МЕГА-ЦУНАМИ МИРОВОГО ОКЕАНА: ОПРЕДЕЛЕНИЕ ТЕРМИНА И ПРОБЛЕМЫ ИДЕНТИФИКАЦИИ В КАТАЛОГАХ

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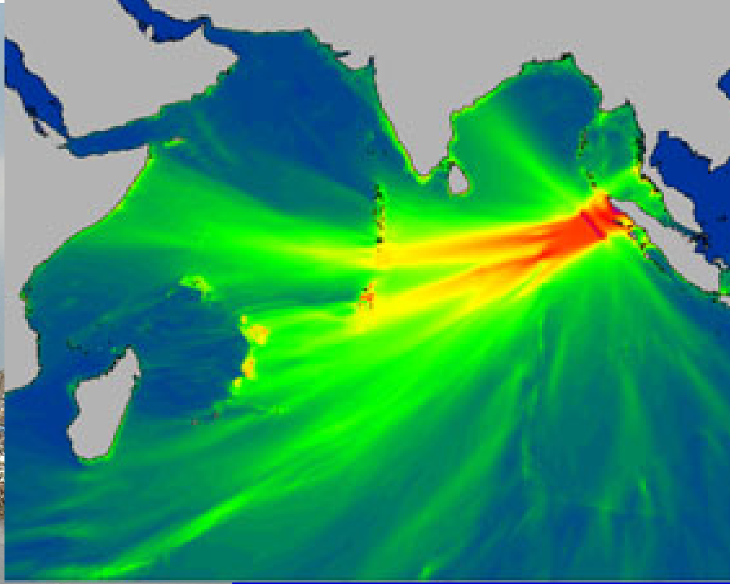
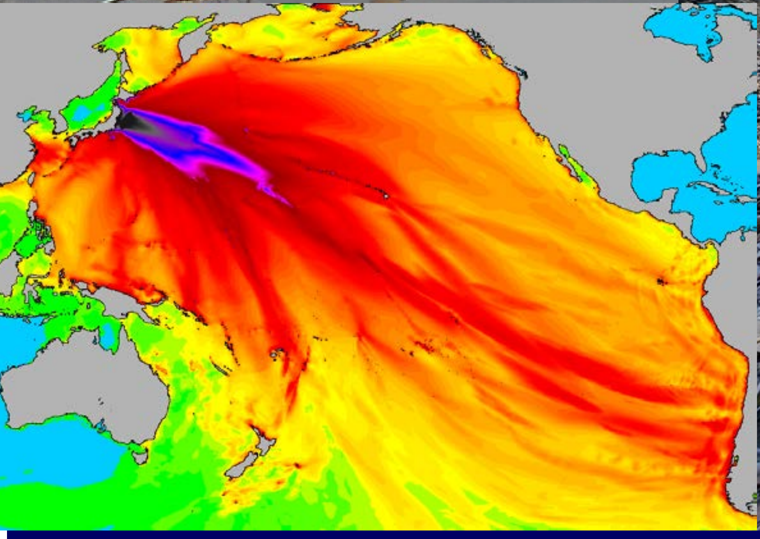
Indian Ocean tsunami of December 26, 2004, 228,000 fatalities. Destruction of the coastal area of Banda Aceh



Tohoku tsunami March 11, 2011, 18,428 fatalities Destruction in Rikuzen-takata, Miyako Prefecture, Japan



Ferrer M., González-de-Vallejo, L.I. Global Historical Megatsunamis Catalog (GHMCat). GeoHazards 2024, 5, 971–1017.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Global Historical Megatsunamis Catalog (GHMCat)

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Abstract: The Global Historical Megatsunamis Catalog (GHMCat) is presented for the first time, including events with the largest waves recorded in historical times. An objective criterion is established to identify megatsunamis based on the maximum wave height (runup) of all recorded events. A threshold value of 35 m for maximum wave height is proposed based on the analysis of the statistical distribution of the maximum wave heights documented. The catalog was compiled through a systematic review and verification of tsunami events from the two existing Global Historical Tsunami Databases (GHTDs). A list of 40 megatsunamis from 1674 to the present is presented, including descriptions of their maximum wave heights, causes and sources according to the available and verified information, along with the main bibliographical references that support the data gathered in the catalog. The majority of megatsunamis have originated from large landslides, predominantly subaerial, with fewer caused by submarine landslides or associated with volcanic explosions. The geographical distribution of source locations shows that megatsunamis most frequently occur in bays and fjords in glaciated areas and in inland bodies of water, such as lakes and rivers. Notably, certain regions of Alaska and Norway experienced an unusual frequency of megatsunamis, particularly in the early 20th century. The information provided by the GHMCat allows for a comprehensive historical overview of megatsunamis, establishing relationships between their causes, wave heights, and geographic distribution over the past 350 years. This may contribute to advancing the study of the causes and origins of megatsunamis and aid in their prevention in high-risk regions.

Keywords: megatsunamis; historical megatsunami catalog; landslide tsunamis; Alaska tsunamis; Norway tsunamis

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1. Introduction

The main objective of this study is to present a comprehensive global catalog of historical megatsunamis, compiling and describing all events documented to date through written records from eyewitnesses or direct observations and measurements.

Megatsunamis, or giant waves, are extreme events that impact cliff shores in any geographical or climatic region, contingent upon the presence of a body of water and the occurrence of a geological triggering process with sufficient energy to cause a sudden and large vertical displacement of water, generating waves of great height.

Despite lacking a strict or universally agreed definition, the term megatsunami has been widely used in scientific publications in recent decades, primarily associated with prehistoric oceanic tsunamis linked to large bolide impacts and giant volcanic-island-flank collapses [1–5]. Additionally, it has been arbitrarily applied to extensive and destructive trans-oceanic tsunamis such as those in Indonesia in 2004 and Japan in 2011, as well as earlier events in the Aleutians in 1946, Chile in 1960, and Alaska in 1964 [6].

Megatsunamis are local events originating from nearby sources, with their effects confined to small areas, as the wave height rapidly decreases with distance from the source. Unlike conventional tsunamis triggered by offshore earthquakes, megatsunamis can reach

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<u>Megatsunami</u> is defined as a giant wave with a height of 35 m or more

Megatsunamis are local events originating from nearby sources, with their effects confined to small areas, as the wave height rapidly decreases with distance from the source.

Most historical megatsunamis have been generated by large subaerial landslides, with some cases involving submarine landslides and a few cases related to violent volcanic eruptions.

In total, 40 megatsunamis (i.e., those with wave heights ≥35 m) have been identified in the two existing Global Tsunami Databases for the period from 1674 to 2024 and Global Historical Megatsunami Catalog (GHMCat) has been formed.

Ferrer M., González-de-Vallejo, L.I. Global Historical Megatsunamis Catalog (GHMCat). GeoHazards 2024, 5, 971–1017.

Appendix A

Table A1. Historical megatsunamis with Hmax ≥35 m recorded in the global databases NCEI/WDS [12] and TL/ICMMG [13] as of June 2024.

Date	Name/Place	Cause *	Runup (m) *
1600 BC	Santorini, Greece	V	90/-
1674	Ambon Island, Indonesia	LEq (6.8)/Eq (8)	100/80
1737	Kamchatka, Russia	Eq (8.5)	15/63
1741	Oshima Island, Japan	V/LV	90/10
1756	Langfjord, Norway	L/-	38/-
1771	Ryukyu Islands, Japan	Eq (7.4)/LEq	85.4
1788	Unga and Sanak Is., Alaska	Eq (8)	88
1792	Kyushu Island, Japan	LV/V	55/57
1853	Lituya Bay, Alaska	L	120
1880	Sitka, Alaska	LEq (6.3)	1.8/60
1883	Krakatoa Island, Indonesia	V	41/35
1896	Sanriku coast, Japan	Eq (8.3)/(8.5)	38.2
1899	Lituya Bay, Alaska	LEq (8.2)	61
1905	Lovatnet Lake, Norway	L	40
1934	Tafjord, Norway	L	62
1936	Lovatnet Lake, Norway	L	74/70
1936	Lituya Bay, Alaska	L	150
1946	Unimak Island, Alaska	LEq (8.6)/Eq (8.6)	42
1958	Lituya Bay, Alaska	LEq (7.8)/L	525
1963	Vaiont Reservoir, Italy	L	235
1964	Port Valdez Bay, Alaska	LEq (9.2)/Eq (9.3)	67
1965	Cabrera Lake, Chile	LV/V	60
1967	Grewingk Glacier Lake, Alaska	L	60
1980	Spirit Lake, EE.UU.	V	250
1985	Yangtze River, China	L	54
2000	Vaigat Strait, Greenland	L	50
2003	Qinggang River, China	L/-	39/-
2004	Sumatra Island, Indonesia	Eq (9.1)	50.9
2007	Aysén Fjord, Chile	LEq (6.2)/L	50/65
2007	Shuibuya Reservoir, China	L/-	50/-
2007	Chehalis Lake, Canada	L	38/37.8
2011	Sanriku coast, Japan	Eq (9.1)	39.7/42
2014	Askja Lake, Island	L/-	60/-
2015	Taan Fjord, Alaska	L	193
2017	Karrat Fjord, Greenland	L	90
2018	Bureya Reservoir, Russia	L	90
2018	Anak Krakatau, Indonesia	LV/V	85

L: Landslide, rockslide, or rock avalanche; LEq: Earthquake-triggered landslide, rockslide or rock avalanche; LV: Volcanic landslide; Eq: Earthquake (magnitude); V: Volcanic. * Where the two global databases differ, data from both are given (NCEI/WDS / TL/ICMMG).

The list of 40 megatsunamis that have been identified in the two existing Global Tsunami Databases for the period from 1674 to 2024

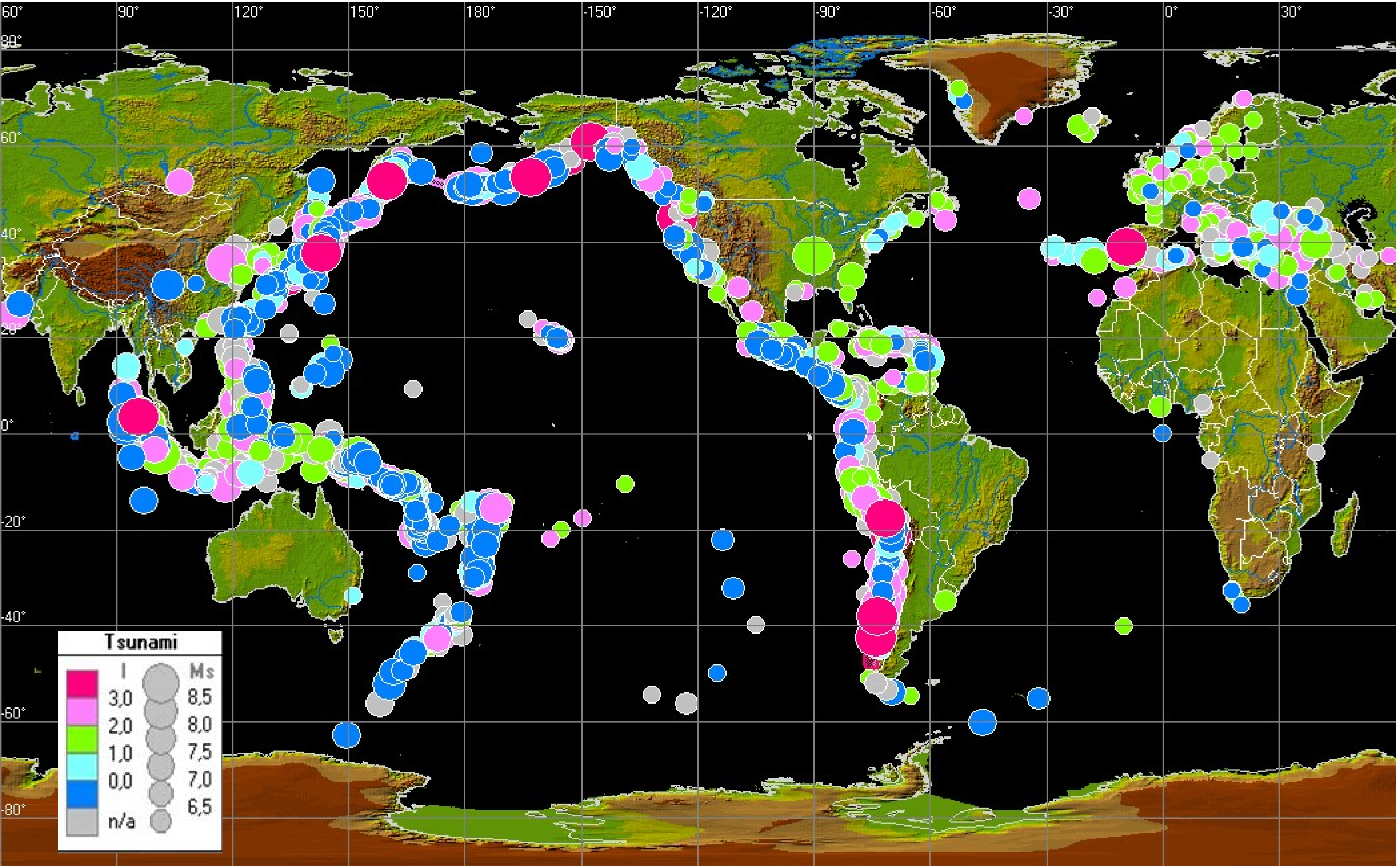
Appendix B. Relationships between Maximum Wave Height and Tsunami-Generating Processes Parameters

The relationships between maximum tsunami wave heights for Hmax >30 m and the physical parameters that characterize the size or magnitude of the geological processes causing the events have been analyzed: earthquake magnitude (M), volume of landslides, and volcanic eruption explosivity index (VEI). Both the volume of landslides and the VEI have been obtained from available literature on each of the investigated events. The earthquake magnitude has been initially obtained from the GHTDs and then verified.

Figure A1 shows the results, indicating that there is no significant relationship between these physical parameters and Hmax for each group: earthquakes, landslides, and volcanic eruptions. In the case of earthquakes (Figure A1A,B), historical events of the greatest magnitude have also been considered (Figure A1B), with no apparent correlation with maximum wave height documented for each case. Similarly, for tsunamis triggered by volcanic eruptions (Figure A1C), an illustrative example of this lack of correlation is the most explosive eruption in recorded history, the 1815 eruption of Mount Tambora in Indonesia, which had a VEI of 7 and generated a tsunami that reached a maximum height of only 3.5–4 m according to contemporary records [145].

Figure A1D,E show that there is no correlation between Hmax and the volume of displaced landslide masses that have entered bodies of water. Most tsunamis originating from large landslides fall within the Hmax range of 40 to 80 m, with volumes varying greatly but primarily below 0.02 km^3 (20 M m^3). From 100 m up to 525 m (Lituya event, 1958) in wave Hmax, a significant disparity in volumes is observed, reaching almost 3 km^3.

