Phenomena similar to tsunami in Russian internal basins

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[1] Descriptions and records of phenomena similar to tsunami in Russian internal basins: rivers, lakes, and artificial water supply reservoirs are collected. During a period of 400 years, nine events of such type were found, seven of which can be considered reliable. The collected material confirms the risk of tsunami and phenomena similar to tsunami in all water reservoirs and the necessity of informing the population about this hazard. *INDEX TERMS:* 4564 Oceanography: Physical: Tsunamis and storm surges; 1799 History of Geophysics: General or miscellaneous; 1719 History of Geophysics: Hydrology; *KEYWORDS:* tsunami, internal basins, paleo-tsunami.

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1. Introduction

[2] The recent catastrophic tsunami, which occurred on 26 December 2004, in the Indian Ocean, attracted the attention of specialists to a serious analysis of tsunami danger in the regions, where this phenomenon was not actually considered dangerous, and the tsunami warning services did not exist. Speaking about tsunami in Russia, first of all, Far East is mentioned as the region, in which tsunami occurs relatively frequently, and tsunami warning service has been developed. Numerous literature sources exist with tsunami description at the Pacific coast of Russia. Here, we mention a few reviewing publications [*Shchetnikov,* 1990; *Soloviev,* 1978; *Soloviev and Ferchev,* 1961; *Zayakin,* 1996]. Historical data together with numerical publications became the basis for developing a scheme of tsunami zoning of Far East [*Go et al.,* 1988]. In the last years, new occurrences of tsunami were recorded in Far East. Among them the catastrophic Shikotan tsunami on 5 October 1994 [*Ivashchenko et al.,* 1996; *Yeh et al.,* 1995], which actually confirmed the validity of the developed scheme of tsunami zoning. At present, the research of traces of paleo-tsunami (strong tsunami in the past) has been developed in Far East. In summer 2005, one of the authors (ID) took part in one of such expeditions on Kunashir and Shikotan islands. We also note that catastrophic Indonesian tsunami in 2004 was recorded by pressure gauge in SeveroKurilsk, which emphasizes one more time the global character of tsunami propagation in the World Ocean.

[3] As to the other regions of Russia, no tsunami warning systems exist there, and tsunami risk studies have been only started there. First of all, we note more than 20 cases of tsunami in the Black Sea, which occurred during the entire historical period [*Dotsenko,* 1995; *Nikonov,* 1997; *Yalciner et al,* 2004; *Zaitsev,* 2006]. The major part of them was local and was induced by earthquakes in the sea. Approximately 10 weak tsunamis are known in the Caspian Sea, the major part of which are related to underwater mud volcanism [*Dotsenko, et al.,* 2000; *Nikonov,* 1996; *Zaitsev et al.,* 2004], (E. Pelinovsky, preprint, 1999). Two occurrences of paleo-tsunami (approximately 10000 years ago) were found in the Baltic Sea [*Morner,* 1999]. We also note a tsunami of asteroid origin in the Barents Sea [*Shuvalov et al,* 2002]. We emphasize that such kind of events can occur in any place (not necessarily in the seas and oceans), and occurred already in Russia. For example, 350 mln. years BP, falling of an asteroid in the region of Kaluga (at that time covered with sea) led to the occurrence of tsunami waves [*Masaitis,* 2002]. At present, much attention is focused on tsunami waves of asteroid origin [*Kharif and Pelinovsky,* 2005].

[4] At the same time, tsunamis and phenomena similar to tsunami occur not only in seas and oceans but also in the so-called internal basins, rivers, lakes, and other reservoirs. Three strongest tsunamis caused by landslides in Italian artificial water supply reservoirs are known very well: Vajont and Pontesei, (see, for example, [*Panizzo et al.,* 2005]). One of the events in 1963 that took away about 2000 lives is described well in literature (including publications in Russian) [*Mamradze et al.,* 1991]. Wave height in Vajont reservoir reached 235 m. We note that such events occurred in the Alps in prehistorical time. For example, in Lake Lucerne in Switzerland a wave whose height reached 3 m was generated by a landslide [*Schnellmann et al.,* 2002]. Several cases of tsunamis of seismic origin occurred in Lake Kineret (Israel) [*Amiran et al.,* 1994]. Resonance oscillations in Lake

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Figure 1. Observed locations of phenomena similar to tsunami in the territory of Russia.

