Izvestiya, Physics of the Solid Earth, Vol. 35, No. 12, 1999, pp. 1036–1042. Translated from Fizika Zemli, No. 12, 1999, pp. 76–82.

Seismogeodynamics of the Caspian Sea Region

V. I. Ulomov, T. P. Polyakova, and N. S. Medvedeva

Schmidt United Institute of Physics of the Earth, Russian Academy of Sciences, Bol'shaya Gruzinskaya ul. 10, Moscow, 123810 Russia

Received June 1, 1999

Abstract—Results of studies of fluctuations in seismic regime of the Caspian Sea and adjacent area are analyzed in order to reveal the correlation of anomalous variations in the sea level with seismicity of the region. The inferred regularities indicate that these phenomena have a common origin. A seismogeodynamic model of the region under consideration is discussed.

INTRODUCTION

The problem of anomalous variations in the Caspian Sea level has been widely discussed in scientific papers from various aspects. The origin of these phenomena has been explained in terms of various concepts ranging from regional factors to cosmic ones [Shilo, 1989; Shilo and Krivoshei, 1989; Rodkin, 1993; Lilienberg, 1994; Kaftan and Tatevyan, 1996]. Our regional-scale is based on new seismic data that were not available to other researchers [Ulomov, 1993a, 1993b, 1998; Ulomov *et al.*, 1993]. The Iran–Caucasus–Anatolia region, including the Caspian Sea, served as a research area for the Global Seismic Hazard Assessment Program in 1993 through 1997. The researchers from the United Institute of Physics of the Earth, Russian Academy of Sciences, actively participated in this program [Ulomov *et al.*, 1993; Ulomov, 1997].

The choice of the size of the region under study involves data on various responses of the Caspian Sea to local and remote seismic events. Thus, in their macroseismic description of the Iranian earthquake of 1962 with magnitude $M = 7.0$, Ambraseys [1963] and Polyakova [1985] noted a disturbance in the usual level of water on the Caspian coast; and 3 to 4 intensity isoseisms from the Ashkhabad earthquake of 1948 with $M = 7.3$ covered the Caspian Sea area. According to Shilo and Krivoshei [1989], a year before the catastrophic Krasnovodsk earthquake of 1895 with $M = 7.9$ (eastern Caspian coast), the water level dropped by 70 mm and the sea retreated from the coast. An opposite effect was observed after the earthquake: the Caspian sea level sharply rose. Other factors will be discussed below.

SEISMIC CHARACTERISTICS OF THE REGION STUDIED

General features of seismicity of the Caspian Sea and adjacent areas are seen from the map of earthquake epicenters, which is constructed from the Specialized catalog of North Eurasia earthquakes edited by N.V. Kondorskaya and V.I. Ulomov (Fig. 1). Seismic potential of the region is rather high. The strongest earthquakes with magnitudes of up to $M = 8.0$ and higher took place on the southern, western, and eastern Caspian coasts in 856 ($M = 8.1$), 958 ($M = 8.0$), 1668 ($M = 7.8$), and 1895 ($M = 7.9$). The last strong event in this region was the Rudbar, Iran, 1990 earthquake with $M = 7.4$. (Hereinafter, M means the magnitude MS determined from surface waves.)

The characteristic feature of the seismicity in the region under study is the presence of deep ($h \geq 35$ km) earthquake sources associated with relicts of the ancient Crimea–Caucasus–Kopet Dagh subduction zone of lithospheric plates [Ulomov, 1993a, 1993b)]. The deepest earthquakes are confined to the most mobile region of the zone, the Caspian Sea water area: $M = 3.7$, $h = 92$ km, 1982; $M = 5.0$, $h = 80$ km, 1976; $M = 3.5$, $h = 75$ km, 1986; and $M = 5.2$, $h = 74$ km, 1986. These earthquakes distinguish the so-called Northern tectonic underthrust zone, which was associated with rather strong (intensity of 7 to 9) earthquakes of the XX century: $M = 6.4$, 1911; $M = 6.0$, 1961; $M = 6.2$, 1963; $M = 6.2$, 1986; and $M = 6.3$ and 6.2, 1989. A maximum intensity of 7 to 8 was observed during the Caspian earthquake of March 6, 1986, near Neftyanye Kamni Island [Golinskii *et al.*, 1989]. At the same time, most hypocenters of earthquakes in the study region are located in the upper crust at depths of 5 to 15 km.

