NUMERICAL SIMULATION OF EARTHQUAKE AND TSUNAMI MAY 9, 1877 AT THE CHILE COAST

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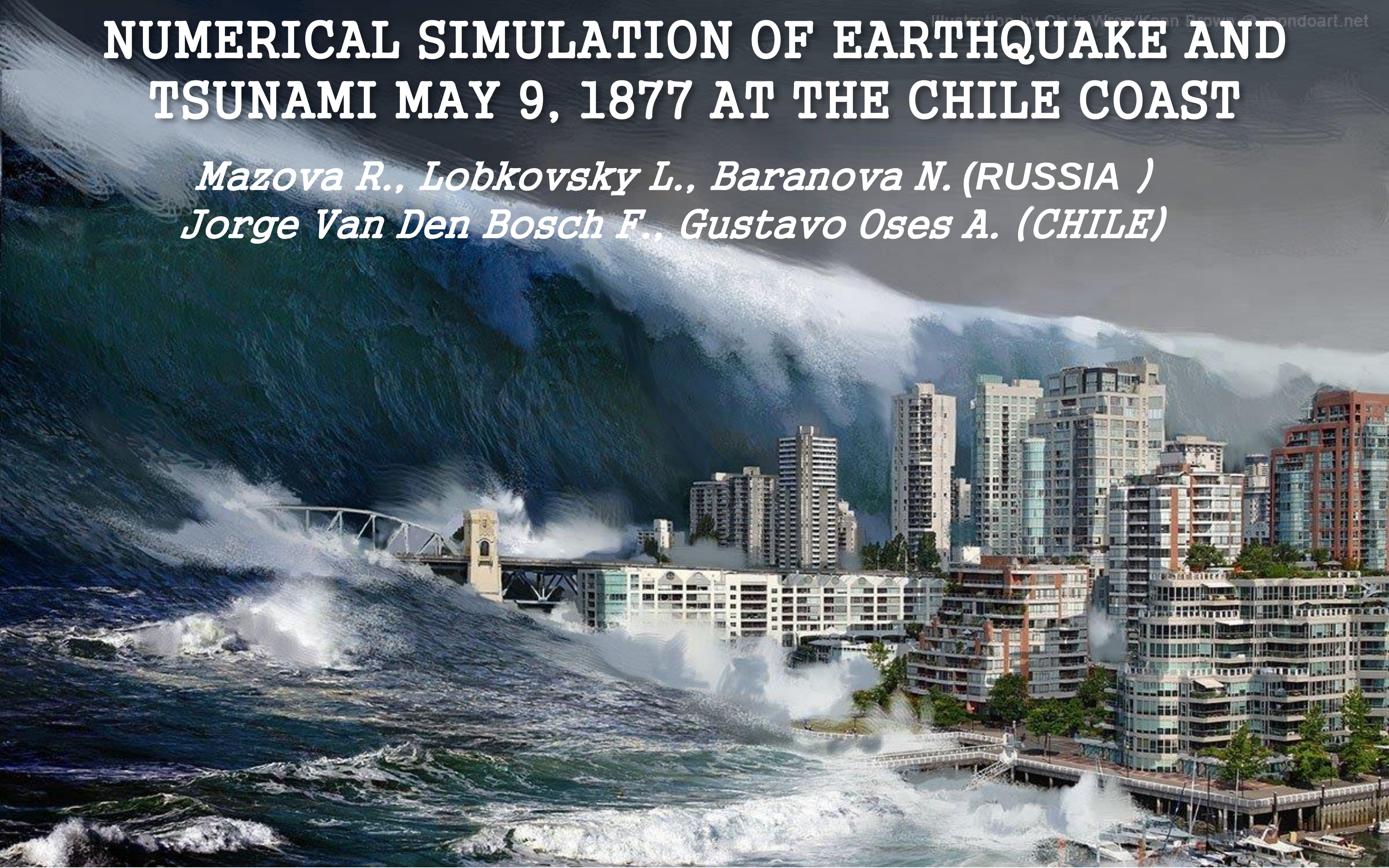