Hebden, (Montana) 11.5 long were recorded after an earthquake with magnitude 7.5 and potential tsunami risk in Lake Tahoe in California-Nevada generated by strong earthquakes is specially described in [*Ichinose et al.,* 2000]. Finally, we mention tsunamis of volcanic origin in lakes. For example, in 1305, a series of pyroclastic flows descended from Mount Tarawera to Lake Tarawera, which caused tsunami waves reaching 6–7 m on the opposite coast of the lake [*De Lange et al.,* 2002]. Eruption of a volcano near Lake Taal in Philippines generated a 5-m tsunami [*De Lange and Healy,* 2001]. Similar events occurred also in Russia, and the first list of such events is given in papers [*Didenkulova,* 2005, 2006] and also provided by Didenkulova et al (Tsunami in 1806 in Kozmodemiansk on the Volga River, 2006, in press). In our study we shall present data evidence about historical phenomena similar to tsunami in internal basins of Russia. A total of nine events were distinguished in different regions of Russia during the period from 1597 to 2006 so that the frequency of their occurrence is approximately 45–50 years (during the last 200 years, tsunami appeared approximately each 25 years). The geography of phenomena similar to tsunami is shown in Figure 1. Seven events can be considered reliable. Earthquakes and landslides are equiprobable sources of these events (each cause generated four tsunamis), and one event was caused by a volcano eruption. They confirm the existence of tsunami risk in all water reservoirs and the necessity of informing the population about this danger.

2. Tsunami of Seismic Origin

[5] Occurrence of tsunamis in lakes and reservoirs, and other internal basins generated by seismotectonic displacements of the bottom is beyond controversy. The data of such observations were accumulated. We already cited a few cases of seismic origin in Lake Kineret [*Amiran et al.,* 1994]. Let us mention the cases of seismic tsunami observations in Russian basins.

[6] First of all let us mention tsunami in Lake Baikal. The most known case occurred on 12 January 1862 (31 December 1861, according to the old calendar) during Tsyganskoye earthquake in the delta of the Selenga River at its southeastern coast. The magnitude of this earthquake is estimated as 7.1 [*Golenetsky,* 1997; *Mushketov and Orlov,* 1893]. "The wave collapsed at the shore, destroyed the winter huts of peasants, and spread over more than 2 km inland destroying the forest on its way" [*Golenetsky,* 1997]. It is likely that during this event a giant seismogenic landslide occurred and a large region of the delta of the Selenga River descended more than by five meters forming Proval Bay whose square is 203 km^2.

[7] A weak tsunami is mentioned in [*Soloviev and Ferchev,* 1961] (amplitude of a few tens of cm) recorded by limnographs during Mid-Baikal earthquake on 29 August 1959 (magnitude of the earthquake was M = 6.5). It is notewor-

thy that more than 300 weak and strong earthquakes are recorded annually only in Mid-Baikal region. The Selenga delta is one of the most active seismic regions here. During the last century, four destructive earthquakes occurred in the delta: the one in 1862 mentioned above (intensity I=8–9, M=7.5), in 1871 (I=8–9, M=6.3), in 1903 (I=8–9, M=6.7), and the one in 1959 mentioned above (I=9, M=6.8) [*Dashevsky and Martynov,* 2002]. The set of seismotectonic data makes us think that earthquakes with magnitudes 7.5–8 and recurrence of 100–200 years are possible in Lake Baikal, which can lead to the generation of tsunami wave with amplitudes up to 1–2 m. However, tsunami risk for the coast of Lake Baikal has not been calculated yet.

[8] *Nikonov,* [2004] analyzed the epos of Karelo-Finns. It follows from this analysis that strong earthquakes occurred in the past in Karelia (on the rivers and lakes, as well as on the coast of the Black Sea) with intensity of 7–8, which were likely followed by tsunamis. Although this information is not definite, but taking into account the construction of hydroelectric and nuclear power stations in Karelia, it should be studied.