ESTIMATE OF REPRESENTATIVITY OF THE DATA USED

The table presents the number of seismic events in the region studied as a function of the magnitude and occurrence time intervals. The broken line bounds the time intervals for which the data on earthquakes (including historical ones) with a given magnitude may be considered representative for the entire region.

To analyze seismic regime, various recurrence plots were constructed: plots including or disregarding aftershocks, interval and cumulative plots, plots for various

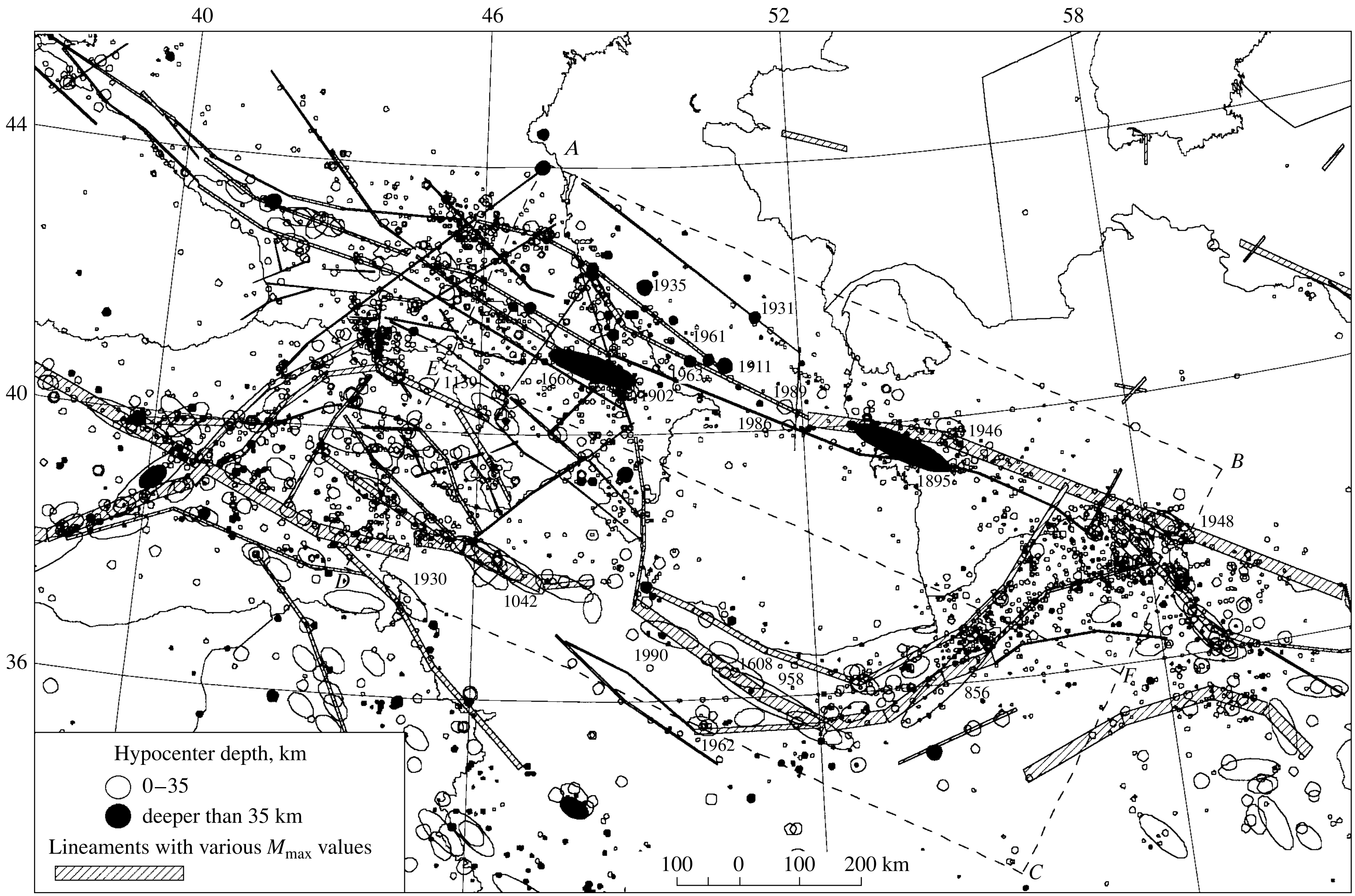

Fig. 1. Seismicity and seismotectonics of the Caspian Sea basin: *ABCD*, boundary of the region under study; *ABFE*, boundary of the northern zone. Earthquake sources are shown after Ulomov *et al.* [1993]. Sources with $M = 7.0 \pm 0.2$, 7.5 ± 0.2, and 8.0 ± 0.2 are given by ellipses corresponding to their sizes (50, 100, and 200 km, respectively) and orientation; sources with $M = 6.5 \pm 0.2$ and smaller are shown as circles of various diameters (25 km and smaller). Sources of the earthquakes mentioned in text are presented along with their occurrence dates (years). Lines of various widths are lineaments representing the axes of generalized fault structures that generate earthquakes of various maximum possible magnitudes (M_{max}).

Table

Years	Magnitude intervals									
	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
1980–1990	340	274	93	23	9	5	1	0	1	0
1970–1979	223	247	87	28	8	2	2	0	0	0
1960–1969	80	127	76	11	7	2	0	1	0	0
1950–1959	0	0	47	30	5	1	1	1	0	0