Joining forces for progress and security

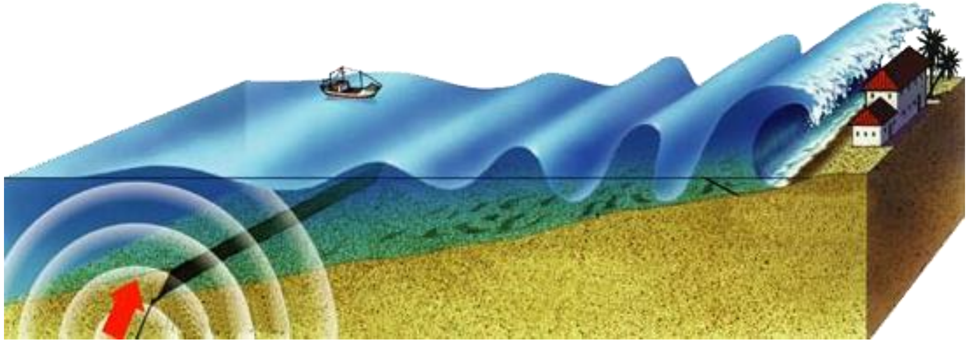
Moscow Institute of Physics and Technology (MIPT) is one of the leading Russian universities, a national research university that trains scientists and engineers to work in the latest fields of science,

The Institute of Oceanology of the Russian Academy of Sciences (IO RAS) is the oldest and largest Russian research center in the field of oceanology,

Nizhny Novgorod Technical University (NSTU) is an advanced technical university whose mission is to train engineering and scientific personnel for industry.

Natural Disaster Mitigation Engineering Center, Department of Engineering, University of Antofagasta (Chile)

for interaction in frame of projects on introducing of innovative geophysical technologies, have combined their scientific potential in the direction of creating modern systems for monitoring the oceanic bowels to study the nature of tsunamis, prediction of their generation and assess tsunami hazard

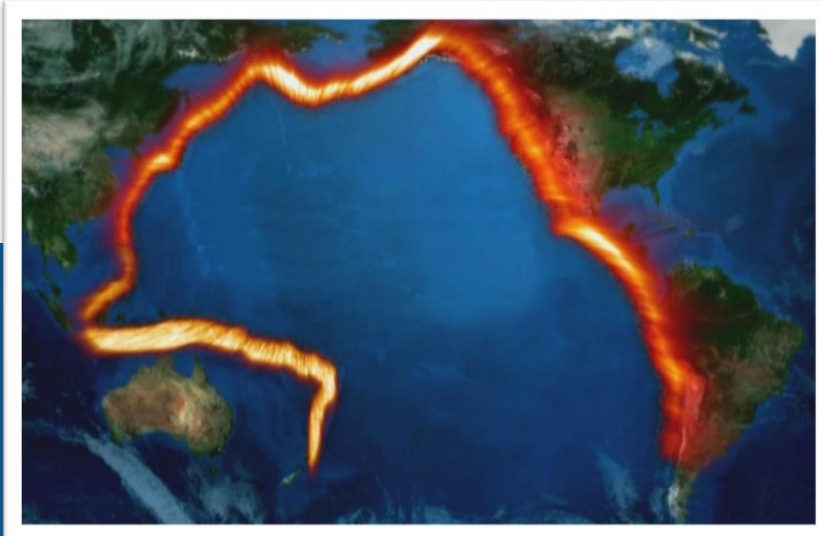


TSUNAMI (Japanese 津 波 - “wave filling the bay”) - sea gravitational waves of large (up to 1000 km) length resulting from a sharp vertical shift of significant sections of the seabed.

The vast majority (more than 85%) of the causes of tsunami generation are seismic in nature, since they are caused by the dumping of accumulated seismic energy in the zone of shear deformation of the contacting oceanic and continental lithospheric plates.

The probability of a tsunami depends on the strength of the earthquake and reaches a value of 0.9 with a magnitude > 7.5 on the Richter scale.

More than 80% of the tsunamis occur on the periphery of the Pacific Ocean off the coasts of Chile, Peru, Alaska, the Kuril-Kamchatka ridge, the Japanese islands, Indonesia and Oceania, which received the characteristic name of the Pacific Ring of Fire



Geodynamic model of the source of strongest tsunamigenic earthquakes

The appearance of anomalous tsunamis can be caused by the mechanism of the earthquake source, characterized by shear movements, with the epicenters of the main shocks of these earthquakes located on a deep-sea terrace (Fig. 1). The movement under the terrace can be accompanied by movements along the transverse faults separating two adjacent block-keys (Fig. 2). This model was tested at the catastrophic event in the Chilean subduction – Maule earthquake (Mw = 8.8), which occurred on February 27, 2010. The interpretation of the displacements of the earth's surface observed in the vicinity of the source of the Maule earthquake at different stages of the seismic cycle was carried out within the framework of the key model of the strongest earthquakes in subduction zones