[9] The major part of lakes and rivers in Russia are in the zones free from seismic activity. However, there were events when weak earthquakes caused tsunamis. For example, on 12 September 1806, near Kozmodemiansk town on the Volga River (in Chuvashia, see Figure 2) Lieut. Balle noticed a "deliberate oscillation in water" caused by an earthquake, which lasted about 5 seconds [*Tatevosyan and Mokrushina,* 2003]. The analysis of geological and historical data allowed the authors of this paper to estimate the parameters of the earthquake of 1806: its magnitude was 3.7 (depth of the source 5 km), and intensity was equal to 6. We note that after the earthquake in Kozmodemiansk two more earthquakes were recorded in the Middle Volga River region with magnitudes from 3 to 4: in Elabug in 1851 and Soksky Ary in 1914 [*Tatevosyan and Mokrushina,* 2003], which points to the necessity of studying possible tsunamis in the Volga River. The event in 1806 is analyzed in our papers [*Didenkulova,* 2006; *Didenkulova et al.,* 2006].

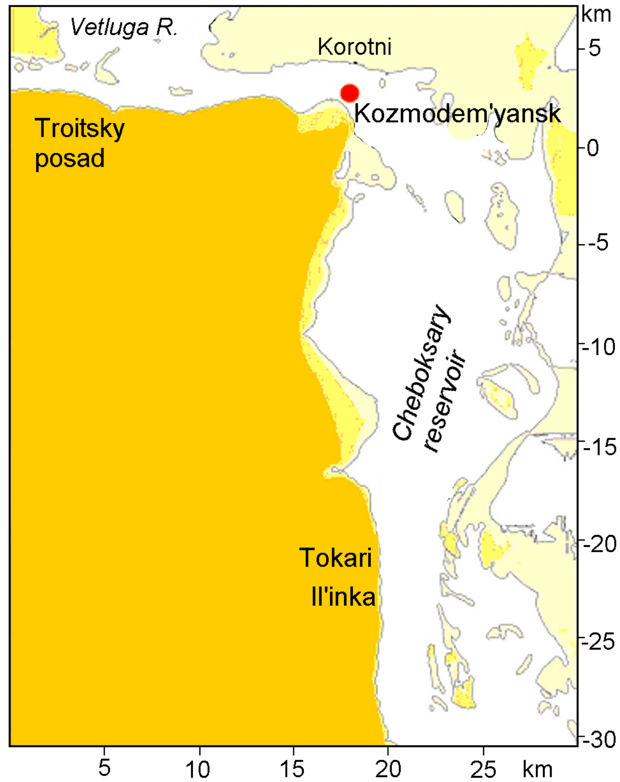

Figure 2. Location of the epicenter of the earthquake on the Volga River in 1806.

[10] The most probable mechanism of the appearance of observed oscillations of water surface is the known effect of seaquake over the source of underwater earthquake [*Alexandrov et al.,* 1986; *Levin and Nosov,* 2005], which is caused by parametric generation of waves at the water surface in the oscillation gravity field. Taking into account that characteristic seismic frequencies of soil oscillations caused by a close earthquake are within the interval from 3 Hz to 5 Hz, the characteristic frequencies of parametrically generated waves at the water surface are 1.5–2.5 Hz, while the wavelengths are 20–70 cm. The maximal amplitude of such wave can be estimated from the known relation for steepness of the limiting Stokes wave, which is equal to 0.143. It follows from this that the amplitude of the limiting wave at the water surface varies in the interval from 3 cm to 10 cm, and such wave can be noted by an observer. It is likely that this was the "deliberate oscillation in water" observed by Lieut. Balle during the earthquake in 1806. Generation of long waves that we usually identify with tsunami is not reported in this case, which can be explained by small amplitude of the earthquake. At the same time, a historical event is known when weak earthquake with the same magnitude 3.7 in 1992 caused a notable tsunami with a wave height of 80 cm on Hainan Island in Tonkin Bay [*Lander et al.,* 2003]. It is not excluded that weak earthquake induced a landslide, which became the source of notable tsunami. These processes are currently studied in detail [*Yalciner et al.,* 2003]. Since one of the coasts of the Volga River is steep, landslides from this coast are very possible (below, we shall present the corresponding data), so that tsunami hazard in the reservoirs located not in a seismic zone should not be underestimated.

