8th Joint ICG/PTWS– IUGG/JTC Technical Workshop:
Understanding and lessons learned from the tsunami generated by the Hunga Tonga-Hunga Ha'apai volcano eruption on 15 January 2022 for development of Tsunami Warning and Mitigation System for tsunamis generated by volcanoes and other non-seismic sources, Nuku'alofa, Kingdom ofTonga, September 11, 2023

Historical Perspectives on Non-seismic Tsunamis: Location, Damage and Fatality Rate

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Plan of today’s presentation

(1) Sources of data on historical tsunamis

(2) Tsunami source classification (NCEI source code)

(3) Landslide-related tsunamis

(4) Volcanic tsunamis

(5) Meteotsunamis

(6) Events with enigmatic nature

(7) Seismic tsunamis – are they free from secondary generation mechanisms (e.g., landslides)

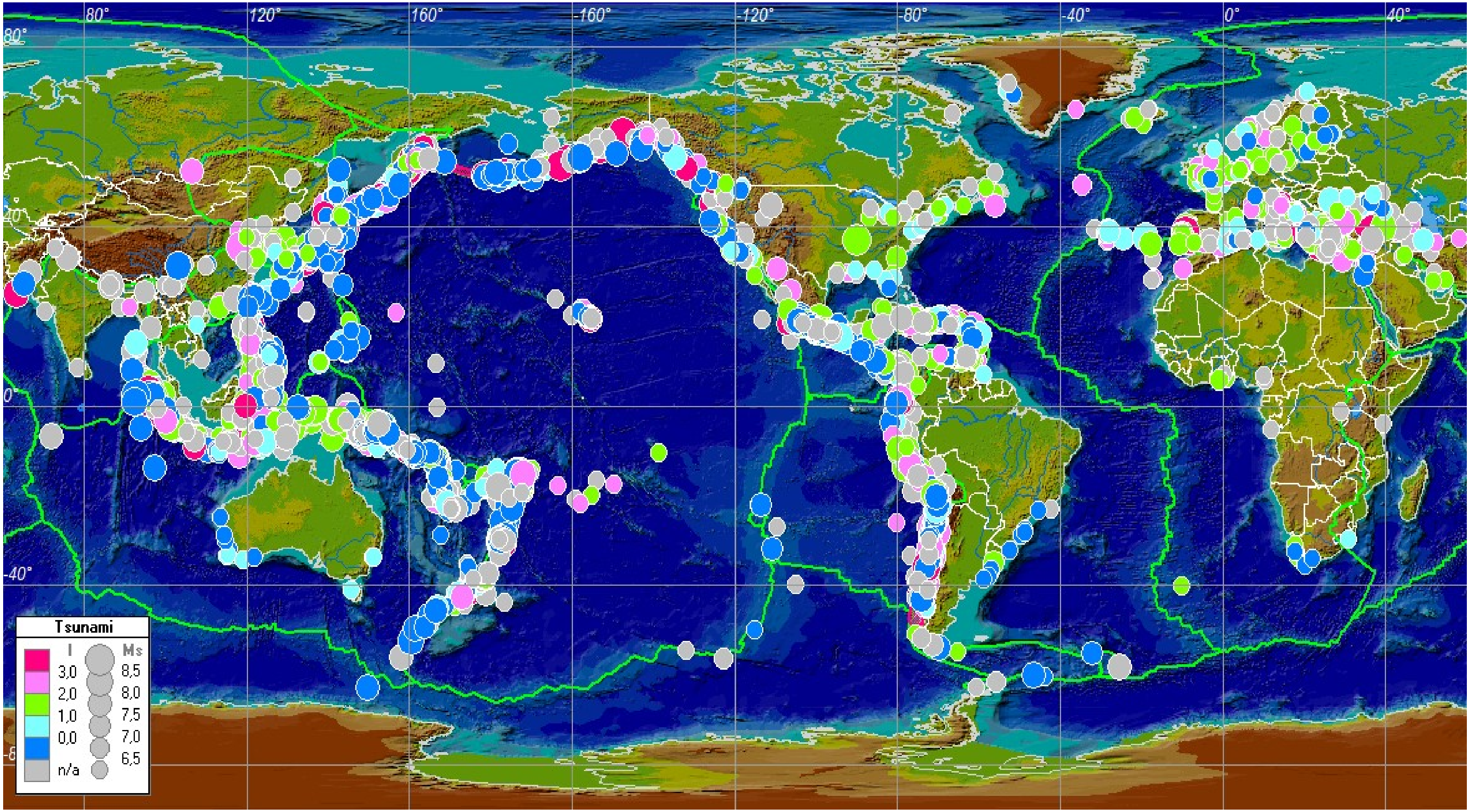
Important preliminary remarks

The main source of tsunami data are historical tsunami catalogs that are collected and published on regional, national, ocean-wide and global levels. Currently, there are almost 150 published tsunami catalogs. Their full list can be found at the Novosibirsk Tsunami Laboratory web-site http://tsun.sscc.ru/tsu_catalogs.htm The basic content of the catalogs has long been converted in tsunami databases.

Currently, there are two global historical tsunami databases that are maintained by the NOAA National Centers for Environmental Information (NCEI) and the Novosibirsk Tsunami Laboratory (NTL).

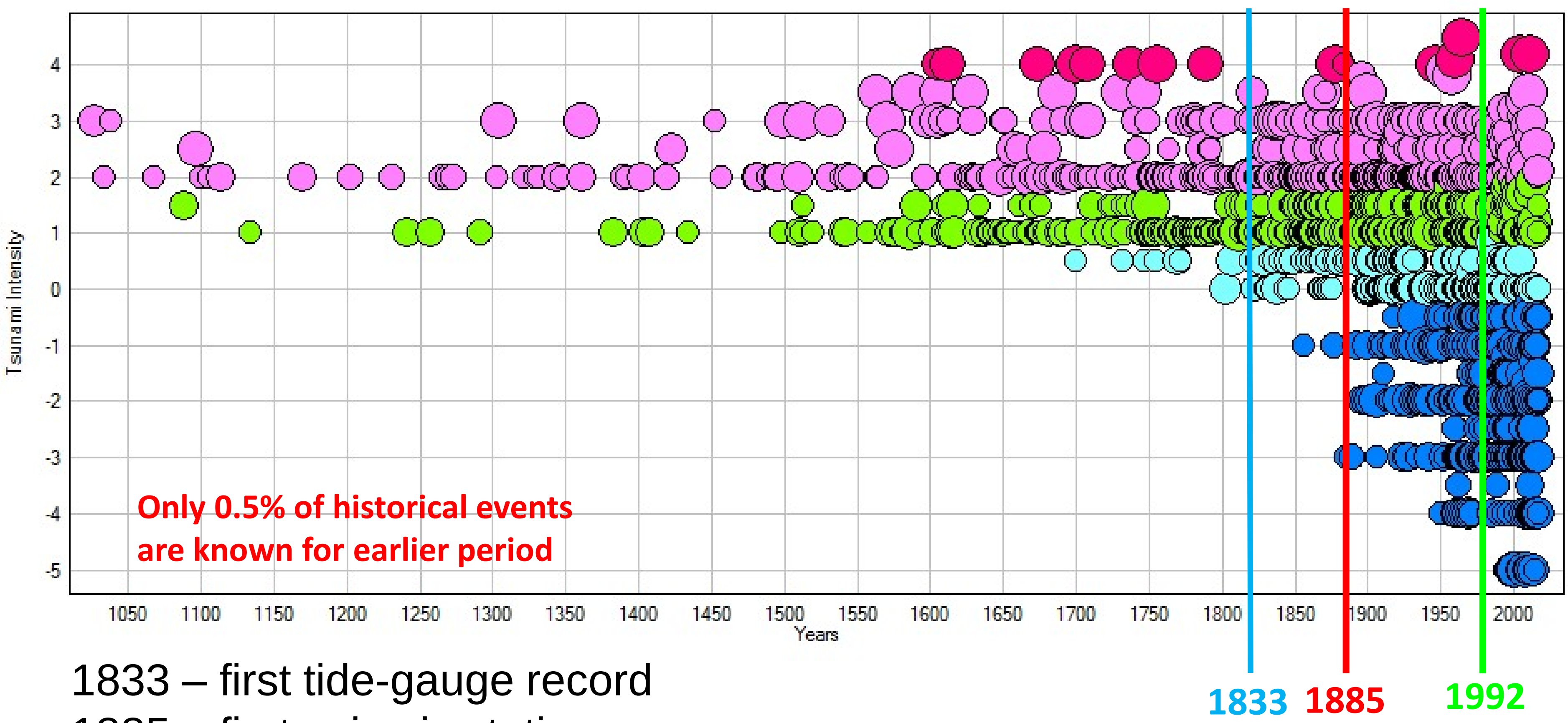
These databases are similar in format and content, the difference between them concerns mainly the parameters of old historical events (validity, location, magnitude, tsunami intensity, type of source) whose parameterization, in the absence of instrumental measurement, requires an expert judgment.

Map of 2740 tsunamigenic sources included in the global database



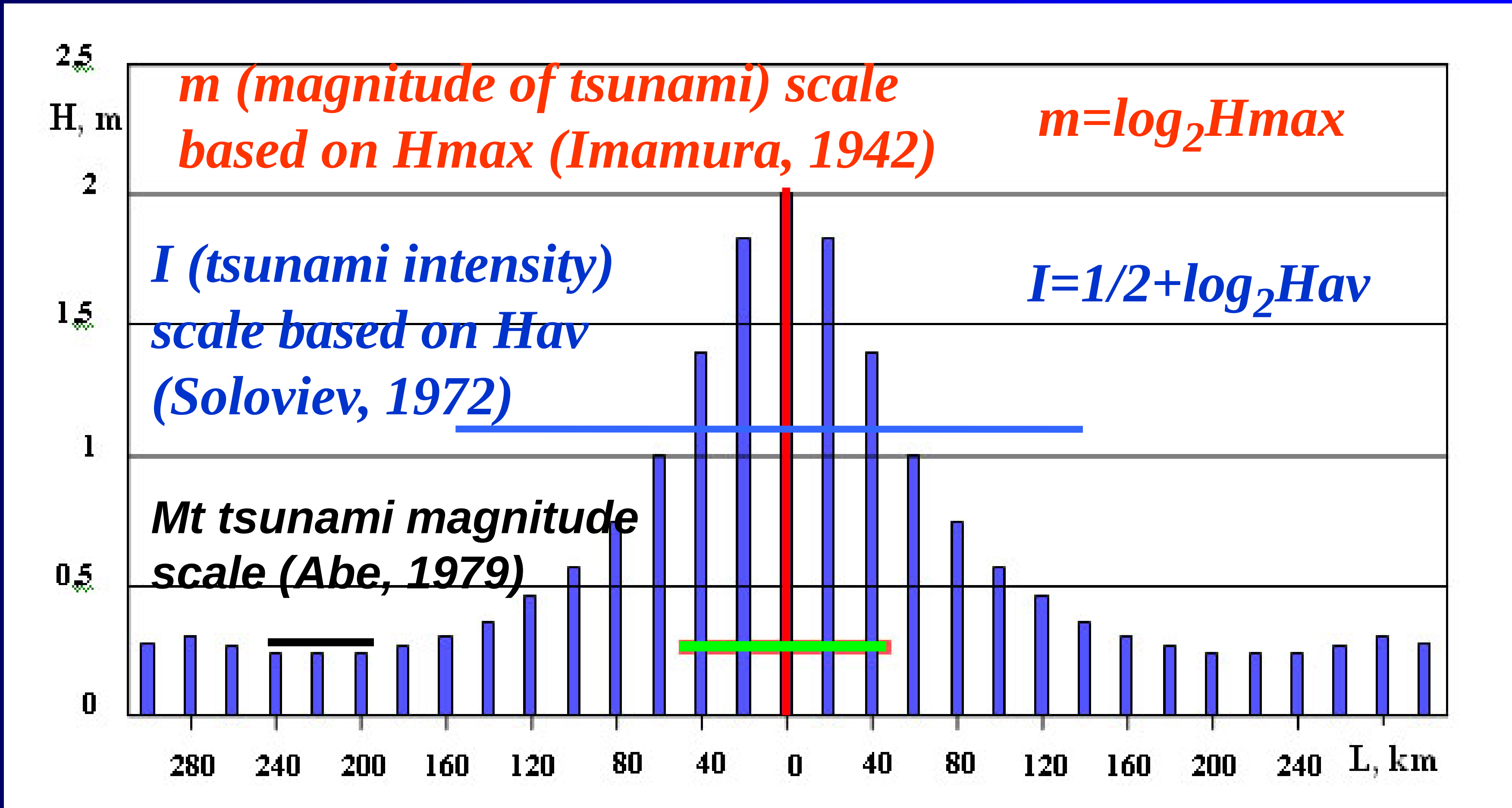
On the global level, geographical coverage of both DBs is very good, all the main tsunamigenic regions have a lot of historical events. However, if we look at the temporal distribution we will see that the situation is far from adequate

Historical tsunami occurrence for the last 1000 years



1833 – first tide-gauge record
1885 – first seismic station
1992 – first post-tsunami field survey

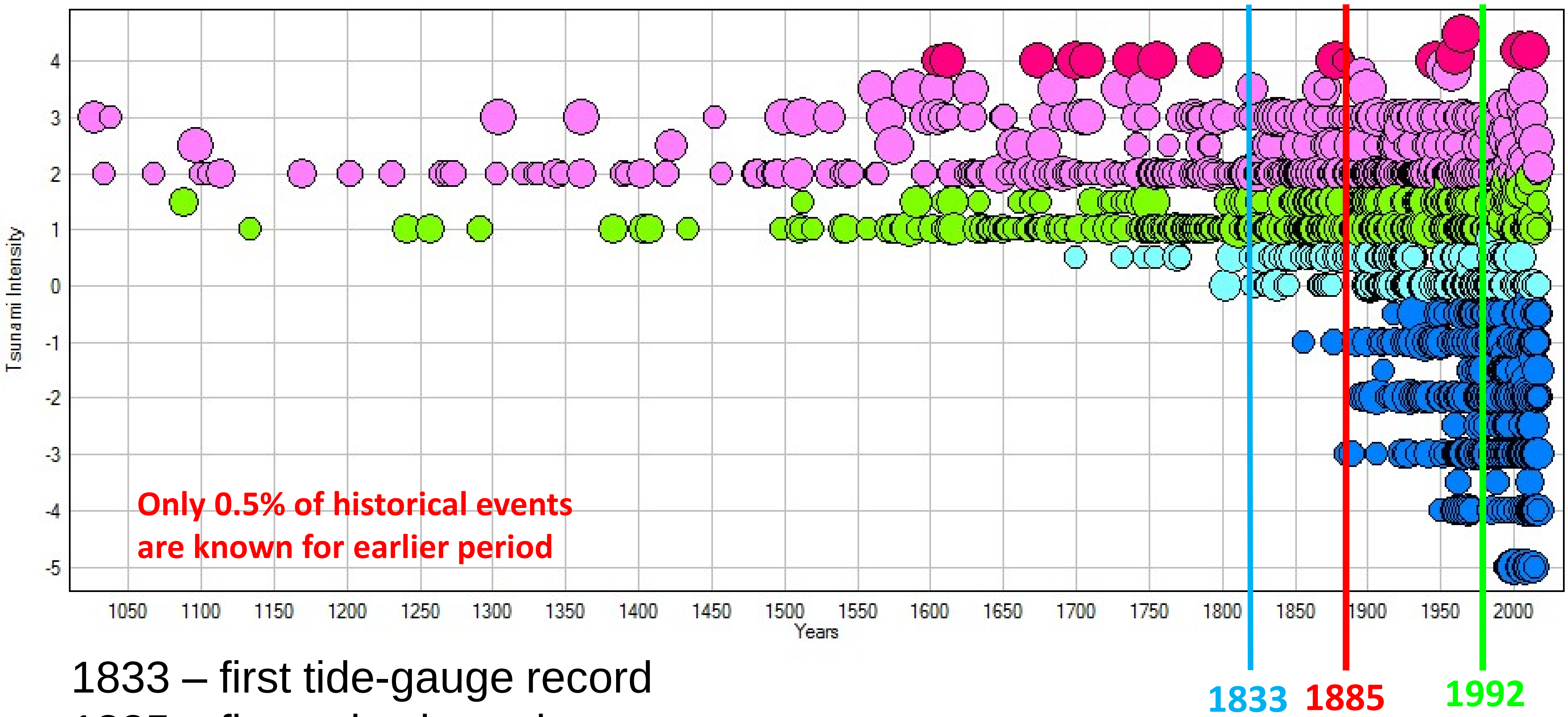
The global tsunami catalog is more or less complete only for the last two centuries, for earlier times there are obvious gaps even for major events.