The paper states a ***remarkable absence of correlation*** *between Hmax and source parameters, such as earthquake magnitude M, landslide volume V, volcanic explosion index VEI*



Map of historical tsunamigenic events occurred from 2000 BC to 2024 with the trans-oceanic mega-tsunamis highlighted in red. About 2750 events are shown. Size of circles is proportional to source magnitude, color represents the tsunami intensity *I* on Soloviev-Imamura scale

Three groups of largest tsunamis of the World Ocean (compared by different parameters)

14 trans-oceanic tsunamis, (H > 5m at D > 5000km) N - number of run-ups	Top-15 tsunamis with highest run-up, sorted by H_{max}	Top-15 tsunamis with largest fatalities, sorted by N_{FAT}
365AD Crete M ~ 8.5	524m 1958 Lituya Bay	227,899 2004 Sumatra
1700 Cascadia M ~ 9	250 m 1963 Vajont Dam	36,417 1883 Krakatau
1737 Kamchatka M = 9+	150m 1936 Lituya Bay	30,000 1755 Lisbon
1755 Lisbon M = 9	120m 1854 Lituya Bay	30,000 1707 Nankaido
1788 Aleutian M = 9	90m 2007 Greenland	27,122 1896 Sanriku
1837 Chile M = 9	90m 2018 Bureya Riv.	26,000 1498 Enshunada
1868 Chile M = 9	88m 1788 Aleutians	18, 428 2011Tohoku
1946 Aleutians M = 8.8	85m 1771 Ishigaki Is.	15,000 1741 Osima
1952 Kamchatka M = 9	70m 1936 Norway	13.486 1771 Ishigaky Is.
1957 Aleutians M = 9	68m 1964 Alaska	10,000 1952 Kamchatka
1960 Chile Mw = 9.5	63m 1737 Kamchatka	10,000 1765 Guanzhou
1964 Alaska Mw= 9	62m 1934 Norway	5,233 1703 Boso Pen.
2004 Sumatra Mw= 9.1	51m 2004 Sumatra	5,000 1605 Nankaido
2010 Chile Mw = 8.8	42m 1946 Aleutians	4,376 1976 Philippines
2011Tohoku Mw=9.1	38m 2011 Tohoku	3,000 1854 Nankaido

Formal criteria for identification of trans-oceanic mega-tsunamis in historical catalogs:

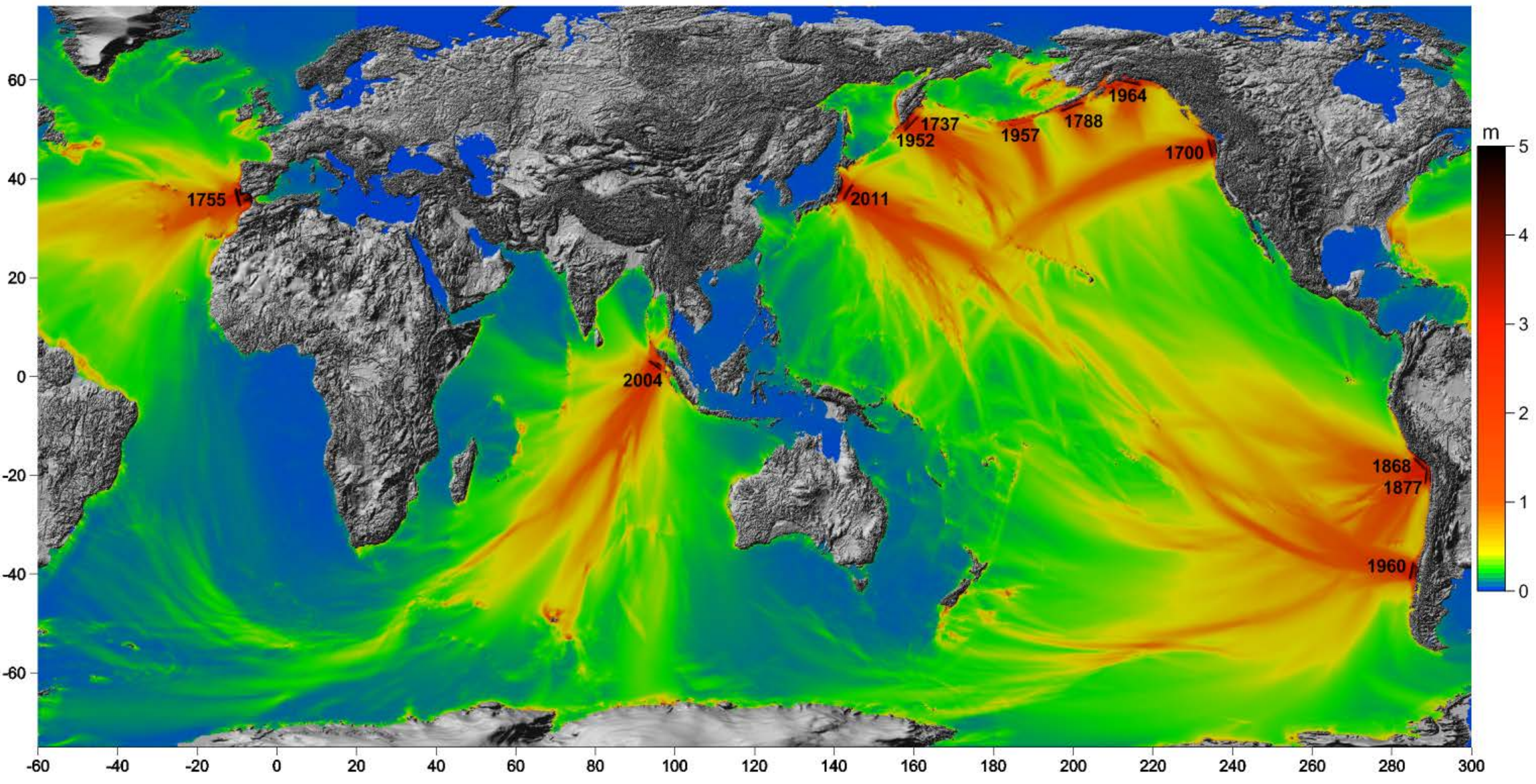
Events that created run-up heights more than 5 m at the distance of longer than 5000 km

Physical meaning of this criteria:
These events are capable to create a damage on the opposite side of an oceanic basin

List of historically known transoceanic tsunamis and their basic parameters

Date and location	*M*	*N*	*I*	Hm_{NF}, m	Hm_{FF}, m	F_{NF}	F_{FF}
July 21, 365, Crete	8+	3	4	Unknown	10	~5,000	~700
January 26, 1700, Cascadia	9	7	3.5	10	2–4	Unknown	0
October 17, 1737, Kamchatka	9	6	4	63	12–15	Unknown	Unknown
November 1, 1755, Lisbon	8.5	51	4	30	7	~1-2.000	Unknown
November 7, 1837, Chile	8.5	20	3.5	8	6	0	62
August 13, 1868, Chile	9	99	3.5	15	5.5	612	7
May 9, 1877, Chile	9	111	4	24	12	512	50
June 15, 1896, Japan	7.6	62	4	38.2	9.0	27.122	0
April 1, 1946, Aleutians	8.4	542	4	42.2	20.0	5	162
November 4,1952, Kamchatka	9.0	314	4	18	9.1	>10.000	0
March 9, 1957, Aleutians	9.1	304	3.5	22.8	16.1	0	0
May 22, 1960, Chile	9.6	537	4	15.2	10.7	~1.000	283
March 28, 1964, Alaska	9.3	292	4	68	4.9	106	18
December 26, 2004, Sumatra	9.0	1015	4.1	50.9	9.6	175.827	52.071
March 11, 2011, Tohoku	9.0	5578	4.2	55.9	3.0	18.497	2

These mega-events constitute less than 1% of all tsunamis, but they are responsible for more than 60% of all fatalities and 80-90% of material damage



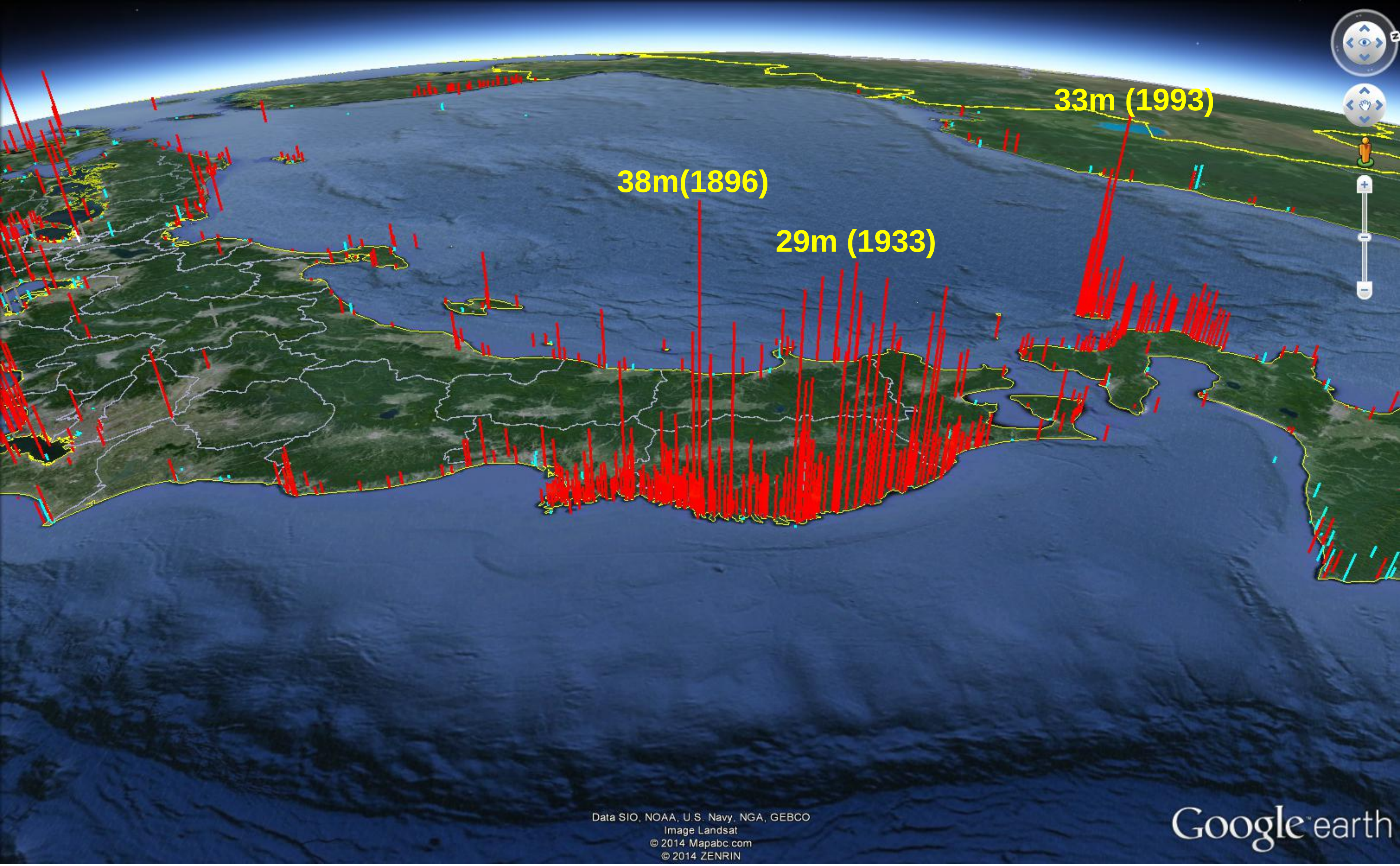
Energy flux for trans-oceanic mega-tsunamis historically known. Insert figure – distribution of fatalities over the tsunami propagation time (up to 85% fatalities occur during the first hour). Calculations are made in ICT SB RAS by means of MGC numerical package for tsunami modeling (Chubarov, Babailov, Beisel, 2011).

Trans-oceanic mega-tsunamis represent a small (less than 1%) fraction of all tsunamigenic events, but in historical perspective of XX-XXI centuries they are responsible for

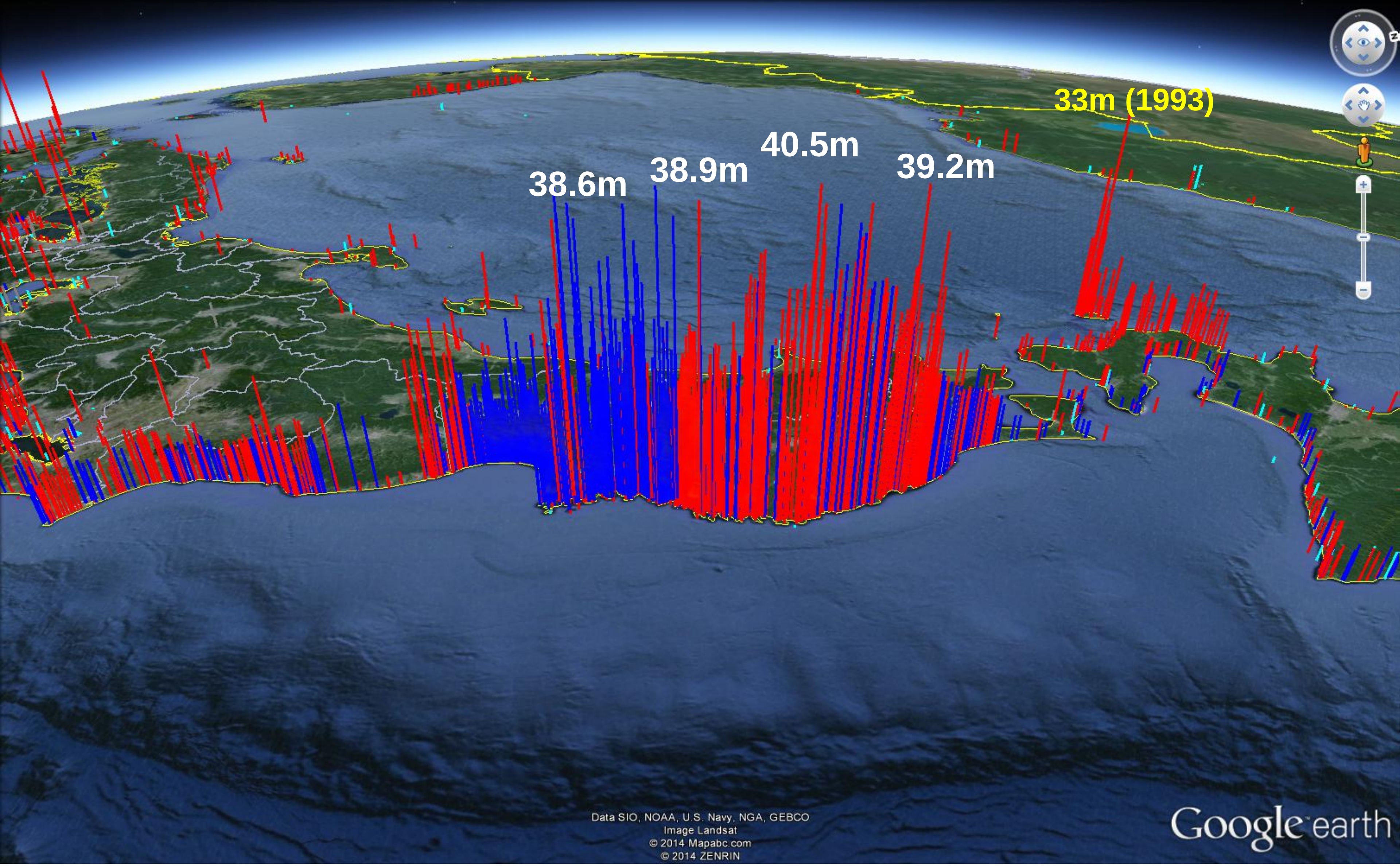
- **more than 50% of all tsunami run-ups in DBs**
- **more than 60% of all tsunami fatalities**
- **more than 70% of total tsunami damage**
- **nearly 90% of total tsunami energy released in the World Ocean**