1940–1949	0	0	13	18	4	3	0	1	1	0
1930–1939	0	0	18	26	17	4	3	0	1	0
1920–1929	0	0	13	14	6	2	3	1	0	0
1910–1919	0	0	9	9	4	0	1	0	0	0
1900–1909	1	0	10	15	6	5	0	1	0	0
1890–1899	4	2	11	4	2	0	1	1	0	1
1880–1889	0	13	5	1	1	2	0	0	0	0
1870–1879	1	2	1	3	2	1	2	1	0	0
1860–1869	1	3	0	5	1	5	2	0	0	0
1850–1859	0	3	4	0	0	2	0	0	0	0
1840–1849	3	3	2	3	1	2	0	1	0	0
1830–1839	0	1	0	1	1	1	1	1	0	0
1820–1829	1	1	1	0	1	0	1	0	0	0
1810–1819	0	0	0	0	0	0	0	0	0	0
1800–1809	0	0	0	0	0	1	3	0	0	0
1790–1799	0	0	0	0	0	0	0	0	0	0
1780–1789	0	1	0	0	0	0	1	0	1	0
1770–1779	0	0	0	0	0	0	0	0	0	0
1760–1769	0	0	0	0	0	0	0	0	0	0
1750–1759	0	0	0	0	0	0	0	0	0	0
1740–1749	0	0	0	1	0	0	0	0	0	0
1730–1739	0	0	0	2	0	0	0	0	0	0
1720–1729	0	0	1	0	0	0	0	0	1	0
1710–1719	0	0	0	0	0	0	1	0	0	0
1700–1709	0	0	0	0	0	0	0	0	0	0
1690–1699	0	0	0	0	0	0	0	1	0	0
1680–1689	0	0	0	0	0	0	1	0	0	0
1670–1679	0	3	0	2	0	1	1	0	0	0
1660–1669	0	1	0	0	0	0	2	0	0	1

time intervals, etc. The recurrence of strong earthquakes in the region was estimated from the plot (Fig. 2) consistent with the concept of a nonlinear seismic regime of weak and strong earthquakes [Ulomov, 1998]. This plot was constructed using the maximum likelihood method for intervals $M \pm 0.2$ with a step of 0.5 and consists of two nearly linear segments corresponding to the magnitude range $M = 4.0$–5.5 with the slope $b = -1.025$ and to $M = 6.0$–8.0 with $b = -0.734$. In accordance with these concepts, the recurrence period in the region under consideration is about 130 years for earthquakes with $M = 8.0$, 60 years for $M = 7.5$, 25 years for $M = 7.0$, and 10 years for $M = 6.5$.