[11] Earthquakes of the same strength occur in Lake Ladoga. For example, on 30 November 1921, an earthquake with magnitude 4.2 occurred at the eastern coast of Lake Ladoga (Figure 3). A possibility that even stronger earthquakes occurred in the past is not excluded [*Nikonov,* 2005]. In the southeastern part of Lake Ladoga, seismic activity manifests itself in the form of subterranean (underwater) rumble sometimes accompanied with slight oscillations of water surface recorded on Valaam and Vysuanny islands [*Nikonov,* 2005]. After the earthquake in 1921, the depth of the southwestern coast of Valaam Island, where a steep underwater slope is located, increased by 50 m, which most likely was accompanied by tsunami. Observations of "slight water oscillations" allow us to speak about reliable occurrence of tsunami on Lake Ladoga.

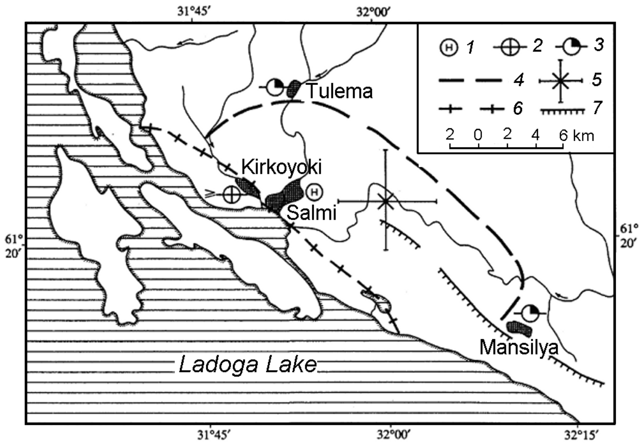

Figure 3. Data on the earthquake on 30 November 1921, at the eastern coast of Lake Ladoga [*Nikonov,* 2005]. Notations: no information on intensity (1); intensity 4–5 (2); intensity 5–6 (3); contour line of intensity 6 (4); location of the epicenter (5); location of deep fracture (6); location of steep coastal cliff formed of loose sediments (7).

3. Tsunamis of Landslide Origin

[12] Many tsunamis in lakes and rivers are caused by landslides: underwater and above-water ones. In particular, this is the nature of tsunami in Nizhniy Novgorod that occurred in 1597 on the Volga River. It is described in detail in [*Didenkulova,* 2006; *Didenkulova and Pelinovsky,* 2002; *Didenkulova et al.,* 2003]. On 18 June 1597, an enormous landslide destroyed completely the Pechera monastery located at a distance of a few kilometers from the Kremlin of Nizhniy Novgorod down the Volga River. Part of the coastal cliff carried away the houses of the monastery and protruded into the Volga over a distance of more than 100 m, which caused "terrible waves" on the river. The anchored vessels down the monastery were thrown ashore over almost 50 m [*Gatsisky,* 2001]. This monastery is shown in Figure 4. The author also [*Gatsisky,* 2001] informs that partial displacements of the slope were observed at least a week before the described event. Many springs opened after the landslide. It is possible to conclude that an increase in the groundwater level and thinning of the ground caused the landslide.

[13] After the landslide, it was decided to build a new monastery at a distance of 3500 ft upstream the Volga. Even in the new place, the history repeatedly reports about sliding down of monastery walls although not so strong as in 1597. For example, in May 1829, during the spring flooding, cracks began to show up behind the houses of the monastery village at a distance up to 400 m along the shore, and the land together with gardens descended. The gardens, which displaced down the slope over a distance of almost 15 m, stopped without damage [*Gatsisky,* 2001]. At present, the monastery is at the risk of destruction again, which is evidenced by a crack in its wall from the Volga River side (Figure 5).

[14] It is noteworthy that the Volga slope is very steep, which facilitates the landslides. It is written in the same chronicle that in 1867 a large landslide occurred over the so-called salt-storage. The landslide hazard is high even at present. For example, according to the data of the Environment Protection Committee of Nizhniy Novgorod