Основные особенности транс-океанских мега-цунами:

- Порождаются крупными субдукционными землетрясениями магнитуды 9+
- Способны вызвать ущерб и потери среди населения на противоположном берегу океанского бассейна
- Имеют большие периоды повторяемости -- порядка 500 лет [215 ÷1100] (в каждом отдельном регионе)
- Максимальные заплески на берегу составляют 20-40 м и не является предельно высокими, но они могут наблюдаться на значительном (> 500 км) протяжении береговой линии
- На побережьях окраинных морей (типа Охотского, Берингова) наибольшие колебаний уровня могут наступать через 12-24-48 час после прибытия первого возмущения
- Имеют увеличенный период волны (до 1 часа) и способны к глубокому (до 5-6 км) проникновению вглубь суши

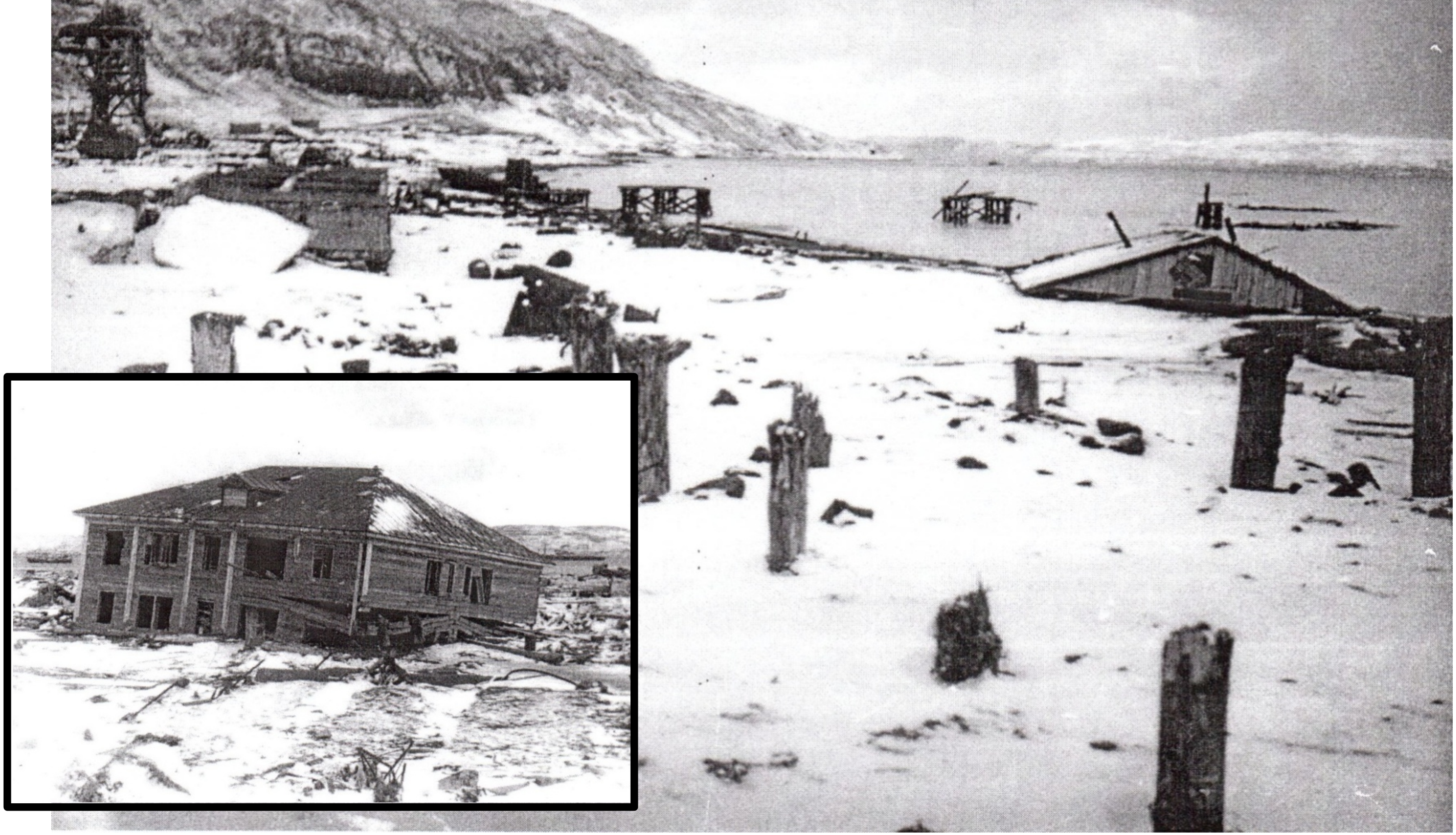


Historical run-up distribution along the coast of Honshu for the period from 684AD to 2011



Historical run-up distribution along the coast of Honshu after 11.03.2011

The earthquake and tsunami of November 4, 1952 so far is the largest natural disaster in the territory of the Russian Federation.



The height of the waves reached 15-20 meters. The number of fatalities is from 10 to 14 thousand people (according to modern estimates). The earthquake caused a transoceanic tsunami, one of the strongest in the 20th century.

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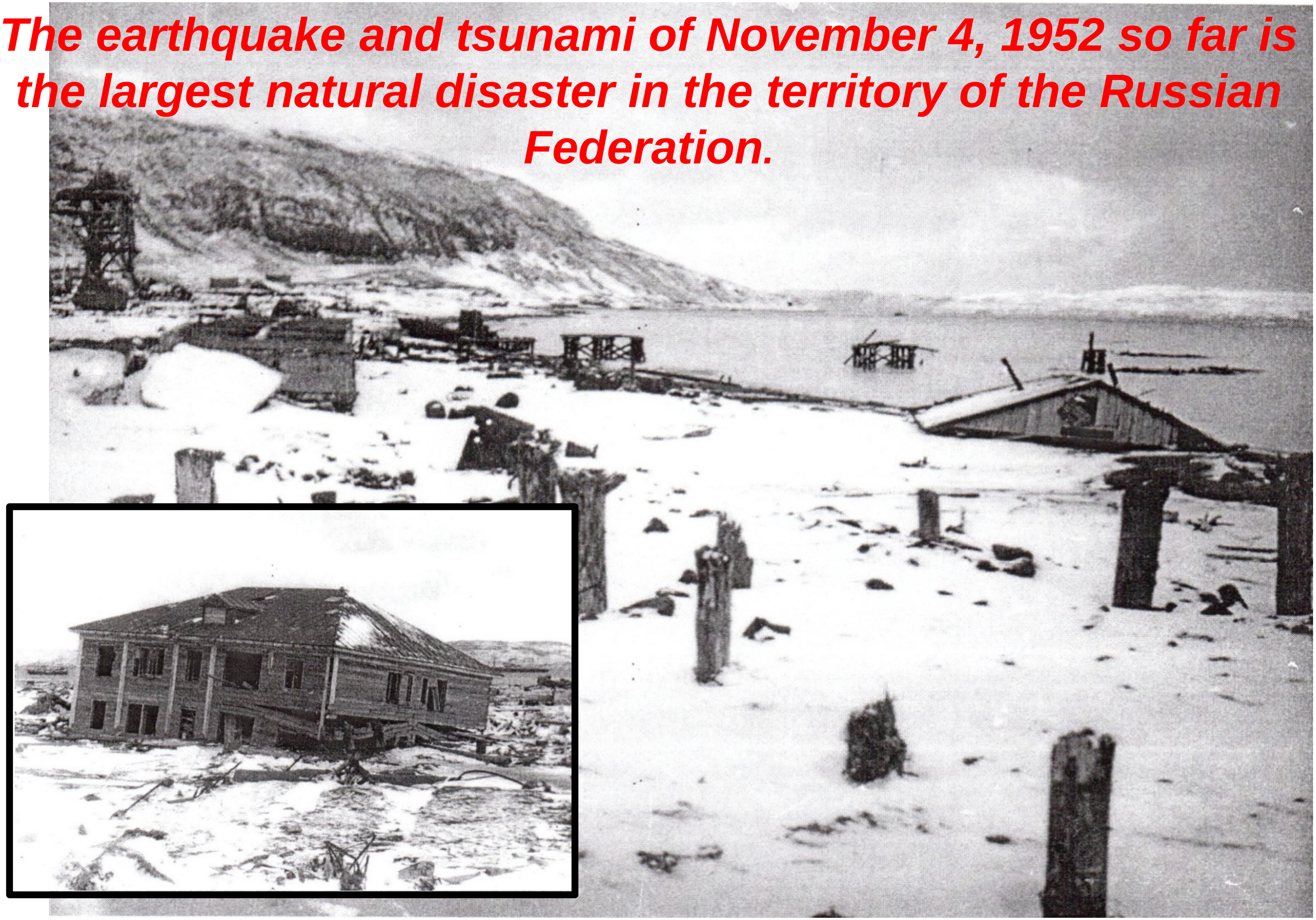

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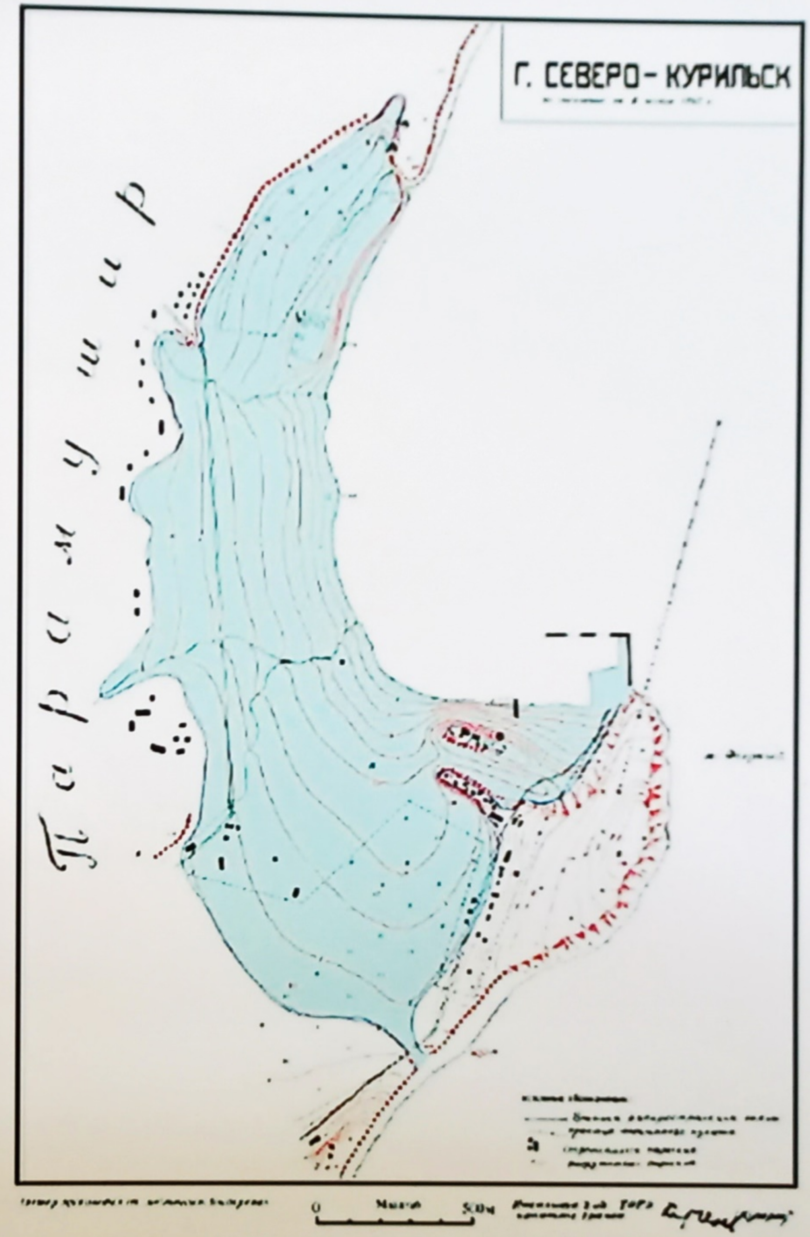
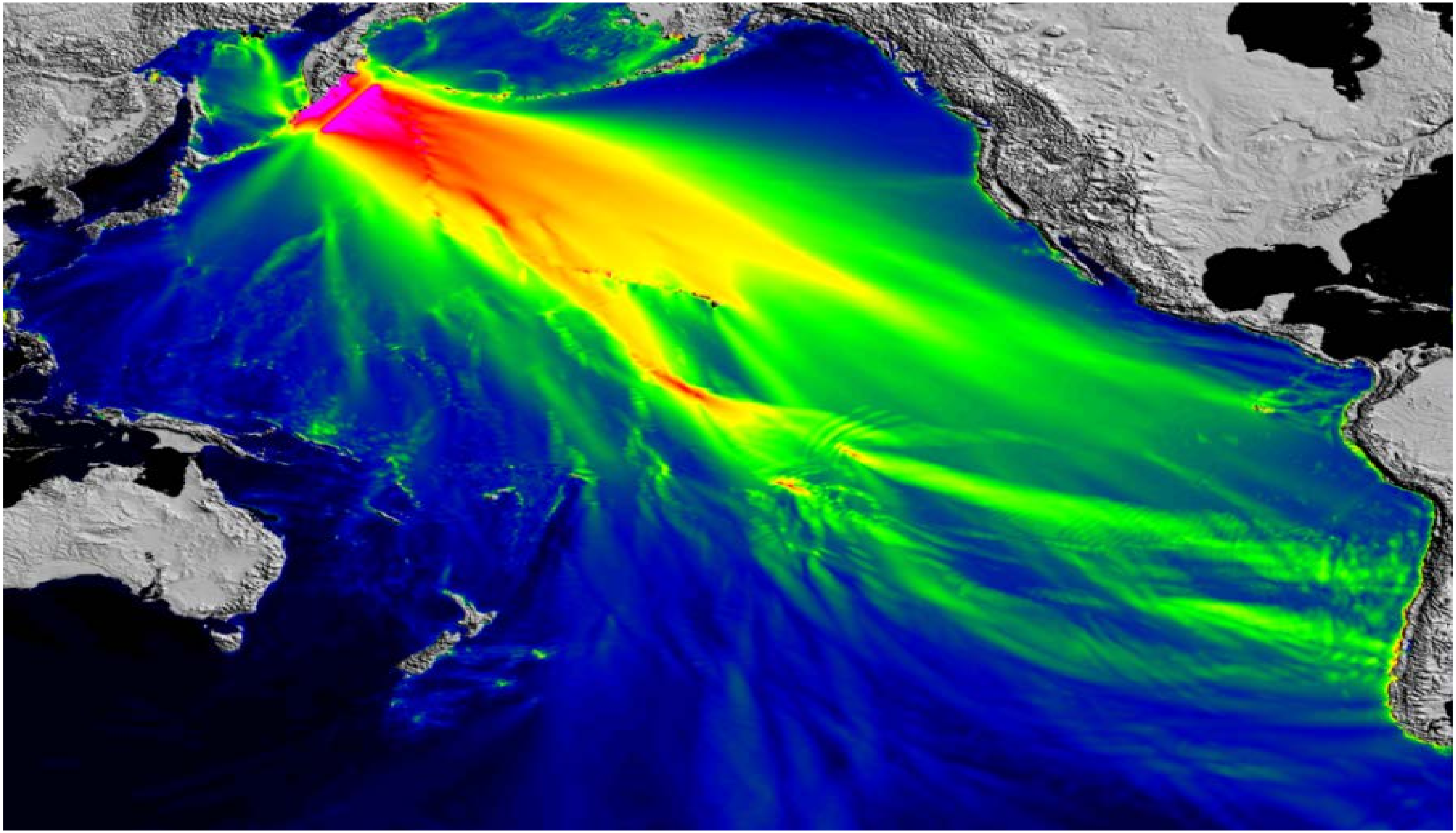