COMPARISON BETWEEN VARIATIONS IN THE SEA LEVEL AND SEISMIC PARAMETERS

The Krasnovodsk earthquake of 1895 with $M = 7.9$ is the strongest seismic event that occurred in the region under consideration during the last 300 years (from the moment of a similar event of 1668 with $M = 7.8$, which

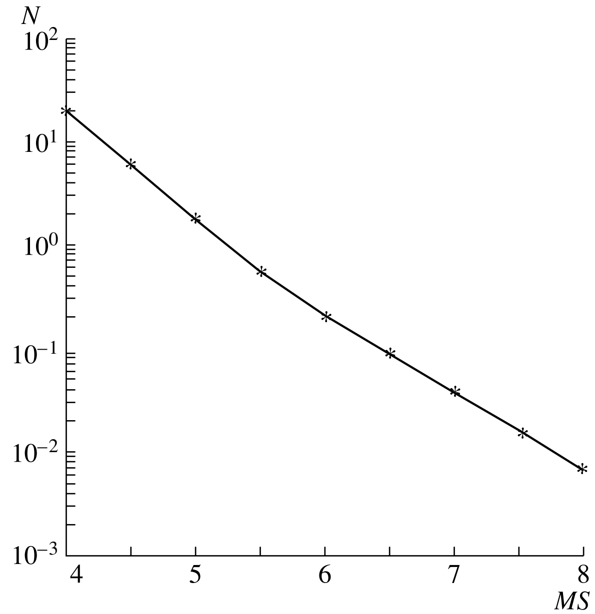

Fig. 2. Recurrence plot of earthquakes (without aftershocks) in the study region over the entire period of observations.

occurred on the opposite Caspian coast (see Figs. 1, 3)). Unique data on the Caspian Sea level during the last 2000 years and on the strongest historical events indicate that, although the $M \geq 7.8$ earthquakes of 856, 958, 1668, and 1895, took place at various sea levels, they mostly coincided with changes in the direction sign of the level variations (Fig. 3). The correlation between seismicity (primarily events with $M = 7.5 \pm 0.2$) and the sea level is most evident in Fig. 4. The average recurrence period of these earthquakes is about 60 years; however, they did not occur in the region under study for about 150 years before 1930 (table). However, three such events took place over the span of 95 years following the Krasnovodsk earthquake.

The sequence of earthquakes with $M = 7.0 \pm 0.2$, $M = 6.5 \pm 0.2$, and $M = 6.0 \pm 0.2$ does not display anomalies, although the time interval $\Delta t = 135$ years between the earthquake of 1695 with $M = 7.0$ (table) and a similar event of 1830 seems to be anomalously long. However, in the period from 1830 to 1996, i.e., before and after the Krasnovodsk earthquake of 1895, the recurrence frequency of these and weaker earthquakes was nearly constant. We note the general similarity between the solid line representing variations in the sea level and the dashed line connecting the maximum values of seismic energy (magnitudes) released during the strongest earthquakes whose magnitudes exceed background values by 0.5 or more.

Sea level variations are also reflected in the parameters of the seismic regime of weak and moderate earthquakes. According to the representativity estimates of seismic data in the region under study (table), they may be compared with variations in the sea level during the period from 1840 through 1990 starting from magnitudes $M \geq 5.8$. We analyzed three time intervals. Two of them (1846–1868 and 1929–1995) coincided with lower sea levels, and the third (1873–1910), with a higher sea level. As seen from Fig. 4, the annual average number of earthquakes with $M \geq 5.8$ coinciding with “lower sea levels” is higher as compared with those coinciding with “higher sea levels,” which confirms a similar hypothesis suggested by Lilienberg [1994]. The slope of the recurrence plot is higher during intervals of abrupt drops (by about 2 m) or rises (by more than 2.5 m) in the sea level and is somewhat lower during periods of the low sea level or its gradual decrease. Supposedly, the reduction in the b value is due to the increase in the number of strong earthquakes with $M = 7.0 \pm 0.2$ and $M = 7.5 \pm 0.2$ that occurred dur-

