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GEODYNAMIC ORIGIN OF VARIATIONS OF SEISMIC REGIME OF CASPIAN AREA AND LEVEL OF CASPIAN SEA

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ABSTRACT

The Caspian Sea has long attracted the attention of geologists, seismologists and other scientists, as well as politicians. The area of study is characterized by very high seismic activity. The problem of anomalous variations in the Caspian Sea level was widely discussed in scientific papers from different points of view. Our study is based on new seismic data that were not available to other researchers.

The correlation of local seismicity with anomalous variation in the Caspian Sea level indicates a common geodynamic origin. The very fast rise in the Caspian Sea level which started in 1978 is supposedly related to intensive accumulation of elastic strain producing a fast upwarping of the seafloor and preparation of earthquakes in this area. A 3-D seismogeodynamic model of this region has been developed.

These results we obtained within the framework of the Joint Research Project “Earthquake Sources in Caspian Area and Long-term Prediction of Earthquakes” (ESCAPE) supported by the United Institute of Physics of the Earth (UIPE, Moscow, Russian Federation) and International Institute of Earthquake Engineering & Seismology (IIEES, Tehran, Islamic Republic of Iran).

1. INTRODUCTION

The Caspian Sea is the largest closed reservoir in the world. It is remarkably rich in natural resources. This region has long attracted the attention of geologists, seismologists and other scientists, ecologists, economists, politicians etc. The area is characterized by very high seismic activity. The largest earthquakes of up to Ms=8.0 and greater occurred on the southern, western, and eastern Caspian shores. The occurrence of seismic events with intermediate-depth hypocenters most clearly reflects the successive development of seismogeodynamic processes involving the whole oceanic crust of the southern Caspian Sea plunging into the upper mantle. The earthquakes with subcrustal sources are directly related to the geodynamics of Apsheron-Cheleken deep structure, which is a subduction zone (Ulomov, 1994, 1997; Ulomov et al., 1999).

The problem of anomalous variations in the Caspian Sea level was widely discussed in scientific papers from various points of view, including seismological approaches (Ulomov et al., 1999; Lavrushin et al., 2001; Ivanova, Trifonov, 2002). Our study is based on new seismic data that were not available to other researchers. The unified catalogue of earthquakes for this region from earliest time until 2002 has been compiled by us. The inferred correlation of local seismicity with anomalous variation in the Caspian Sea level indicates their common geodynamic origin, with is likely to be determined by the specific deformation of the Earth's crust and lithosphere of the area studied.

The very fast rise in the Caspian Sea level which started in 1978 is supposedly related to intensive accumulation of elastic strain producing a fast upwarping of the sea bottom and preparation of earthquakes in the area. It is shown that the 1990 Rudbar, Iran, and the 2000 Balkhan, Turkmenistan, earthquakes with Ms=7.4, and the double earthquakes with Ms=6.4 and Ms=6.2 occurring in late 2000 in the western offshore zone of the Caspian Sea on the Apsheron peninsula, Azerbaijan, are related to these processes. Studies showed that patterns in the development of seismicity such as clustering of earthquakes in time and the quasi-sinusoidal shape of the curves describing sequences of seismic events are evidence of the existence of very long period strain waves involving whole regions. A new method is proposed for the monitoring of regional seismogeodynamic processes, and results of studying time variation patterns in the occurrence of earthquakes of various magnitudes are discussed. A 3-D seismogeodynamic model of this region has been developed.

2. VARIATIONS IN SEISMICITY AND CASPIAN SEA LEVEL

Our results are based on a new methodology and additional seismological data. We study sequences of earthquakes within an area that contains genetically related features in the lithosphere of East Caucasus, Albourz Mountain, Kopet Dag and the Caspian Sea (Figure 1).