Карта города Северо-Курильска до цунами (слева) и территория, залитая при цунами 5 ноября 1952 г. (справа)

Severo-Kurilsk, September 2022. Concrete military defense unit overturned and displaced on several hundred meters upstream of a small river

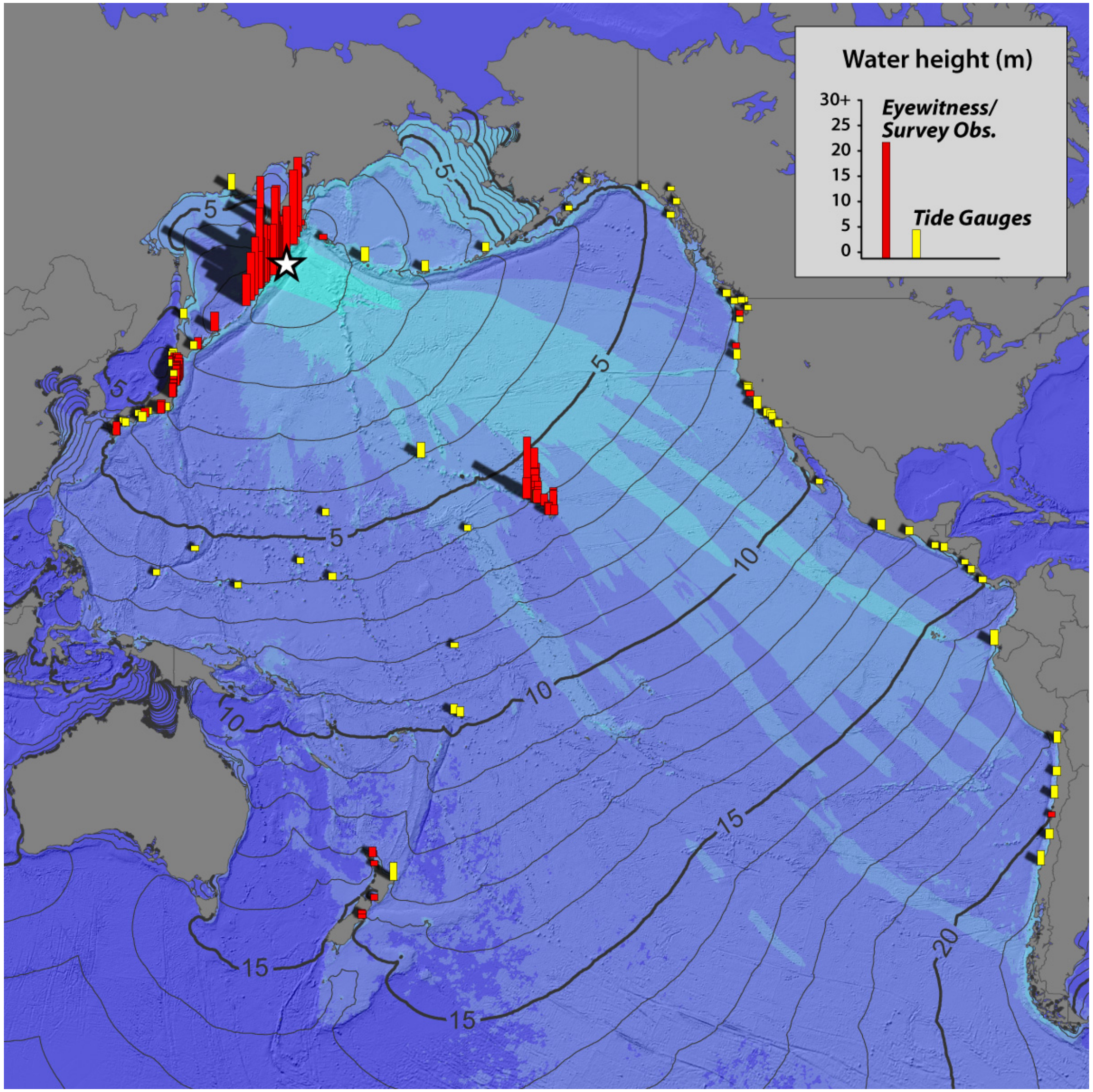
Severo-Kurilsk, September 2022. Concrete protective room in the state bank displaced on 1.5 km from the intital location

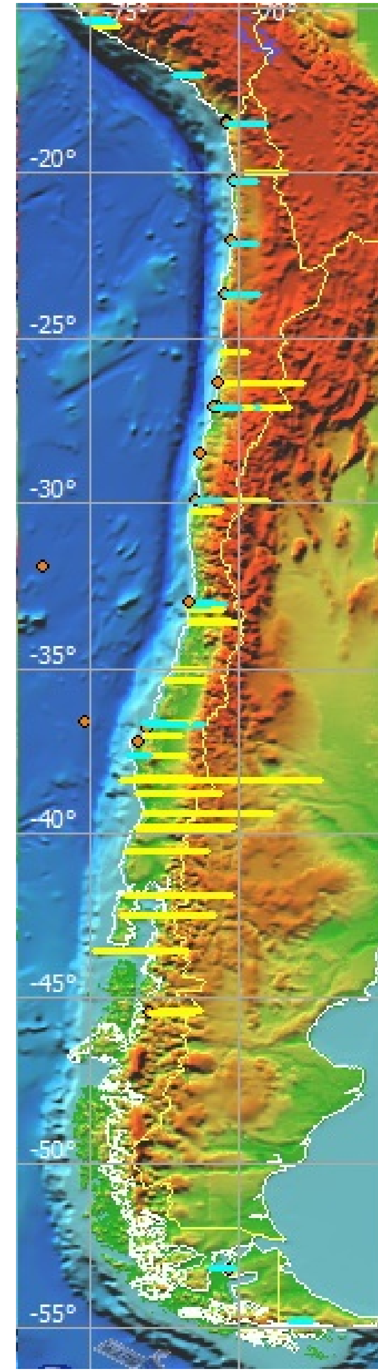
Numerical model of the Kamchatka tsunami of November 4, 1952



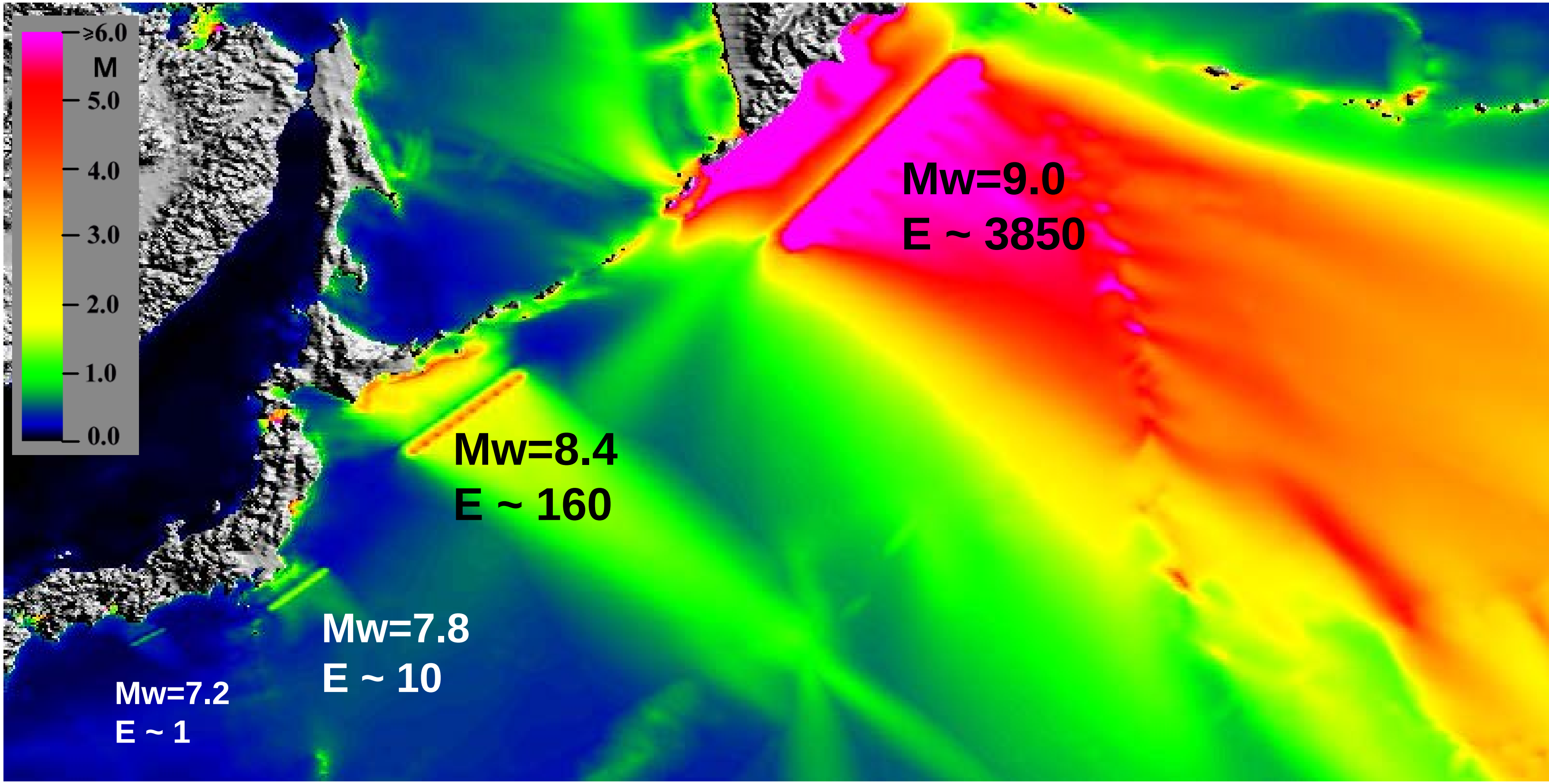
Расчет на сетке 3000x3000 на 36 час физического времени произведен с помощью платы FPGA за 2 мин процессорного времени

Трансокеанское распространение Камчатского цунами 1952 года

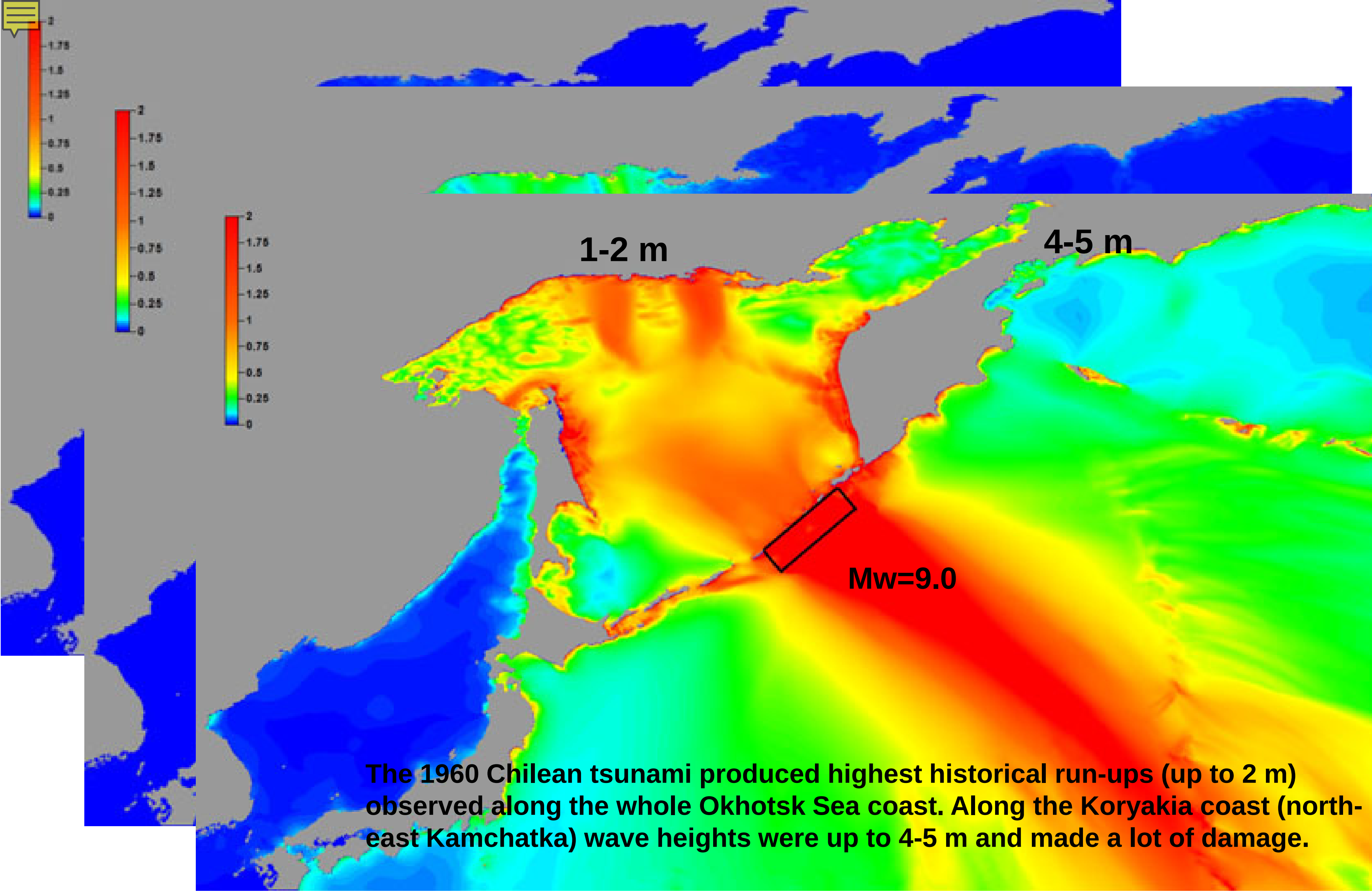




n southern Chile (south of 35°S) the 1952 Kamchatka tsunami was the only noticeable event during 84 years (from 1868 to 1960)

