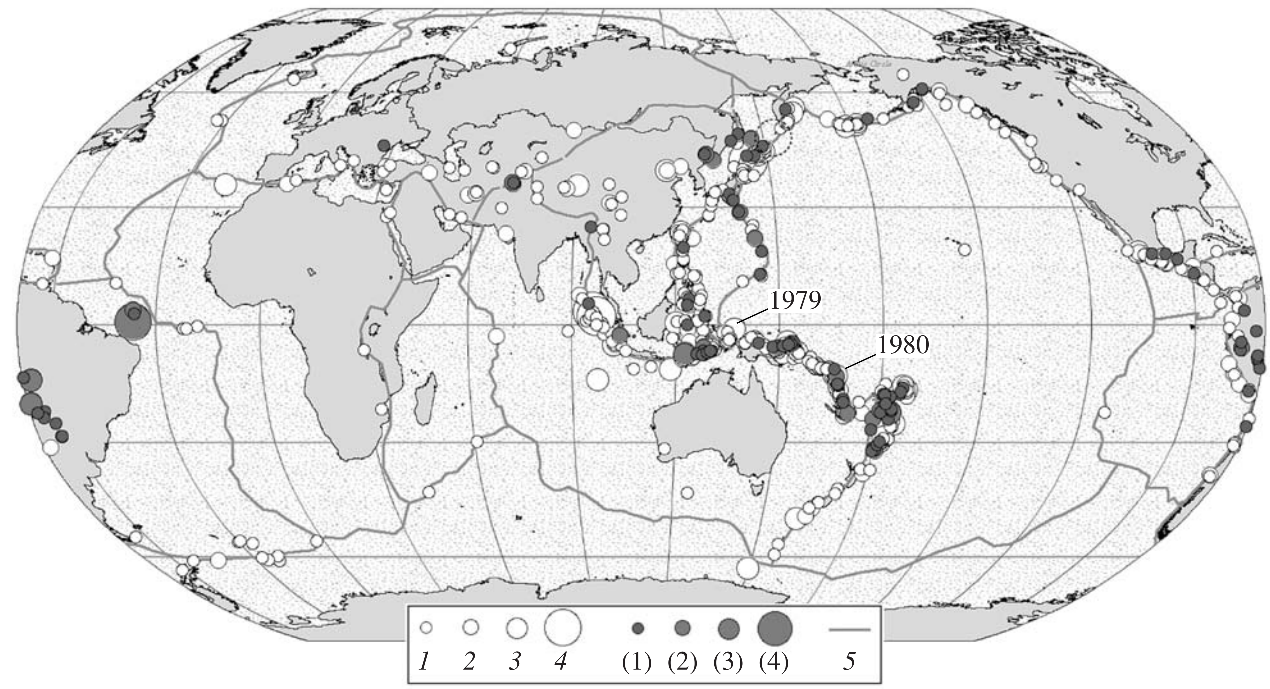

Fig. 1. Epicenters of large earthquakes of the Earth that occurred in the period 1965–2006: (*1–4*) (open circles) earthquakes of the respective magnitudes 7.0 ± 0.2, 7.5 ± 0.2, 8.0 ± 0.2, and 8.5 ± 0.2 with hypocenters no deeper than $h = 70$ km; the epicenter of the November 15, 2006, $M = 8.3$ earthquake in the central part of the Kurile arc is encircled by a dotted line; the earthquakes of 1979 and 1980 ($M = 8.0 \pm 0.2$) preceding the seismic quiescence and a rapid ocean level drop are indicated by arrows; (1)–(4) (solid circles) earthquakes of the same magnitudes with source depths $h > 70$ km; (*5*) boundaries of lithospheric plates. Of state frontiers, only the frontier of Russia is shown (the epicenter of the 2003 Gorno-Altaisk earthquake of $M = 7.3$ is seen in the south of Siberia).

large earthquakes that occurred throughout the Earth in the period from 1965 to 2006 were the subject of study. These earthquakes were differentiated in the magnitude intervals $M = 8.5 \pm 0.2$, $M = 8.0 \pm 0.2$, $M = 7.5 \pm 0.2$, and $M = 7.0 \pm 0.2$, completely overlapping a wide energy range, from $M = 6.8$ to $M = 8.7$. The last interval also included two large earthquakes of $M \geq 8.8$. Henceforth, the magnitude M means the value M_s determined from surface waves.

Figure 1 shows the position of all seismic sources. The total number of events in the catalog was more than 600. The intervals equal to $\pm 0.2\, M$ include the magnitude determination uncertainty. A step of $0.5M$ is largely due to the predominant distribution of geoblock sizes in the hierarchical structure of the fault–block geophysical medium [Sadovsky, 1979; Ulomov, 1987, 1998].

Over the 40-yr period, beginning from 1965, no seismic event in the entire magnitude and depth ranges under consideration was missed in world catalogs and in the ANSS catalog [*The Advanced* …], used in this work. All these data being strictly ordered, the phenomena discovered in this work and described below unbiasedly reflect the real situation.

Cumulative plots characterizing the accumulation rate of seismic events all over the Earth in the studied magnitude intervals are presented in Fig. 2a. Figures 1 and 2 are borrowed from the paper [Ulomov, 2007], which was submitted for publication in the middle of September 2006. Two months later, on November 15, 2006, an earthquake with $M = 8.3$, the largest on the Earth in this year, occurred in the central Kurile Arc. This earthquake occurred within a seismic gap in which a seismic event of $M > 7.7$ was expected according to the long-term prediction by Fedotov [2005]. In Figs. 1 and 2a, this earthquake is shown by a dotted circle. In Fig. 2a, the cumulative number of earthquakes N and the years of their occurrence are plotted on the abscissa and ordinate axes, respectively. Events with hypocenters in the depth ranges $h \leq 70$ km (shallow) and $h > 70$ km (deep) are shown by open and solid circles, respectively. The thick segments approximate data on shallow earthquakes, and the thin segments mark sequences of deep seismic events. The linear approximations are actually everywhere characterized by a high correlation coefficient (0.9 or higher). Because of a very large number of shallow earthquakes with $M = 7.0 \pm 0.2$, only the central fragment of the corresponding plot is presented in the inset in Fig. 2a (to the right). Its horizontal scale is compressed for clearness by a factor of about 2.5. The thin line approximates the entire set of these events over the 40-yr period, and the thick lines are constructed by analogy with the other plots.