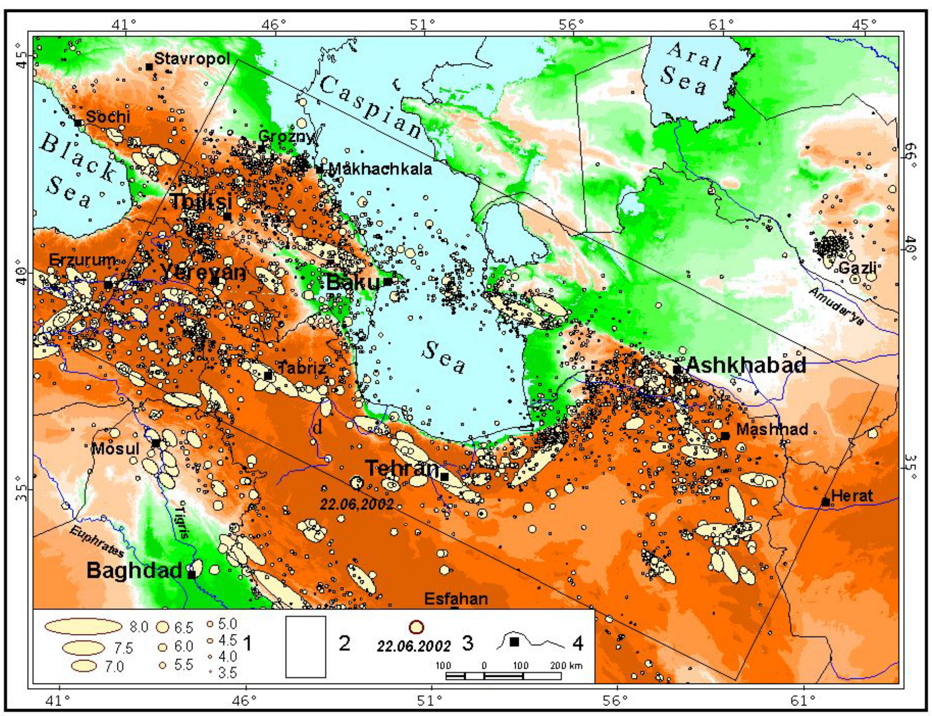

Figure 1. *Seismicity of the Caspian basin and adjacent areas: 1 - earthquake sources of various magnitudes; 2 - boundary of the area of study; 3 - source of M=6.5 earthquake in northern Iran (for explanation see main text); 4 - state boundaries and city limits. The sources with M=7.0±0.2, 7.5±0.2, 8.0±0.2 are shown as ellipses that indicate their length and orientation, while those with M=6.5±0.2 or smaller are shown as circles (not to scale) of decreasing diameter.*

The choice of the area size was influenced by data on seismicity, seismotectonics and seismogeodynamics there. The area of study has a high seismic potential. Great earthquakes (magnitude 8.0 or higher) have occurred on the southern, western and eastern Caspian coasts (856 A.D., M=8.1; 958 A.D., M=8.0; 1668, M=7.8; 1895, M=7.9). The recent largest seismic events in the area were the 1990 Rudbar, magnitude 7.4 earthquake in the northern Iran and the 2000 Balkhan, magnitude 7.3 quake in the western Turkmenia near the eastern Caspian coast. (Here and below, the magnitude is the Ms based on surface wave data).

Being separated from the world ocean, the Caspian basin is responds to the slightest regional and local geodynamic deformations by corresponding changes in its water surface. Figure 2 shows earthquake sequences occurring in the area since 1830 until today. Also shown is a curve representing Caspian sea level changes since 1838. The magnitude ranges considered are the following: M=8.0±0.2; 7.5±0.2; 7.0±0.2; 6.5±0.2; 6.0±0.2. All seismic events are completely reported within the time period of interest, while the record of high magnitude earthquakes (M>7.0) is complete for as long a period as a few hundred years.