100km tsunami source

Idealized distribution of tsunami run-ups along the strait coast for a typical tsunamigenic source with Mw=7.6 located on the continental slope at the distance of 150 km from the coast

Historical tsunami occurrence for the last 1000 years



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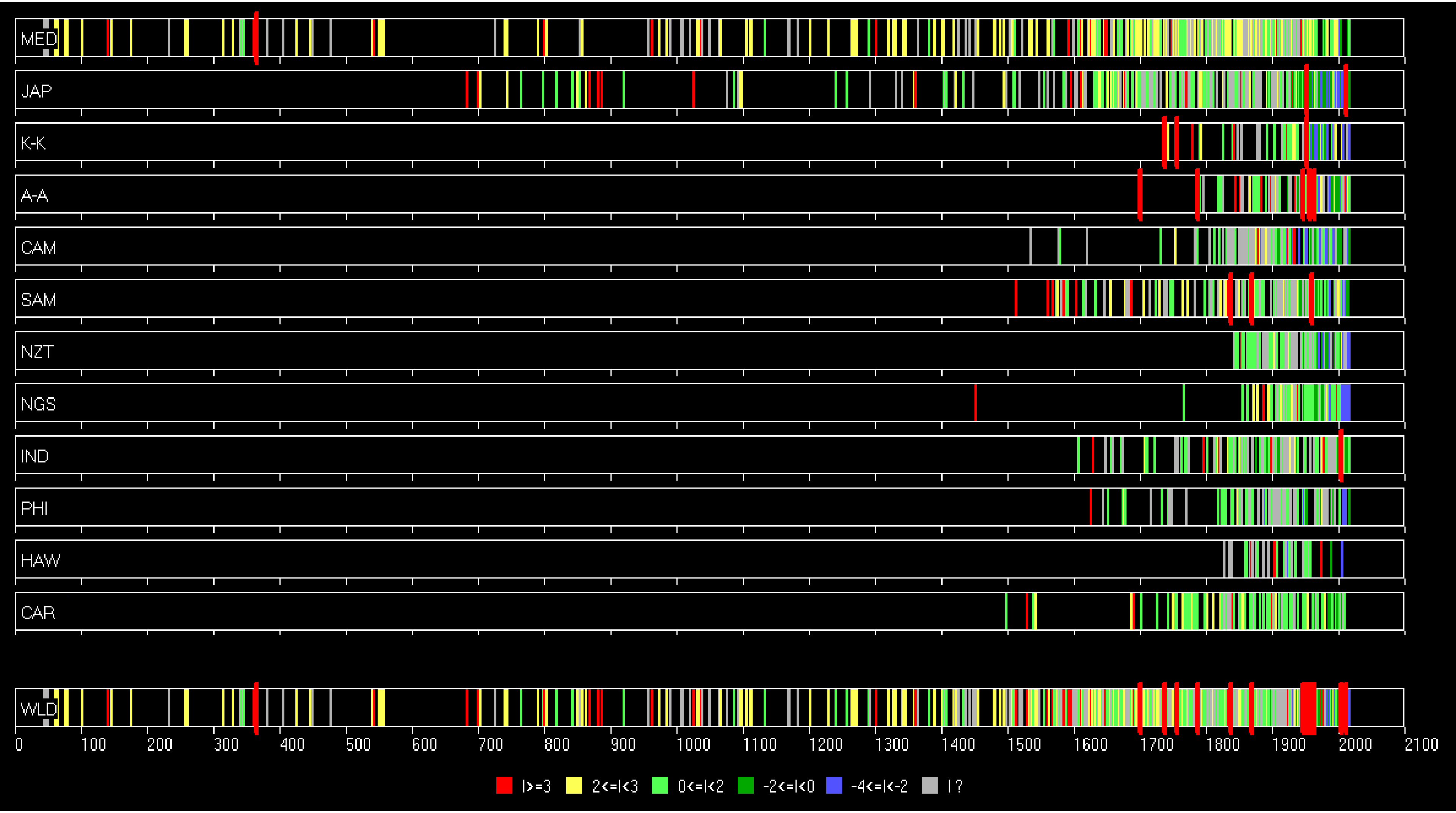
Comparative length of the historical tsunami catalogs (for the last 2000 years).



Each vertical line represents a particular tsunami event. Color corresponds to tsunami intensity on the Soloviev-Imamura scale. When excluding MED and JAP catalogs, the average length of other regional catalogs is only 350 years

Tsunami classification by source type

NCEI DatabaseTsunami Cause Code

0 Unknown

1 Earthquake

2 Questionable Earthquake

3 Earthquake and Landslide

4 Volcano and Earthquake

5 Volcano, Earthquake, and Landslide

6 Volcano

7 Volcano and Landslide

8 Landslide

9 Meteorological

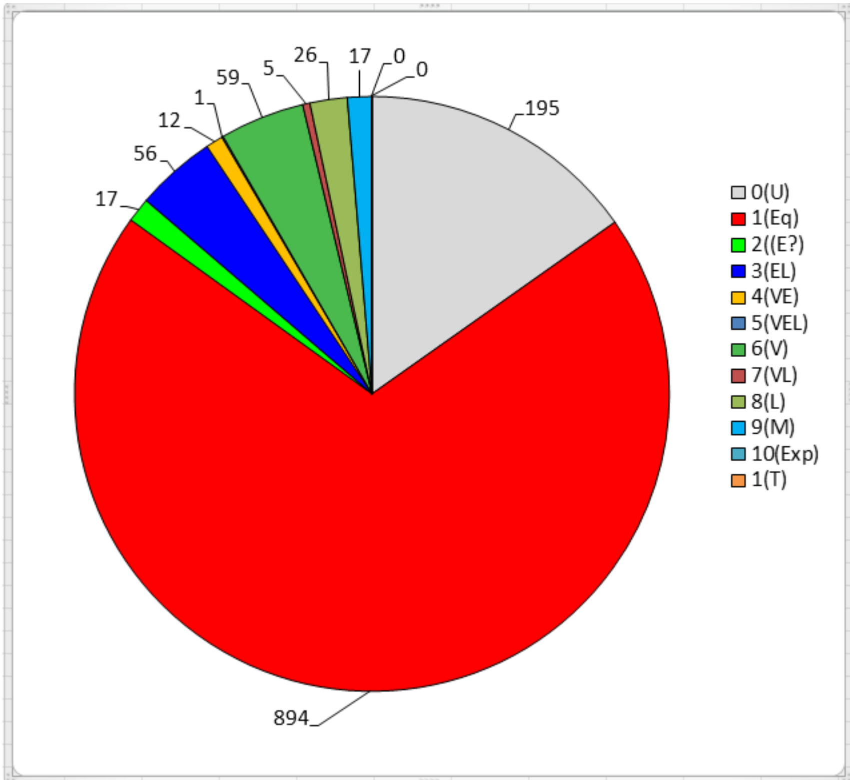
10 Explosion

11 Astronomical Tide

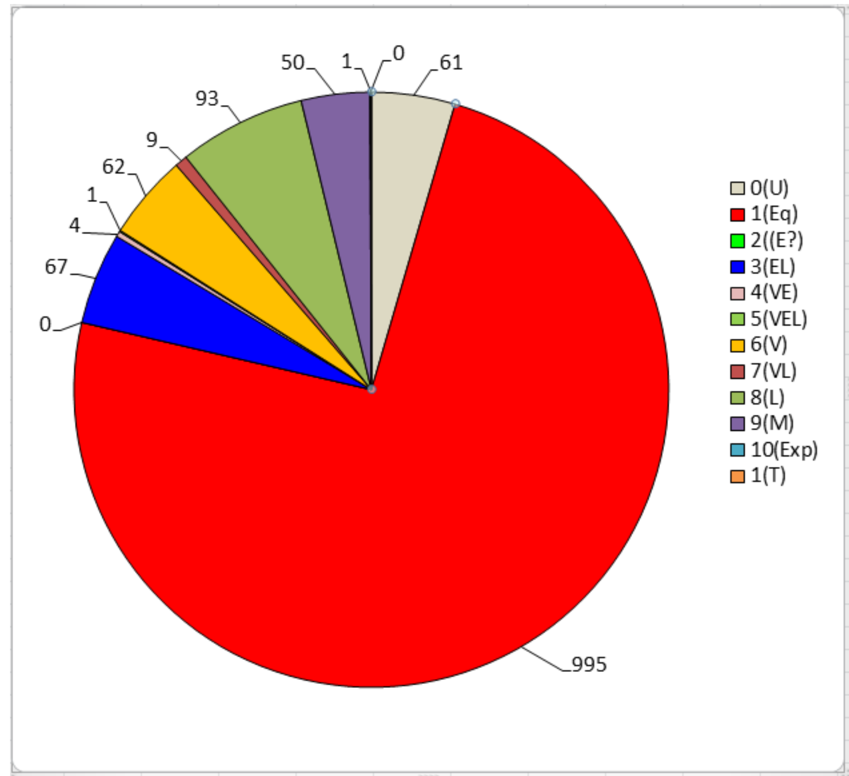
Currently there are 12 different **Tsunami Source codes** in the NCEI Tsunami DB format (including code 0 for unknown sources).
Of them, only two (1 and 2) relates solely to ***seismic tsunamis***.
Most uncertainties, related to source classification, are connected with type 3 (Earthquakes and Landslides) and type 7 (Volcano and Landslides).
They are due to uncertainties about degree of involvement of secondary mechanism (landslide) in the tsunami generation process. It can vary from almost 100% (1958 Lituya Bay tsunami) to several per cents for many earthquakes occurred in oceanic basins and especially in marginal seas

Breakdown of tsunami causes based on the NCEI database content

2000 BC – 1903 (29%)



1904 – 2023 (26%)

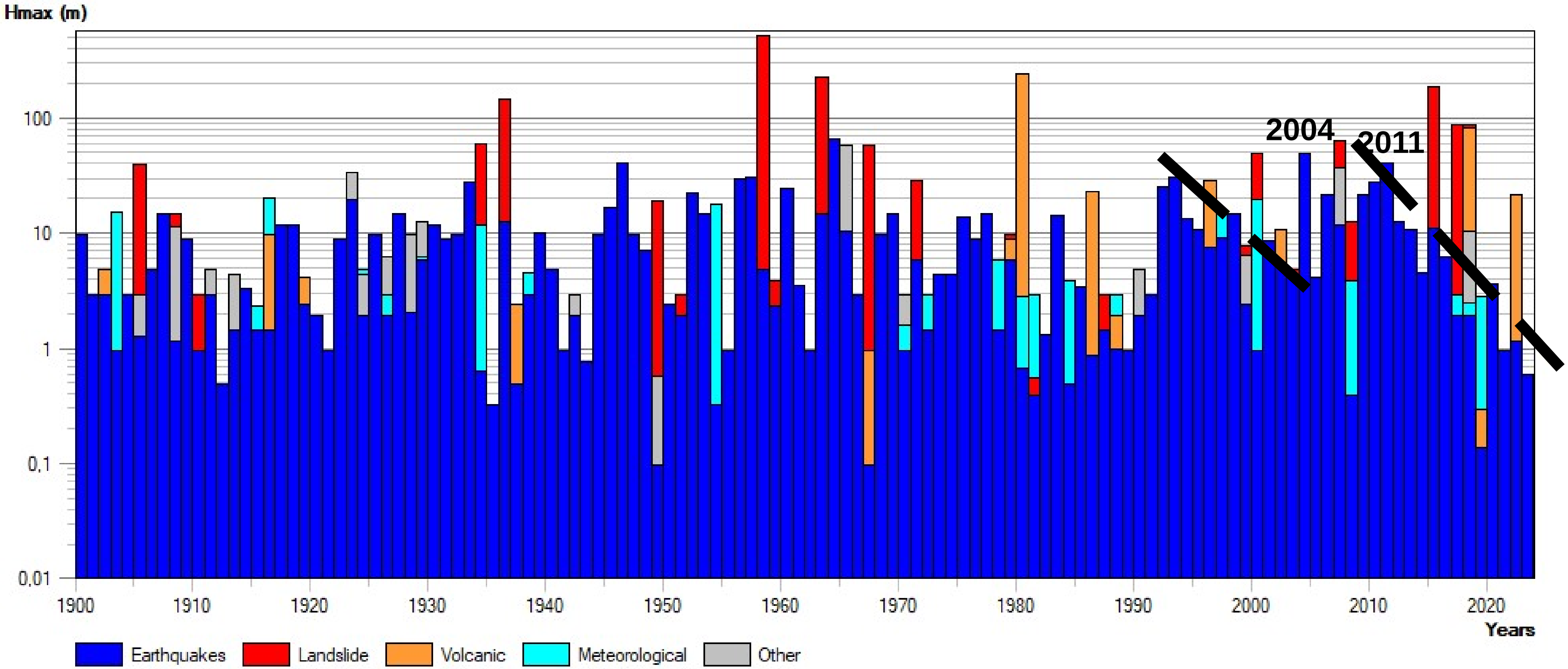


Fraction of tsunamigenic events of different origin for two time periods:

Pre-instrumental (2000 BC – 1903)

Instrumental (1904 – 2023)

*Gusiakov V.K. Global Occurrence of Large Tsunamis and Tsunami-like Waves Within the Last 120 years (1900–2019). Pure Appl. Geophys. 2020, **177,** 1261–1266 .*