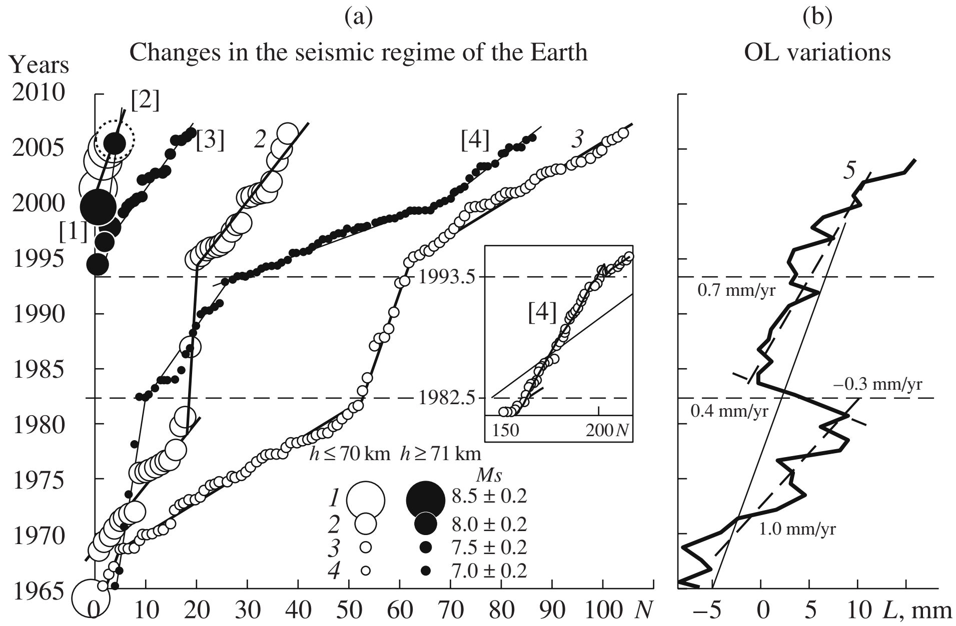

Fig. 2. (a) Cumulative plots of the accumulation of global seismic events with the magnitudes 8.5 ± 0.2, 8.0 ± 0.2, 7.5 ± 0.2, and 7.0 ± 0.2 that occurred in the period 1965–2006: (*1–4*) (open circles) linear approximation of the occurrence times of earthquakes with hypocenters no deeper than $h = 70$ km; the epicenter of the November 13, 2006, earthquake with $M = 8.3$ is encircled by a dotted line; (*1–4*) (solid circles) the same for seismic events with hypocenters at depths $h > 70$ km. (b) A fragment of Fig. 4 (see below) borrowed from [Antonov et al., 2005]; the long-term trend of the OL rise has a rate of 0.4 mm/yr estimated in the paper cited; the rates along three other segments shown by broken lines are estimated in the present work. See the text for other explanations.

The slopes of the approximating lines characterize the accumulation rates of seismic events of the corresponding magnitudes: the smaller the slope of a line, the higher the rate. A steepness increase reflects a decrease in the recurrence rate of earthquakes. If earthquakes occurred rhythmically, i.e., with the same frequency in each sequence, all their occurrence times, in particular, during the entire 40-yr period under consideration, would lie exactly on straight lines. However, in reality, deviations from this pattern are caused by a nonlinear development of geodynamic processes affecting the stress–strain state of the medium and, accordingly, seismicity manifestations. Under regional conditions, this phenomenon was described in [Ulomov et al., 1999, 2002, 2005, 2006], and on the global scale, it was considered for the first time in [Ulomov, 2007].

Analysis of the configurations of the cumulative plots revealed an interesting phenomenon reflecting specific features of the temporal evolution of global seismogeodynamic processes. First of all, we mean a substantial slowdown in the recurrence of all shallow earthquakes during the approximately 11-yr time interval (from the middle of 1982 through the middle of 1993) bounded by the horizontal dashed lines in Fig. 2. This slowdown is also clearly seen in the fragment of the $M = 7.0 \pm 0.2$ plot in the inset in Fig. 2a.

As is seen from the figure, the accumulation rates of events in the considered magnitude intervals change rather rapidly, which is expressed in abrupt bends in all plots at the ends of the anomalous 11-yr interval (1982.5–1993.5). However, before and after the revealed relative seismic quiescence, the occurrence frequency of shallow earthquakes not only was substantially higher but also was characterized by virtually the same accumulation rate of seismic events.

In order to compare the occurrence frequencies of earthquakes within the magnitude ranges under consid-

Numbers of earthquakes of various magnitudes in the 11-yr time intervals before, during, and after the revealed seismic quiescence

Hypocentral depths $h \leq 70$ km				
Y, years	$M = 7.0 \pm 0.2$	$M = 7.5 \pm 0.2$	$M = 8.0 \pm 0.2$	$M = 8.5 \pm 0.2$
1993.5–2005.5	141	39	17	4
1982.5–1993.5	40	9	1	0
1971.5–1982.5	111	36	12	0
Average	97	28	10	~1
Hypocentral depths $h > 70$ km				
1993.5–2005.5	53	12	4	1
1982.5–1993.5	22	0	0	0
1971.5–1982.5	2	0	0	0
Average	26	4	~1	~0

eration, the numbers of events in 11-yr time intervals before (1971.5–1982.5), during (1982.5–1993.5), and after (1993.5–2005.5) the seismic quiescence are given in the table. In all cases, the time is measured from the middle of the year, as in the anomalous period of seismic quiescence. It is seen that, in the interval 1982.5–1993.5, earthquakes with $M = 7.0 \pm 0.2$ and 7.5 ± 0.2 occurred three to four times, and earthquakes with $M = 8.0 \pm 0.2$ ten or more times, less frequently than in the preceding and subsequent 11-yr periods. The largest seismic events with $M = 8.5 \pm 0.2$ and more, which were altogether absent during the first two intervals, started to occur nearly annually from 2001 through 2006[1]. They included the catastrophic earthquakes of December 26, 2004, with $M = 8.8$ and March 28, 2005, with $M = 8.5$, which occurred off the Sumatra coast and were accompanied by gigantic tsunamis that caused numerous victims. The previous 1964 Alaska earthquake with $M = 8.5$ was equally large, and the 40-yr time interval under consideration began actually from this earthquake.

The fact that deep seismic activity began immediately after the general quiescence of the shallow seismicity is no less important. No earthquakes with magnitudes $M = 7.5 \pm 0.2$ and higher were observed before this period, whereas twelve earthquakes with $M = 7.5 \pm 0.2$, four earthquakes with $M = 8.0 \pm 0.2$, and one earthquake with $M = 8.8$ occurred in the conclusive time interval. The last earthquake was unique in its magnitude and occurred in the Atlantic Ocean at a depth of about 90 km off the eastern coast of South America. However, earthquakes with $M = 7.0 \pm 0.2$ occurred very seldom up to their conclusive active stage. Thus, while five such earthquakes occurred annually from the middle of 1993 and later, their recurrence rate in the period of seismic quiescence was lower by a factor of 2.5 (and before, even by a factor of 26.5).

The average recurrence rates of shallow and deep earthquakes in the corresponding magnitude intervals are also presented in the table. They virtually coincide with the values taken from the generally accepted integral recurrence plots of earthquakes of the Earth. This fact and the aforementioned completeness of the analyzed earthquake catalog confirm the realistic nature of the results obtained.