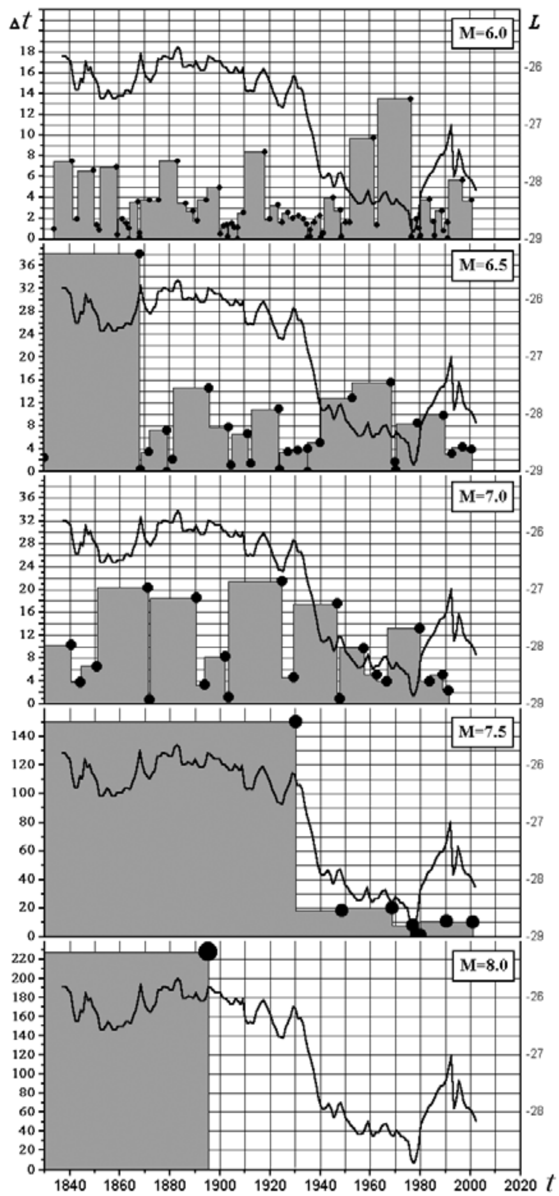

***Figure 2**. Sea level changes L (in meters) for the Caspian Sea and changes of time intervals Δt (in years) between seismic events in an earthquake sequence (filled circles) of magnitude M during time t (1830-2001).*

The quantity Δt is the time interval between successive seismic events of appropriate magnitude M in each earthquake sequence considered. Corresponding to these values, but on a smaller scale, is also the width of histograms whose areas are proportional to these "delays" in the occurrence times of next earthquakes. The more frequent the earthquakes, the closer are the relevant occurrence times to the horizontal axis, and the smaller are the amplitude and area of the histogram. And conversely, larger «delays» increase the area and height of the histogram. Obviously, if seismic events occurred uniformly over time, they would all of them be on a horizontal line whose height on the vertical axis corresponds to the period of this rhythm. As a matter of fact, the distribution of the events obeys a certain pattern due to deep-seated seismogeodynamic processes. The L scale on the right in this figure is relevant to the Caspian sea level changes. For convenience of comparison with seismicity data the curve is duplicated in Figure 2 for each earthquake sequence.

One notes the following anomalous segments on the curve: 1 - 1930 to 1940, a rapid and considerable (nearly 2 meters) sea level fall; 2 - subsequent slow subsidence of water surface during nearly 40 years; 3 - a rapid sea level rise between 1978 and 1992. Another lowering seems to have started recently. The lesser high frequency sea level changes are likely caused by the combined effect of very diverse exogenous and endogenous factors (climatic, hydrologic and other).

One can see that the sea level and interevent time variations correlate well based on several criteria. The relation is best seen for the larger seismic events. For instance, the magnitude 8.0 Krasnovodsk earthquake which occurred on the eastern Caspian coast in 1895 preceded the rapid sea level fall by less than 40 years. No such events had been observed in the area of interest during more than two hundred years before that event (we mean the hypothetical earthquake of 1668 on the western Caspian coast somewhere near the modern town of Shemakha).

One has a no less convincing sequence of $M=7.5\pm0.2$ earthquakes containing seven events following one another very rapidly since 1930, i.e., since the start of the rapid fall in Caspian sea level after a 150-year «silence». Of these, two occurred in Turkmenia (1948, Ashkhabad; 2000, Greater Balkhan), the others being in northern Iran and eastern Turkey. A new sea level fall started after the two last ones occurring in Rudbar, northern Iran in 1990 and in Greater Balkhan, Turkmenia in 2000.

A similar pattern of more frequent earthquakes was also observed for the magnitude range $M=7.0\pm0.2$. Since 1946 until 1992, the frequency of such earthquakes increased more than twice compared with the whole preceding period. The set of seismic events of this rank coinciding with the rapid Caspian sea level rise include the damaging 1988 Spitak, Armenia and the 1991 Racha-Dzhava, Georgia (former USSR) earthquakes.