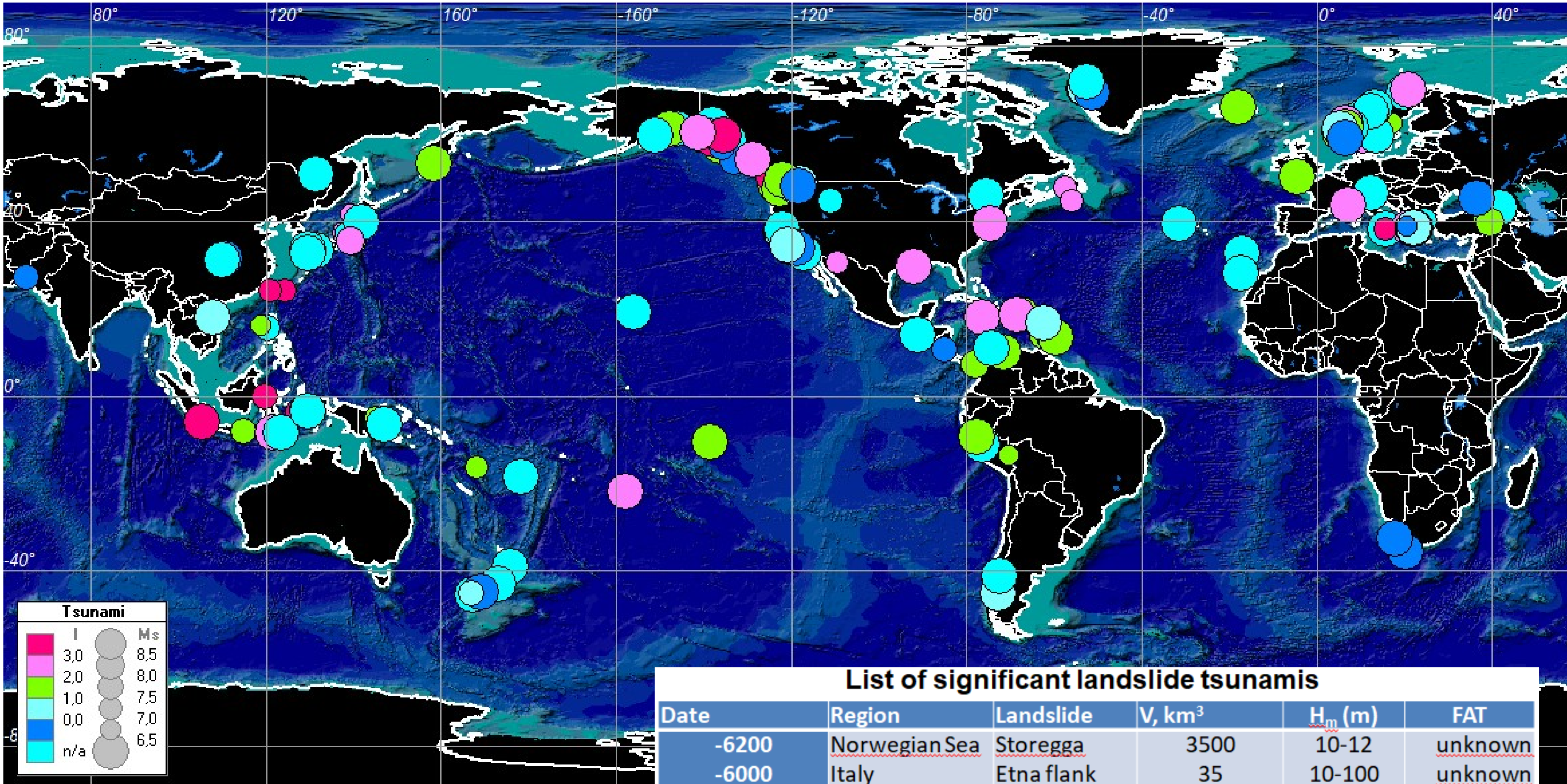
Annual Hmax observed or measured in the World Ocean during the last 124 years (from 1900 to 2023). Only **59%** of annual Hmax are resulted from seismic tsunamis. The rest (non-seismic of Hmax) **constitutes 41% and** are divided between landslide-generated **(16%)**, volcanic **(9%),** meteorological **(8%)** and unknown or complex-origin **(8%)** events.

During the last 14 years (2011-2023) 13 fatal tsunamigenic events occurred globally and claimed 5501 victims in total.

Of them, only 3 were clearly “seismic” tsunamis with 12 fatalities.

In the rest of 10 events, the non-seismic mechanism was clearly involved and they are resulted in 5489 fatalities that is 99.9% of total (2 leading events were the 2018 Sulawesi and Anak Krakatau tsunamis)

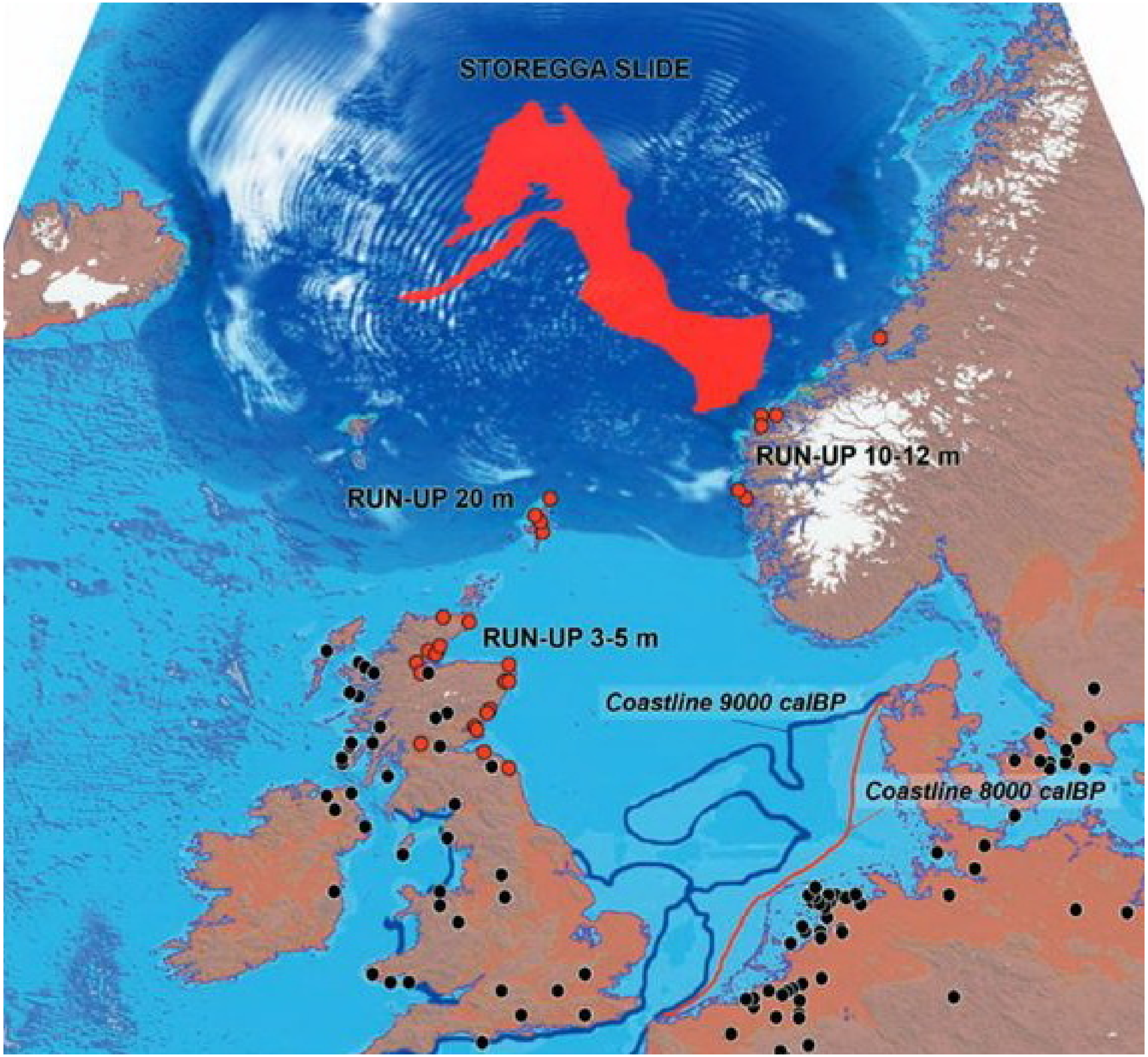
Global map of landslide-generated tsunamis. 182 sources are shown.



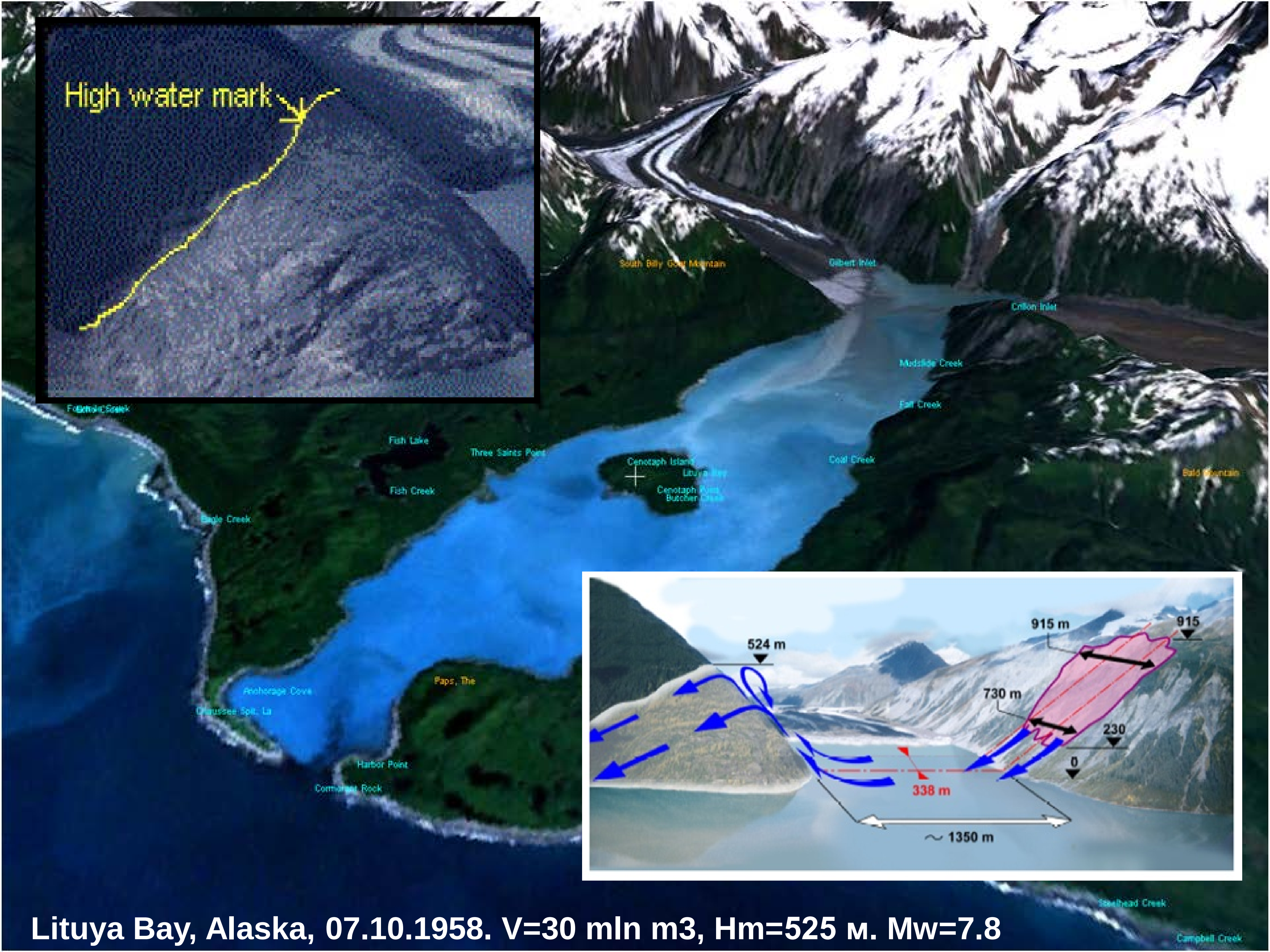
Color represents the tsunami intensity on Soloviev-Imamura scale. Estimated fatalities about 2,000 (obviously not complete)

List of significant landslide tsunamis

Date	Region	Landslide	V, km^3	H_m (m)	FAT
-6200	Norwegian Sea	Storegga	3500	10-12	unknown
-6000	Italy	Etna flank	35	10-100	unknown
1853	Alaska	Lituya Bay	unknown	120	unknown
07.04.1934	Norway	Tafjord	0.002	62	41
27.10.1936	Alaska	Lituya Bay	unknown	150	0
10.07.1957	Alaska	Lituya Bay	0.03	525	2
30.10.1963	Northern Italy	Vajont	0.285	250	1920
18.10.2015	Alaska	Taan Fjord	0.06	193	0
17.06.2017	Greenland	Karrat Bay	0.01	90	4
21.04.2007	Chile	Aisen Fjord	0.02	65	8
11.12.2018	Russian Far East	Bureya	0.025	90	0
					Total ~2000

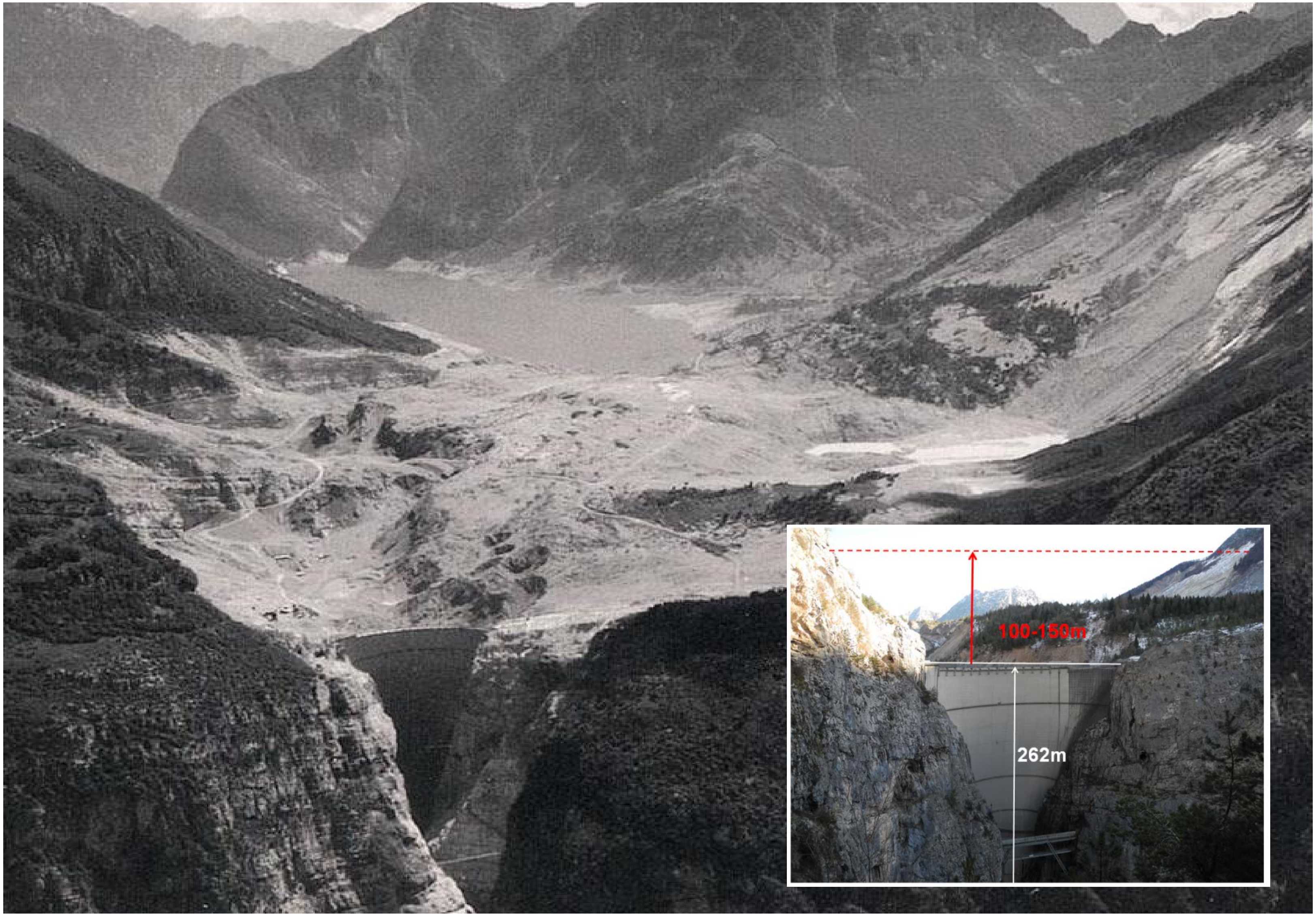


The Storegga landslide in the Norwegian Sea. Tsunami with heights up to 10-12 m. Age 6225–6170 BC. Total volume ~3,500 cu. km



