TSUNAMIS IN THE CASPIAN SEA: HISTORICAL EVENTS, REGIONAL SEISMICITY AND NUMERICAL MODELING*

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INTRODUCTION

Wide assimilation of the Caspian Sea natural resources suggests both analysis of physical parameters of historical events and development of effective methods to forecast and mitigate marine hazardous phenomena in the region, in particular, tsunami. Tsunami waves in the Caspian Sea have been studied insufficiently due to low recurrence of these events in the region, absence of sea level measurements accompanying tsunamis and, at last, little information (even descriptive) on tsunamis. Certain results of the Caspian tsunami examination are presented below. They are based on visual observations of historical tsunamis, information on seismic activity in the region, and numerical modeling of long wave propagation in the Caspian Sea basin.

HISTORICAL TSUNAMIS IN THE CASPIAN SEA

The first attempts for complex investigation of Caspian tsunamis were undertaken during the last ten years. The descriptive information on the Caspian tsunamis and tsunami-like phenomena for the period from 743 to 1989 is presented by Smirnova *et al.* [1993], Nikonov [1996], Pelinovsky [1999], and Dotsenko *et al.* [2000 a,b] with different degrees of completeness. A generalization of these data is given in the Table. Thirteen historical events have been selected; the respective locations are shown in Figure 1. Unusual oscillations of the sea level were observed after the earthquakes of 743, 918, 957, 1668, 1895, 1902, 1986, and 1989. Other events, observed in 1868, 1876, 1933, and 1939, were possibly caused by various natural sources, e.g. by unknown local earthquakes, landslides or explosions of mud volcanoes. Perhaps, the 1986 and 1989 weak phenomenon (M =6.1-6.2 and $I_0 \sim 8$) of "sea shaking as high-frequency quasi-standing sea level oscillations of the Caspian Sea" is also related to tsunami. The estimations from [Soloviev and Poplavskaya, 1982] give the possible local tsunami caused sea-level rise of 3 m in case of "seaquakes" with intensity 8. Similar response of the ocean to tsunamigenic earthquakes sometimes occur in the Pacific [Soloviev and Go, 1974].

The collected information allows the conclusion that tsunamis in the Caspian Sea have repeatedly happened in the past and are possible here in the future. Historical events have not been destructive but several of them led to noticeably negative consequences. The recurrence of this natural phenomenon in the region is relatively low. Tsunamis were mainly observed in the central part of the Caspian Sea and in the region of the Apsheron Sill. The latter area has a high level of seismic activity [Panahi and Kasparov, 1988]. Tsunamis in the Caspian Sea were generated both by offshore and inshore earthquakes.

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In accordance with visual observations, the heights of the historical tsunamis were found not exceeding 1-2 m. The wider interval of possible tsunami heights in the Caspian Sea (up to 0.5-2.6 m) was proposed by Pelinovsky [1999] on the basis of empirical relations for the Pacific, and if taking into account the estimations from [Soloviev and Poplavskaya, 1982], they can reach 3 m.

Table

Historical tsunamis and tsunami-like events observed in the Caspian Sea [from Smirnova *et al.,* 1993; Nikonov, 1996; Pelinovsky, 1999; Dotsenko *et al.*, 2000 a,b]

Year, date	Location	Form of manifestation
743	Derbent	The area of the coast with fortifications was submerged in the sea.
918	Derbent	The part of the coast with fortifications was submerged in the sea.
957	Derbent	The fall of sea level caused horizontal displacement of the shoreline on 150 m from the equilibrium position.
1668	Terka	Part of the beach was submerged in the sea. The rise of water level was observed in the delta of the Terek River.
26.04.1868	Baku	Short-time rise and fall of sea level with amplitude about 0.45 m were observed.
09.03.1876	Oblivnoy (island)	Unusual sea level oscillations occurred after strong underwater boom in conditions of dead calm. Event was observed from the ship.
27.06.1895	Krasnovodsk Bay	Flooding of north and west areas of Uzun-Ada as result of high rise water in the bay. Waves of large height caused flooding of buildings and dock. A few wooden houses were taken away to the sea. Pipeline was destroyed.
31.12.1902	Baku	Unusual waves resulted in dangerous motion of ships in the port. Event was observed after destructive earthquake near Shimaha.
09.05.1933	Kuuli-Mayak	Sudden rise of sea level up to 1.35 m for 10 minutes. Fishing boats and equipment were taken away to the sea.
12.04.1939	Livanov Shoal	The passing of a solitary wave of large height was observed from two ships which were 15 miles from each other.
26.04.1960	Baku	Oscillations of sea level up to 1 m were observed for 2-3 hours.
06.03.1986	Livanov Shoal	Unusual high-frequency sea level oscillations of 2-3 cm amplitude were observed over epicenter of earthquake during 1-1.5 minutes. The event was fixed from the seiner and 45 fishing ships.