Interest also attaches to the histograms of two other earthquake sequences with $M=6.5\pm0.2$ and $M=6.0\pm0.2$. The seismic sources of such earthquakes which were of lower magnitudes and higher rate of occurrence seem to be more sensitive to differentiated fluctuations of geodynamic stress and strain in smaller and more numerous geoblocks located close to the Caspian Sea. This can clearly be discerned in the histogram structure. The considerable increase in frequency (decreased histogram height) coincides in time with the rapid 1930-1940 fall and with the no less rapid rise since 1978. It is a noteworthy fact that the Caspian earthquakes of 1935, 1989 and 2000 are $M=6.5\pm0.2$ events; they occurred in the sea area during each of the anomalous sea level changes. The rate of $M=6.0\pm0.2$ earthquakes considerably decreased during the period of relatively low Caspian sea level. One important circumstance is that the $M=6.5\pm0.2$ earthquakes started occurring practically every 4-5 years after a 38-year quiescence since 1868.

3. THE 3-D MODEL OF THE CASPIAN REGION

It has been pointed out above that the seismicity in the region typically involves the occurrence of deep (down to 100 km) earthquakes related to relicts of the older Crimea-Caucasus-Kopet Dag subduction zone. When occurring under the sea, these earthquakes delineate a tectonic zone that has produced some rather large events during the 20th century: 1911, M=6.4; 1961, M=6.0;

1963, M=6.2; 1986, M=6.2; 1989, M=6.3 and 6.2. The largest of the “coastal” seismic events known to have occurred there include the 1895 Krasnovodsk, western Turkmenia magnitude 7.9 earthquake and the 1668 magnitude 7.8 event which occurred on the opposite coast of the Caspian Sea. That the zone in question is due to subduction is also corroborated by the ophiolite belt extending on both sides of the Caspian Sea and by other geological factors that all bear out the above concept.

The correlation noted here between local seismicity and anomalous sea level changes points to a common geodynamic cause, which is most probably due to peculiar deformation of the crust and entire lithosphere in the region of study. The occurrence of seismic events that, though of lower magnitudes, are not shallow, provides the best evidence of deep-seated geodynamic processes which involve the entire subducted oceanic crust of the southern Caspian and of all of the Transcaucasia. As shown by Ulomov et al. (1999), it is quite possible that the anomalous changes in the Caspian sea level are due to alternating slow bending strain and rapid seismic slip down the dip of the subduction zone (Figure 3).