Lituya Bay, Alaska, 07.10.1958. V=30 mln m3, Hm=525 м. Mw=7.8

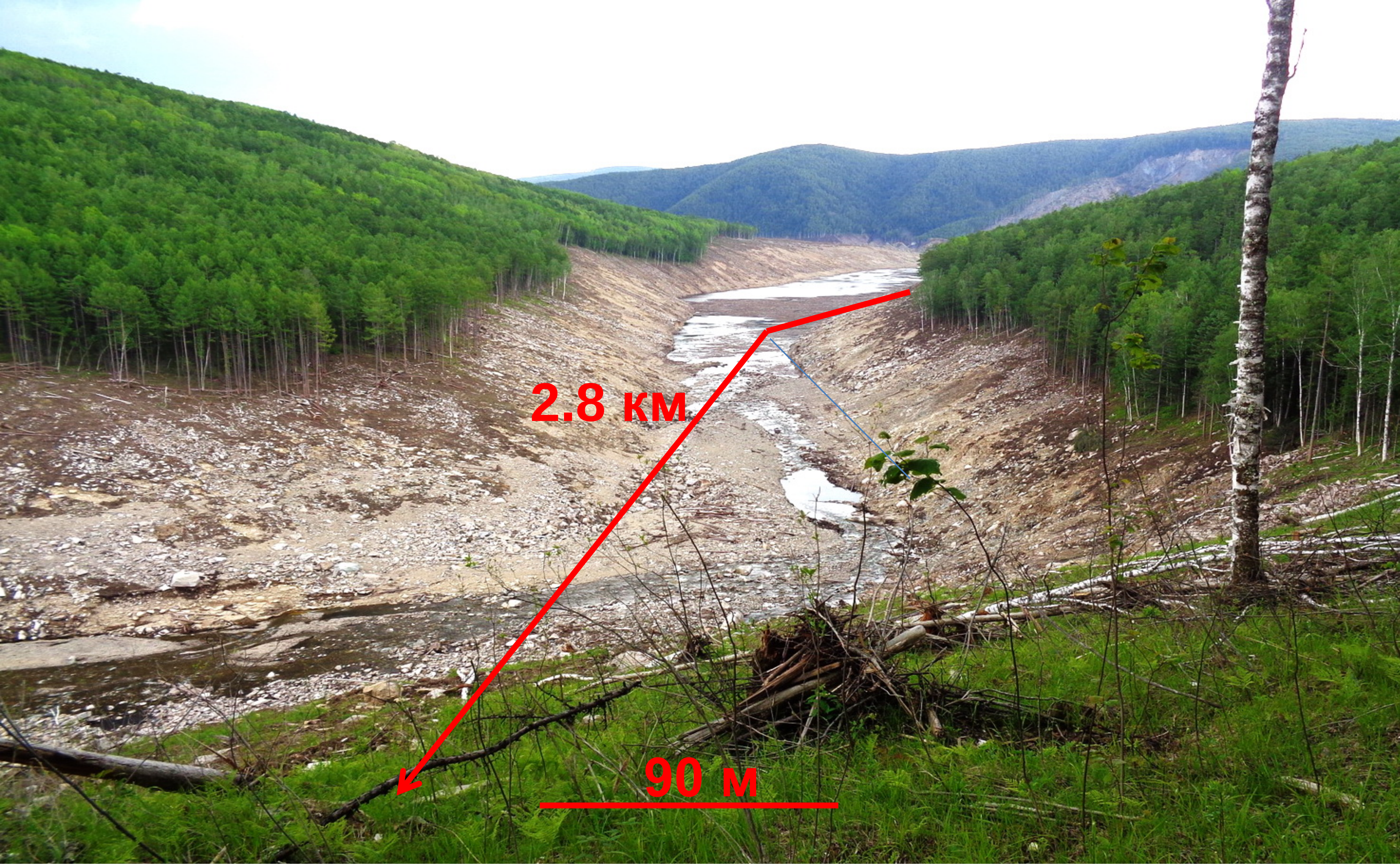
The October 10, 1963 Vajont Dam (northern Italy) catastrophe. 250 m wave and 1910 fatalities. Estimated volume of landslide is about 270 million cubic meters.



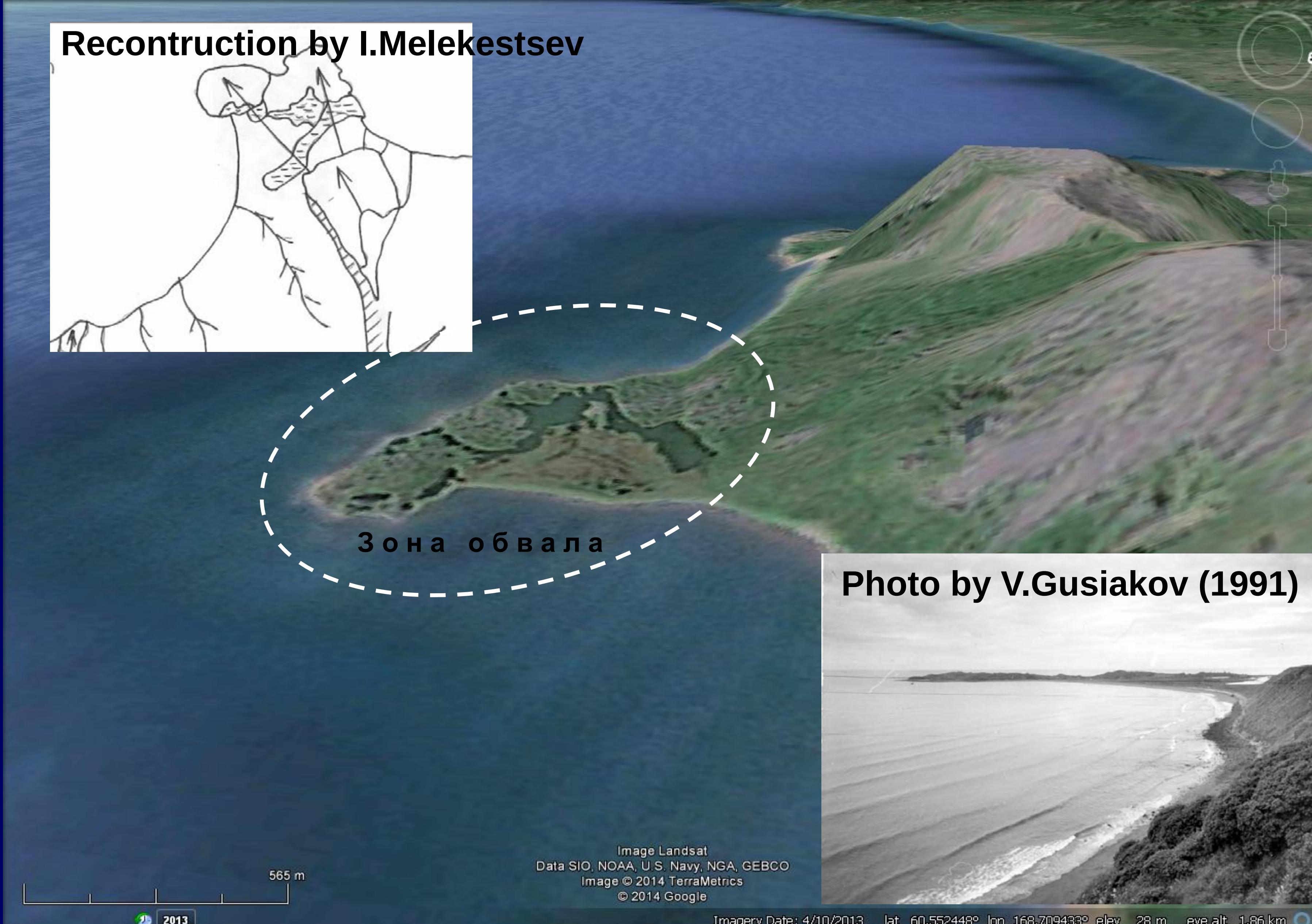
Aerial view of Vajont Dam and Reservoir, taken a few days after the disaster

Burea landslide of December 11, 2018

High resolution photo of the escarpment bowl and the slide body made from quadrocopter on 19.06.2019.



The maximum run-up height was measured in the same valley at the distance of 2.8 км from the landslide. The limit of inundation was marked by pieces of wood left by water on the altitude of 90 meters above the initial water level.



A large (volume of about 500 million cubic meters) seismotectonic collapse at the cape "Baptized by Fire" (northen Kamchatka), undoubtedly accompanied by a destructive local tsunami. C14 date of the event 1660±40 BP. (Melekestsev, Kurbatov, 1997)

Seismogenic landslide at the Cape Bolshoy Utrish (NE coast of Black Sea). Estimated volume 0.3-0.5 km3. (Popkov et al. 2017). Supposed age – middle Holocene. Exact dating of slide is still absent. Run-up at the nearest coast could be hundreds of meters

Paleo-tsunami in the Baikal Lake. Volume of slide ~45 km^3, age ~125 Ka
Tsunami wave overtopped the mountain ridge with elevation 600 m above lake level

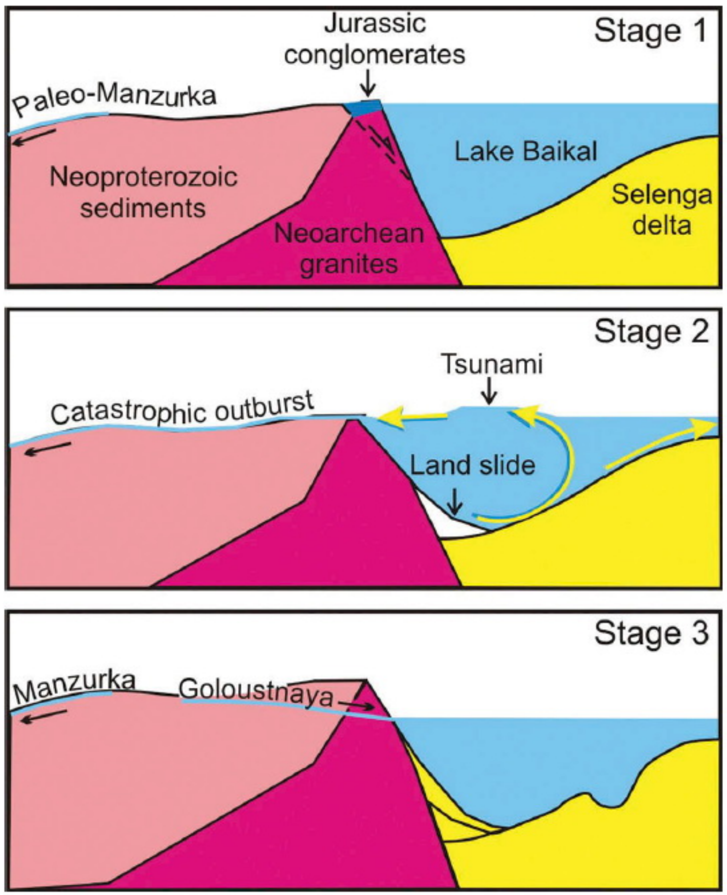


Figure 7. Schematic representation of a model for the catastrophic outburst of Lake Baikal waters through the Palaeo-Manzurka due to a giant landslide and followed by a mega-tsunami (stage 2). Stages 1 and 3 denote the pre-

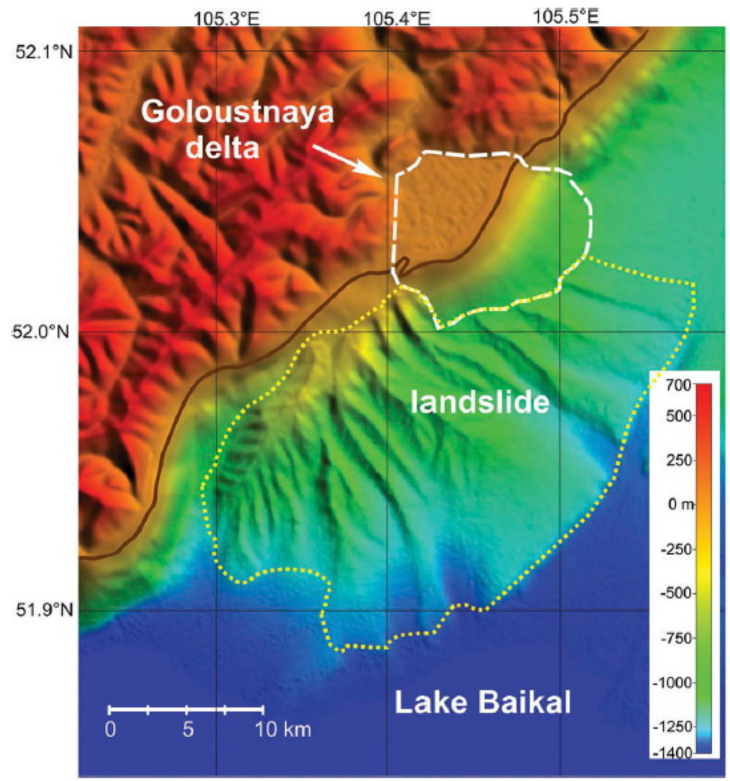
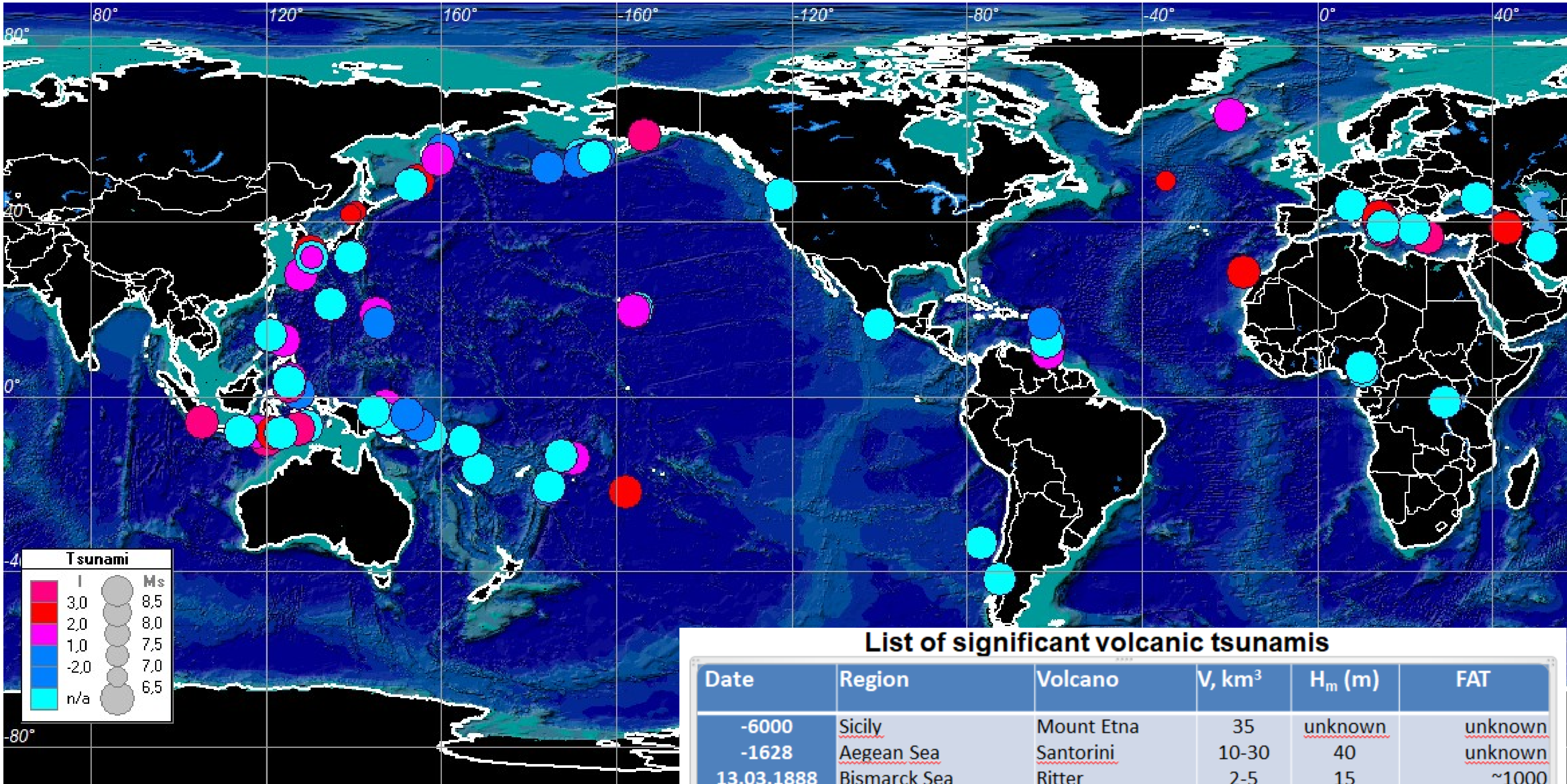