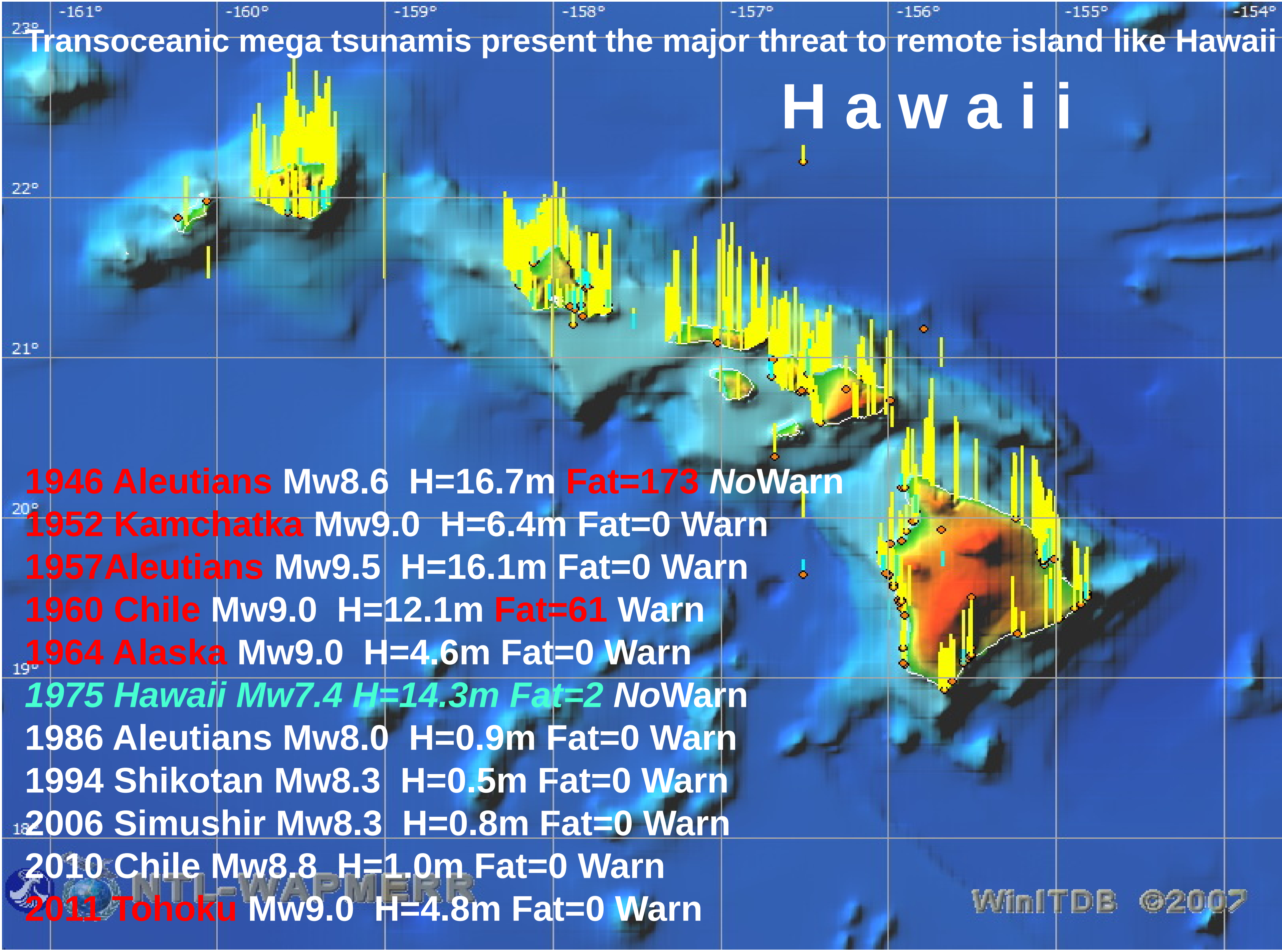


Comparison of glow maps for model subduction sources with different magnitudes Mw 9.0, 8.4, 7.8 and 7.2 on a regional scale. The ratio of the initial (static) tsunami energy for these earthquakes is also shown.



Tsunami propagation in the Kuril-Kamchatka region for Mw=7.8, 8.4 and 9.0 sources, made in ICT SB RAS by means of MGC package for tsunami modeling (Chubarov, Babailov, Beisel, 2011).

Transoceanic mega tsunamis present the major threat to remote island like Hawaii



1946 Aleutians Mw8.6 H=16.7m Fat=173 *No*Warn

1952 Kamchatka Mw9.0 H=6.4m Fat=0 Warn

1957Aleutians Mw9.5 H=16.1m Fat=0 Warn

1960 Chile Mw9.0 H=12.1m Fat=61 Warn

1964 Alaska Mw9.0 H=4.6m Fat=0 Warn

*1975 Hawaii Mw7.4 H=14.3m Fat=2 No*Warn

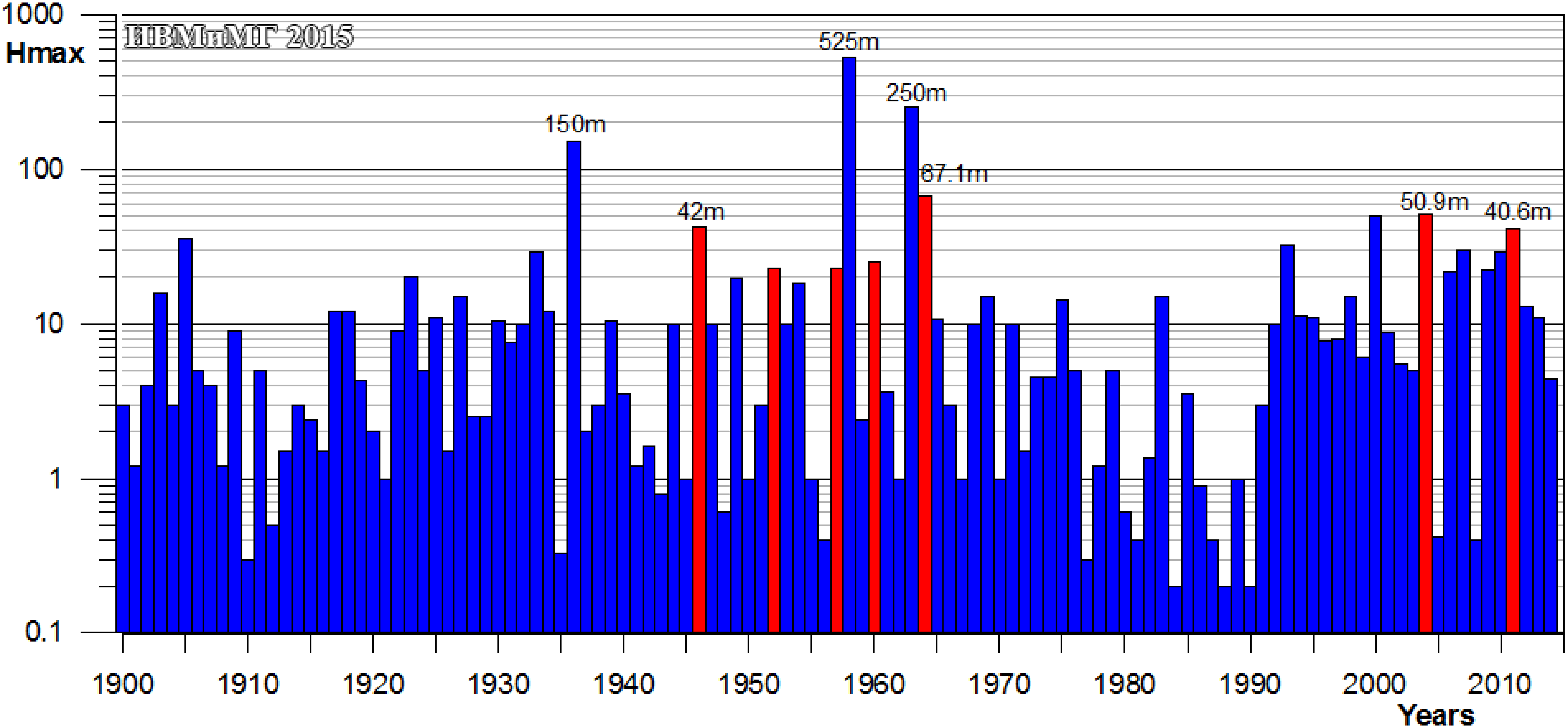
1986 Aleutians Mw8.0 H=0.9m Fat=0 Warn

1994 Shikotan Mw8.3 H=0.5m Fat=0 Warn

2006 Simushir Mw8.3 H=0.8m Fat=0 Warn

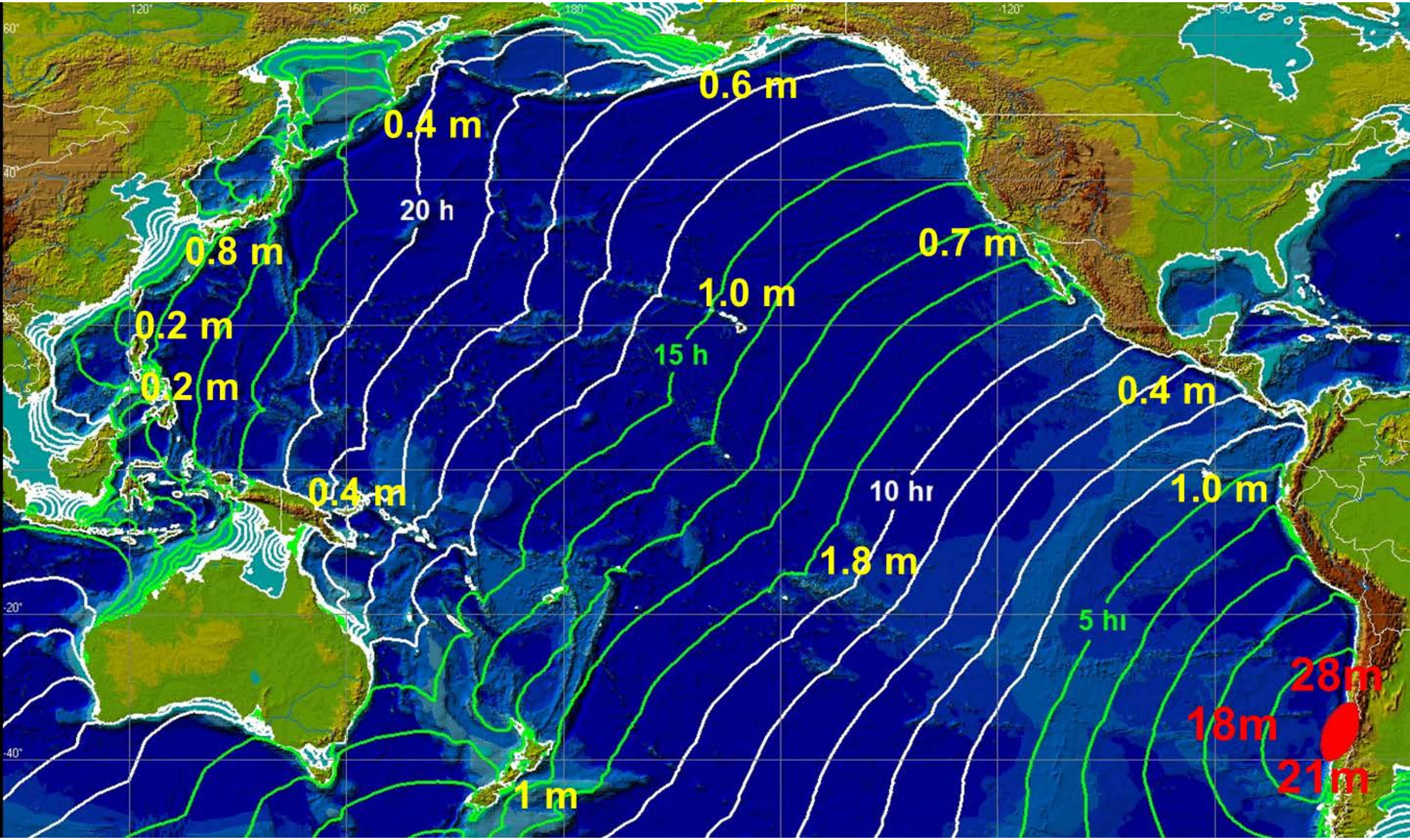
2010 Chile Mw8.8 H=1.0m Fat=0 Warn

2011 Tohoku Mw9.0 H=4.8m Fat=0 Warn



Maximum tsunami run-up heights recorded in the World Ocean during 1900-2024. Red color marks trans-oceanic mega-events resulted from M9 class subduction earthquakes (1946 Aleutians, 1952 Kamchatka, 1957 Aleutians, 1960 Chile, 1964 Alaska, 2011 Indonesia, 2011 Tohoku)