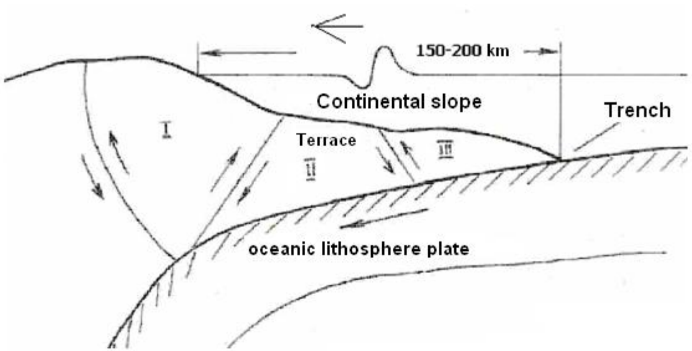


Fig.1. The scheme of breaks and movements in the source of tsunamigenic earthquakes

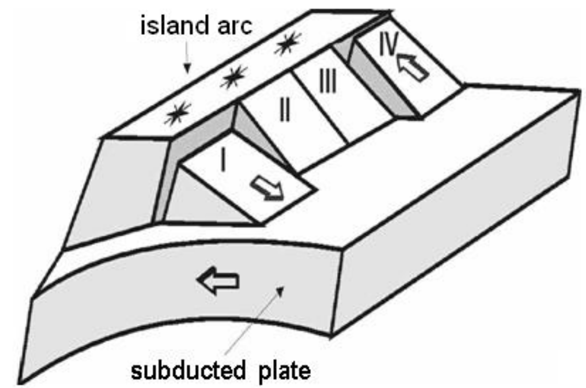
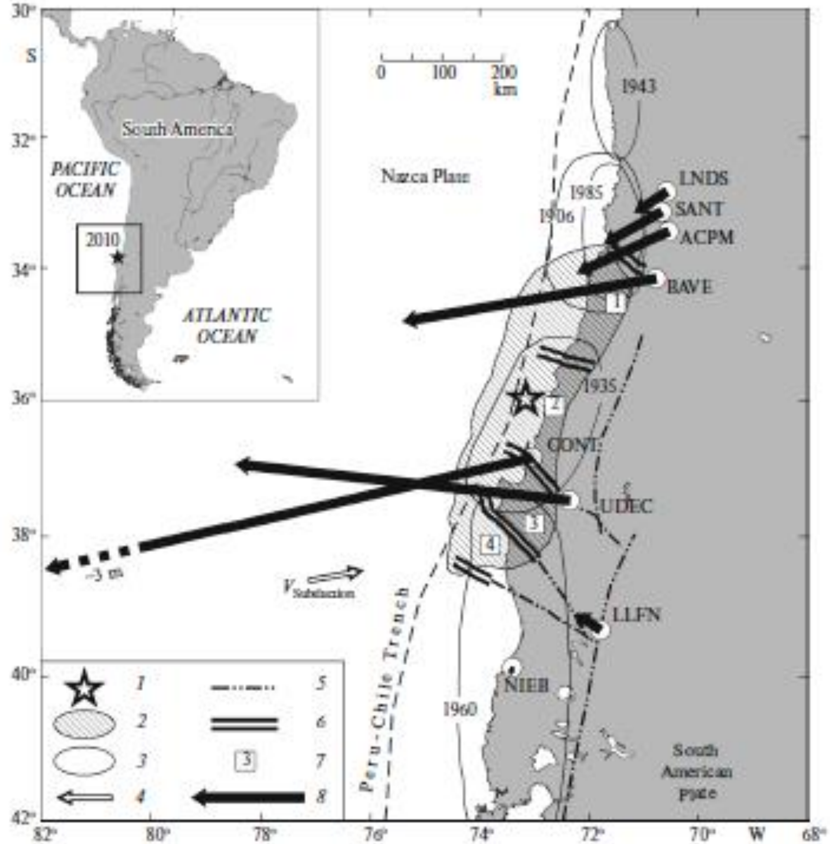


Fig.2. Keyboard model of the subduction zone [Lobkovsky, 1988; Lobkovsky et al., 2004]