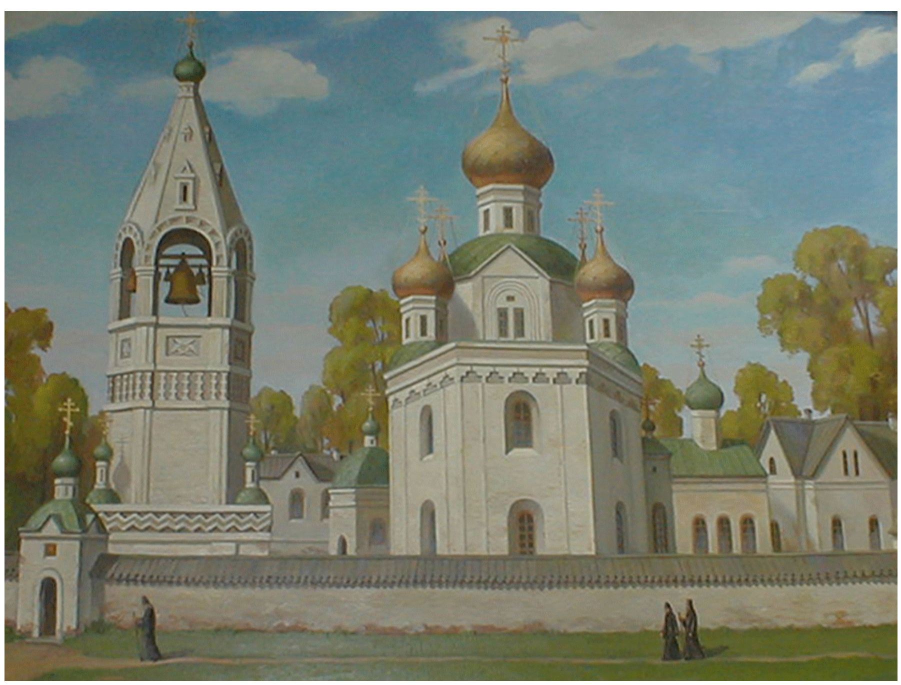

Figure 4. Old Pechera monastery covered up with a hill in the 16th century.

Figure 5. A crack near the foothill of the Pechera monastery that broke the wall.

region (they are presented in our paper cited above), only in 2000, in Nizhniy Novgorod at the locations of landslide slopes of the Oka and Volga rivers three new landslides were formed and 33 old ones activated. In 2000, the maximal landslide activity was recorded. The largest among the newly formed landslides was the one in Pochinsky ravine (within the city). Its length is 45 m, width is 30 m, the depth of displaced rocks is 5 m. The main causes of the occurrence of landslides are precipitation, high level of ground waters, and erosion of the coast. On 9 November 2004, the last significant landslide occurred in Bogorodsky region near Nizhniy Novgorod. A ground volume of approximately 10 thousand cubic meters collapsed from a high shore of the Oka River from a height of approximately 50 m (Yu. Smirnova, 2004). We organized investigation of this event (Figure 6) to check whether it induced a tsunami. However, it was found that the landslide stopped not reaching the water level. However, this event evidences one more time the necessity of estimating the tsunami generated by landslides.

[15] It is worth noting that landslide phenomena are also characteristic of other regions of the Volga River. For example, a landslide is described in [*Tatevosyan and Mokrushina,* 2003], which occurred in 1839 in Fedorovka village near Syzran (approximately 450 km from Nizhniy Novgorod). During this event, notable unrest and oscillations of land were observed, which lasted three days, later they decayed gradually. This landslide could possibly be accompanied by the generation of waves in the river, and we include this event in the summary as a possible tsunami. We also note landslide events at the shore of Sura River in Poreyskoye village of Simbirsk region in 1865 and in Saratov in 1884 [*Tatevosyan and Mokrushina,* 2003].

[16] A description of tsunami in 1885 on Irtysh River is given in book [*Levin and Nosov,* 2005]. The wave generated as a result of landslide turned over and threw to the opposite coast a vessel that passed at a distance of one kilometer from the place of the collapse.

[17] Among tsunami waves observed in artificial water supply reservoirs the most impressive example is the formation of a wave 235 m high in Vajont (Italy) reservoir on 9 October 1963, which occurred as a result of collapsing of cliff rocks with a volume up to 270 mln. cubic meters near the dam [*Panizzo et al.,* 2005]. This event was already mentioned in the Introduction. The giant wave propagated to the valley of Piave River covering Longerone town, which resulted in the death of all its inhabitants. The event of 1963 was the second in the history of the reservoir. On 4 November 1960, during the first filling of the basin, a landslide occurred (with a volume of 700,000 m^3) that caused a 10-meter tsunami wave at the coast. In the other Italian water supply reservoir (Pontesei), a 20-meter tsunami wave generated on 22 March 1959 by a landslide killed a bicyclist that moved along the road [*Panizzo et al.,* 2005]. Formation of big waves in Russian water supply reservoirs is also recorded (Krasnoyarsk reservoir in 1970); however, specific data were not given [*Mamradze et al.,* 1991], thus we relate this case to possible tsunamis.