The nature of planetary changes in the seismic regime can be interpreted in terms of contemporary ideas of the global dynamics of lithospheric plates (seismicity is its most impressive manifestation). Thus, events with $h > 70$ km (solid circles in Figs. 1 and 2a) are associated with the subsidence of lithospheric plates into the upper mantle in subduction zones, island arcs at the periphery of oceans, and relicts of such zones on continents (for example, in the eastern Carpathians and at the NW and SE terminations of the Himalayas; see Fig. 1) [Ulomov, 1974, 1993b]. Shallow sources (open circles) are widespread mainly on continents and in oceanic rift zones. However, both types of sources are undoubtedly caused by a coherent seismogeodynamic process encompassing the entire Earth as a whole.

In order to explain the observed pattern of global seismogeodynamics in the period under consideration, we cannot exclude at least the two following scenarios. Thus, it may be assumed that the general seismic quiescence in this period was caused by a slow (creeplike) and virtually aseismic subsidence of the lithosphere in subduction zones, weakening the total stress state in the lithosphere and decreasing the number of seismic movements in it. Due to the temporary absence of significant hooks on sliding planes, no large earthquakes occur in subduction zones.

According to another scenario, the observed general seismic quiescence is, on the contrary, associated with the accumulation of geodynamic stresses in the lithosphere of continents and oceans, due to, among other factors, the slowdown of lithosphere subsidence processes in subduction zones. After active subduction is resumed, a general release of lithospheric stresses begins and the entire depth range becomes active. Other explanations are also possible. Nevertheless, the observed clearly expressed quiescence and other changes in the seismic regime in the entire depth range of seismic sources are an indisputable fact, and the nature of this phenomenon is associated with specific features of the Earth's geodynamic development. It is also possible that both scenarios took place simultaneously but were realized differently in numerous subduction zones.

In this respect, the joint analysis of seismogeodynamic and hydrodynamic processes performed in seismicity studies of the Caspian Sea [Ulomov et al., 1999; Ulomov, 2003] has an important advantage, because the only short subduction zone in the central Caspian Sea was considered in these papers (below, this is described in greater detail). The Caspian Sea and the ocean are similar in that both are closed water basins and can be regarded as indicators actively responding to global and regional seismogeodynamic processes.

GLOBAL CHANGES IN THE OCEAN LEVEL

The ocean level (OL) is an integral indicator of global water exchange. A large number of factors widely differing in their origin affect the OL formation; they are united by specialists into three main groups: cosmic and geophysical forces, geological–geodynamic processes, and hydrometeorological processes [Doganovskii and Malinin, 2004].

Cosmic and geophysical factors include tide-generating forces of the Moon and Sun, free and forced oscillations of the Earth's poles, nonuniform changes in the Earth's rotation velocity, and so on. These factors, owing to their periodicity, are easily recognizable and filtered (eliminated) during averaging of time series.

[1] While the paper was in press, the earthquakes of January 13, 2007 ($M = 8.2$), and April 21, 2007 ($M = 8.1$), occurred in the central part of the Kurile Arc and near the Solomon Islands (SW Pacific Ocean), respectively (Ed.)

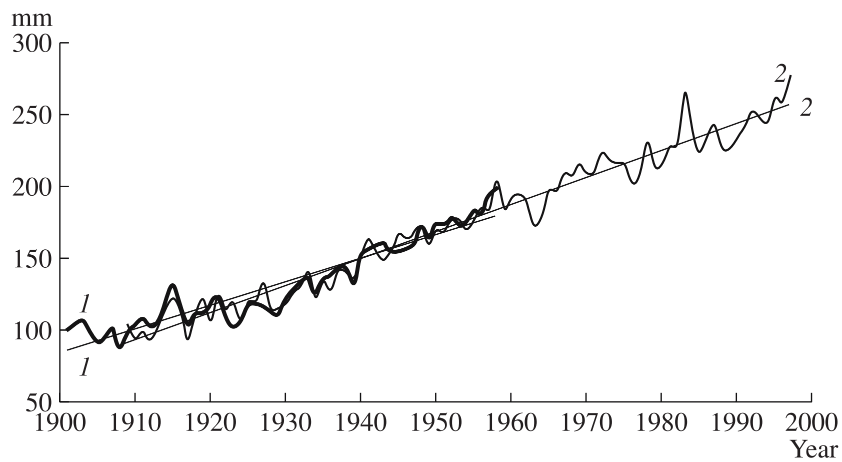

Fig. 3. Averaged OL variations and their linear trends calculated from data of various authors (*1*) and from Malinin's model (*2*) [Malinin, 2005].

Geological–geodynamic processes include submarine earthquakes, volcanic eruptions, crustal tectonic movements, deposition of bottom sediments, and other processes and phenomena that cause OL variations of the deformation type, preserving the total water mass. Water exchange of oceans and seas with deep (juvenile) water accompanied by changes in water volumes also belongs to this category. Occasional pulsed OL variations in the form of tsunami waves and large seiches are characteristic of this group.

Hydrometeorological processes include the atmospheric pressure, changes in the seawater density, wind, currents, and other components of the water balance that form a wide spectrum of OL variations with periods from a few minutes to hundreds and thousands of years. For example, OL changes due to storm surges can reach a few meters.

Thus, volume variations in the water surface level are caused by changes in the amount of water, whereas "deformational" OL variations are associated with a redistribution of the water mass in basins that does not change its volume. On the whole, the total volume of the hydrosphere consisting of water of the ocean, cryosphere, lithosphere, and atmosphere remains virtually constant over a sufficiently long historical period [Doganovskii and Malinin, 2004].

The averaged curve of global OL variations constructed by Malinin [2005] for nearly a century-long time interval on the basis of his own calculations and data of other researchers is presented in Fig. 3. All series are reduced to the same reference system with the origin at a value of 100 mm recorded in 1901. Malinin notes that the presence of a well-pronounced linear trend is the main feature of OL variations. The average rate of the OL increase is 1.6 mm/yr. Two periods of significantly different OL variations are rather clearly expressed. Thus, while the level virtually did not change during 1901–1923, it began to rise rapidly since 1924. Over the period 1924–1958, the OL increase attained 2.8 mm/yr. An anomalously large OL rise observed in the calculated (model) plot in 1983 is also noteworthy.

Satellite altimeters have measured the OL with a very high accuracy only beginning from August 1992. These measurements show that the OL has increased since 1993 at a rate of 2.5 mm/yr. Importantly, the method of satellite altimetry basically differs from traditional observations with tide gauges and provides estimates of the level surface of the ocean virtually all over its water area and not only along coastlines.

Changes in the surface level of oceans, including those revealed from satellite altimetry data, are explained by specialists by the expansion or compression of the water mass due to changes in its temperature and salinity that in turn can be caused by global climate changes [Antonov et al., 2005]. Along with relatively short-period OL variations, a prolonged general rise of the ocean surface at an average rate of 1–2 mm/yr is observed. There are other estimates of the OL variation rate, for example, 2.9 ± 0.4 mm/yr [Leuliette et al., 2004]. Levitus et al. [2005] indicate that the upper layer up to 700 m thick accounts for a considerable part (about 75%) of global temperature variations. Variations similar in form but smaller in value are characteristic of the layer 0–3000 m.