Leading forecast and warning of a possible catastrophic event



As a result of many years of satellite-borne geodetic observations after the 2010 Maule earthquake, heterogeneities of the velocity field of displacements of points on the Earth's surface both in the direction deep into the continent and along the oceanic trench are revealed. During the earthquake in Chile in 2010, fast coseismic displacements were recorded at the GPS stations functioning at that time. The location of a number of stations directly above the earthquake source allows us to estimate the magnitude of these rapid displacements, which were of the order of 1 m, and at the station closest to the earthquake epicenter, exceeded 3 m, i.e. were maximum at the boundaries of blocks (see figure) (Lobkovsky et al., DAN, 2017)

Coseismic displacements recorded by stations of regional geodynamic networks during the Maule earthquake 02/27/2010

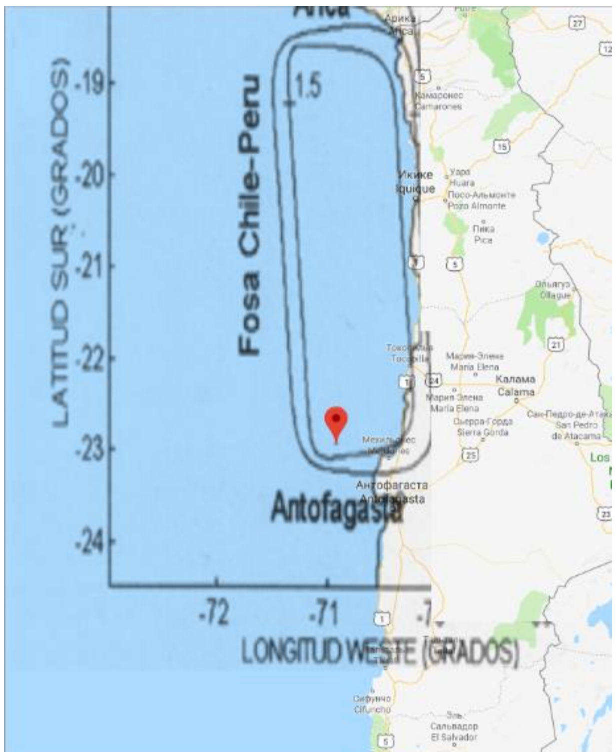
Catastrophic earthquake in Chile on May 9, 1877

The interpretation of long-term satellite geodetic observations after the 2010 Maule earthquake based on the keyboard concept of the structure of subduction regions allowed us to apply this concept to the Chilean subduction zone to analyze Earth surface displacements observed in the vicinity of the earthquake source during a catastrophic earthquake on May 9, 1877.

On May 9, 1877, local time in Iquique, an earthquake was recorded with M = 8.5 (8.8) and the subsequent tsunami. The highest intensity was observed between the cities of Iquique and Antofagasta, Tokopiglia, Gatiko, Kobika were severely affected. All these cities are destroyed, the death toll is 2541 people. 5 minutes after the earthquake in the area of Tokopilia, Gatiko, Kobikha, tsunami waves from 5 to 15 m came. The second wave came 15 minutes after the main shock with a height of 20 to 23 m.

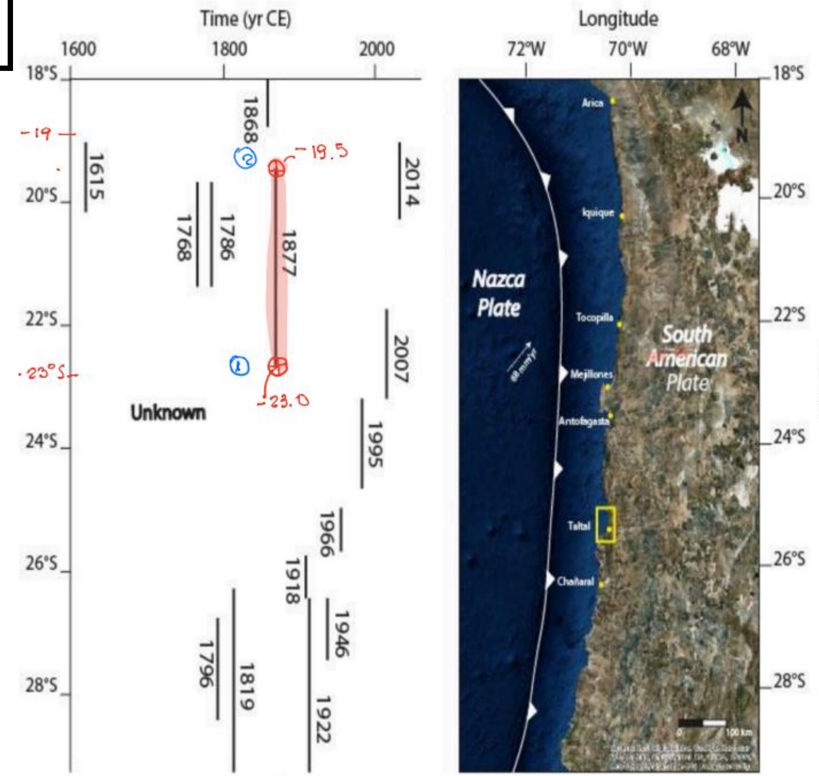
Catastrophic earthquake in Chile on May 9, 1877