POSSIBLE ZONES OF TSUNAMI GENERATION IN THE CASPIAN SEA

The regions of the Caspian Sea having the highest level of seismic activity may be considered as the most probable zones of tsunami generation by underwater earthquakes. The magnitude value $M = 6.8 \pm 0.15$ by the Richter scale was proposed by Dotsenko *et al.* [2000] as the threshold for underwater tsunamigenic earthquakes in for the Caspian Sea. It is the same as for the Mediterranean Sea [Soloviev *et al.*, 2000]. This value mentioned is less than $M = 7.2$ which is the threshold magnitude for the western part of the Pacific

[Soloviev *et al.*, 1972], where mean depth of the tsunamigenic earthquake focal sources is significantly deeper (30-50 km) than in the Caspian Sea (15-20 km).

Seismological analysis of the central and southern parts of the Caspian Sea was done by Panahi and Kasparov [1988]. They used instrumental data for the years 1931-1982. General description of the seismic activity in the central part of the Caspian Sea is also given by Dotsenko *et al.* [2000] who examined strong underwater earthquakes of 1895, 1986 and 1989.

There are seven zones S1,…, S7 of highest seismic activity in the Caspian Sea [Panahi and Kasparov, 1988]. All of them have sufficiently small horizontal scales. Geographical positions of these zones are shown in Figure 1. These zones may be considered as the most probable areas of seismic tsunami generation in the Caspian Sea [Dotsenko *et al.*, 2000 a,b].

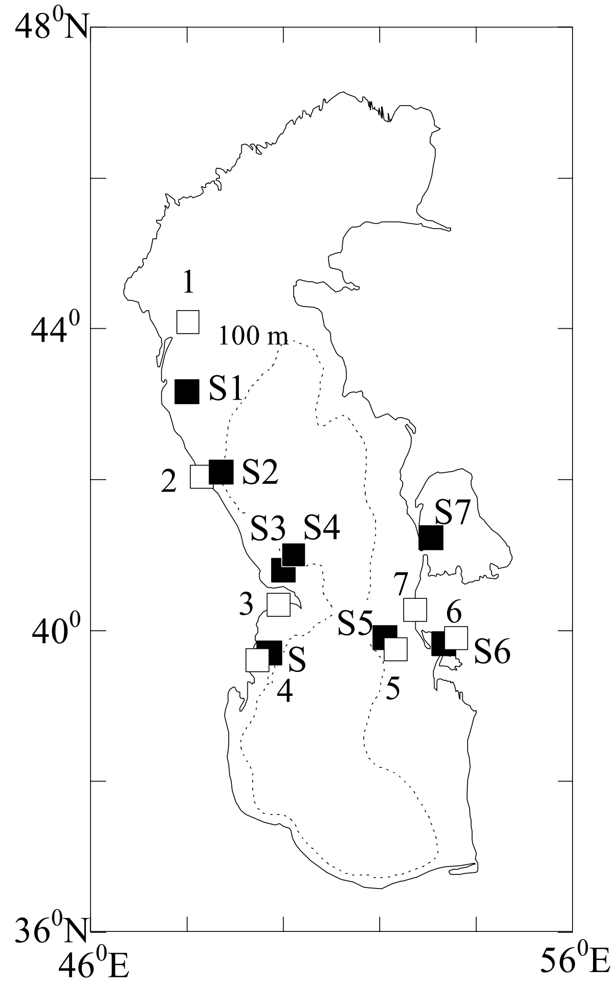

Figure 1. Locations of observation sites of tsunamis and tsunami-like water oscillations are marked by empty squares. Zones S1, ..., S7, S of the highest seismic activity in the Caspian Sea region are marked by solid squares. Geographical locations of the region: 1 Terka, 2 Derbent, 3 Baku, 4 Oblivnoy Island, 5 Livanov Shoal, 6 Krasnovodsk Bay, and 7 Kuuli-Mayak (according to [Panahi and Kasparov, 1988]).