OL variations are geographically nonuniform and depend, to an extent, on the latitude. Thus, the Pacific Ocean level changes predominantly in the tropical zone, whereas the Atlantic and Indian oceans contribute to the general pattern in the subtropical zone. Nevertheless, under the conditions of communicating vessels, the general level of all oceans is smoothed one way or another. Appreciable fluctuations observed approximately every ten years are revealed against a long linear trend of the OL rise. As noted above, according to Doganovskii and Malinin [2004], volume OL variations are associated with changes in the total amount of water in the world basin, and deformational (in their

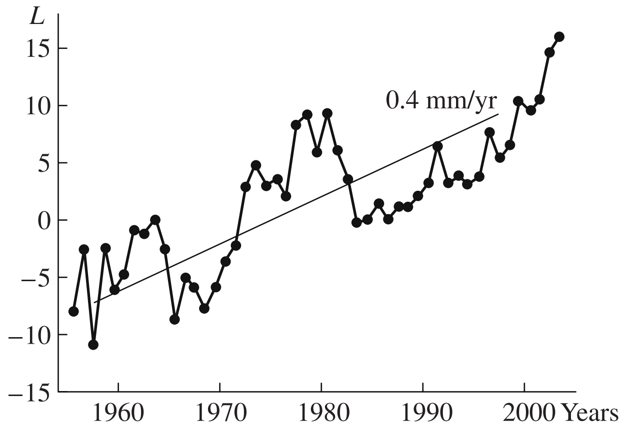

Fig. 4. OL variations over the period 1955–2003 for the layer 0–700 m (yearly average smoothing) according to data from [Antonov et al., 2005].

terminology) OL changes are caused by such a redistribution of the water mass (without changes in its volume) that the level rises in some regions and drops in others.

The average annual OLs over the period 1955–2004 for the layer 0–700 m are presented in Fig. 4, which is borrowed from the work [Antonov et al., 2005], distinguished by a high rating. As regards a global seismic activation that started in 1993 and was noted above, it is noteworthy that Antonov et al. [2005] revealed an anomalous OL trend of 1993–2003 whose intensity was more than threefold higher compared to the trend observed during the entire period of observations (1955–2003). These authors admit that their OL measurements of 1993–2003 contain values that cannot be accounted for by temperature changes alone. On the other hand, we found that global seismic processes have become very active beginning precisely from 1993. This also needs interpretation.

In order to compare seismogeodynamic and hydrogeodynamic processes over the time interval under consideration (1965–2006), a fragment of Fig. 4 represented in the general time reference system is shown in Fig. 2b. The long-term trend of the OL rise at a rate of 0.4 mm/yr is borrowed from [Antonov et al., 2005], and the rates along three shorter segments calculated in our work are shown by broken lines. It is worth noting that an abrupt change in the OL variation sign is observed in the early 1980s and the highest rate of the OL decrease is fixed in the interval 1982–1983, when a rapid decrease in the general seismic activity of the Earth began (Fig. 2). This OL decrease immediately followed two large ($M = 8.0 \pm 0.2$) earthquakes that occurred in the southwestern, Indonesian part of the Pacific Ocean in 1979 and 1980 and concluded a long series of similar events before the seismic quiescence of 1982–1993 (Fig. 1).

It is also surprising that, beginning from 1993 (i.e., from the time moment of the intense seismic activation revealed in our study), the best-expressed positive trends were observed in the western tropical part of the Pacific Ocean and between Australia and New Zealand, i.e., in a region that is a seismological "focus" of intense manifestation of the seismogeodynamics of lithospheric plates moving toward this region from all sides (Fig. 5). The lithosphere of the Earth seems to be drawn into this global "funnel" of the Indian–Pacific basin.

However, in the opinion of Malinin, who considers deformation-type OL changes as a result of crustal tectonic movements and seafloor sedimentation, since tectonic movements have opposite signs in various regions of the Earth and compensate each other, they do not strongly affect the average global OL. Seafloor sedimentation favoring an OL rise is also very small on time scales of several tens of years.

Thus, although the relation between OL changes and global warming seems to be evident, estimates of the trend value are still uncertain.

CHANGES IN THE CASPIAN SEA LEVEL

The Caspian Sea is a unique natural reservoir of the Earth isolated from the ocean. Therefore, this water basin can be regarded as an indicator of the development of regional and local geodynamic processes. In its dimensions, the Caspian Sea is the largest lake on the Earth. Its water surface is 28 m below the ocean level, and the area of this surface amounts to 18% of the total area of all lakes of the Earth and substantially exceeds the surface areas of some seas.

The relation between changes in the seismic regime and the water surface level, supporting the common deep origin of both phenomena, was discovered in [Ulomov et al., 1999; Ulomov, 2003] from studies of seismogeodynamics of the Caspian region. These studies showed that the Caspian basin is sensitive to the smallest deformations of the lithosphere and is a peculiar indicator of local geodynamics and seismicity. Based on results derived from the analysis of the deep structure and dynamics of the lithosphere and from the study of the regional seismicity structure and contemporary tectonic movements, a 3-D seismogeodynamic model was proposed in [Ulomov, 2003] according to which seismic activation is preceded by bending of the base of the South Caspian depression and the appearance of excess water in the sea. On the contrary, large earthquakes and the subsidence of the corresponding parts of the crust in the subduction zone of the Central Caspian region are followed by a general drop in the water level. We obtained estimates of geodynamic deformations of the relict oceanic lithosphere in the South Caspian region that are responsible for the accumulation of elastic stresses and the nucleation of offshore earthquakes.

In its deep structure, the Caspian Sea is divided into three main parts: northern, central, and southern. From the standpoint of seismogeodynamics, most interesting is the Central Caspian region, which is the zone of