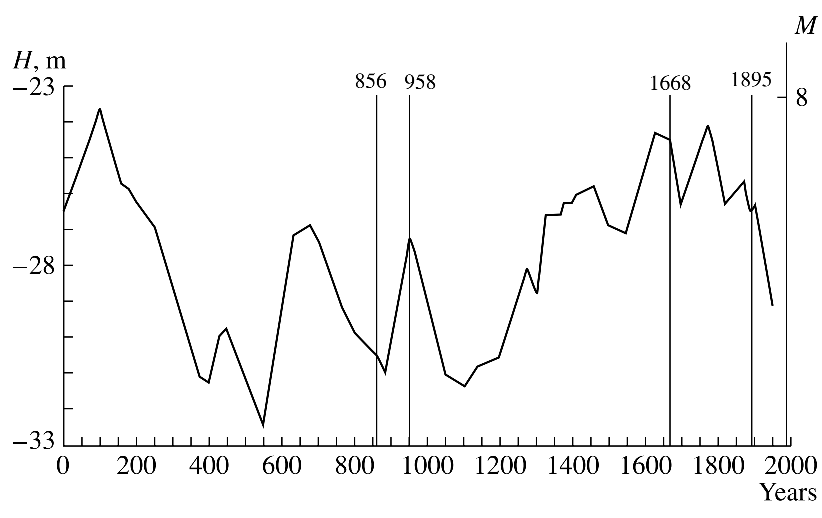

Fig. 3. Variations in the Caspian Sea level during the last 2000 years [Kaftan and Tatevyan, 1996] and dates (years) of the strongest ($M \geq 7.8$) historical earthquakes.

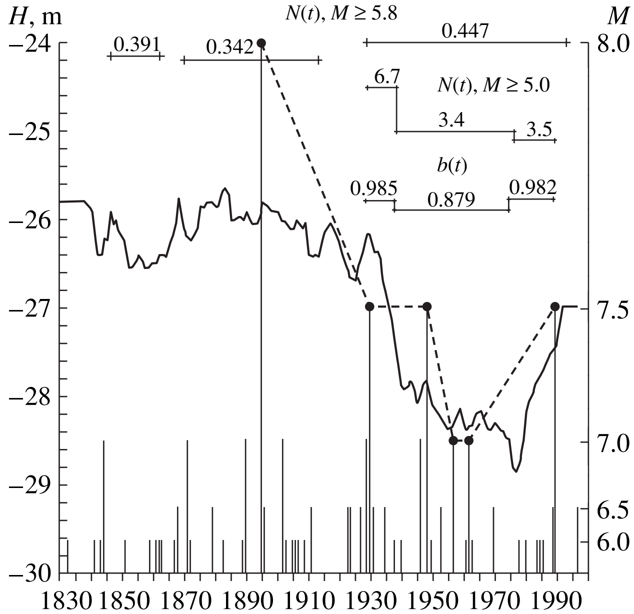

Fig. 4. Time variations in the Caspian Sea level beginning from 1830 [Lilienberg, 1994; Svitoch, 1998] and seismicity of the region studied: vertical lines are strong earthquakes with $M \geq 5.8$. $b(t)$ and $N_{M \geq 5}(t)$ are the recurrence plot slope and seismic activity during periods of an abrupt drop (1929–1940), gradual decrease (1941–1977), and abrupt rise (1978–1995) in the sea level. $N_{M \geq 5.8}(t)$ is the yearly average number of earthquakes with $M \geq 5.8$ during periods of low (1846–1868 and 1929–1995) and high (1873–1910) sea levels. The dashed line connects extremely high values of the released seismic energy (magnitudes) that exceed the background level by an order of magnitude or more.