The largest zone of seismic activity S6 (Figure 1) coincides with the easternmost section of the Tersko-Caspian Deep Breaking [Golinsky *et al.*, 1989]. There is a high recurrence of strong earthquakes in this zone. Zone S5 is one of smaller size places in the Apsheron Sill inside the marine part of the Apsheron-Cheleken breaking. Note that the entire area of the sill is an area of high earthquake recurrence. Two strong underwater earthquakes of 1986 and 1989 occurred specifically in this area [Golinsky *et al.*, 1989; 1993]. Four zones S1, S2, S3, and S4 of high seismic activity belong to the western part of the Caspian Sea (Figure 1). Two of them (S1, S2) are located at the western edge of the Skifsko-Turansckaya Plate, the others (S3, S4) are located to the north from the Apsheron Peninsular. Finally, a small-size zone S7 of high seismic activity is situated in the Kara-Bogaz-Gol on the eastern side of the sea.

For the basin of the Caspian Sea, Panahi and Kasparov [1988] showed also the areas, which have only half the relative level of seismic activity compared to S1,…S7. They are essentially wider and situated in regions of Krasnovodsk, the Apsheron Sill, western coast of the central part of the sea, and in the southern part of the Apsheron Peninsular.

The central part of the southern bottom depression has low seismic activity. Nevertheless, small zone S of high seismic activity exists in the western part of this region [Panahi and Kasparov, 1988]. Zone S presents an interest for interpretation of the 1976 tsunami.

A comparison of regions, where Caspian tsunamis were observed, and zones of the highest seismic activity shows their high proximity (Figure 1). This means that most of the historical tsunamis could arise at zones of the highest seismic activity. In particular, tsunamis of 743, 918 and 957 were observed near Zone S2. Tsunamis of 743, 918 and 957 were close to Zone S2. Positions of 1876, 1939,1986 and 1989 tsunamis almost coincide with seismic zones S and S5.

Tsunamis of 1868, 1902 and 1960 occurred in the region, which is separated from zones S3 and S4 by the Apsheron Peninsular. We cannot exclude the possibility of wave transmission from zones S3, S4 or S to the southern coast of the peninsular due to wave trapping by the shelf and the following propagation along the coast.

At last, Zone S6 is the most probable area of tsunami generation by the 1895 Krasnovodsk Earthquake. Probably, the unusual level oscillations near Kuuli-Mayak (1933) and in Krasnovodsk Bay (1986) with earthquake epicenters in Zone S5 were the results of tsunami propagation along the coastline and subsequent resonant generation of high-frequency seiches in Krasnovodsk Bay.

Ulomov *et al.* [1999] showed that earthquakes in the Caspian Sea have the following return periods: 130 years (for $M = 8.0$), 60 years (for $M = 7.5$), 25 years (for $M = 7.0$), and 10 years (for $M = 6.5$). Thus, if the value of threshold magnitude equals to M=7.2 than we may forecast that earthquake-generated tsunami in the Caspian Sea occurs every 17-18 years, and strong tsunami is possible once in 60 years.

MATHEMATICAL MODELING OF TSUNAMI PROPAGATION IN THE CASPIAN SEA

The development of a regional numerical model of wave propagation in the Caspian Sea from the underwater earthquake source area is important for understanding of sea dynamics. The reason is the absence of actual tsunami measurements and very poor general information on tsunami in this region. The ray model was suggested by Dotsenko *et al.* [2000 a,b] to study two-dimensional tsunami refraction in the basin of the Caspian Sea. The evolutionary shallow-water model was proposed by Dotsenko *et al.* [2001 a,b] to estimate the heights of tsunami waves radiated from elliptical source zones.

Wave rays are found as solution of the initial-value problem for system of three ordinary differential equations [Aleshkov, 1981]

$$dx/dt = C(x,y)\cos\theta,\ dy/dt = C(x,y)\sin\theta,$$
$$d\theta/dt = C_x(x,y)\sin\theta - C_y x,y)\cos\theta, \qquad (1)$$
$$x(0) = x_0,\ y(0) = y_0,\ \theta(0) = \theta_0,$$

where $x(t)$, $y(t)$ are the zonal and meridional coordinates of a point along the wave ray at the moment of time $t \geq 0$, $\theta(t)$ is the angle of ray inclination relative to x-axis for point (x,y), $C = \sqrt{gH(x,y)}$ is the long-wave speed in a basin of depth $H = H(x,y)$, (x_0, y_0) is the position of the seismic source, g is the gravity acceleration.