Figure 8. Bathymetry map of the region of the supposed landslide (with minor modifications after Khlystov *et al.* 2014). Note: Khlystov *et al.* (2014) interpreted the landslide as a palaeodelta of Goloustnaya covered by its modern deltaic sediments.

major earthquake. The remnants of the giant landslide are evident from both underwater relief and the char-

Ivanov et al (2016) Catastrophic outburst and tsunami flooding of Lake Baikal // International Geology Review. http//dx.doi.org/10.1080/00206814.2015.1064329'

Global map of volcanic tsunami sources. 140 sources are shown.

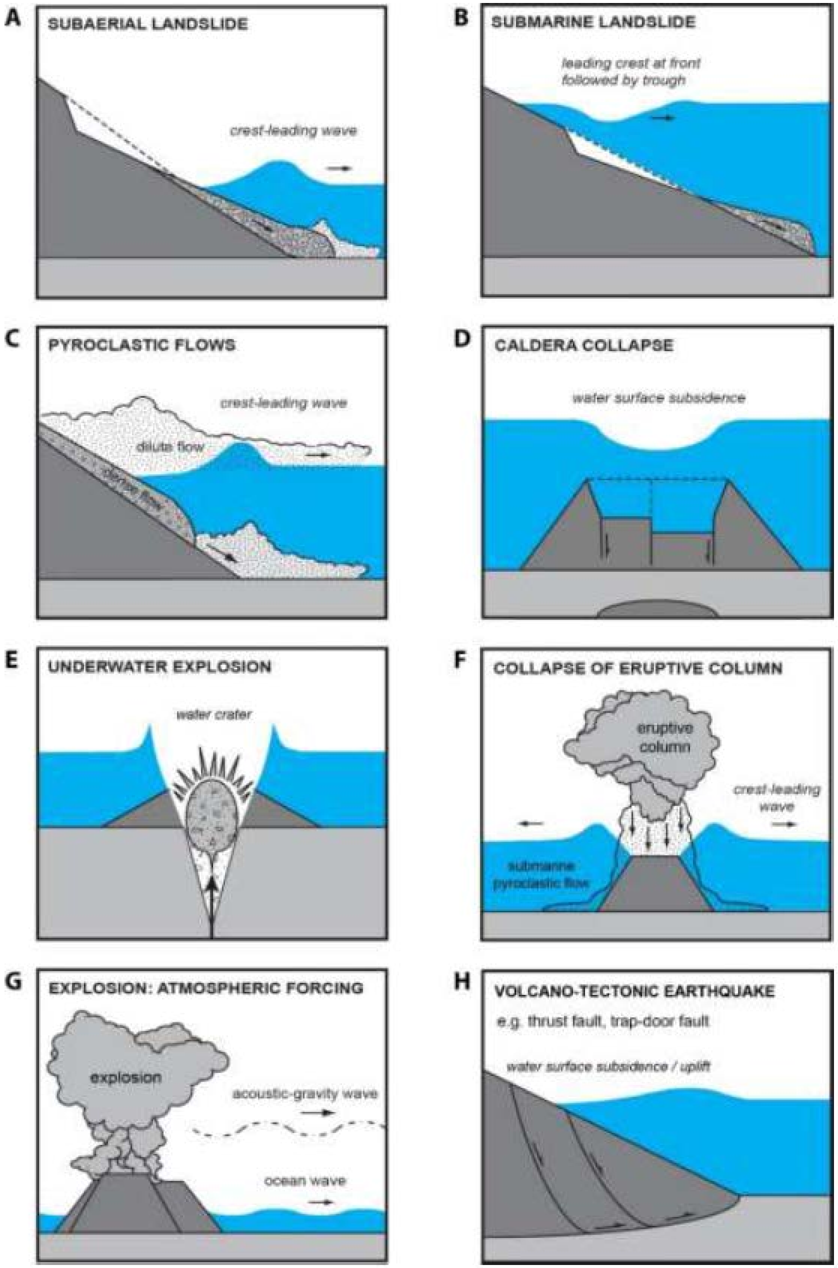


List of significant volcanic tsunamis

Date	Region	Volcano	V, km³	H_m (m)	FAT
-6000	Sicily	Mount Etna	35	unknown	unknown
-1628	Aegean Sea	Santorini	10-30	40	unknown
13.03.1888	Bismarck Sea	Ritter	2-5	15	~1000
29.08.1741	Sea of Japan	Oshima	2.4	13	2000
21.05.1792	East China Sea	Mount Unzen	0.34	57	11000
27.08.1883	Indonesia	Krakatoa	18-20	35	36417
13.03.1888	Bismarck Sea	Ritter	2-5	15	~1000
19.02.1965	Chile	Yate	0.06	60	27
29.11.1975	Hawaii islands	Kilauea	-	14	2
21.08.1976	Cameroon	Lake Nyos	0.0003	24	1700
18.05.1980	USA	Saint Helens	0.21	250	0
22.12.2018	Indonesia	Krakatoa	0.0003	85	447
15.01.2022	Tonga	Hunga Tonga	-.	22	6
					Total ~ 45000

Color represents the tsunami intensity on Soloviev-Imamura scale. Estimated fatalities about 45,000

Basic types of volcanic tsunamis, generated by volcano activity and instability *(after Paris et al., 2014).*

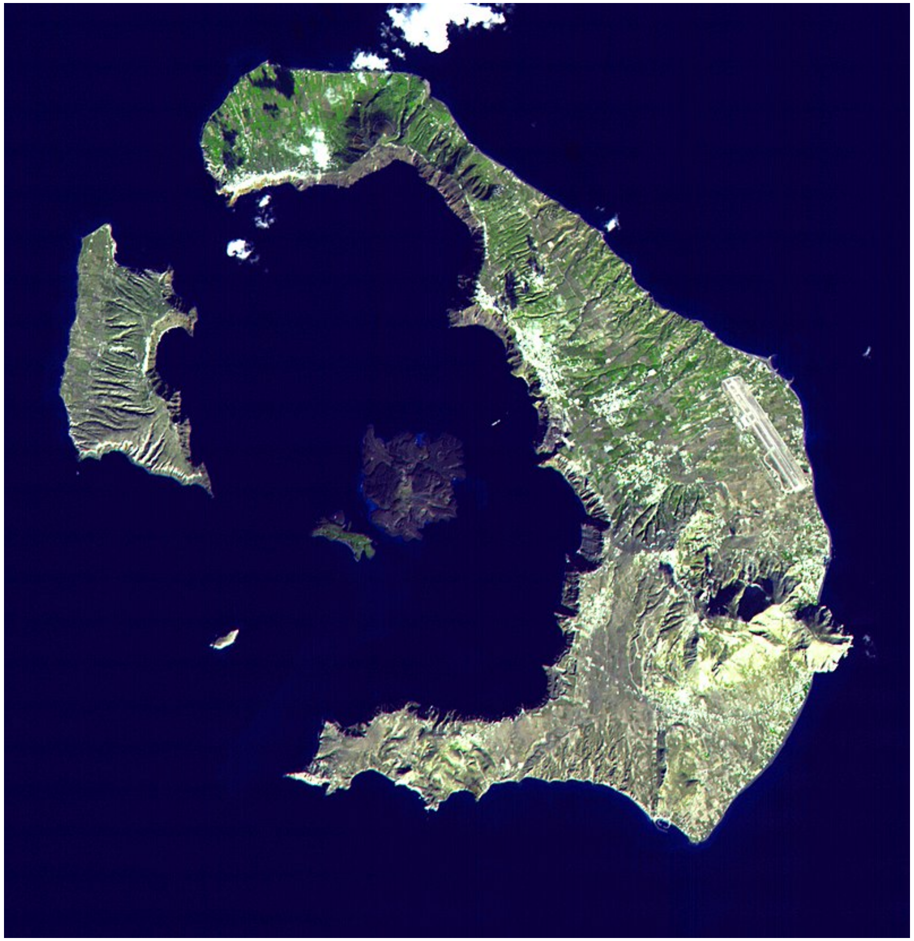


As a rule, process is complex and in each particular case, even in most studied cases, like Krakatau 1883, it is difficult to clearly identify the leading mechanism of tsunami generation

One more type of mechanism is still absent - “volcanic lake overturn”

21.08.1986 Lake Nyos limnic erupion
1700 fatalities, Hmax = 24 m

1628 BC Santorin eruption



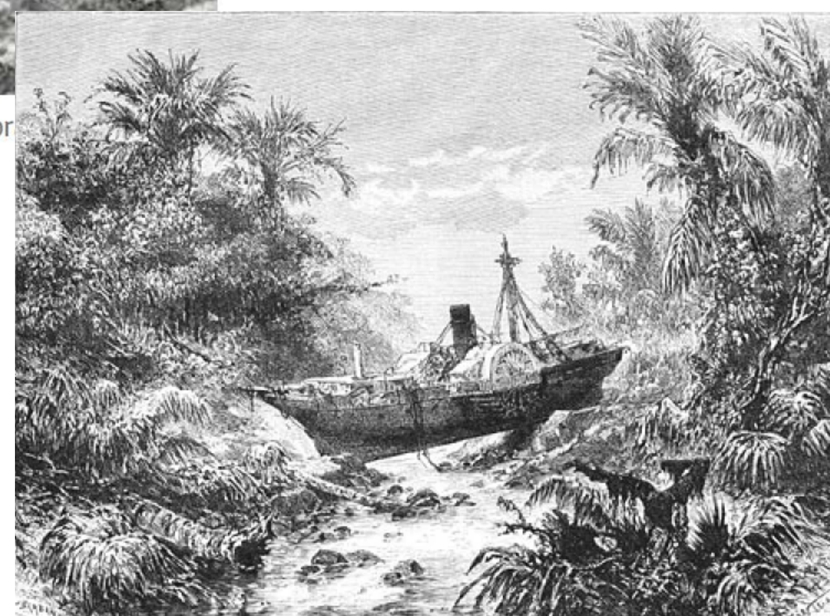
Dates of eruption vary in the range from 1524 to 1681 BCE. The eruption generated 35 to 150 m high tsunami that devastated the northern coastline of Crete and can lead to decline of the Minoan culture. No doubt, tsunami resulted in numerous fatalities but its number is difficult to assess.

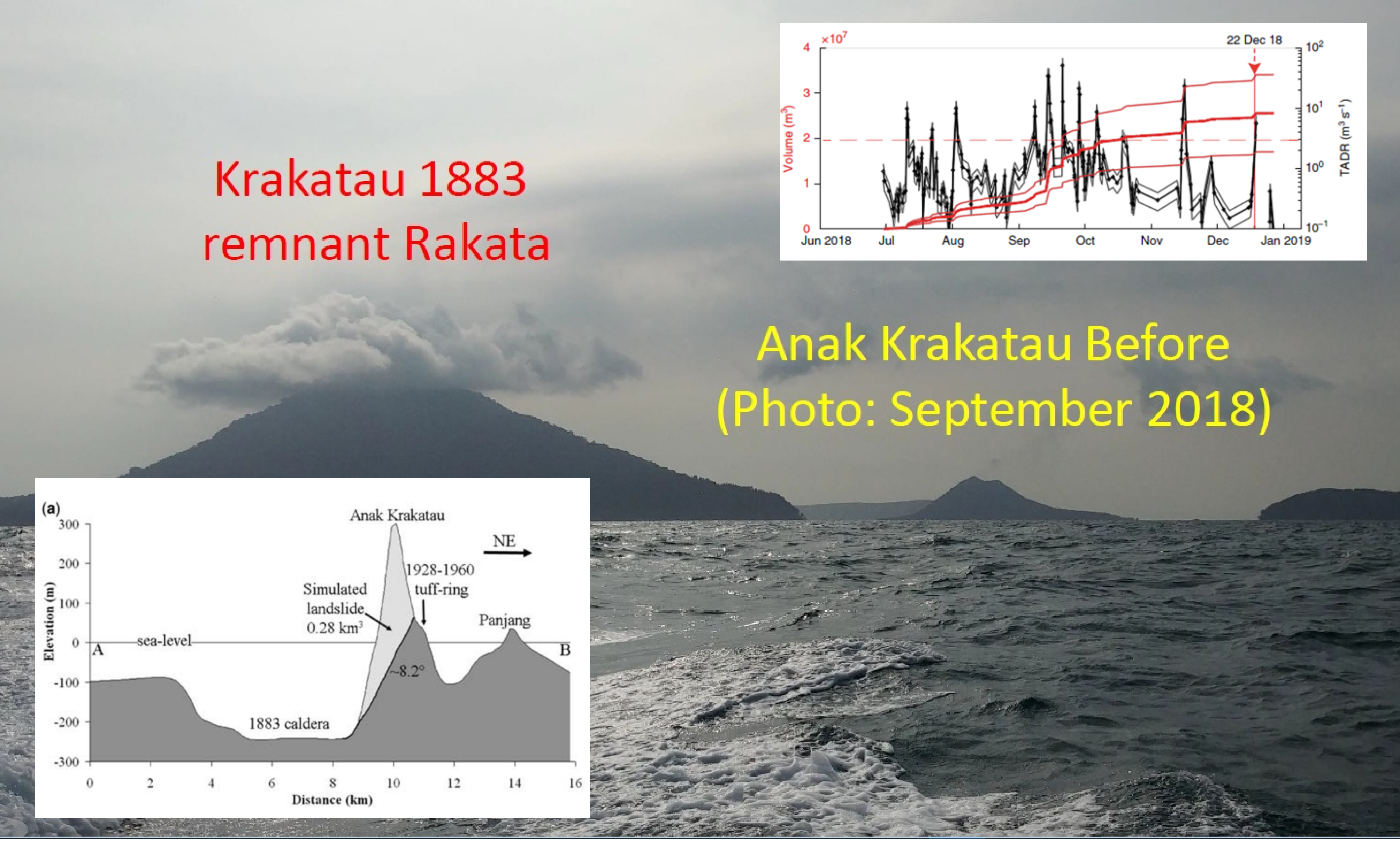
The 1883 Krakatoa eruption and tsunami

Eruption of the volcano on Krakatoa, August 1883. Photograph: Dea Picture Libr
Agostini/Getty Images