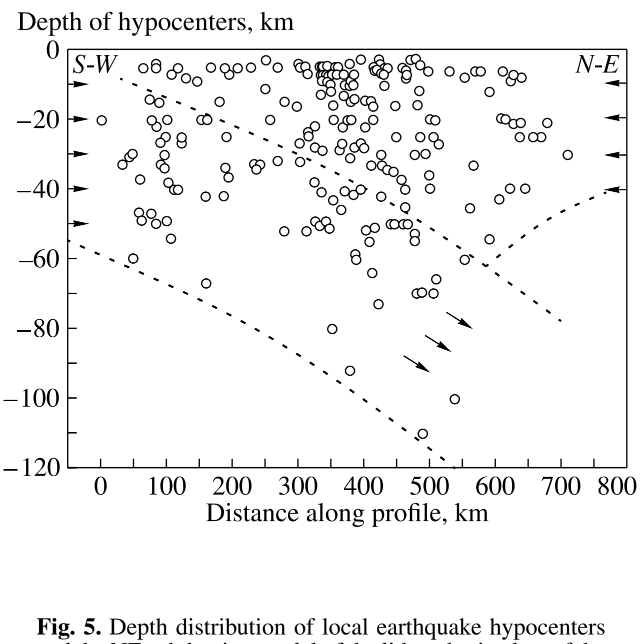

Fig. 5. Depth distribution of local earthquake hypocenters and the NE subduction model of the lithospheric plate of the southern Caspian Sea (delineated by the broken line), related to regional geodynamic compression forces (horizontal arrows).

ing this time interval. The interval of the abrupt drop in the sea level is characterized by the greatest number of earthquakes with $M \geq 5.0$.

SEISMOGEODYNAMIC MODEL OF THE CASPIAN SEA

The Krasnovodsk earthquake of 1895 with $M = 7.9$ and a similar event of 1668 with $M = 7.8$ (Figs. 1, 3), as well as other, weaker earthquakes with subcrustal sources, are directly related to the seismogeodynamics of the Apsheron–Cheleken deep structure representing the subduction zone of the oceanic crust of the southern Caspian Sea, dipping northeast (Fig. 5). The subduction origin of this structure is supported by the ophiolitic belt extending on both sides of the Caspian Sea and by other factors [Khain and Lomize, 1995; Ulomov 1993a; Khalilov *et al.*, 1987; Akhmedova, 1998a, 1998b]. The inferred correlation of local seismicity with anomalous variations in the Caspian Sea level indicates their common geodynamic origin, which is likely to be determined by the specific deformation of the Earth's crust and lithosphere of the region studied. The occurrence of seismic events even with small magnitudes, but with deep hypocenters most clearly reflects the successive development of deep seismogeodynamic processes involving cover the whole oceanic crust of the southern Caspian Sea and Transcaucasia, plunging into the upper mantle. Ulomov [1993a, 1993b] noted that anomalous variations in the Caspian Sea level and migration of seismic activity in the Iran– Caucasus–Anatolia region are due to alternating slow bending deformations and fast seismic movements along fault structures, including subduction zones of the central Caspian Sea. In this respect, the sequence of deep sources of earthquakes with $M \geq 5.3$, striking northwest (Fig. 6) from the source of the Krasnovodsk, 1895, earthquake ($M = 7.9$, $h = 55$ km) is of interest, because the high-amplitude movement of rocks, associated with this earthquake, might have produced a deformation wave propagating along the Apsheron–Cheleken structure [Ulomov, 1998].

The seismogeodynamic model developed here does not imply any change in the direction sign of the subducting lithospheric plate. Under the conditions of N–S compression of the Caucasus–Kopet Dagh lithosphere, the slab is only variously deformed and continues to plunge into the upper mantle, with accompanying creep and seismic motions of various amplitudes. The rise in water level of the Caspian Sea is contributed by the preseismic swelling of the Earth's crust within the sea area due to the slowing-down of its zones undergoing subsequent subsidence into the upper mantle and accumulating elastic stresses. Vice versa, fast motions on faults accompanied by their subsidence and successive release of accumulated elastic stresses contribute to the decrease in sea level. Actually, the very fast increase in the Caspian Sea level, which suddenly started in 1978, is supposedly related to intense accumulation of elastic