A square computational grid of 41×78 nodes with 15-km mesh size was used for bathymetry of the Caspian Sea. The problem (1) was solved numerically by the Runge-Kutta method. Numerical experiments using the ray model showed the essential influence of bottom topography on tsunami wave refraction. The main singularities of the bathymetry in the region are two bottom depressions in the central and southern parts of the Caspian Sea, zonal oriented the Apsheron Sill, and a wide shallow-water area northward from the Mangishlak Sill (northern part of the sea).

Two typical charts of tsunami refraction in a basin of the Caspian Sea are shown in Figure 2. The angle between neighboring rays near the seismic source is 18^0 at the initial stage of tsunami propagation. As a result, exactly 1/20 part of the total energy of the sea seismic disturbance in the tsunami source is contained in each elementary ray tube.

The analysis of refraction charts showed that if the seismic source is located at the middle of deep-water bottom depression in the southern part of the Caspian Sea, the radiation of tsunami waves is almost isotropic. The wave refraction increases when waves cross the sides of bottom depression and then propagate over the shelf. This leads to strong trapping of the wave energy by the east and west coastal zones of the Caspian Sea.

The relatively shallow-water Apsheron Sill plays a role as a wave-guide for the Caspian tsunamis. Although wave radiation (wave length being characteristic for tsunamis) from the generation area in the case of a circular source is uniform at the initial stage, the wave propagation along the sill with time becomes dominant for the wave energy transport. The wave trapping by bottom topography results in increase of tsunami risk both along the west (Apsheron Peninsular) and east (Krasnovodsk-Cheleken part of the coast) boundaries of the Apsheron Sill.

The waves radiating into the open sea are affected by strong refraction caused by the sides of the southern bottom depression if the seismic source is located on the southern shelf of the Caspian Sea. Numerical results presented by *Dotsenko et al.* [2000 a,b] show the effect of trapping of the radiated energy by the shelf for all zones of high seismic activity S1, …, S7. The only exception is Zone S5 located in the region of the Apsheron Sill.

Based on the results of computational experiments presented above and in the papers by Dotsenko *et al.* [2000 a,b], we may conclude that for any source located in one of the seven zones of high seismic activity in the Caspian Sea (Figure 1), the generated tsunami will have a local character. Due to this reason, tsunami manifestation is the most intensive for the coast located near the respective seismic source. Apparently, this is the reason why the information on historical tsunamis is so scant and why the sites of tsunami observations are located in the vicinity of the zones of the highest seismic activity.

Using the regional evolutionary model [Dotsenko *et al.*, 2001 a,b] we can estimate tsunami heights near the coast. The water response to the underwater earthquake is taken as the initial tsunami disturbance; it includes a local sea level elevation and zero velocity field [Marchuk *et al.,* 1983]. A nonlinear shallow-water model with a quadratic bottom friction coefficient was applied to examine evolution of tsunami waves in the basin of the Caspian Sea. The depth of the basin at the coastlines is taken to be 1 m.

The mathematical formulation of the initial-value problem [cf. Marchuk *et al.,* 1983] includes a system of three shallow-water equations describing the depth-averaged motion:

$$u_t + uu_x + vu_y = -g\zeta_x - gk^2D^{-4/3}u(u^2 + v^2)^{1/2},$$
$$v_t + uv_x + vv_y = -g\zeta_y - gk^2D^{-4/3}v(u^2 + v^2)^{1/2}, \qquad (2)$$
$$\zeta_t + (Du)_x + (Dv)_y = 0,$$

the reflection condition $u_n = 0$ on the coastal boundary, and the initial conditions

$$u = v = 0,\ \zeta = \zeta_0(x,y)\ (t = 0).$$

Here $u(x,y,t)$ and $v(x,y,t)$ are the horizontal components of velocity, $\zeta(x,y,t)$ is the sea level elevation, u_n is the velocity component normal to the boundary, $\zeta_0(x,y)$ is the initial elevation of sea level, $D = H(x,y) + \zeta(x,y,t) > 0$ is the entire water depth, k=0.013 is the Manning's relative roughness coefficient.