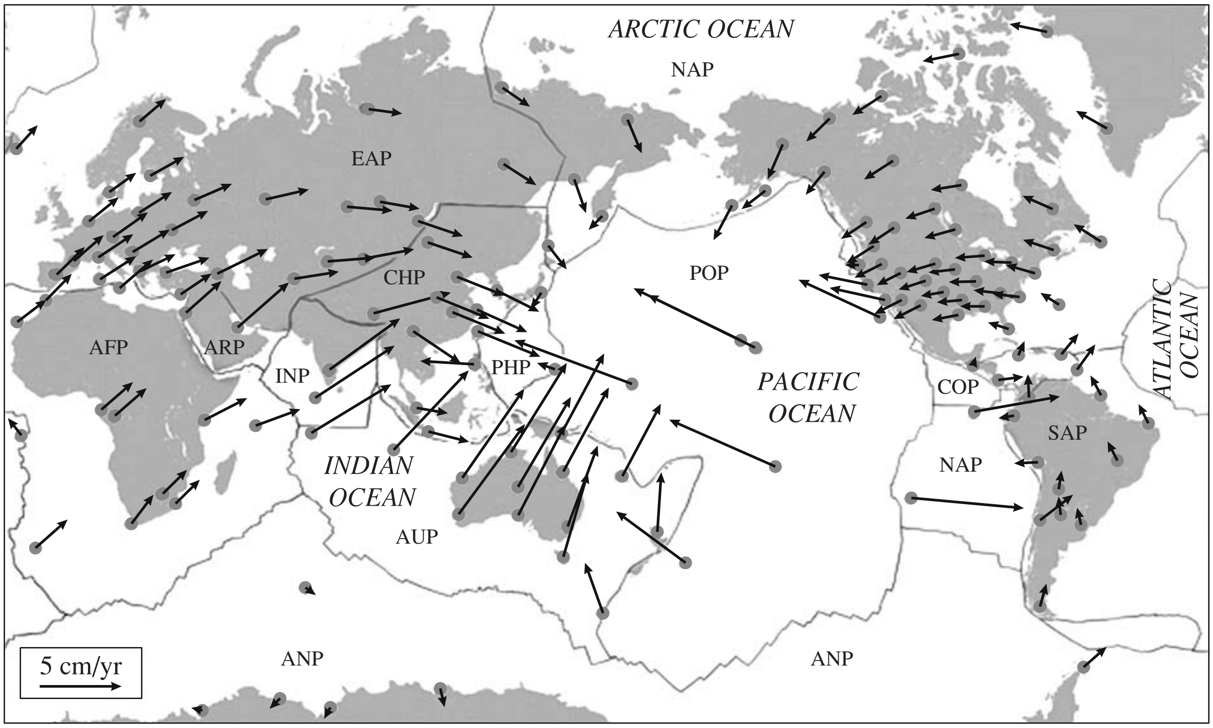

Fig. 5. Directions and velocities of contemporary horizontal motions of lithospheric plates (arrows) determined from GPS measurements at sites (black dots) on continents and islands (from http://sideshow.jpl.nasa.gov/mbh/series.html). Lithospheric plates: EAP, Eurasian; NAP, North American; POP, Pacific; AFP, African; ARP, Arabian; INP, Indian; CHP, Chinese; AUP, Australian; PHP, Philippine; YAP, South American; COP, Cocos; NAP, Nazca; ANP, Antarctic. The scale of motions is indicated in the lower left corner. Boundaries between plates are shown by gray lines.

active junction of the Caucasus–Kopet Dagh Alpine geological structure and the Scythian-Turan epi-Hercynian platform. This zone is traceable by the trans-Caspian Cheleken-Apsheron sill, as well as by a narrow band of offshore earthquake sources and maximum gradients of isostatic gravity anomalies, the magnetic field, the heat flow, and other geophysical fields. The crust of the South Caspian depression has an oceanic structure.

The location of seismic sources at fairly large depths in the central part of the Caspian Sea most clearly reflects the development of seismogeodynamic processes caused by the interaction of lithospheric plates across the Cheleken-Apsheron relict subduction zone. The ophiolitic belt extending on both sides of the Caspian Sea also indicates the subduction origin of this zone. Appreciable tsunamis in the central Caspian Sea also relate this region to oceanic subduction structures. As regards the seismic activity level, it is significantly lower in the water area of the Caspian Sea as compared with the coastal territory, where earthquakes with $M = 8.0 \pm 0.2$ are known.

The 3-D seismogeodynamic model of the Caspian region [Ulomov, 1993] is schematically shown in Fig. 6 as three geoblocks cut from this model. The two end blocks (a, c) represent coastal land areas, and the middle block (b) represents the Caspian Sea with its subduction zone (the Elburz mountainous structures in the south and the Scythian plate in the north). All three blocks experience in the south the geodynamic pressure of the Arabian and Iranian lithospheric plates.

Under the conditions of N–S compression, blocks of the region are deformed and thicken, forming mountainous structures. The oceanic crust of the southern Caspian Sea, experiencing the pressure of the Elburz

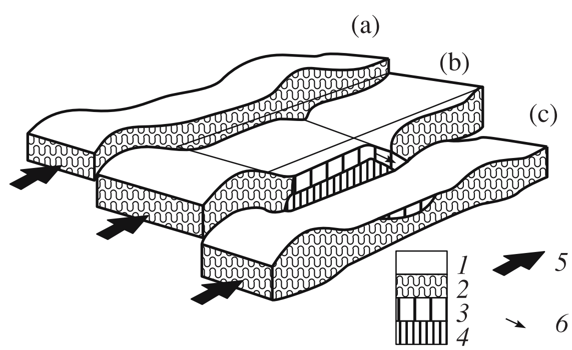

Fig. 6. Schematic 3-D seismogeodynamic model of the Caspian region [Ulomov, 2003]. Main geostructures (blocks): (a) Caucasus–Talysh; (b) Elburz–Caspian; (c) Kopet Dagh–Turan; (*1*) water mass of the Caspian Sea; (*2*) continental lithosphere; (*3*) relicts of oceanic lithosphere; (*4*) asthenosphere; (*5*) direction of forces developed by the Arabian and Iranian lithospheric plates; (*6*) direction of subduction of the South Caspian oceanic lithosphere under the Scythian-Turan plate.

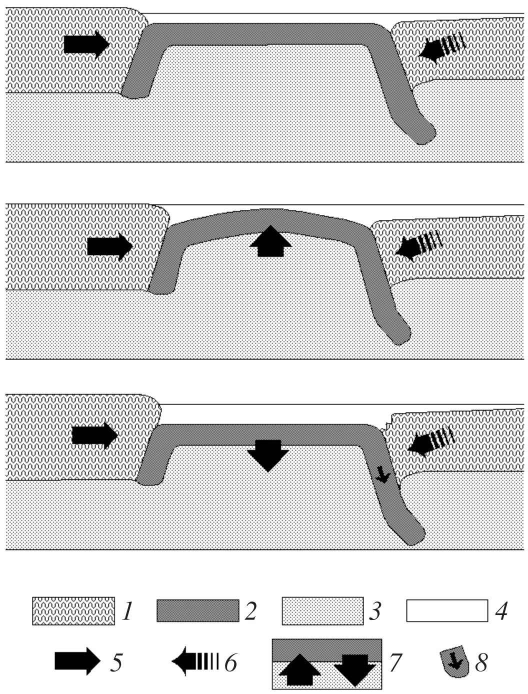

Fig. 7. Illustration of the mechanism of horizontal compression (top), upwarping (middle), and subsequent subsidence of the South Caspian oceanic lithosphere (bottom): (*1*) continental lithosphere; (*2*) oceanic lithosphere; (*3*) asthenosphere; (*4*) water mass; (*5*) direction of the force exerted by the Elburz Mountains; (*6*) subsidence direction of the bent part of the Scythian-Turan plate in the North Caspian region; (*7*) directions of bending and subsidence of the South Caspian oceanic lithosphere; (*8*) subduction direction of the lithospheric plate.

Mountains, is forced to plunge under the continental crust of the Scythian-Turan plate all along the length of the Cheleken-Apsheron sill in the central Caspian Sea. In essence, the Caspian Sea owes its existence precisely to this subsidence (subduction).