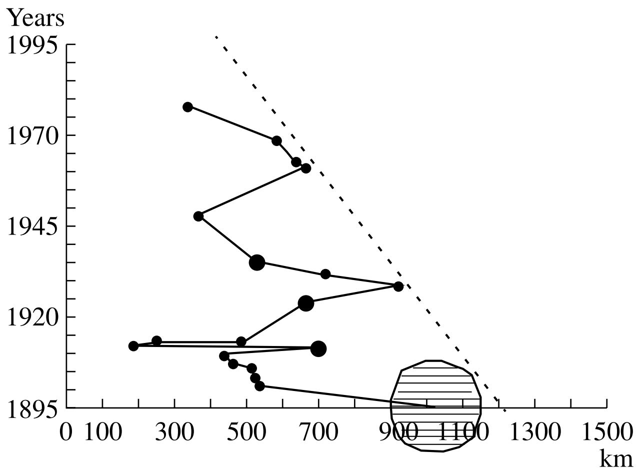

Fig. 6. The NW trend (dashed line) of deep ($h \geq 34$ km) sources of earthquakes with $M \geq 5.3$ that occurred after the strong Krasnovodsk, 1895, earthquake within the northern zone (Fig. 1).

deformations producing a fast upwarping of the sea bottom and preparation of the next, rather strong earthquake in the region studied. Taking into account the NW trend of seismic activity noted above, we expect the appearance of such an earthquake on the northeastern coast of the Caucasus, where Ulomov [1993a, 1993b] has previously discovered a rather large potential seismic source.

Unlike models of other authors [Shilo, 1989; Lilienberg, 1998], our hypothesis of unidirectional geodynamic motion in the study region is supported by the stability of focal mechanisms of strong local earthquakes of 1961 ($M = 6.0$), 1963 ($M = 6.2$), 1986 ($M = 6.1$), and 1989 ($M = 6.3$) [Balakina *et al.*, 1993]; their fault plane solutions were independent of periods when the Caspian Sea level was low or rapidly rising.

CONCLUSIONS

The studies of fluctuations in the seismic regime of the Caucasus–Kopet Dagh region and anomalous variations in the Caspian Sea level, whose nature still remains vague, revealed regularities indicating that these phenomena have a common deep origin. We proposed the seismogeodynamic model of the region considered, which explains the inferred regularities. In terms of this model, strong earthquakes with $M \geq 7.5$ associated with abrupt subsidence of the related crustal zones are followed by a general decrease in the sea level, and, *vice versa*, almost all earthquakes are preceded by upwarping of the sea bottom and, respectively, by "excess" water in the Caspian Sea. If this preseismic upwarping of the crust occurs on the coast, as was the case before the Krasnovodsk, 1895, earthquake, the water level increases near other coastal areas remote from the epicentral zone of the future earthquake. An inverse pattern is observed after an earthquake. We also showed that the number of earthquakes with $M \geq 6$ is higher during phases of the low sea level, as compared with high sea level periods. We suggested that a rather strong earthquake may be in the preparation stage in the region considered.

ACKNOWLEDGMENTS

The work was supported by the Russian Ministry of Sciences within the framework of the International project "Seismic Hazard in the Black Sea–Central Asia region."

REFERENCES

Akhmedova, S.V., Position of Strong Earthquake Sources in the Turan–Iran Region, *"Urbanization and Earthquakes," Int. Conf.*, Abstracts, Ashkhabad, 1998a, pp. 29–30.

Akhmedova, S.V., Variations in Seismic Processes in a Hierarchically Structured Medium, *"Urbanization and Earthquakes," Int. Conf.*, Abstracts, Ashkhabad, 1998b, pp. 74–75.

Ambraseys, N.N., Buyin-Zahra(Iran) Earthquake of September 1962: A Field Report, *Bull. Seismol. Soc. Am.,* 1963, vol. 53, pp. 705–740.

Balakina, L.M., Zakharova, A.I., Moskvina, A.G., *et al.*, Investigation into Focal Mechanisms of Strong Crustal Earthquakes in Central Eurasia, *Seismichnost' i seismicheskoe raionirovanie Severnoi Evrazii* (Seismicity and Seismic Zoning of North Eurasia), issue 1, Moscow, 1993, pp. 123–131.

Golinskii, G.L., Kondorskaya, N.V., Zakharova, A.I., *et al.*, The Caspian Earthquake of March 6, *Zemletryaseniya v SSSR v 1986 godu* (Earthquakes in the USSR in 1986), Moscow: Nauka, 1989, pp. 58–77.