[18] It is clear from the facts described above that land-

Figure 6. Landslide that collapsed from the high shore of the Oka River in November 2004.

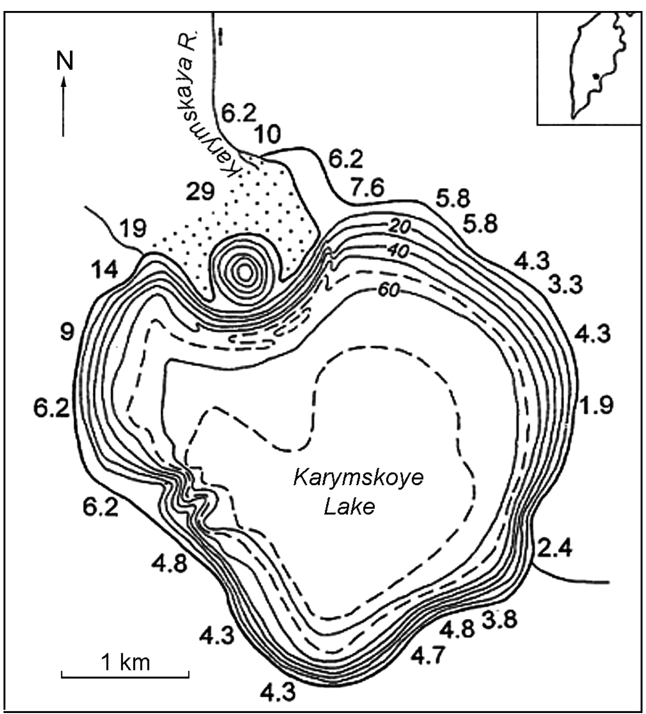

Figure 7. Bathymetry of Lake Karymskoye with indication of measured wave heights at the coast.

slide phenomena are frequently accompanied with wave generation and calculation of tsunami waves should be part of estimating the landslide phenomena in rivers, lakes, and water reservoirs.

4. Tsunamis of Volcanic Origin

[19] In the Introduction we described the data about volcanic tsunamis in the lakes of New Zealand and Philippines. One of the known examples of tsunami of volcanic origin in Russia is eruption of underwater volcano in Lake Karymskoye on 2 January 1996, which lasted 10–20 hours [*Belousov et al.*, 2000]. The size of the lake is relatively small: its diameter is 4 km and the depth is 40–70 m. It is shown in Figure 7. Measured runup of tsunami waves is also shown in this figure. The eruptions were of explosion character and appeared every 5 minutes. Eruption of the volcano was recorded on video tape, which testifies that velocities of eruption reached 110 m s^{-1}, while the elevation of the tsunami source was 130 m with axial symmetry, which propagated in radial directions with velocities of 20–40 m s^{-1}. The runup of tsunami wave at the closest coast (approximately 1 km from the crater) exceeded 30 m and caused erosion of the shore (Figure 8).

[20] Karymskoye tsunami confirms the main properties of

Table 1. Characteristics of phenomena similar to tsunami in internal basins of Russia

no.	Year	Location	Source	Manifestation	Reliability
1.	1597	Volga River, Nizhniy Novgorod	landslide	Horizontal inundation of 40 m	reliable
2.	1806	Volga River, Kozmodemiansk	earthquake, M = 3.7	"deliberate oscillation"	reliable
3.	1839	Volga River, Syzran	landslide	Water oscillations	probable
4.	1862	Lake Baikal	earthquake, M = 7.1	Horizontal inundation of 2 km	reliable
5.	1885	Irtysh River	landslide	Wave	reliable
6.	1921	Lake Ladoga	earthquake, M = 4.2	Small oscillations	reliable
7.	1959	Lake Baikal	earthquake, M = 6.5	Amplitude of 10 cm	reliable
8.	1970	Krasnoyarsk water reservoir	landslide		probable
9.	1996	Lake Karymskoye, Kamchatka	Volcano eruption	Runup of 30 m	reliable