The subduction process consists of several alternating stages schematically shown in Fig. 7 (from top to bottom). The horizontal compression and the increase in elastic stresses in the oceanic lithospheric plate (top panel) bend it upward (middle panel) and squeeze out the seawater mass, raising its level. As shown in [Ulomov, 2003], upon reaching critical values of elastic bending, the northern edge of this plate sinks under the continental lithosphere of the northern Caspian Sea, which is accompanied by the seafloor flattening in the southern part of the sea and a corresponding drop of its level (bottom panel). This subsidence can be realized through both rapid seismic motions and slow creep. The calculations performed in [Ulomov, 2003] showed that even insignificant displacements of the plate edge in the southern Caspian Sea should lead to significant variations in the sea level.

Figure 8 shows variations in the time intervals ΔY (the number of years) between successive earthquakes of various magnitudes that occurred within the Caspian region over the period 1890–2002. The curve of variations in the sea level L over this time interval is also shown in this figure. Earthquakes within the magnitude intervals $M = 8.0 \pm 0.2$, 7.5 ± 0.2, 7.0 ± 0.2, 6.5 ± 0.2, and 6.0 ± 0.2 that occurred in the Caspian Sea and on the nearest coasts were considered. All seismic events are absolutely reliable. This figure is a fragment of the figure presented in [Ulomov, 2003], but the time axis is here vertical for convenience of comparison with Fig. 2

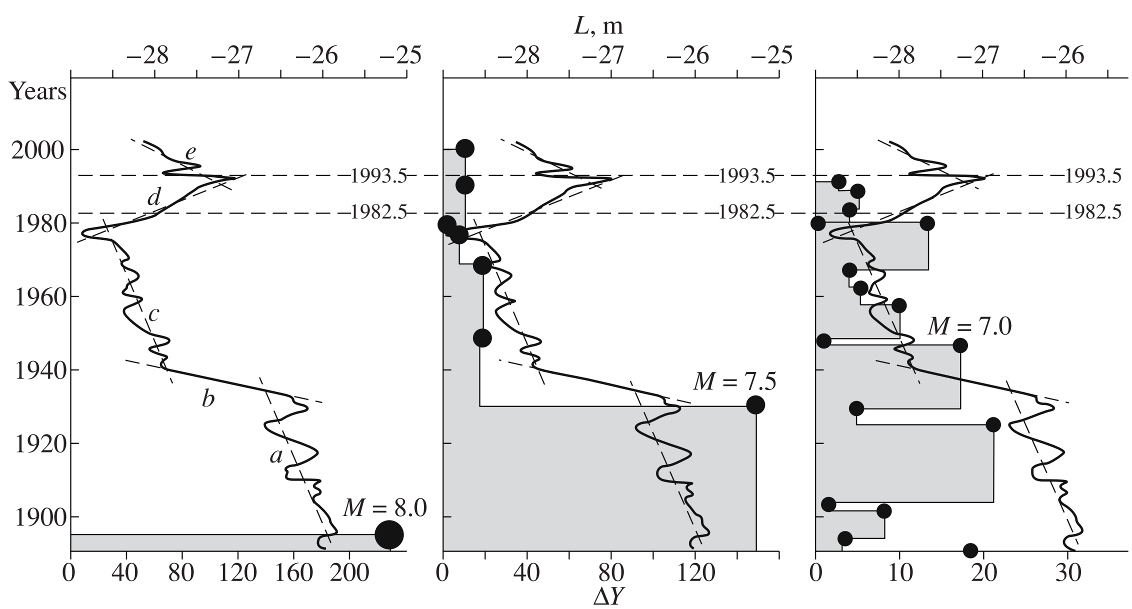

Fig. 8. Variations in the time interval ΔY (the number of years) between successive seismic events (solid circles) of various magnitudes M and the Caspian Sea level L (m) during the time T (1890–2002); (*a–e*) stages of sea level variations.

and the interval 1982.5–1993.5 considered in the preceding sections is marked by broken lines.

The value ΔY is the time interval between successive earthquakes of corresponding magnitudes M in each sequence. These values correspond to the widths of histograms whose areas are proportional to such "delays" in the occurrence times of current earthquakes. The more frequent the earthquakes, the closer the corresponding ΔY values to the abscissa axis and the smaller the amplitude and area of the histogram. Vice versa, longer delays increase the areas and heights of histograms. It is evident that, if seismic events of a given magnitude occurred uniformly in time, the histograms would have the same height and area, and the occurrence times of these earthquakes would lie exactly on a vertical line with an abscissa corresponding to the period of such a rhythm. However, the actual distribution of seismic events has a certain regular pattern caused by deep seismogeodynamic processes.

Less significant high-frequency fluctuations of the sea level are associated with the influence of diverse endogenous and exogenous factors, including climatic, hydrologic, and other. If this high-frequency component is eliminated, the curve L can be approximated by linear segments at each of the distinguished stages: (*a*) 1890–1930, a relatively slow sea level decrease; (*b*) 1930–1940, a very rapid and intense sea level drop (by nearly 2 m); (*c*) 1940–1978, a slow and long-term decrease; (*d*) 1978–1992, a very rapid and intense (by nearly 2 m) rise in the Caspian Sea level; and (*e*) 1992–2002, a rapid drop of the sea level.

Analysis of time intervals between successive earthquakes and comparison of variations in the seismic regime and sea level reveals their fairly good correlation. In accordance with the seismogeodynamic model of the Caspian Sea described above, this relation is most distinct for the largest seismic events. As seen from the left panel in Fig. 8, illustrating events with $M = 8.0 \pm 0.2$, the Krasnovodsk earthquake of 1895 ($M = 7.9$), which occurred on the eastern coast of the Caspian Sea more than two centuries after a similar earthquake of 1668 on the opposite coast (in the area of the city of Shemakha in Azerbaijan), was followed by a long (nearly 100-yr) interval of a sea level decrease including three stages (*a*–*c*) of variation in the rate of this process. (Note that no reliable information on the altimetry of the Caspian Sea before 1838 is available.)

No less convincing is a sequence of $M = 7.5 \pm 0.2$ earthquakes that started, after the 150-yr seismic quiescence, with the earthquake of 1930, which occurred west of the southern Caspian coast against the background of a relatively high sea level. It is noteworthy that this earthquake was followed by a series of underground shocks along the Derbent trench in the central Caspian water area; their sources are the deepest in the Caspian Sea. The two largest of these shocks occurred in 1931 ($M = 6.2$, the hypocentral depth $h = 110$ km) and in 1935 ($M = 6.3$, $h = 100$ km). During all these events, the water level decrease in the Caspian Sea substantially accelerated (stage *b*), and seven earthquakes with 7.5 ± 0.2 occurred one after another at the next stage (*c*), characterized by a certain slowdown of the decrease in the sea level and by its sharp variations of various signs (*d* and *e*). The time interval between these earthquakes averaged about 10 yr, which is a very high recurrence rate, taking into account that such events were not observed in this region for one and a half centuries. After the earthquake of 1930, the Ashkhabad catastrophe of 1948 was the first in this chain of $M = 7.5 \pm 0.2$ events. This earthquake almost completely destroyed the capital of Turkmenistan. After a time interval of nearly the same length, in 1968, a similar earthquake occurred in eastern Iran, in the same structure south of Ashkhabad. Afterward, three earthquakes of the same strength took place in a very short time interval (1976–1979) coinciding with a sign change of variations in the sea level (the drop–rise stage) and its abrupt rise in 1978. The first of these earthquakes occurred in 1976 west of the Caspian Sea; the other two occurred in 1978 and 1979 east of the Caspian Sea at nearly the same distance from the sea. The next two seismic events of the same rank, separated by the same 10-yr interval, took place in the immediate proximity of Caspian coasts. These were the destructive Rudbar (northern Iran) earthquake of 1990 and the no less strong 2000 earthquake in offshoots of the Greater Balkhan Range in western Turkmenistan (Fig. 1).