Maximum un-up 35 m

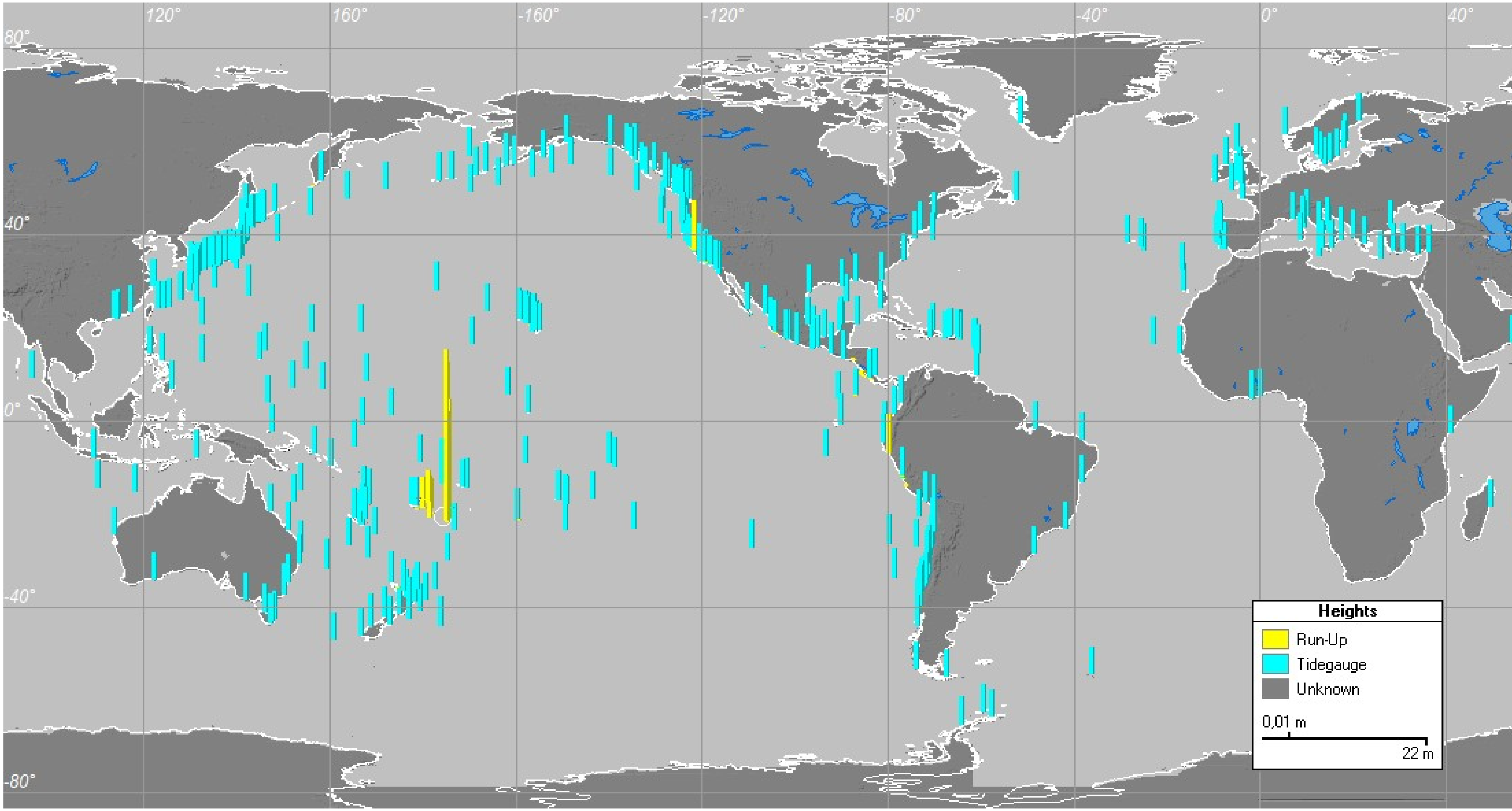
Number of fatalities -36,417, presently adopted In the catalogs, can be not correct. Some contemporary sources indicated digits up to 80,000 victims





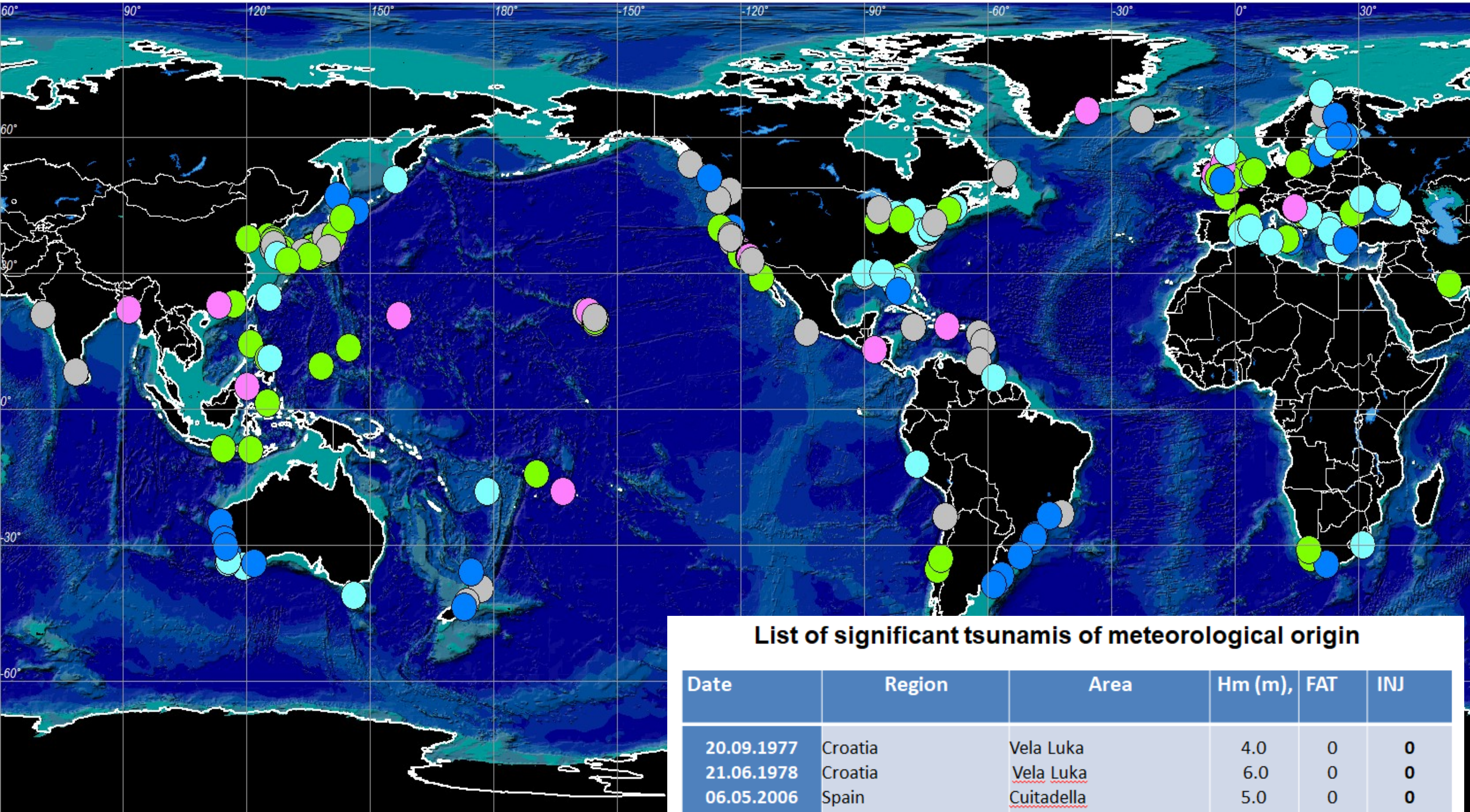
Fritz H., Solihuddin T., Synolakis C., Prasetya P., Borrero J, Skanavis V., Husrin S., Kongko W., Istiyanto D., Daulat A. , Purbani D., Salim H., Hidayat R., Asvaliantina V, Usman U., Kodijat A. The 2018 Anak Krakatau tsunami: Near-source field survey on Islands in the Sunda Strait // International Symposium on the Lessons Learnt from the 2018 Tsunamis in Paluand Sunda Strait 26-28 September 2019, Auditorium BMKG, Jakarta - Indonesia.

Observed and measured run-up heights (yellow) and wave amplitudes (blue) for Hunga-Tonga – Hunga-Huapai tsunami of January 15, 2022



664 heights are shown for the Hunga-Tonga event (4th place in the Global Tsunami DB by number of heights mesurements). The rest of 31 tsunamigenic events for the last two years (since July of 2021) have only 180 heights measurements in total

Source map of 233 meteotsunamis currently available in the NTL/ICMMG Tsunami DB



Color represents the event intensity on Soloviev-Imamura scale. Confirmed meteotsunami fatalities since 1954 – 23 people (possibly not complete)

List of significant tsunamis of meteorological origin

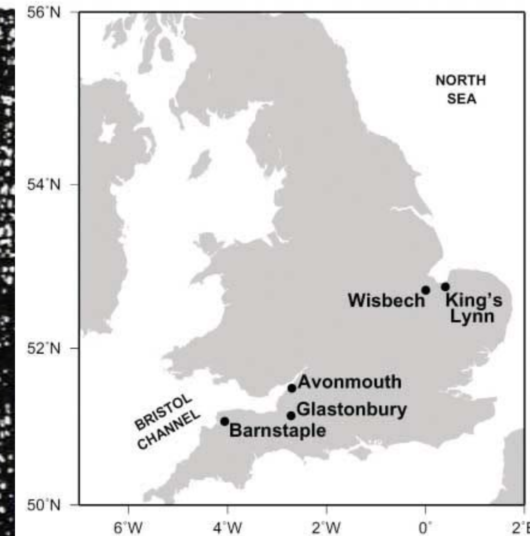
Date	Region	Area	Hm (m),	FAT	INJ
20.09.1977	Croatia	Vela Luka	4.0	0	0
21.06.1978	Croatia	Vela Luka	6.0	0	0
06.05.2006	Spain	Cuitadella	5.0	0	0
03.31.1979	Japan	Nagasaki Bay	4.8	3	0
10.28.2008	USA	Boothday Harbor	4.0	0	0
10.05.1984	Croatia	Ist Island	4.0	0	0
08.22.2007	Croatia	Ist Island	4.0	0	0
07.04.1992	USA, Florida	Daytona Beach	3.6	0	75
06.26.1954	USA	Michigan	3.0	7	0
03.19.2017	Iran	Dayyer	3.0	6	0

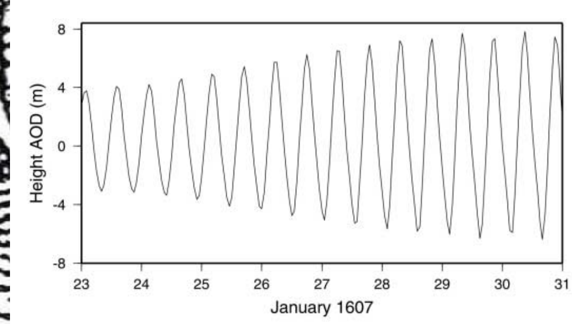
Meteotsunami of June 21, 1978 In Vela Luka (Croatia)

The maximum range of water ocsillation exceeded 6 m. Total duration of the event – several hours. Large damage, but there were no human fatalities

An enigmatic flood of 1607 in Bristol Channel

17th century woodcut, Bristol Channel
(source: S. K. Haslett, 2008. *Coastal Systems* (2nd ed), Routledge, London).





1607 Bristol Channel Flood occurred on January 30 at 9 am of local time on a fine day. It flooded more that 570 km of coastline and killed 2000 inhabitants (British worst natural disaster). Along the coast, the flood left transported and imbricated boulders and, at some locations, clear signs of bedrock sculpturing *(Bryant, Haslett, 2007).*

Pararas-Carayannis G. (2019) Meteotsunami of 29 August 1916 at Santo Domingo – Analysis of the destruction of the USS "Memphis"