TTT map and observed far-field heights of the 2010 Maule tsunami
Mw=8.8 I=3.5

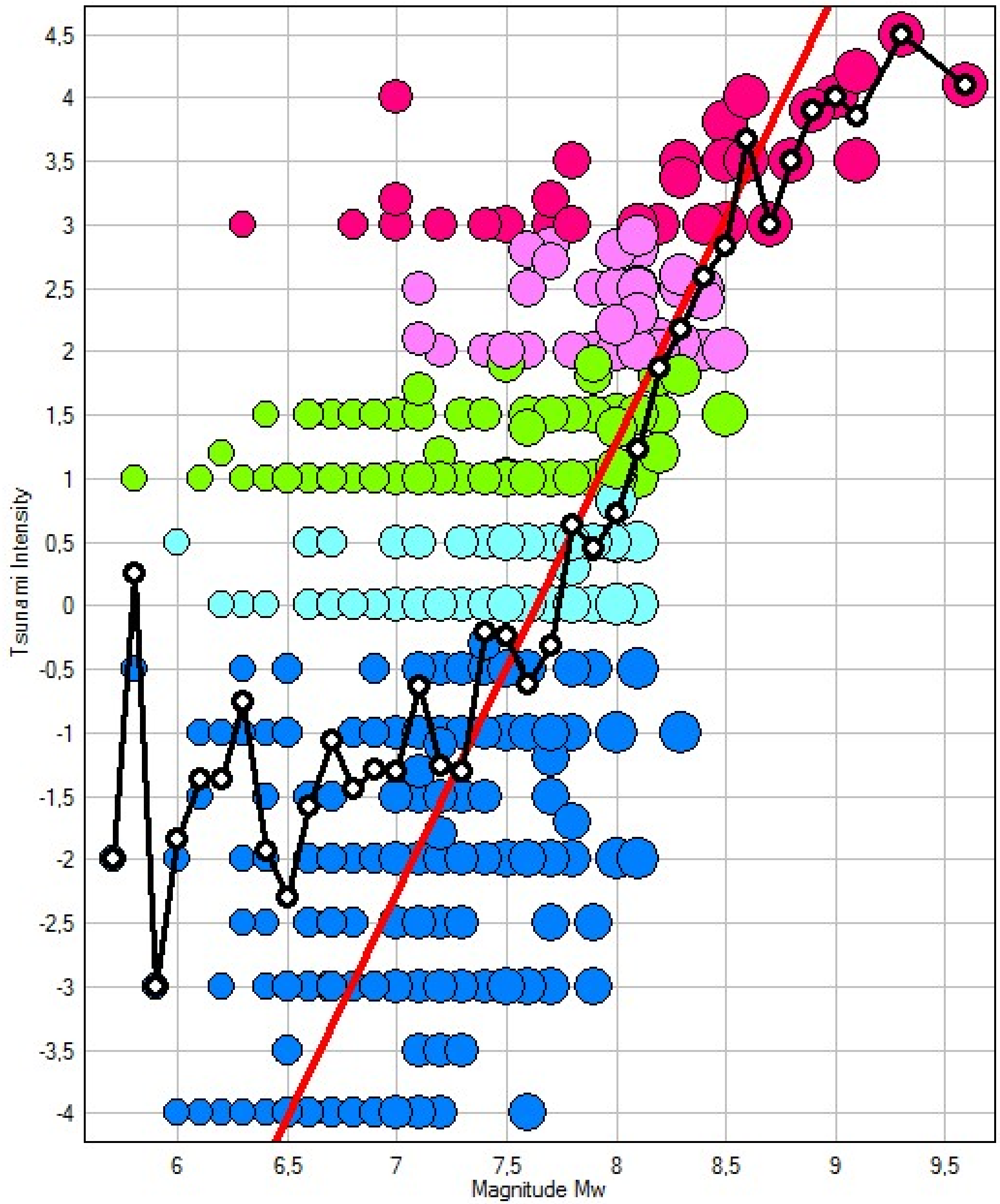


Despite of great near-field heights (greater than 1960 Chilean tsunami), the 2010 Maule tsunami cannot be counted as trans-oceanic mega-tsunami

$I = \frac{1}{2} + \log_2 H_{av}$

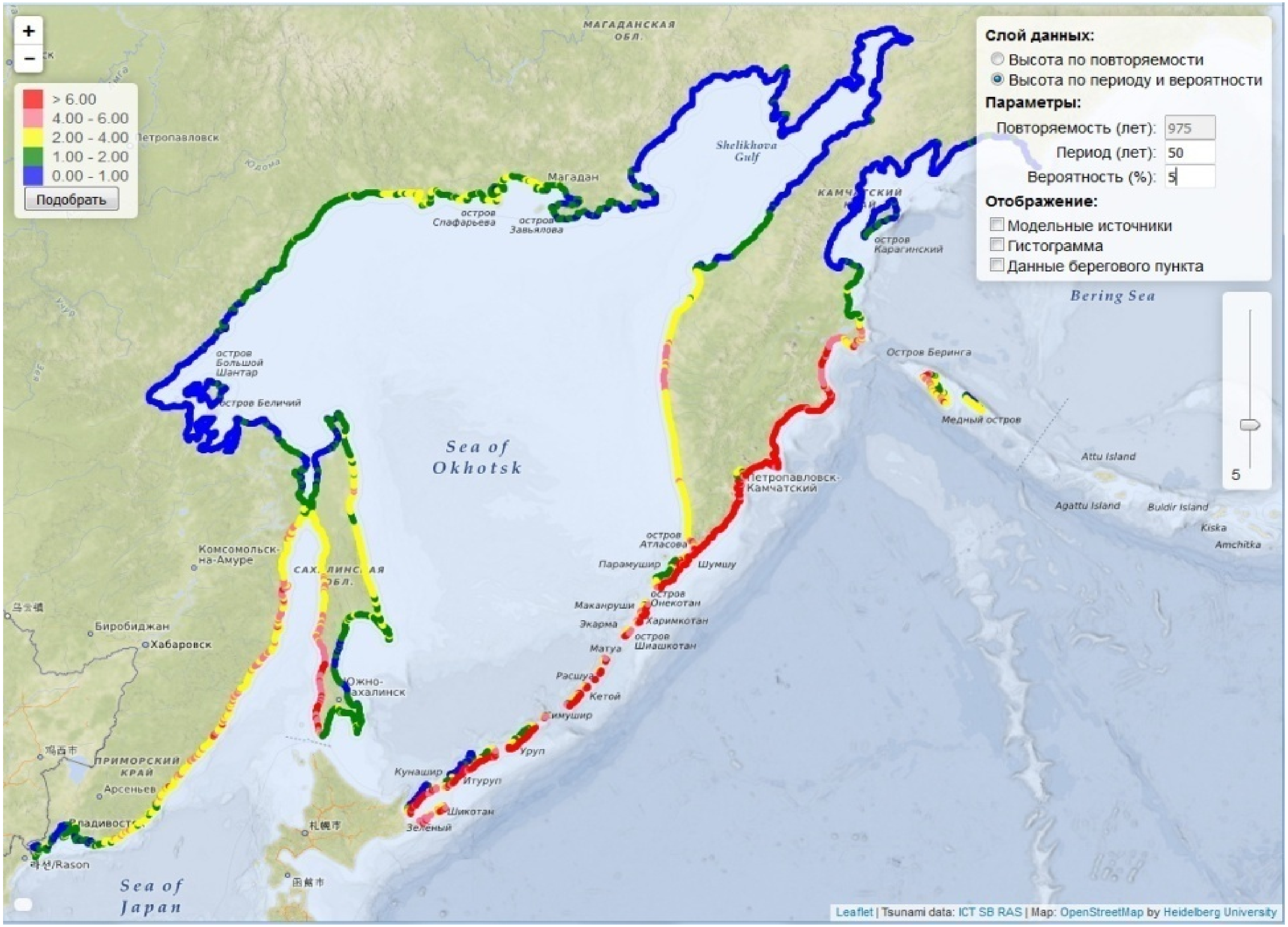
(Soloviev, 1972)

$I = 3.55\ Mw - 27.1$

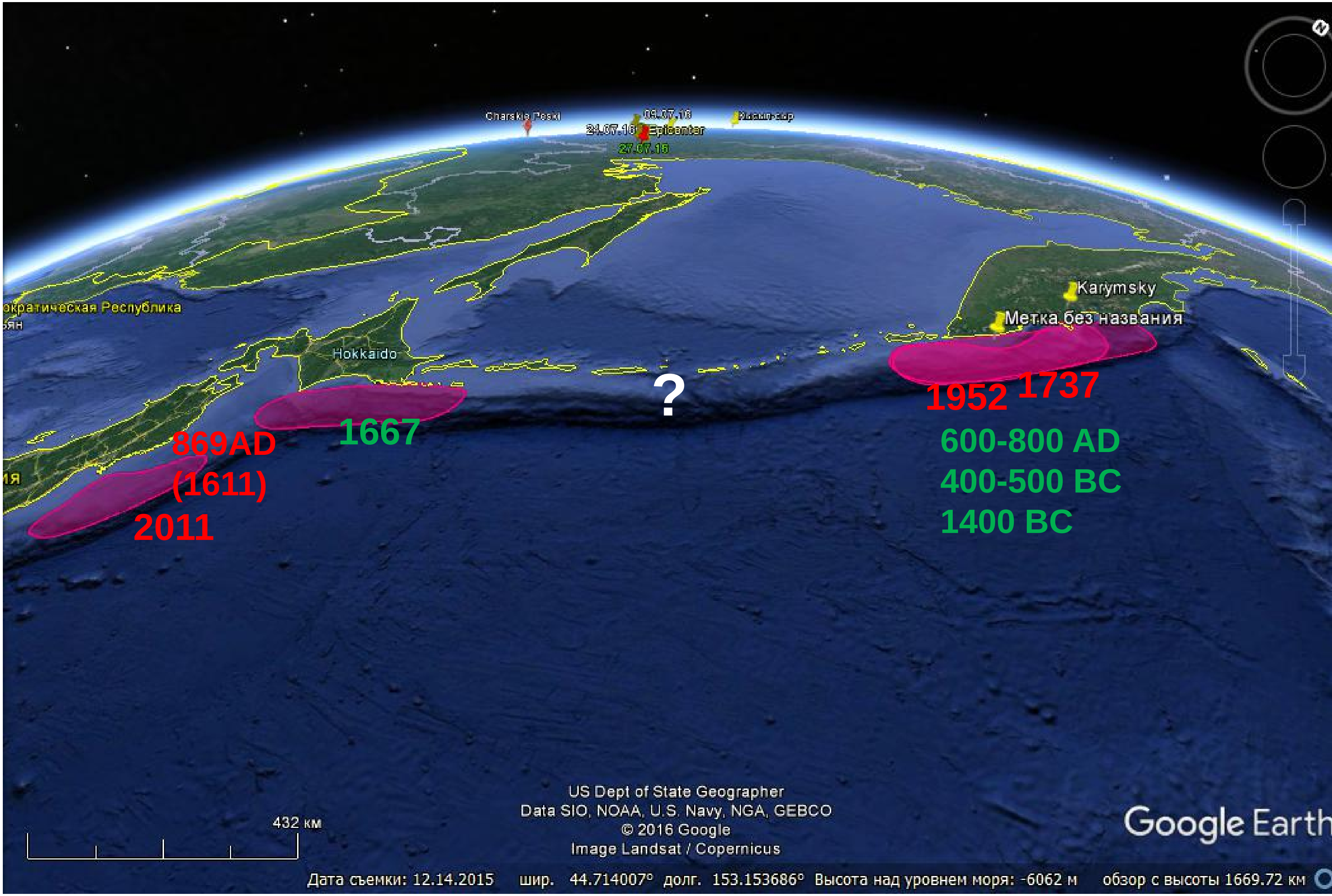


Dependence of tsunami intensity *I* (on Soloviev – Imamura scale) on *Mw* magnitude for Pacific tsunamigenic earthquakes for the period 1904-2022.

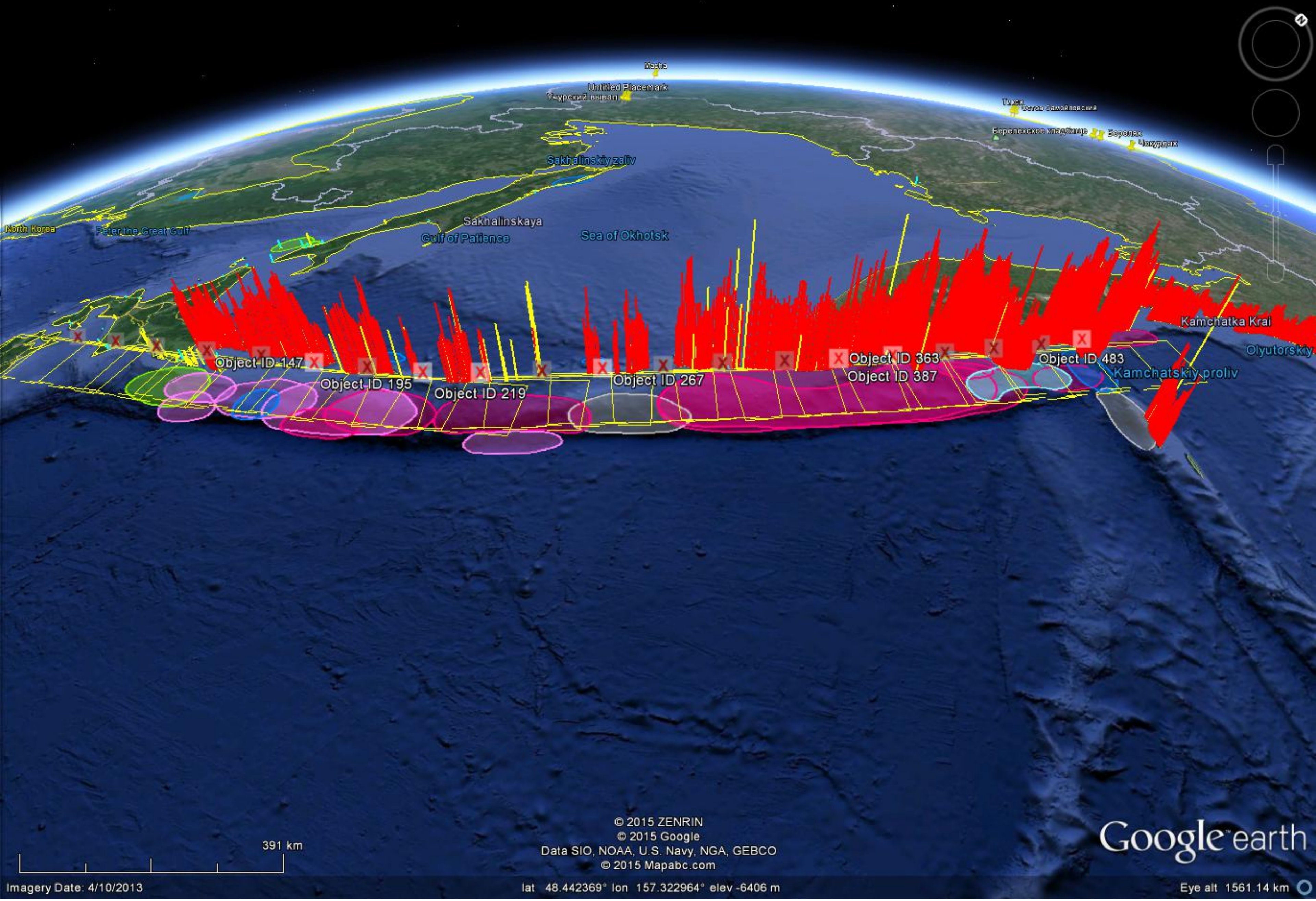
Long-term prediction of mega-quakes and their input in tsunami hazard maps