The last sign change of the rise–drop type was observed immediately after the Rudbar earthquake, and the following sea level drop was no less rapid. At present, it is rather difficult to search for a more detailed relation between sea level variations at the *c*–*e* stages and the last seven earthquakes with $M = 7.5 \pm 0.2$, except that their very high recurrence rate coincided in time with sharp variations in the sea level. However, it is important to note that a sharp sign change and a very rapid sea level rise at the stage *d* almost coincided in time with a global slowdown of the seismic flow in 1982.5–1993.5, as well as with the sign change and rise in the OL.

Complex seismogeodynamic and hydrogeodynamic processes in the Caspian region continue. Notwithstanding the rapid sea level rise in 1978, its height was still much lower than the heights preceding both the Krasnovodsk (1985) and Iranian (1930) earthquakes. Following the concept of predominant interepicentral distances between the sources of earthquakes of a fixed magnitude, the position of the potential source of a forthcoming earthquake with $M = 7.5 \pm 0.2$ is predicted in [Ulomov et al., 2007] with a fairly high probability.

The sequence of earthquakes with $M = 7.0 \pm 0.2$ (right-hand panel in Fig. 8) that, beginning from 1946, have relatively seldom occurred at the stage *a* is characterized by a twofold recurrence rate. This period covers the stages *c* and *d* of sea level variations. No earthquake of this strength has occurred at the stage *e* as yet. As in

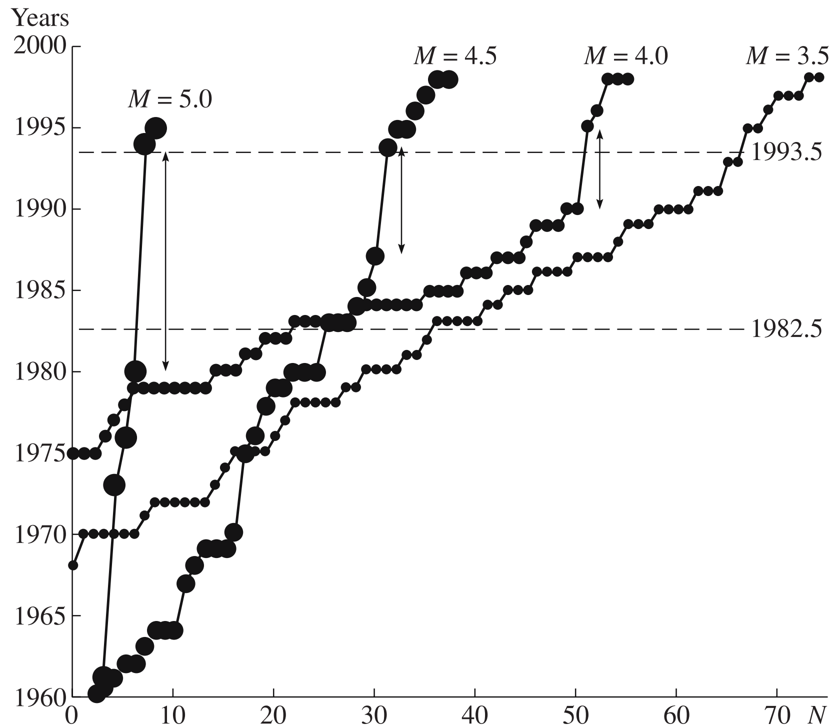

Fig. 9. Sequences of seismic events of moderate and low magnitudes in the subduction zone of the Central Caspian region during 1960–1993. N is the cumulative number of earthquakes, and the years of their occurrence are plotted on the vertical axis. The time interval (1982.5–1993.5) of the global seismic quiescence is bounded by horizontal broken lines. The vertical bidirectional arrows show the time intervals between the relative seismic quiescence and the occurrence of seismic events with $M = 5.0 \pm 0.2$, 4.5 ± 0.2, and 4.0 ± 0.2.

the previous case with $M = 7.5 \pm 0.2$, no closer correlation between seismicity and sea level variations is recognizable, except that the recurrence rates of both types of events increased at the last stages.

It cannot be ruled out that powerful global geodynamic processes affected in some way the Iran–Caucasus–Anatolian region, including the closed Caspian basin. One should also pay attention to a certain seismic quiescence in nearly the same time interval (1982.5–1993.5) in relation to moderate and weak earthquakes with $M = 5.0 \pm 0.2$, 4.5 ± 0.2, 4.0 ± 0.2, and 3.5 ± 0.2 in the subduction zone of the central Caspian Sea (Fig. 9). With decreasing magnitude, these anomalous zones become gradually less contrasting and even completely disappear in the sequence of the weakest earthquakes ($M = 3.5 \pm 0.2$). Incidentally, this fact emphasizes once more that it makes no sense to search for anomalies in the seismic regime of some or other region and the Earth as a whole by summing up the total number of earthquakes without their differentiation by magnitudes because an infinite set of weak seismic events will smooth the general pattern.

A further search for the correlation between seismogeodynamic and hydrogeodynamic processes in water areas of the Caspian Sea and the world ocean should take into account the dimensions of earthquake sources and their distance from water basins.

DYNAMIC PROCESSES IN SEISMIC SOURCES

The interrelation and interdependence of seismogeodynamic and hydrogeodynamic processes are also observed at a local level.

Changes in the groundwater regime associated with earthquakes have long been noted. In our country, the first quantitative hydroseismic investigations were carried out in 1901–1902 by F. Mol'dengauer, who, systematically observing a thermal mineral spring in Borzhomi, established a dependence between disturbances in the regular activity of the spring and seismic phenomena in the Caucasus. Investigations of the origin of the 1966 Tashkent earthquake ($M = 5.2$) allowed us to revive seismogeodynamic methods in domestic seismology. Analyzing changes in the content of inert gas radon in thermal mineral water of the Tashkent artesian basin in periods preceding and following this earthquake, we revealed a relation between the source zone deformation and radon emission. For the first time, we proposed a four-stage model of the nucleation and occurrence of tectonic earthquakes [Ulomov and Mavashev, 1967; Ulomov, 1974]. Largely owing to these prognostic investigations, systems of hydrogeodynamic monitoring became widespread in our country and abroad in the 1960s–1970s. These systems enhanced the efficiency of instrumental observations of earthquake nucleation processes.