SOUTH END	Dislocation	Long	Width	Rhumb	DIP	DEPTH	. Angle of Displacement
23° S 71° W	12 m.	490 Km.	150 Km.	359°	19°	10 Km.	90°



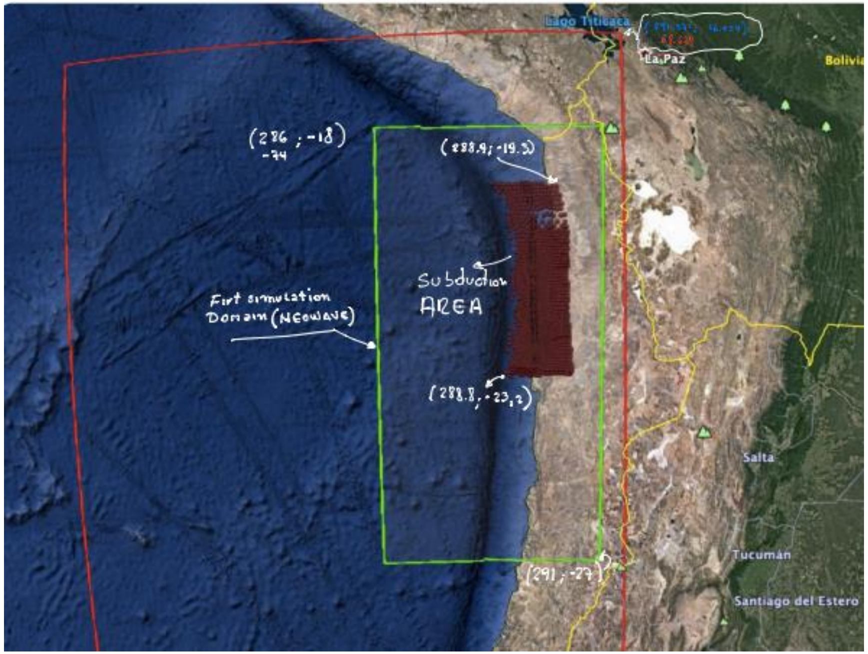
Source:
latitude -22.977158
longitude -71.07658

Land deformation generated by Tsunami 1877 *(Jorge Van Den Bosch F., Gustavo Oses A., Chile)*