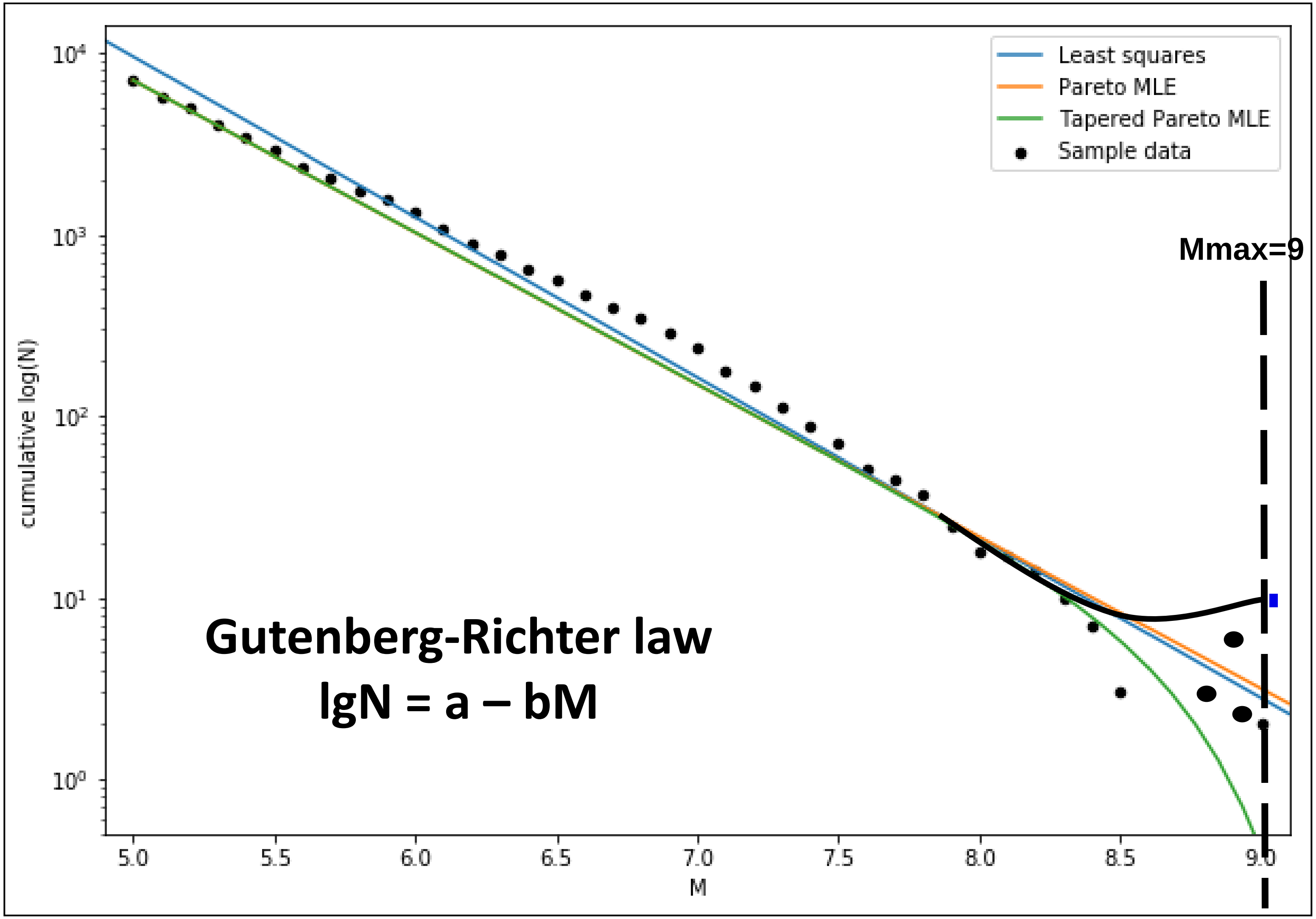
Карта цунамиопасности Дальневосточного побережья РФ, показывающая высоты волн с ожидаемой вероятностью превышения 5% в течение интервала 50 лет (средний интервал повторяемости 975 лет).



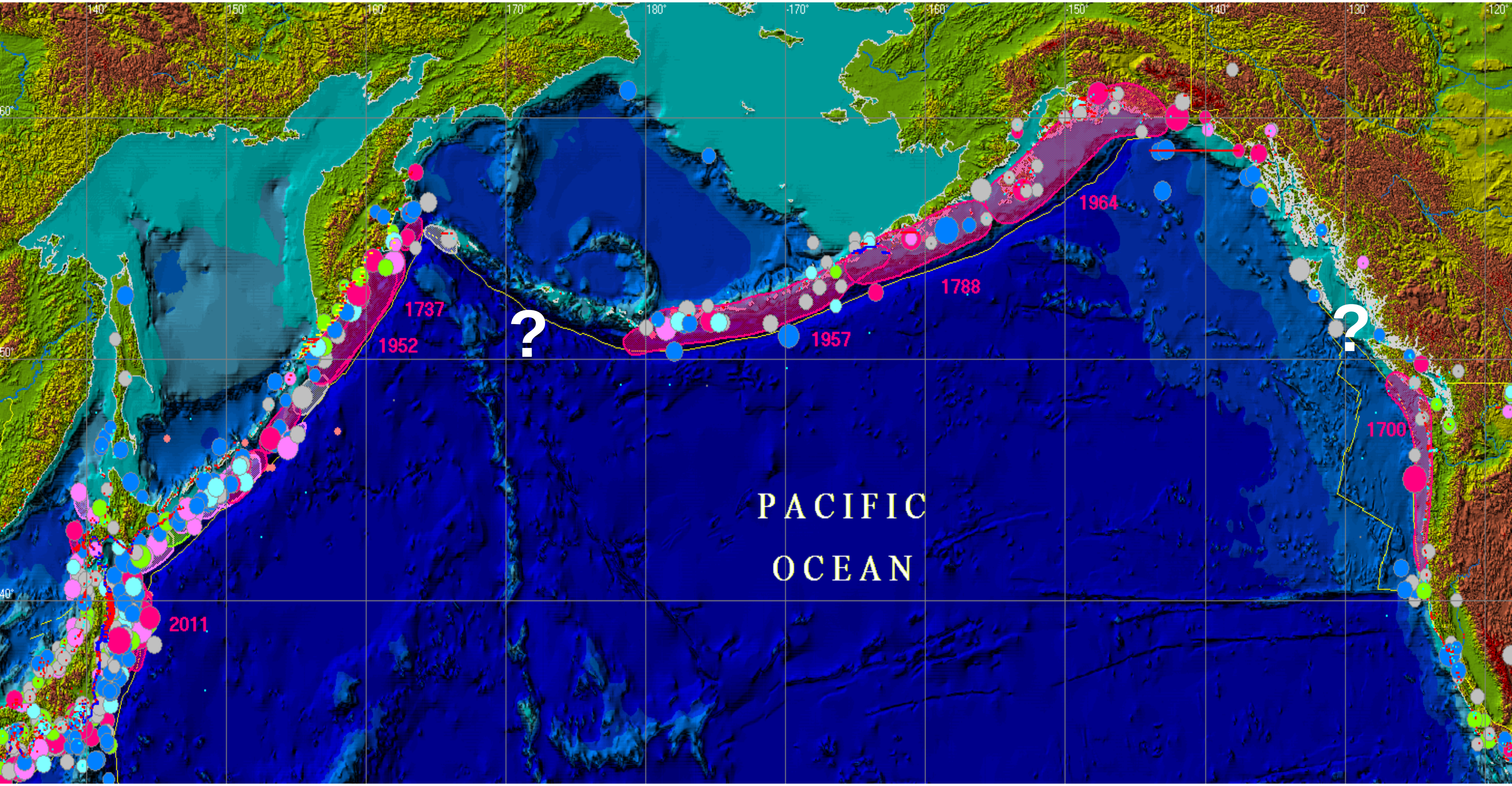
Known historical and geologically identified pre-historical mega-tsunamis in the Kuril-Kamchatka and Japan regions resulted from M9 subduction quakes



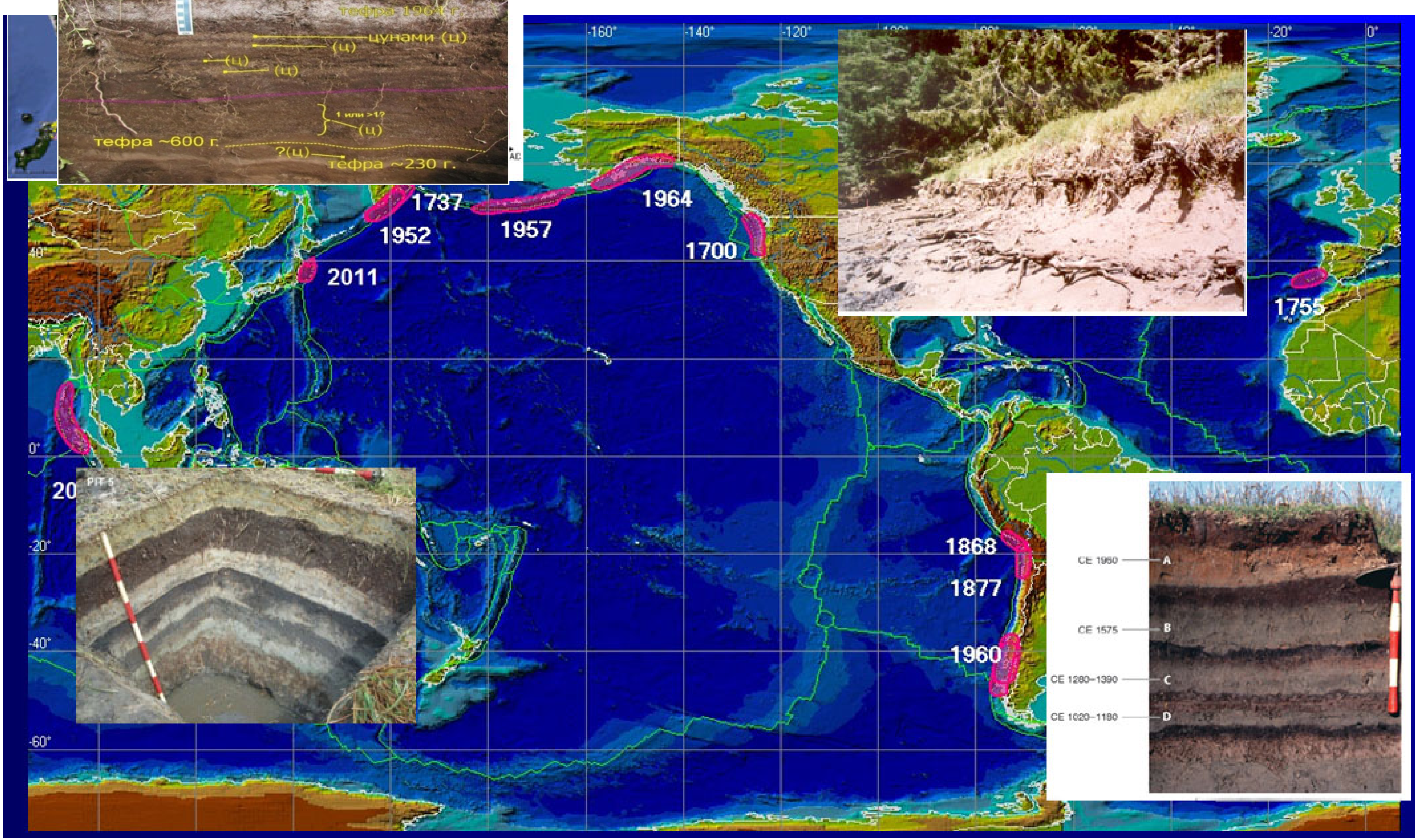
Historically known run-up heights along the Kuril-Kamchatka coast for 1737-2024 and results of numerical modeling for a set of hypothetical model sources of magnitude Mw=9.0



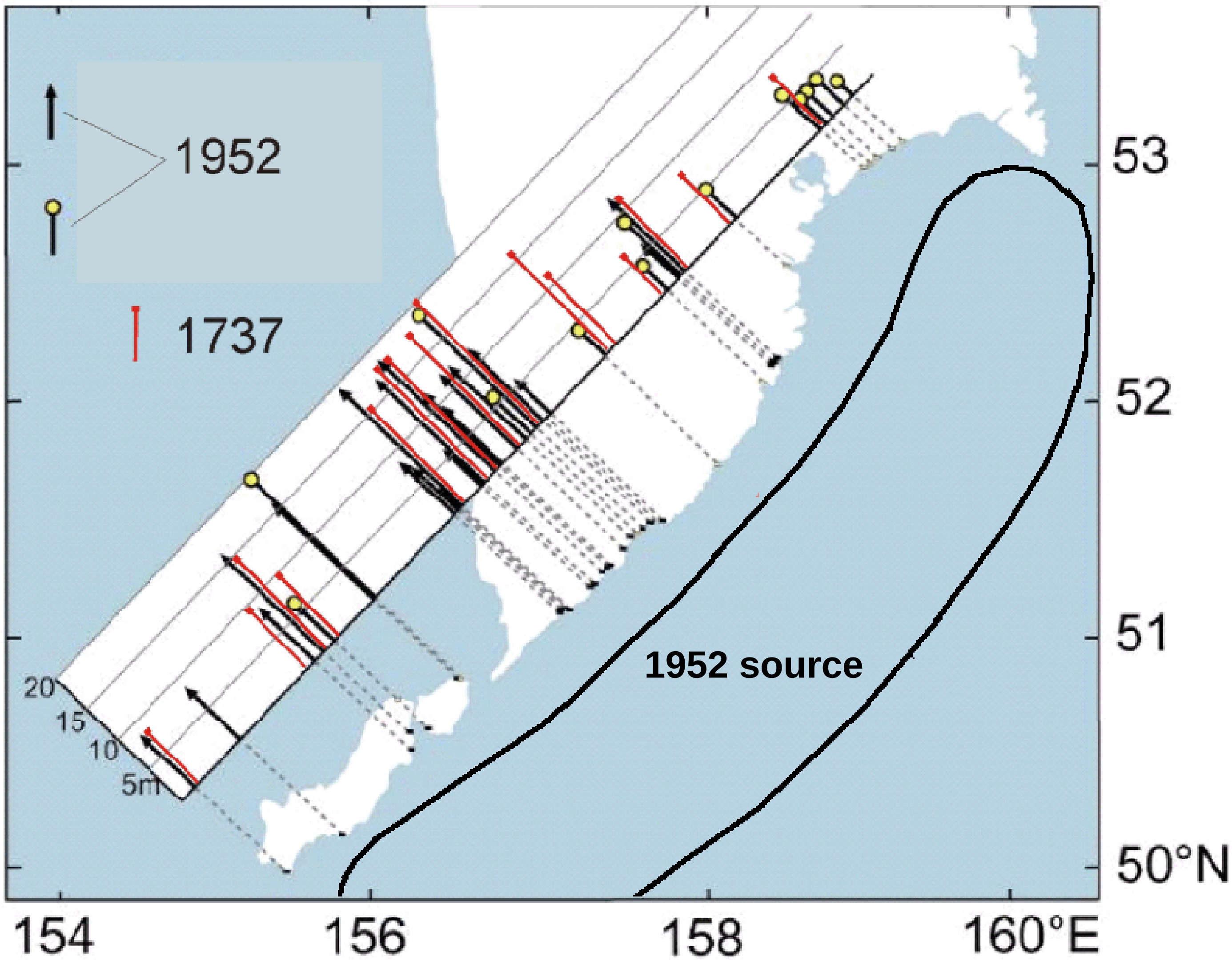
Earthquake recurrence law (Gutenberg-Richter law) for the Kuril-Kamchatka zone. Black dots show the number of events in the seismic catalog for 1700 - 2015 with magnitude M > Mi. Solid lines are its possible approximations.