Among other geophysical prognostic indicators, anomalies in the pressure, velocity of motion, thermal regime, and chemical and gas compositions of deep water have occupied a priority place along with radon emission, and the borehole–aquifer system has become a source of information on changes in elastic stresses and strains in the source zones of forthcoming earthquakes [Ulomov et al., 1977; Zuev and Ulomov, 1984].

As was shown in [Ulomov, 1974], seismic and seismogeodynamic processes develop similarly on various spatiotemporal and energy scales, from individual seismic sources to the largest regional and global seismogenerating structures. It was suggested for the first time that the fracture of the crust affected by groundwater is a part of the seismic source development process. This inference was confirmed by three very large earthquakes (magnitudes of 7.0, 7.3, and 7.2) that occurred in 1976 and 1984 in the area of the Gazli gas field in western Uzbekistan. This area was previously regarded as virtually aseismic. These earthquakes, unordinary in their magnitudes, were classified as induced seismicity events [Ulomov, 1976, 1986]. The four-stage model of deformation processes in a seismic source proposed by the author in 1966 was further developed by American geophysicists (with reference to our priority publication [Ulomov and Mavashev, 1967]) and incorporated in their dilatancy–diffusion model, also based on concepts of water injection into fractures arising in a potential seismic source.

Thus, the role of water in earthquake source formation is significant. It was found that a water column about 100 m or more in height not only produces an additional load deforming the crust but also considerably increases the liquid pressure in fractured zones of local tectonic faults. The pore pressure increase in rocks of regions of present-day tectonic activity appreciably weakens their strength and leads to the development of micro- and macrocracks; additional injection of water; and finally, seismic motions on faults. Such seismicity manifestations primarily include anthropogenic earthquakes, initiated by human activities (induced seismicity). As has been demonstrated by numerous examples, higher seismic activity of crustal regions and the occurrence of strong earthquakes could be related to the construction of large artificial reservoirs, injection of chemical solutions into deep boreholes, and so on.

DISCUSSION

Joint investigations of global and regional changes in the seismic regime and water surface levels of the ocean and the Caspian Sea revealed regular patterns confirming that both phenomena have a common deep origin. The seismological information available for the 40-yr period under consideration (1965–2006) is most reliable and is presented in world catalogs of earthquakes. We studied a wide range of problems related to global changes in the climate and OL. Preference was given to satellite altimetry, which provides information on the water surface level all over the ocean water area, as distinct from tide gauges measuring the level only along coastlines.

We revealed that considerable changes in the seismic regime of the Earth took place in the interval 1982–1993. During this period, the recurrence rate of large earthquakes in the magnitude ranges $M = 8.5 \pm 0.2$, 8.0 ± 0.2, 7.5 ± 0.2, and 7.0 ± 0.2 decreased by three or more times, after which an intense activation of global seismicity started in the entire depth range of seismic sources. This seismicity activation was most clearly demonstrated by a nearly annual occurrence (beginning from 1994) of large deep earthquakes with $M = 7.5 \pm 0.2$ or more that had previously been absent during three decades. The anomalous period of seismic quiescence of 1982–1993 was also observed at a regional level as a decrease in the recurrence rate of weak earthquakes with $M = 5.0 \pm 0.2$, 4.5 ± 0.2, and 4.0 ± 0.2 in the Caspian Sea basin.

As for anomalous variations in the water surface level, the results obtained for the Caspian Sea appear to be most convincing. They showed that, in this region, seismogeodynamic and hydrogeodynamic regional parameters correlate not only with each other but also with global changes in the seismic regime. Thus, the rapid change of the long-term decrease in the Caspian Sea level to its rapid rise in 1978 followed by its new decrease beginning from 1992 virtually coincided in time with the global seismic quiescence of 1982–1993. Although this relatively short-term rise of the Caspian Sea level looks anomalous against the background of a general local seismic activation, we could not perform a more detailed analysis because of a relatively low offshore seismicity. However, in a global aspect, this phenomenon does not contradict our phenomenological model of the sea level rise with decreasing seismicity, i.e., with a slowdown of the lithosphere consumption in the subduction zone and its upwarping under the action of plate-driving forces.

As distinct from the Caspian region with its single subduction zone, the hydrologic regime of the ocean can be seismologically related to a great number of such zones, including those located on the periphery of the Pacific Ocean. Some subduction zones can be activated, whereas the lithosphere subsidence in other zones slows down. Nevertheless, the relation of OL variations to seismic regime changes in the period 1982–1993 is recognizable in this case as well. Thus, against the background of a general long-term rise in OL associated with global warming of the climate, the rapid OL drop at a rate of 0.3 mm/yr observed in the period 1981–1984 was comparable with the long-term rate of its rise (0.4 mm/yr) and was followed by an OL rise at nearly the same rate as before. Note that such a rapid OL drop started immediately after two large ($M = 8.0 \pm 0.2$) earthquakes that occurred in the SW, Indonesian part of the Pacific Ocean in 1979 and 1980 and concluded the long series of similar events before the seismic quiescence of 1982–1993. In this respect, it is interesting that, according to observations of oceanologists, the most intense variations were observed after 1993 precisely in this part of the Pacific Ocean.

It is equally important that even supporters of the ideas of a nearly absolute influence of temperature on OL variations had to admit that some values obtained in the period considered by them (1993–2003) cannot be accounted for by temperature changes alone [Antonov et al., 2005]. It conceivable that a very intense global seismogeodynamic activation that started in 1993–1994 was responsible for these facts that remain still unexplained by oceanologists.

CONCLUSIONS

A large number of various factors, including dynamics of lithospheric plates and global seismicity, control the water surface level on the Earth. The factors mentioned above have not received proper attention as yet, although the interrelation of seismogeodynamic and hydrogeodynamic processes and phenomena has long been known at the level of regional and source seismicity [Ulomov and Mavashev, 1967; Ulomov, 1971].

The Earth is a structurally complex dynamic system, and the modern system approach should be applied to the study of processes developing under strongly nonequilibrium conditions of its geospheres, with their inherent self-organization phenomena [Gol'din, 2002; Nikolis, 1989; Prigogine and Stengers, 1984; Sadovsky, 1979; Ulomov, 1990, 1993a, 1993b].

Dynamics of the crust and lithosphere is due to the accommodation processes of volumes of the geophysical medium to applied long-term force actions, including those on the planetary scale. From this standpoint, the alternation of increases in elastic stresses with their subsequent releases in the form of slow deformations or rapid stress drops in earthquake sources is the most efficient self-organizing regime of geodynamics. The fractal structure of the medium predetermines its specific response to external deformations. Thus, in the case of weak forces applied to the medium, the seismic regime is nearly stationary and characterized by the occurrence of weak earthquakes. If the forces increase, for example, as a result of large seismic or creep motions, the seismogeodynamic system is transformed into a qualitatively new and more organized state and sources of large earthquakes interrelated in space and time arise [Ulomov, 1987, 1990]. Although the geodynamic system continuously changes its state, the Earth as a whole is in dynamic equilibrium, which is favored by the observed periodicity of the accumulation and release of geodynamic stresses.

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