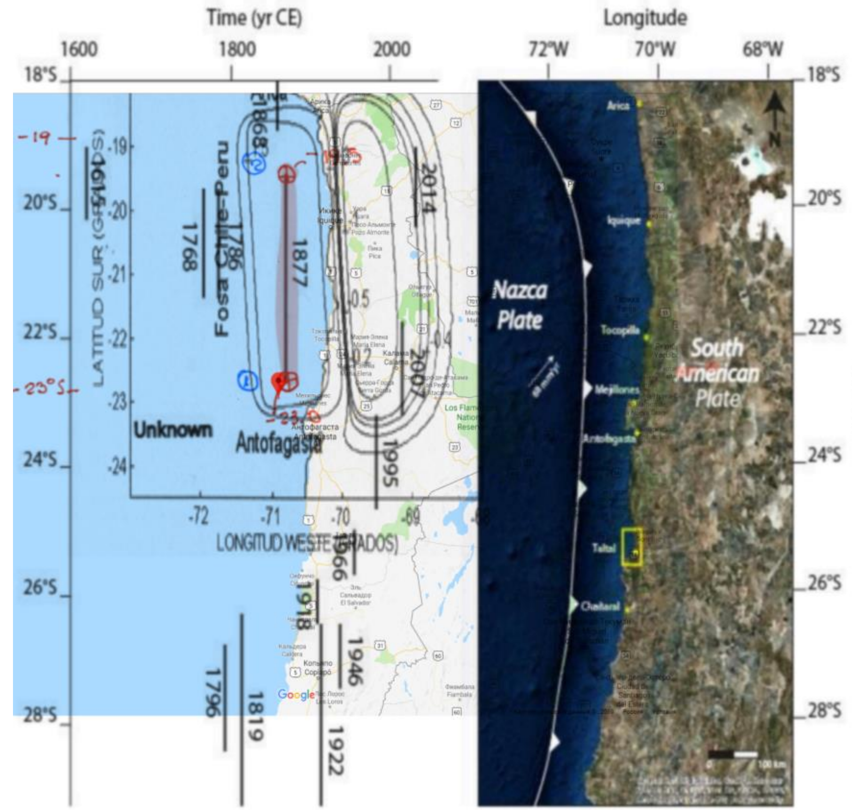


Data Base of Tsunamis and Paleotsunamis
Vagas G., 2018 Uchile

Catastrophic earthquake in Chile on May 9, 1877



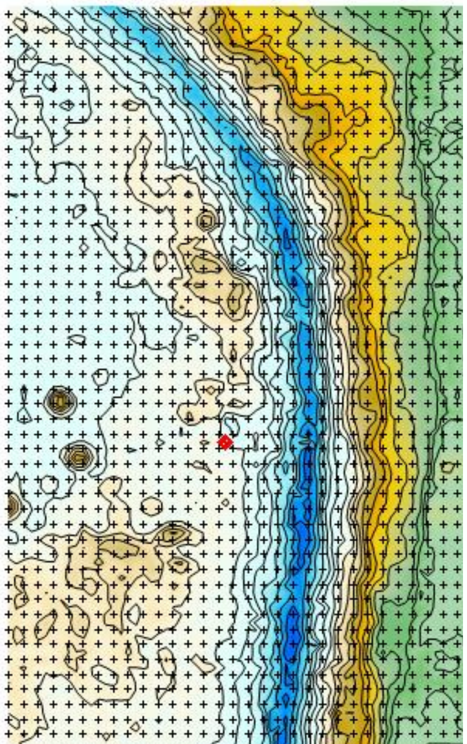
1. The brown region corresponds to the subduction region, for which information on 300 hypocenters in this region was processed for various earthquakes, and later, this information was used to model the earthquake of 1877.
2.The green zone corresponds to the simulation area.



The computation area and the epicenter of the earthquake proposed in (Comte at.al, 1991, Diaz, 1992, Barrientos at al.2009)

Catastrophic earthquake in Chile on May 9, 1877

Region of numerical simulation



Bathymetry of the computation area

(291.371; -16.0

68.629

(289.94; -19.308)

BIGONE 1877 AREA

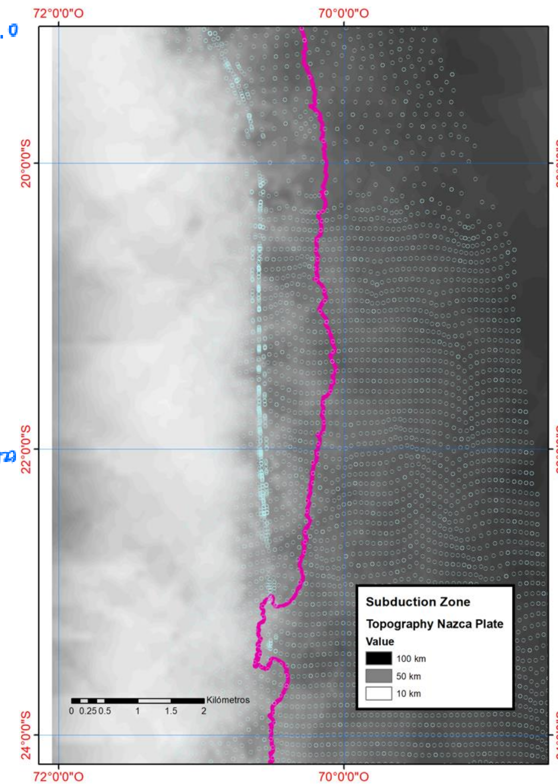
(288.808; -23.246

TOTAL DATA

Region of numerical simulation (*Jorge Van Den Bosch F., Gustavo Oses A., Chile)*