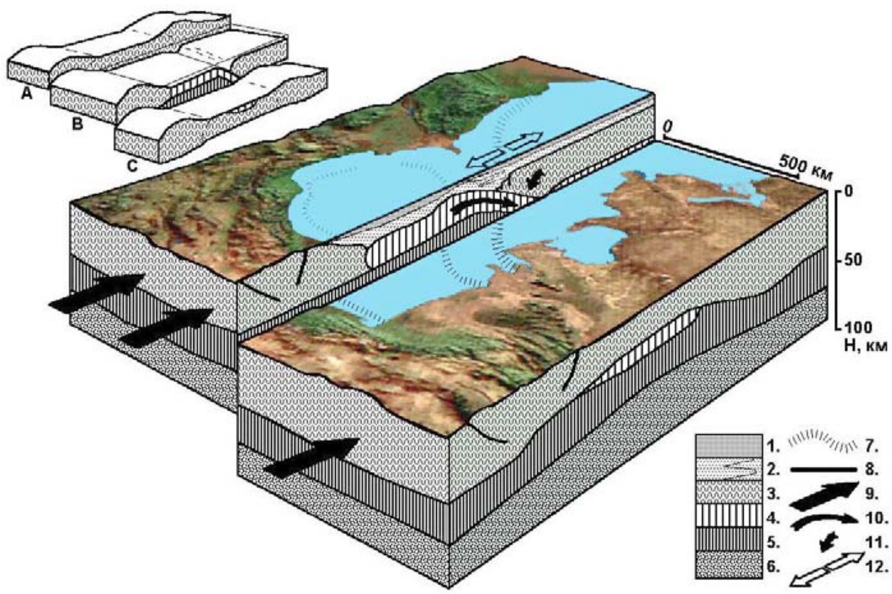

***Figure 3**. 3-D geodynamic model of the Caspian region (after V.I. Ulomov).*
Bottom: 1 - water layer; 2 – folded and faulted seafloor sediments; 3 – “granitic” layer; 4 - relicts of oceanic crust; 5 – “basaltic” layer; 6 - subcrustal substratum; 7 - highs in the gradient of isostatic anomalies; 8 - major tectonic faults; 9 - direction of pressure exerted by Arabian plate; 10 - direction of subduction for the southern Caspian oceanic lithosphere pluging under the Turanian-Scythian plate; 11 - direction of motion for the northern Caspian lithosphere as this is being involved into subduction; 12 - horizontal tension in the bending northern Caspian lithosphere producing normal slip movements in local earthquakes. Top - schematic dynamic three-block model: A - Caucasus block, B - Albourz Mountain - Caspian block, C - Kopet Dag - Turanian block.

The earthquake mechanisms in the subduction zone are absolutely different from those in the rest of the area of study. They invariably involve normal slip due to nearly north-south horizontal tension and vertical compression. The seismogeodynamic model developed here also envisages a change in the sign of motion for the subducted lithospheric plate. With a nearly north-south compression which dominates the Caucasus-Kopet Dag region, the oceanic lithosphere of the southern Caspian basin plunges into the upper mantle in the Cheleken-Apsheron part of the central Caspian Sea. The continental lithosphere of the northern Caspian Sea is also involved in the subduction, experiencing intensive bending and tension in its upper horizons.

Subduction seems to consist of several alternating phases: plunge - stop - bending - plunge and so on (Ulomov et al., 1999). The plunge may proceed either as a slow creep or in the form of rapid seismic slip episodes. The rise in the Caspian sea level can be due to stopped (or decelerated) plunge of the subducted plate and an upward bending of it. The accumulation of elastic stresses in the bending lithosphere leads to a stress release by activating seismic and creep slip movements. A next plunge of the "straightening" lithosphere produces a sea level fall and so on. Our concept of unidirectional geodynamic movements in the region is corroborated, unlike other models due to different workers, by stability in offshore earthquake mechanisms, which have by no means been affected by periods of "low state" and "rapid rise" in the Caspian Sea level.

It is appropriate to remark here that, according to old Persian maps and Arabian written records, the Caspian Sea consisted at that epoch of two distinct basins separated by a narrow isthmus which connected the eastern and the western coasts of the present-day Caspian Sea and which was formerly part of the famous Silk Way. As a result of an unknown geologic disaster, the isthmus was instantaneously destroyed; traces of it can now be found on the Caspian seafloor only, a chain of extant islands along the Cheleken-Apsheron structure indicating where it was situated formerly. That issue can probably be resolved by looking into Genoese and Venetian archives where old trade ways are described which were carefully concealed by the Genoese...

4. ON LONG TERM EARTHQUAKE PREDICTION

The sequences of M=7.5±0.2, 7.0±0.2 and 6.5±0.2 events are shown in Figure 4 in a slightly different manner with a view to monitoring of seismogeodynamic processes and long-term earthquake prediction, namely, as cumulative number of events plotted against time.