volcanic tsunami: small size of the source, very high wave heights near the epicenter, and rapid decay of the height with distance. We note that in 1883, the famous eruption of Krakatau volcano in Soende Strait (Indonesia) led to a runup of the waves with maximal value equal to 45 m causing 36,000 deaths at the coasts of the strait. Tsunami waves from this eruption were recorded in many countries. The analysis of pressure gauge records of this tsunami was made in [*Pelinovsky et al.,* 2005]. The Karymskoye eruption is weaker than the Krakatau, but however it led to very high waves (30 m) so that long term hazard of volcanic tsunamis in Kamchatka and Kuril Islands should be specially calculated.

5. Conclusion

[21] We tried to bring together the data about tsunamis and phenomena similar to tsunami in internal reservoirs of Russia: rivers, lakes, and artificial water supply reservoirs, where tsunami hazard is neglected. The characteristics of phenomena similar to tsunami are given in Table 1. A total of nine reliable or almost reliable events, which occurred in 1597–2006 are distinguished. Their time distribution is shown in Figure 9 (partly reliable events are denoted with bars of half-length). During the last 200 years, tsunamis actually occurred once in 25 years on the average in internal basins of Russia. We note that tsunamis in internal basins are generated by the same sources as in seas and oceans: earthquakes, landslides, volcanic eruptions. Earthquakes and landslides are responsible for the main part of the events (four events caused by each source), while one event was caused by underwater volcano eruption (Figure 10). The geography of phenomena similar to tsunami is shown in Figure 1 of the Introduction. Four events occurred in the European part of Russia, and five in Siberia and Far East. Our special interest is focused on the tsunami on the Volga River in the region of Nizhniy Novgorod, whose probability of occurrence is not at all insignificant (three reliable events in the Volga region). All these events point to the fact that estimating the tsunami hazard in these regions and informing the population about possible consequences of visiting the coasts of the basins are necessary.

[22] Finally, in the conclusion we note that, in principle

Figure 8. Lake Karymskoye in Kamchatka. A crater of volcano with a diameter of 600 m is seen in the center. A region of erosion up to 30 m high, which appeared after the tsunami in 1996 is seen on the coast in the right side.

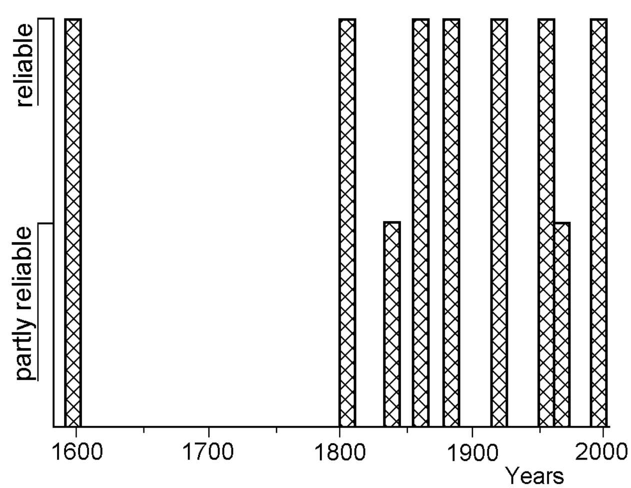

Figure 9. Distribution of tsunamis by years.

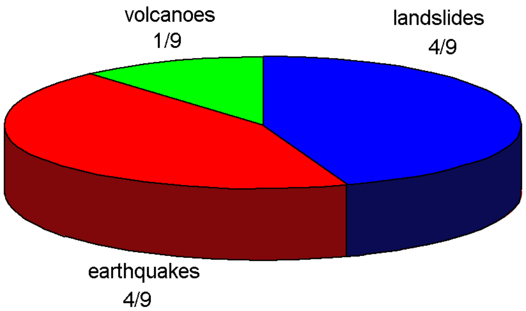

Figure 10. Distribution of phenomena similar to tsunami in internal basins of Russia by the mechanisms of their generation.

we should include two cases of tsunami of asteroid origin in this summary, which were mentioned in the Introduction: tsunami in the Barents Sea (140 mln. years BP) and tsunami in the region of Kaluga town (350 mln. years BP). However, according to the traditions, tsunamis of asteroid origin are discussed separately.

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