(278.679; -48.746)

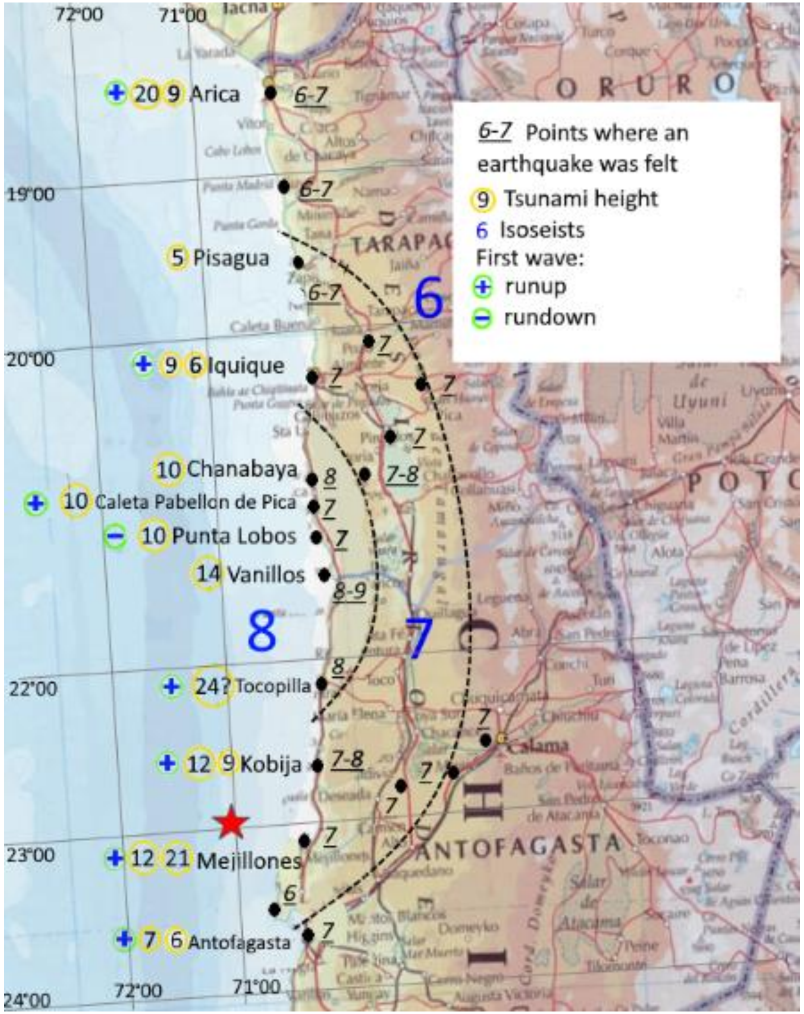
- 81.321



Subduction Zone. Topography Nazca Plate (*Jorge Van Den Bosch F., Gustavo Oses A., Chile)*

Catastrophic earthquake in Chile on May 9, 1877

According to the work of S.L.Solovyov, the calculated magnitude of the earthquake of May 9, 1877 was 8.5 (according to other works - 8.8).
The vertical component of the displacement of the wave surface above the earthquake source can be obtained using the Iida formulas for maximum height of the vertical displacement of the water surface above the source of the earthquake for M=8,5, for M=8,8.



The area of the greatest intensity of the earthquake and the epicenter of the earthquake (according to the works of Solovyev, 1975; Diaz, 1992, Barrientos et.al., 2009); large blue numbers indicate the areas where the tsunami was most intense; the numbers in the yellow circles are data on the tsunami heights in a concrete point (according to works of Solovyov, 1975; Diaz, 1992, Barrientos et.al., 2009); the signs (+) and (-) near the numbers on the left determine the nature of the approach of the first wave to the shore: (+) the wave runup to the shore, (-) the wave rundown from the shore; dotted black lines are the isoseisms.