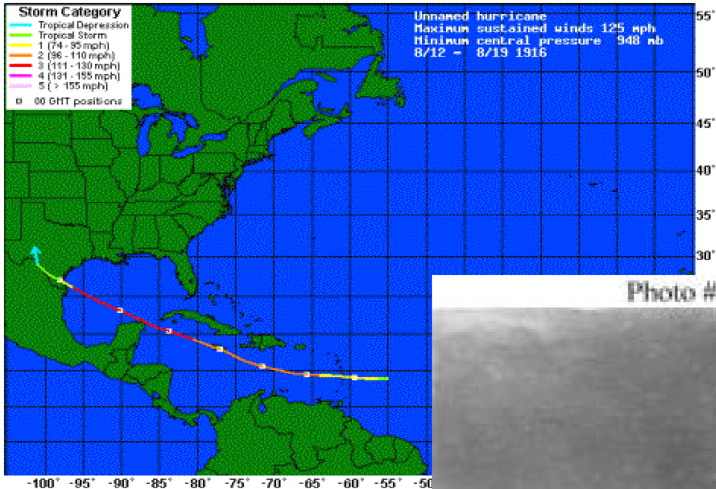
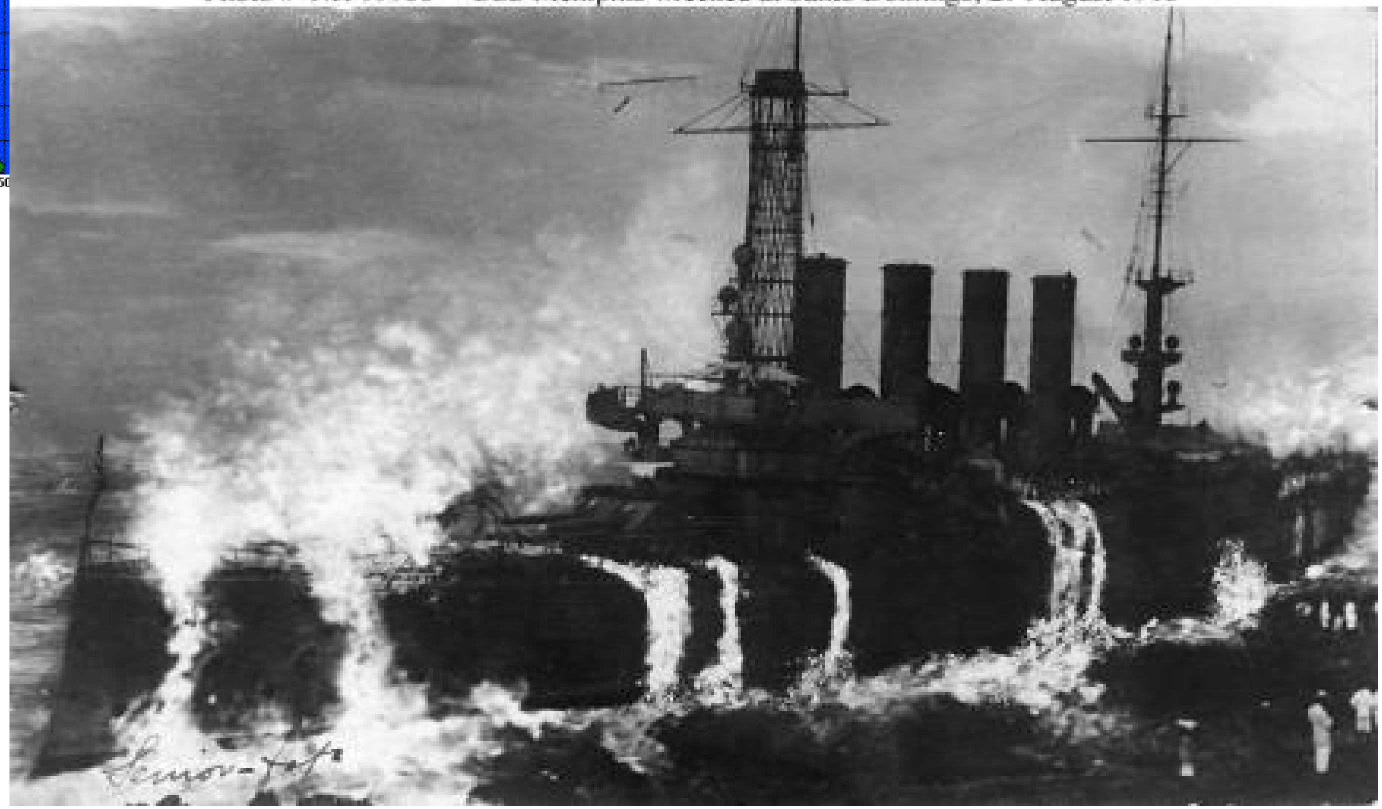
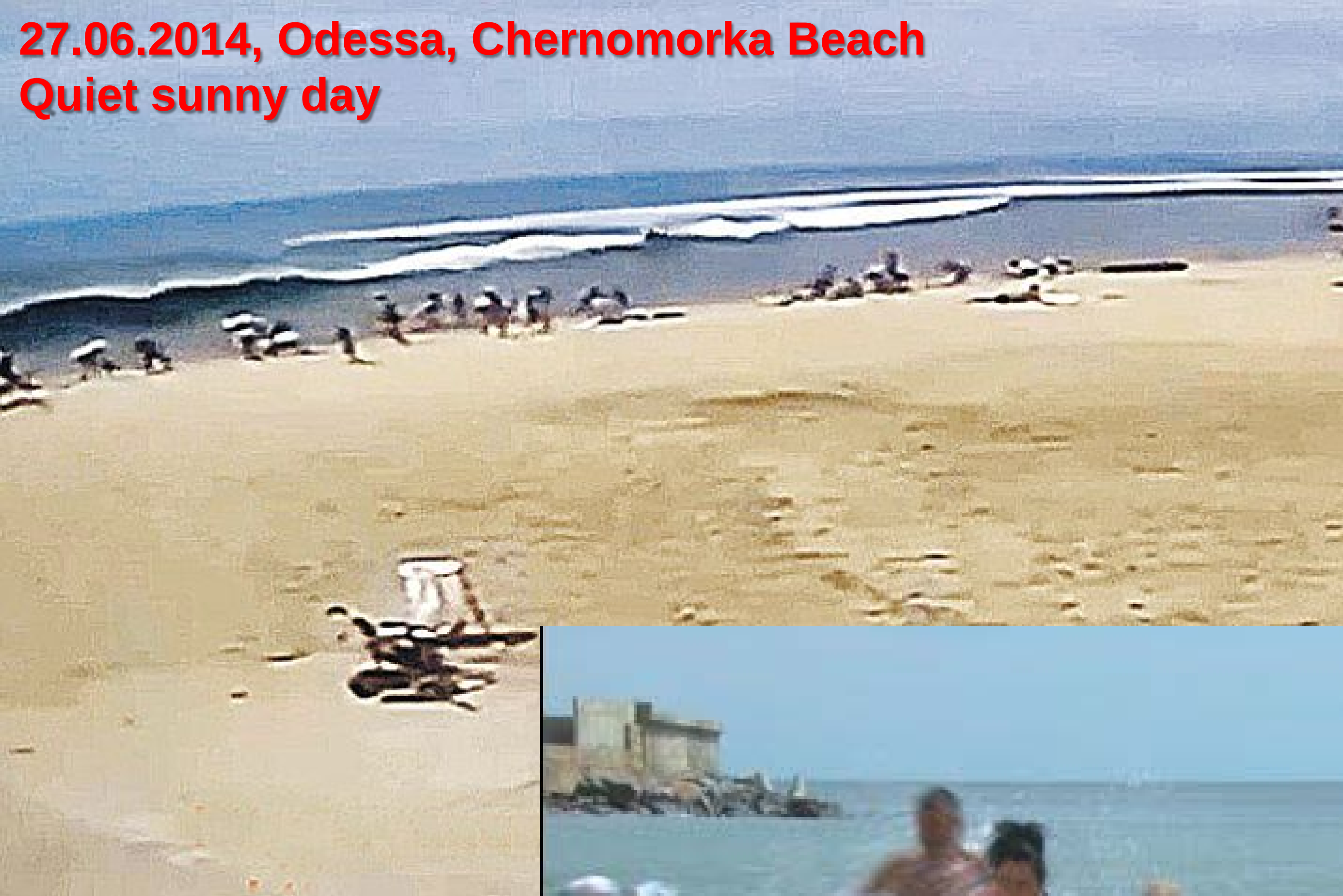


Photo # NH 99960 USS Memphis wrecked at Santo Domingo, 29 August 1916



The USS 14,500-ton cruiser "*Memphis*" on the rocks of Santo Domingo being pounded by 21-m waves of the 29 August 1916 meteotsunami and of the superimposed storm swells (Pararas-Caraynnis, 2019). The most significant wave that hit *Memphis* was about 21 m in height. 43 persons died and 204 were injures during this event.

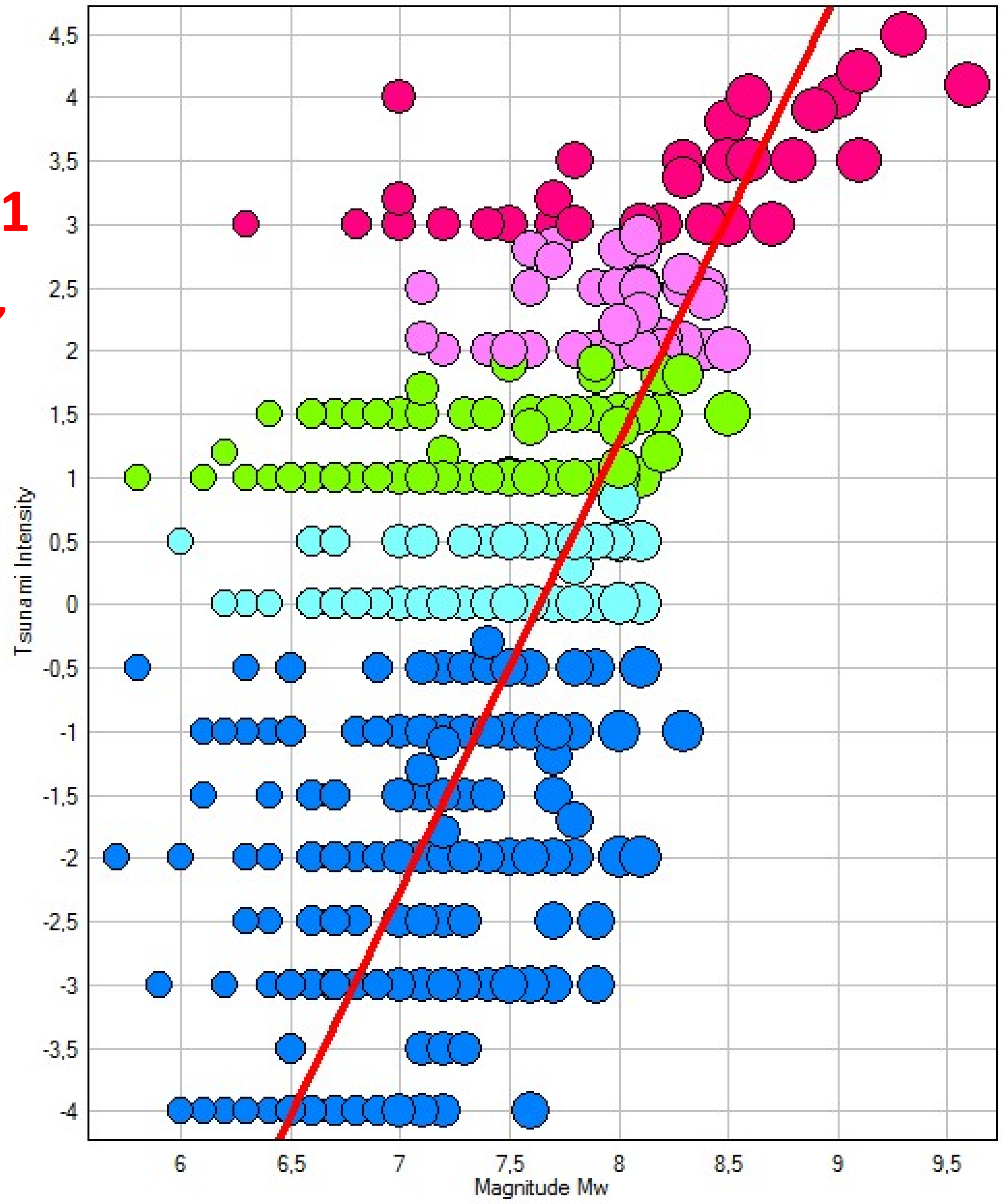


Odessa tsunami of June 27, 2014 11:50 local time Two single waves with height of 1.0 – 1.5 m soddenly hit the beach, flooding range was 40-50 m

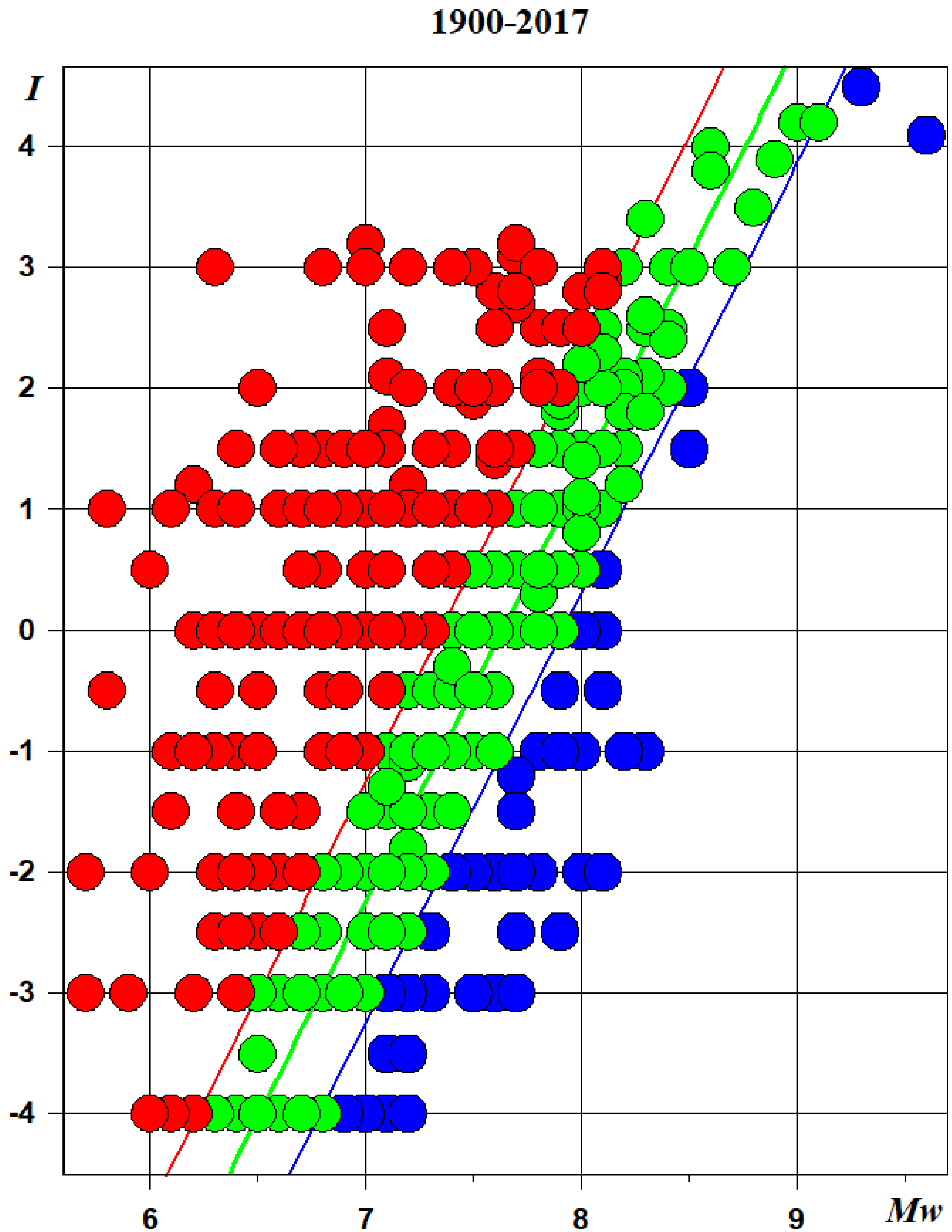
There were no fatalities, but about 20 people applied for medical help (Nikonov, Fleifel, 2015)