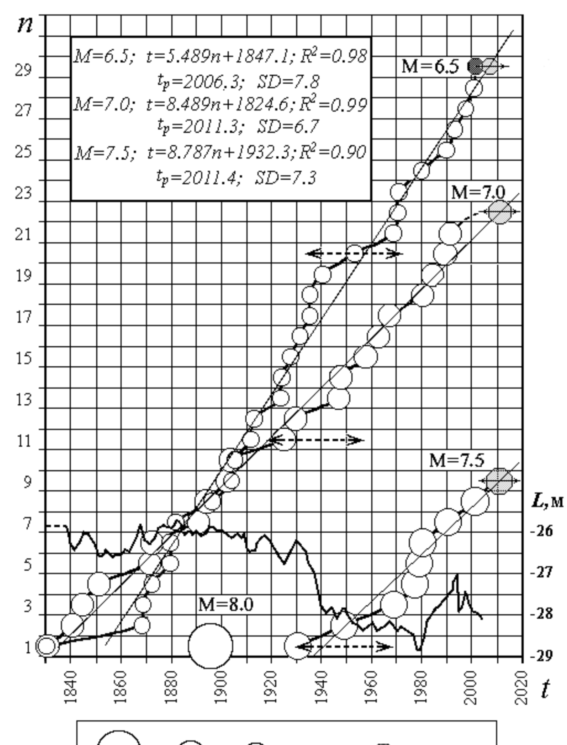

Figure 4. *Sequences of earthquakes of various magnitudes and long-term earthquake prediction for the area of study. n - number of occurrence of an earthquake; t - period of observation (in years); Earthquake size: 1 - M=8.0±0.2, 2 - M=7.5±0.2, 3 - M=7.0±0.2, 4 - M=6.5±0.2; 5 - predicted earthquakes (arrow length is one standard deviation SD from predicted time t_p); 6 - M=6.5 earthquake occurring June 22, 2002 in northern Iran after these plots had been constructed; 7 - smooth interpolation of original data using splines; 8 - long-term linear trend; 9 - Caspian Sea level variation; 10 - anomalous periods in the evolution of seismic processes.*

Here, n denotes the number of occurrence for an event in each chronologic sequence. The straight lines derived by the method of least squares are fitted to represent the entire set of events in each sequence. The relevant equations with their parameters: correlation (R^2), standard deviation (SD) and the predicted occurrence times for future earthquakes (t_p), are all shown in the same figure.

If seismic events had occurred uniformly over time, they all of them would have been located strictly on these lines. However, the actual picture, even though it does show a long-term stationarity, reveals anomalies that correlate with sea level changes. These are intervals of about 40 years duration where the earthquakes of relevant magnitudes have lower rates of occurrence (double dashed arrows in Figure 4). The low sea level period was of about 40 years duration as well (1940 to 1978). Inspection of the M=7.0 and M=6.5 sequences reveals another anomalous low sea level interval, that between 1830 and 1870. Remarkably enough, a 40-year cycle is also found for the occurrence of large earthquakes in the neighbouring Central Asia (Ulomov, 1974).

One can use cumulative plots of the number of earthquakes and long-term seismicity parameters to produce forecasts (to some degree of reliability) of time intervals where future earthquakes of a magnitude are likely to occur. One notes the important circumstance that the times of occurrence of such events on the t-n plane have a single degree of freedom, considering that an event can «move» in the horizontal direction only without being able to go beyond the limits corresponding to its number of occurrence. This permits more specific statements about predicted time intervals. For instance, an M=7.5±0.2 earthquake (no. 9) must occur in the area between 2004 and 2019 (the mean 2011.4, standard deviation SD=7.3 yr). An M=7.0±0.2 earthquake (no. 22) can occur during the period 2004-2018. However, judging by the accelerated occurrence of preceding events, it is much more likely that such an earthquake will occur much earlier, i.e., before 2004.

One example of a corroborated forecast for the M=6.5 sequence is a recent damaging earthquake which occurred June 22, 2002 in the northern Iran within the area of study here considered (see Figure 1). That earthquake was not involved in our calculation, but it nevertheless falls into an expectation interval (1998-2014) which indicated an extremely high probability of the occurrence of such an earthquake.

5. CONCLUSION

This study in seismicity fluctuations observed in the Iran-Caucasus-Kopet Dag region and in local changes of the Caspian Sea level has revealed certain patterns that indicate a common deep-seated cause of both of these phenomena. These patterns open new vistas for long-term earthquake prediction in the Caspian region.

We suggest a seismogeodynamic model for the area which postulates a long-term sea level fall to follow the occurrence of large earthquakes due to rapid subsidence of the relevant crustal areas and, conversely, seismicity increases are to be preceded by seafloor bending and by the appearance of an «excess» water in the Caspian. However, if this «preseismic upwarping» of the crust occurs on the shore, as was the case before the 1895 Krasnovodsk earthquake, sea level will rise at other coasts that are more distant from the epicentral area of the future earthquake.

We conclude by emphasizing once more the imminent hazard of large (M=7.0±0.2 or larger) earthquakes in the near future for this area. The location of future quakes is to be determined by examining the migration of seismogeodynamic processes and revealing earthquake-prone segments of seismogenic features, e.g., with the help of advanced GPS techniques.

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