Kaftan, V.I. and Tatevyan, S.K., The Caspian Sea Level, Rotation of the Earth, and Solar Activity, *Kosmicheskaya geodeziya i sovremennaya geodinamika* (Satellite Geodesy and Recent Geodynamics), Moscow: Inst. Astronomii Ross. Akad. Nauk, 1996, pp. 122–133.

Khain, V.E. and Lomize, M.G., *Geotektonika s osnovami geodinamiki* (Geotectonics and Fundamentals of Geodynamics), Moscow: Mosk. Gos. Univ., 1995.

Khalilov, E.N., Mekhtiev, Sh.F., and Khain, V.E., On Geophysical Evidence Supporting a Collisional Origin of the Greater Caucasus, *Geotektonika*, 1987, no. 2, pp. 54–60.

Lilienberg, D.A., New Approaches to the Recent Endogenic Geodynamics of Mountain Morphostructures, *Izv. Ross. Akad. Nauk, Ser. Geogr.*, 1994, no. 2, pp. 16–36.

Lilienberg, D.A., Novel Ideas about Regularities and Mechanisms of Recent Geodynamics of Mountain Structures, *Izv. Ross. Akad. Nauk, Ser. Geogr.*, 1998, no. 6, pp. 32–47.

Polyakova, T.P., *Seismichnost' tsentral'noi chasti Sredizemnomorskogo poyasa* (Seismicity of the Central Mediterranean Belt), Moscow: Nauka, 1985.

Rodkin, M.V., *Rol' glubinnogo flyuidnogo rezhima v geodinamike i seismotektonike* (Deep Fluid Regime Implications for Geodynamics and Seismotectonics), Moscow: Natsional'nyi Geofizicheskii Komitet, 1993.

Shilo, N.A., The Origin of Caspian Sea Level Variations, *Dokl. Akad. Nauk SSSR*, 1989, vol. 305, no. 2, pp. 412–416.

Shilo, N.A. and Krivoshei, M.I., Relationship between the Caspian Sea Level Fluctuations and Crustal Stresses, *Vestn. Akad. Nauk SSSR*, 1989, no. 6, pp. 83–90.

Svitoch, A.A., Geoecological Catastrophe in Seaside Towns of Daghestan, *Priroda*, 1998, no. 5, pp. 16–27.

Ulomov, V.I., Seismogeodynamic Activation Waves and Long-Term Earthquake Prediction, *Fiz. Zemli*, 1993a, no. 4, pp. 43–53.

Ulomov, V.I., Global Ordering of Seismogeodynamic Structures and Some Aspects of Seismic Zoning and Long-Term Earthquake Prediction, *Seismichnost' i seismicheskoe raionirovanie Severnoi Evrazii* (Seismicity and Seismic Zoning of North Eurasia), issue 1, 1993b, pp. 24–44.

Ulomov, V.I., On the Identification and Seismological Parameterization of Earthquake Source Zones. The Caucasus and Adjacent Area, *Historical and Prehistorical Earthquakes in the Caucasus*, D. Giardini and S. Balassanian, Eds., NATO ASI, Series 2: Environment, vol. 28, ILP Publ. no. 333, Dordrecht: Kluwer, 1997, pp. 503–522.

Ulomov, V.I., Modeling of Earthquake Source Occurrence Zones Based on Lattice Regularization, *Fiz. Zemli*, 1998, no. 9, pp. 20–38.

Ulomov, V.I., Polyakova, T.P., Shumilina, L.S., Chernysheva, G.V., Medvedeva, N.S., Savarenskaya, O.E., and Stepanova, M.B., Experience of Mapping Earthquake Sources, *Seismichnost' i seismicheskoe raionirovanie Severnoi Evrazii* (Seismicity and Seismic Zoning of North Eurasia), issue 1, 1993, pp. 99–108.

Ulomov, V., Strakhov, V., and Giardini, D., Seismic Hazard Assessment in Northern Eurasia, *Ann. Geofiz.*, 1993, vol. 36, nos. 3–4, pp. 83–92.