The Caspian Sea was covered by a 79×153 grid with uniform grid steps of 7.5 km. The minimum depth on the boundary of the computational domain was 1 m. A staggered implicit-explicit finite difference scheme was used to solve problem (2). Smooth initial sea level elevation of height a_0 located inside a circular area of radius R with a central point (x_0,y_0) had a form

$$\zeta_0(x,y) = a_0\cos^2(0{,}5\pi r/R)\ (r \le R),\ \zeta_0(x,y) = 0\ (r>R,$$

where $r = [(x-x_0)^2 + (y-y_0)^2]^{1/2}$.

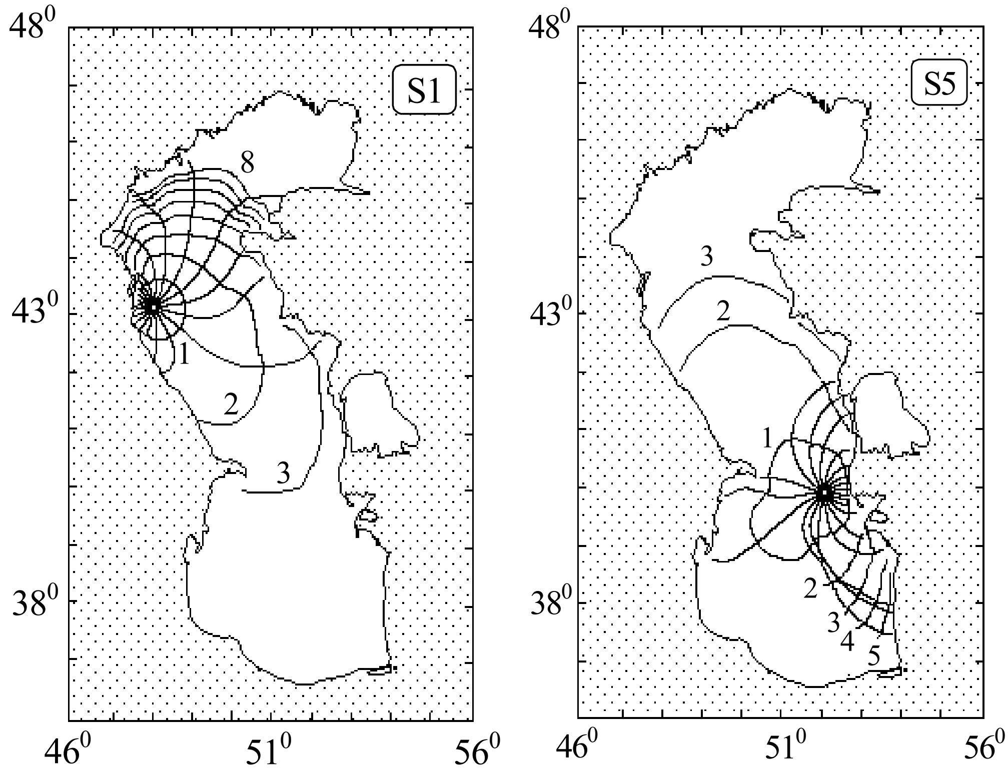

Figure 2. Long-wave refraction for tsunamis generated by seismic sources placed in Zone S1 and in the middle part of the Apsheron Sill (Zone S5). The tsunami propagation time (in hours) is shown near the corresponding wave fronts (according to Dotsenko *et al*., 2000]).

The numerical experiments supported the assumption that the Apsheron Sill may be a wave-guide for the Caspian tsunamis (Figure 3). Waves from the circle source area radiated isotropically in all directions. The refraction of the waves with time leads to the prevalence of wave transmission in the meridional direction. The wave trapping by the sill is apparently an important regional feature of the Caspian tsunamis. Moreover, the Apsheron Sill is one the regions of the highest seismic activity of the Caspian Sea [Dotsenko *et al.*, 2000a; Panahi and Kasparov, 1988]. The epicenters of two major underwater earthquakes of 1986 and 1989, mentioned above, were located in the eastern part of the sill [Golinsky *et al.*, 1989, 1993]. Thus the coast of the Apsheron Peninsular and the part of the eastern Caspian coast between Krasnovodsk and Cheleken are the main zones of heightened tsunami risk.