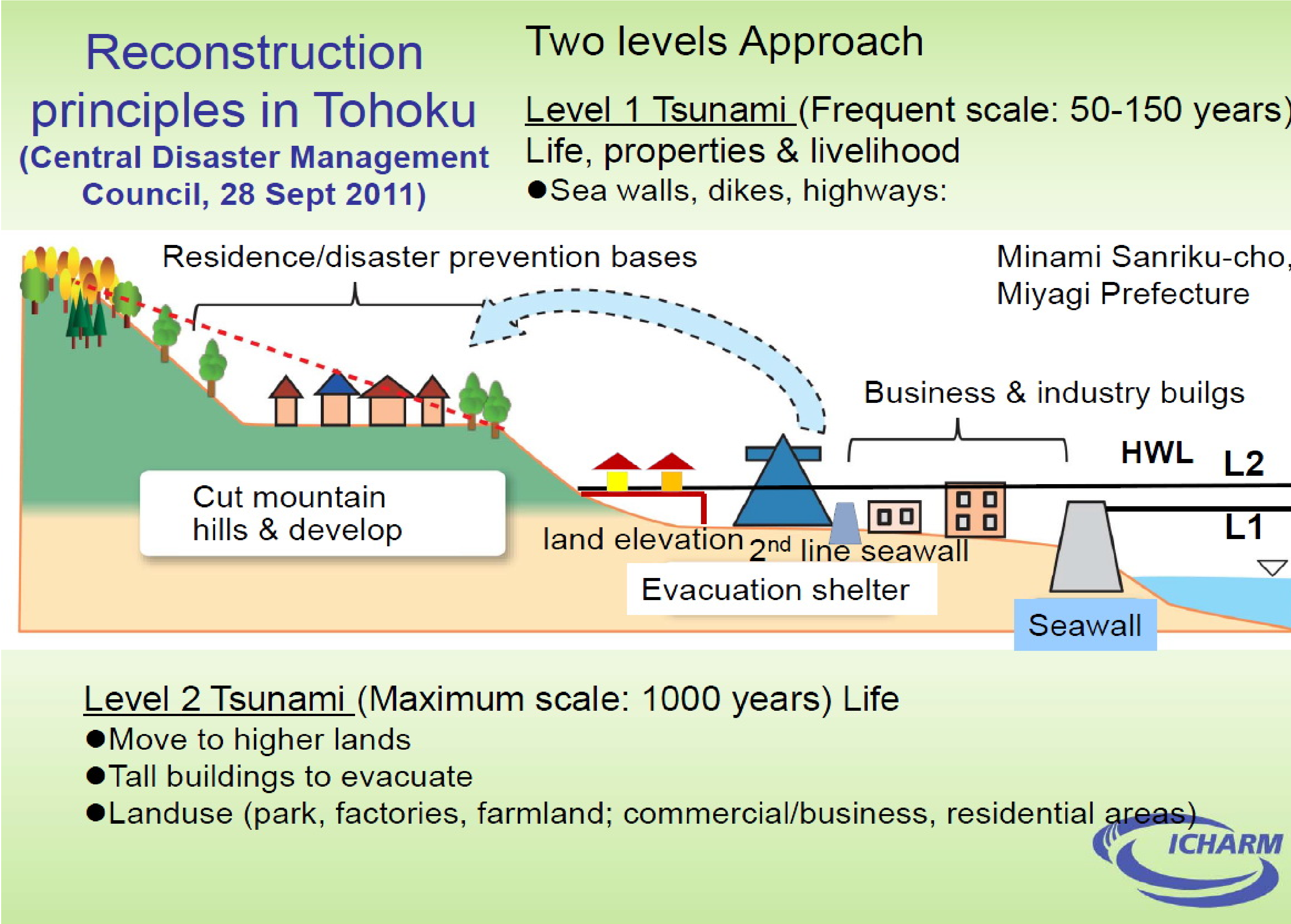
Map of historical tsunamigenic earthquakes for Japan–Kuril-Kamchatka – Alaska-Aleutian regions. Nearly 500 historical events are mapped. M9 class events are shown as elliptical sources and marked by year. Big questions exist about a gap in the western Aleutians and western Canada-US coast.



Source map of mega-tsunamis in the Pacific and Indian oceans occurred from 1700 to present



Restored (by paleo-geological tracing) run-up heights of the 1737 and 1952 tsunamis along the Paramushir – Kamchatka east coast (Pinegina, 2014)



New paradigm in tsunami hazard mitigation in Japan – two-level strategy in tsunami hazard management (Takeuchi, 2013)

В.К. ГУСЯКОВ

GROUND ZERO:

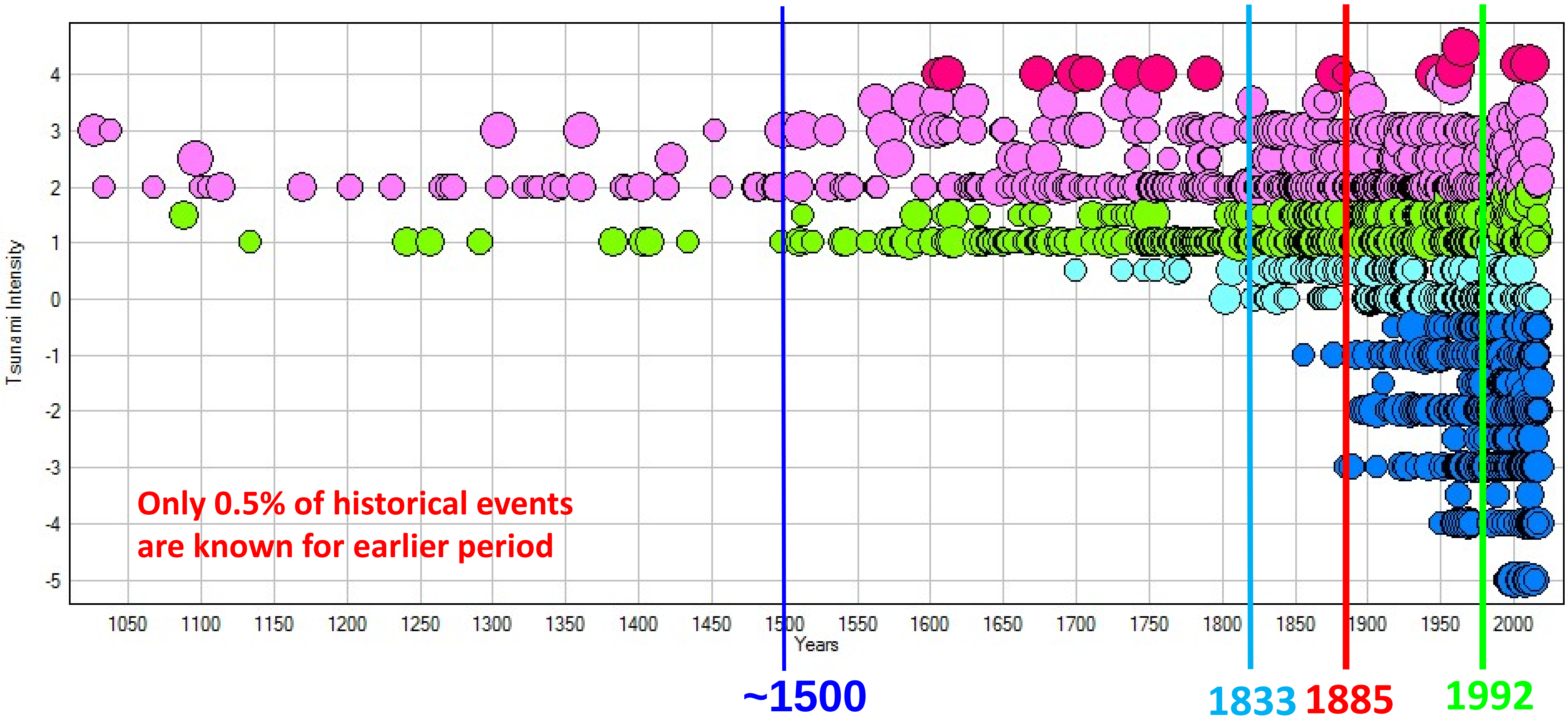
Мегаземлетрясения — главная угроза безопасности морских побережий

В зоне полного разрушения: 15-метровая волна, обрушившаяся на западное побережье Суматры утром 26 декабря 2004 г., сносила все на своем пути. *Фото автора*

З А К Л Ю Ч Е Н И Е

- Trans-oceanic tsunamis resulted from M9 class subduction earthquakes gives the major input in overall tsunami hazard (<1% of events responsible for >50% of all fatalities).
- They produce high (>10m) run-ups over extended portion (~1000km) of coastline and constitute major hazard for the coast of marginal seas
- With few exceptions (1896 Sanriku, 1946 Aleutians) the magnitude value Mw=9.0 looks like a threshold for generating of trans-oceanic tsunamis
- Geological methods of paleotsunami tracing is indispensable tool for long-term tsunami hazard assessment and needs to be used in all regions
- Trans-oceanic mega-tsunamis resulted from M9 class subduction earthquakes, constitute a separate group of tsunamigenic events and in any consideration they should be clearly distinguished from all other “ordinary” tsunamis

February of 2012. Prof. Y.Tsuji (Tokyo University) at the basement of a living house in Rikudzen-takata city, Miyako prefecture.



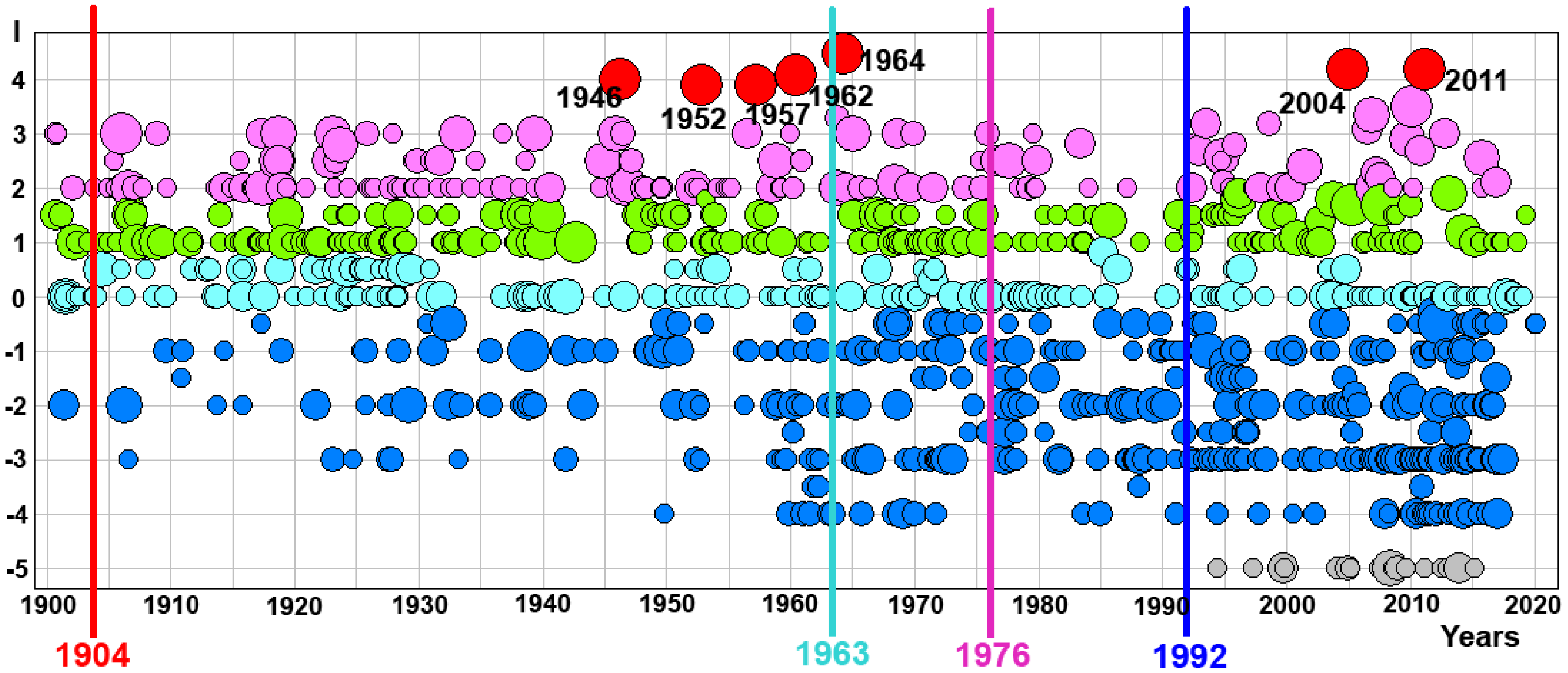
Tsunami occurrence in the World Ocean from 1000 AD to present. Vertical axes is the tsunami intensity *I* on Soloviev-Imamura scale

~ 1500 – beginning of the era of great geographical discoveries

1833 год – the first sea level station (Brest, France)

1885 год – the first seismic station

1992 год – the first international post-tsunami field surveys (Nicaragua)



1904 – beginning of global instrumental earthquake catalog
1963 – deployment of global seismic network WWSSN
1976 – beginning of deployment of broadband network of STS-type stations
1992 – beginning of detailed instrumental measurements of tsunami consequences

Tsunami occurrence in the World Ocean from 1900 to 2024. M9 trans-oceanic mega-tsunamis stay clearly out of all other events