I = 3.55 Mw –27.1

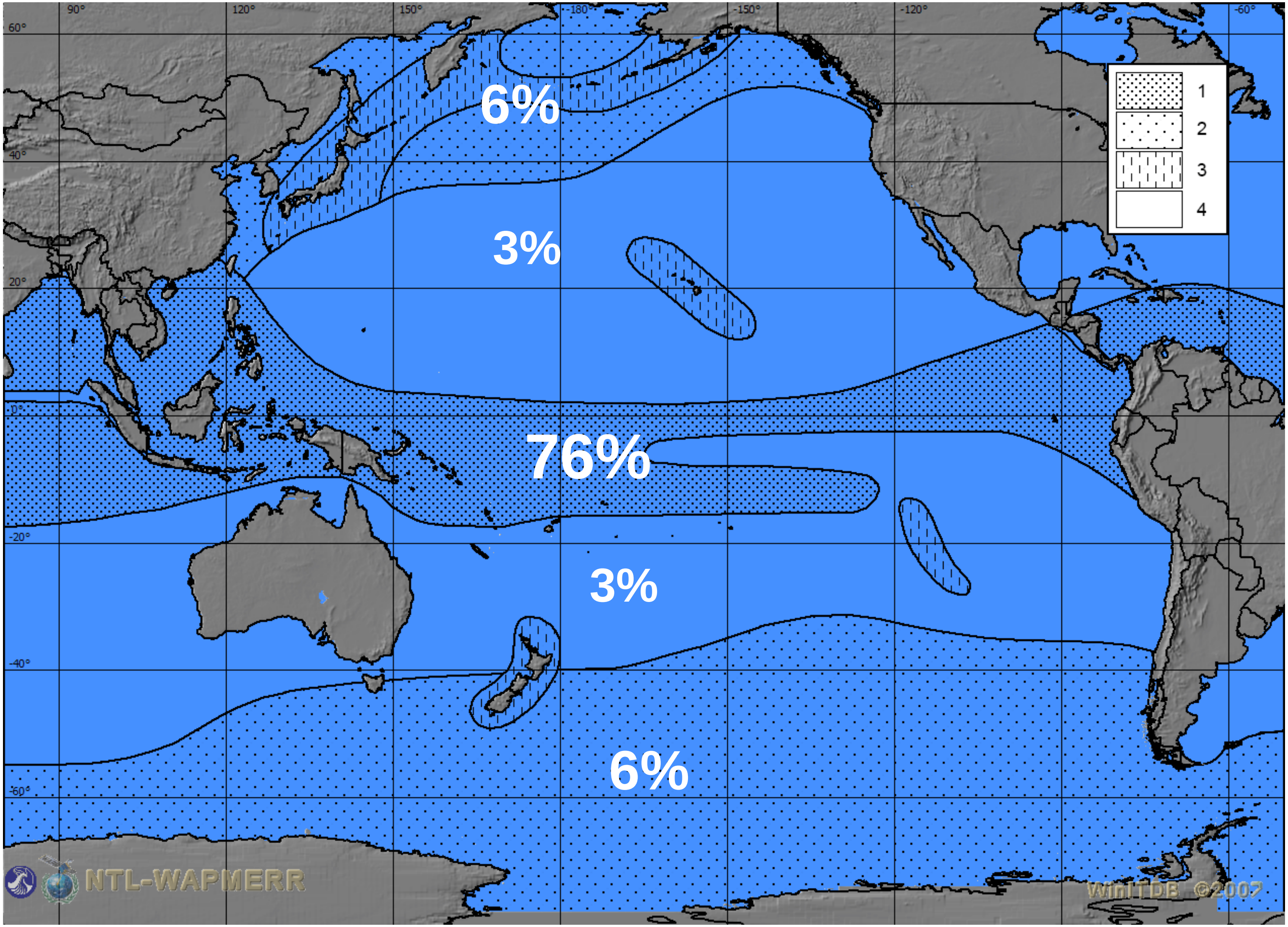
(Gusiakov, Chubarov, 1985)



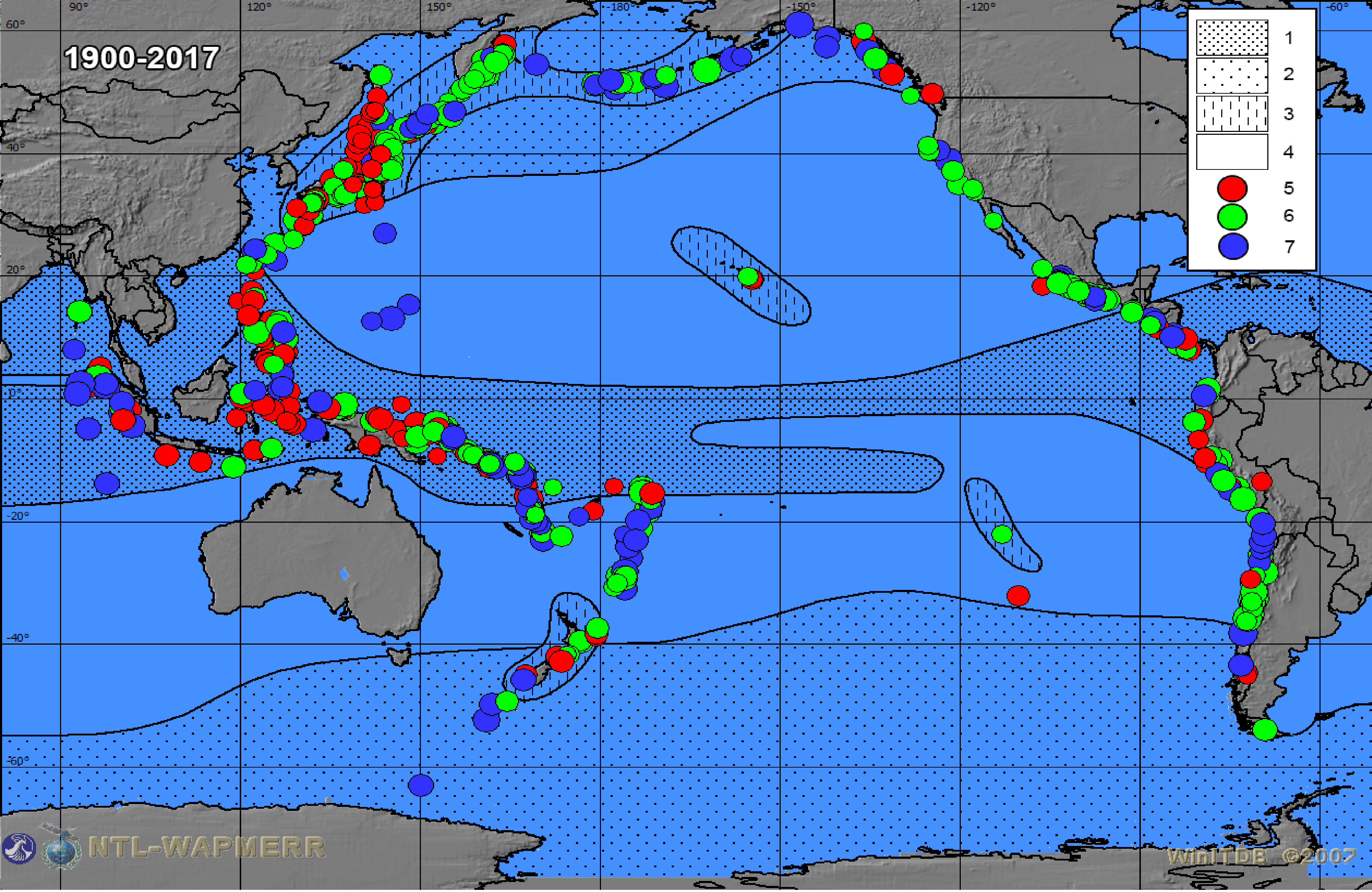
Dependence of tsunami intensity (on the Soloviev-Imamura scale) on magnitude Mw for Pacific underwater earthquakes for the period 1901-2020.



Dependence I(Mw) for “red”, “blue” and “green” tsunamigenic events in the Pacific Ocean (for 1900-2017)



The main zones of lithogenesis in the Pacific Ocean (1 - equatorial humid zone, 1 - northern and southern humid zones, 3 - zone of effusive-sedimentary lithogenesis, 4 - northern and southern arid zones), identified in the monograph by A.P. Lisitsin (1974) " Sedimentation in the oceans."



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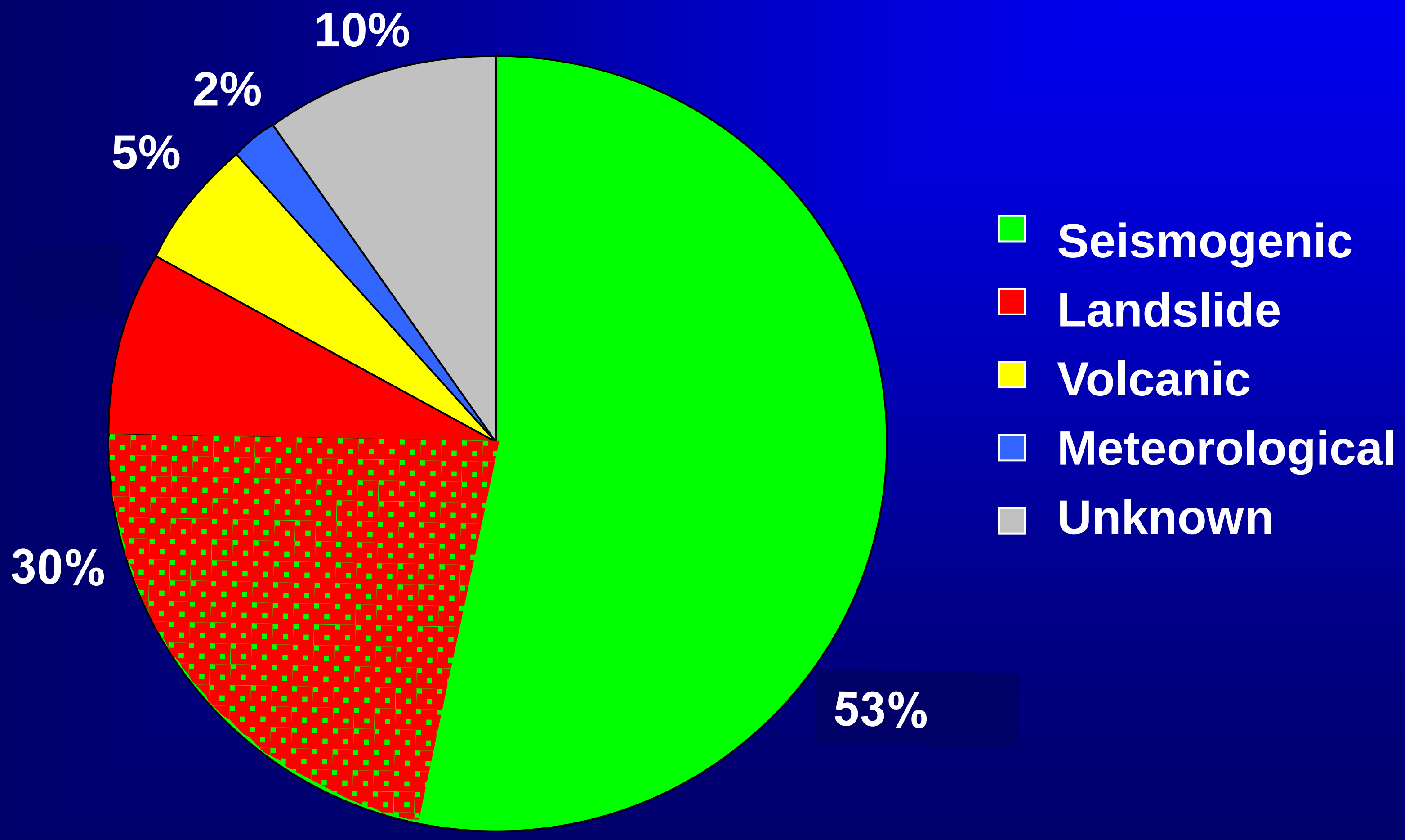
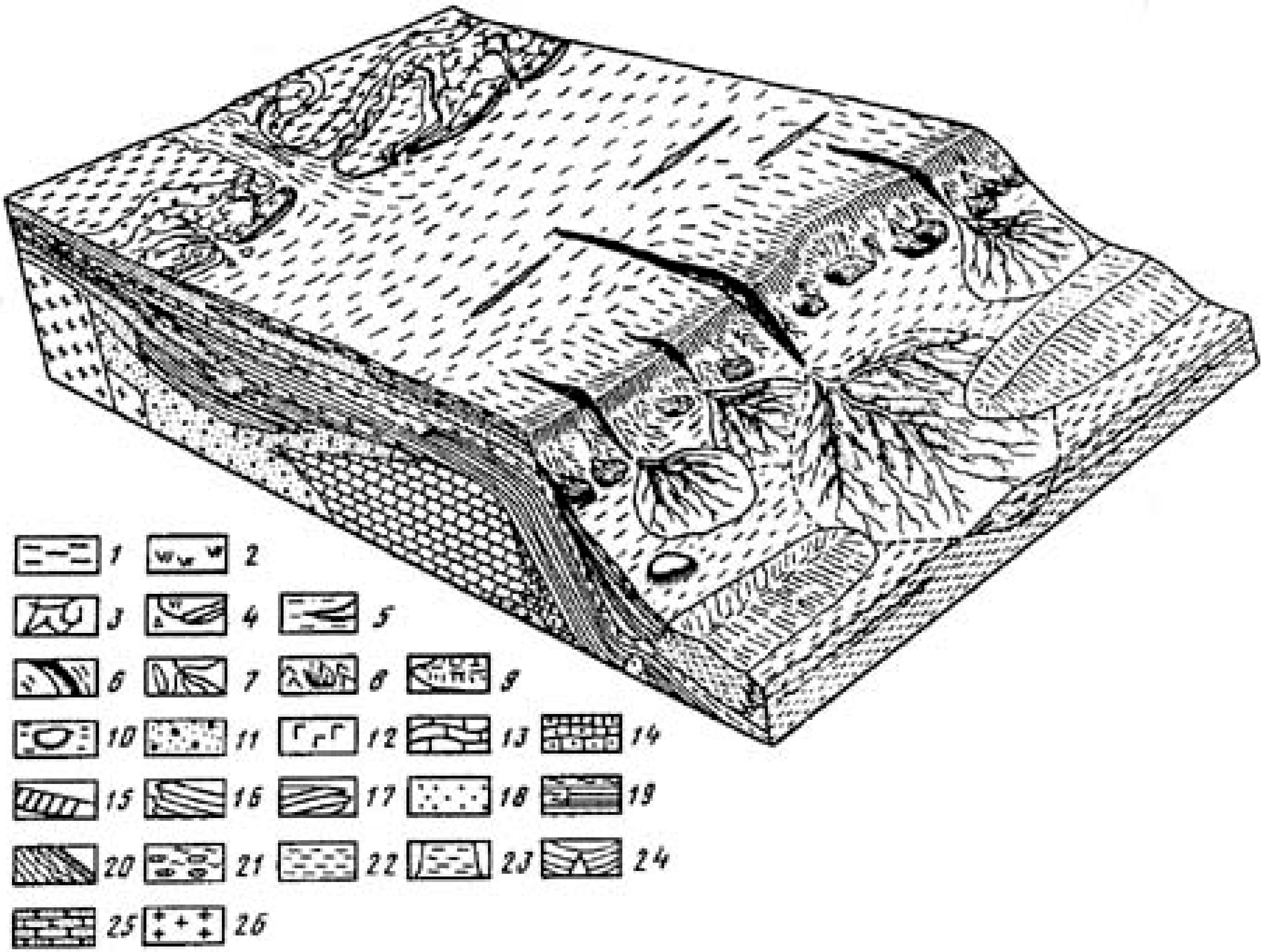
Cause of Tsunami



Lisitsyn A.P. Avalanche sedimentation and breaks in marine sediments // Moscow: Nauka, 1988, 309pp.



Two levels in oceanic sedimentation

Some conclusions

- Any kind of statistics about breakdown of generation mechanisms for non-seimic tsunamis should be considered with caution having in mind the large uncertainties in historical data especially for pre-instrumental period.

- Operational prediction of landslide-generated tsunamis is hardly possible since their triggering mechanism varies greatly or even can be absent at all.

- The main problem in prediction of volcanic tsunamis is large variety of their generation mechanisms which can be unique in each particular case.

- Meteotsunamis present the growing hazard especially in the coastal areas where seismogenic tsunamis rarely occur. Besides their occurrence is not covered by the existing TWSs.

- In general, non-seismic tsunamis represent less than a quarter of all tsunamigenic events but can produce the greater hazard due to their short propagation time, unexpectedness and unpredictability

THANKS FOR YOUR ATTENTION