CONCLUSIONS

Descriptive information on 13 historical events of tsunami type in the Caspian Sea from 743 to 1989 has been collected and analyzed. This information shows that tsunamis in the Caspian Sea occurred in the past and can happen here in the future. Noticeable seismically-generated tsunamis in the Caspian Sea may occur every 17-18 years, while strong tsunamis are possible once in 60 years. Most tsunamis have been observed in the central part of the Caspian Sea and in area of the Apsheron Sill. Both inshore and offshore earthquakes may generate tsunamis in the Caspian Sea. In accordance with

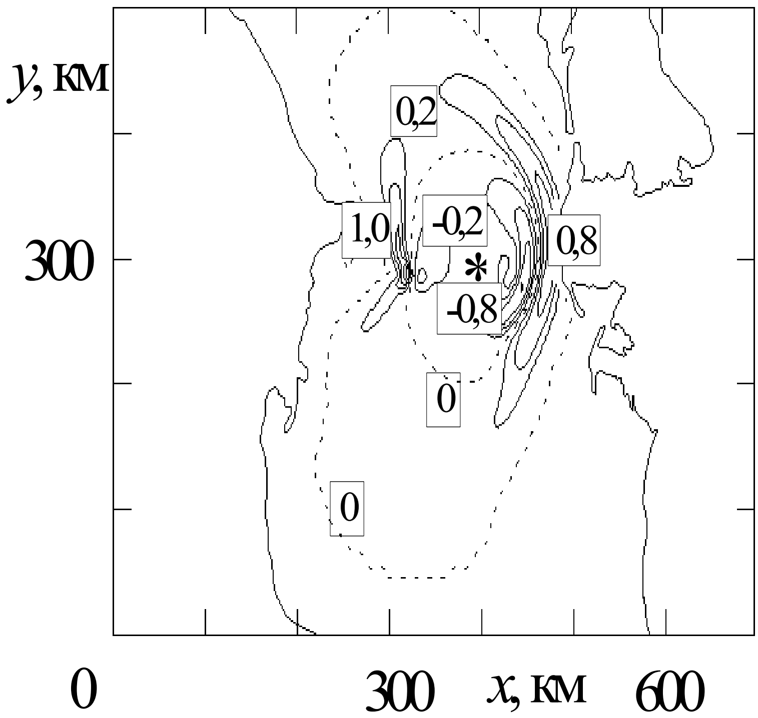

Figure 3. Sea level distribution at t = 20 min for tsunami wave propagated from the source area located on the Apsheron Sill (marked as ♦). The radius (R = 47.3 km) and height (a_0 = 2.5 m) of the initial circle disturbance is approximately corresponds to an earthquake with magnitude M = 7.5.

visual observations, the heights of historical tsunamis have not exceeded 1-2 m, but it is possible to wait for tsunamis of 3 m high (e. g. in case of the earthquakes 1986 and 1989).

Seismic activity is not the only possible reason of tsunami generation in the Caspian Sea. Underwater landslides, explosions of mud volcanoes and other factors can probably produce locally destructive tsunamis, however the authors could not find yet reliable information on such events.

Seven zones of highest seismic activity are the most feasible geographic areas of tsunami generation in the Caspian Sea. Six of them are on the west and east shelf of the sea, while one is inside the Apsheron Sill. It is noteworthy that the regions of historical tsunami observations are located in the vicinity of these zones (see Figure 1).

Numerical modeling of long waves propagation based on ray and evolutionary models showed almost isotropic radiation of tsunami waves from the sources located in the deep-water areas in the central and southern parts of the Caspian Sea. Strong trapping of tsunami waves by the eastern and western shelves of the sea takes place for all zones of seismic tsunami generation. As a result, the tsunamis have local character if their sources are located in these shelf zones.

The relatively shallow Apsheron Sill plays a role as a wave-guide for the Caspian tsunamis (Figure 3). At the first stage, the waves generated here radiate in zonal and meridional directions. Then due to the wave refraction at the sides of the sill, the tsunami propagation becomes mainly meridional. The wave trapping by bottom topography causes heightened tsunami risk along the coast of the Apsheron Peninsular and along the Krasnovodsk-Cheleken seacoast.

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