Catastrophic earthquake in Chile on May 9, 1877

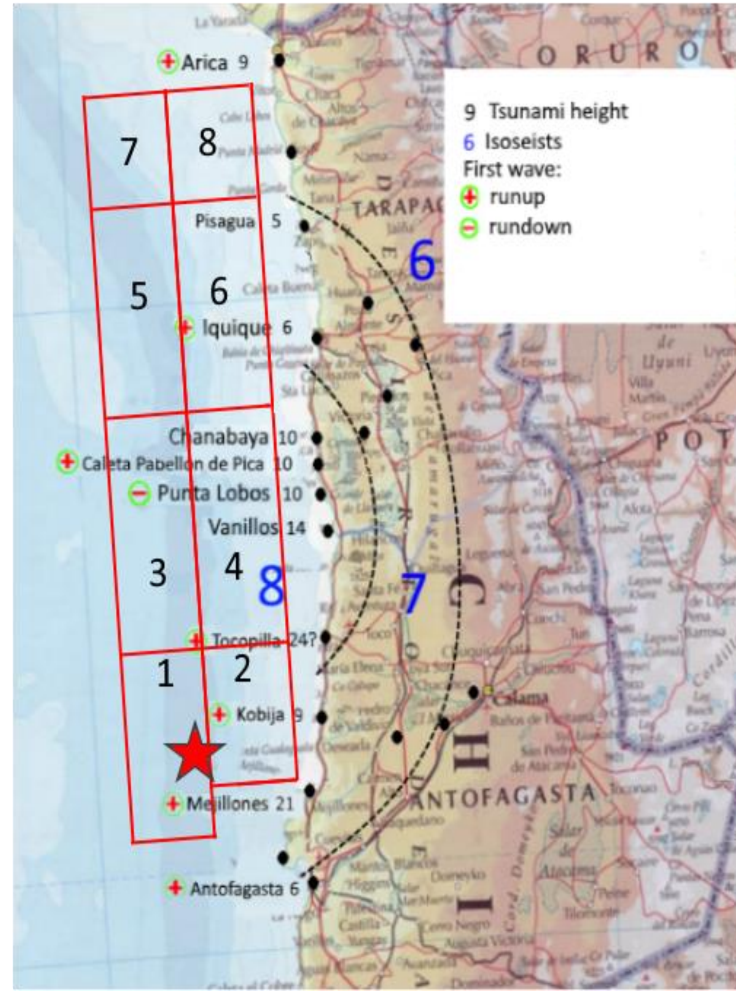
Using Wells formulas we get:

lg L = 0.59 Mw - 2.44 +/- 0.16, (L (km)),

lg W = 0.32 Mw - 1.01 +/- 0.15, (W (km)),

For magnitude 8.5, The rupture extension in the source is ~ 500;
rupture plane width ~ 70km;
For magnitude 8.8:
The rupture extension in the source is ~ 800 km,
the width of the rupture plane is ~ 90 km.

In the first 12 scenarios of calculating the generation and propagation of tsunami waves, we based on the data of Chilean works, which indicated the localization of the epicenter of the earthquake in the area of Antofagasta and the possible direction of the movement of aftershocks from the south from Antofagasta to the north to Arica.

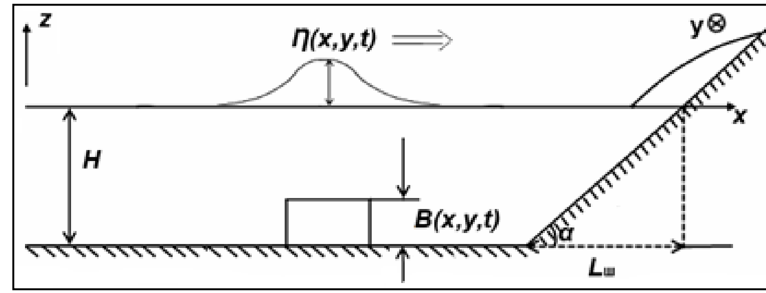


8-block source of the earthquake of 1877 formed according to the initial data of Chilean researchers

Tsunami wave generation and propagation model

The wave generation and propagation were described by the nonlinear system of equations of shallow water which in two-dimensional case can be written as

$$\begin{cases} \dfrac{\partial u}{\partial t} + u\dfrac{\partial u}{\partial x} + v\dfrac{\partial u}{\partial y} + g\dfrac{\partial \eta}{\partial x} = f_1 \\ \dfrac{\partial v}{\partial t} + u\dfrac{\partial v}{\partial x} + v\dfrac{\partial v}{\partial y} + g\dfrac{\partial \eta}{\partial y} = f_2 \\ \dfrac{\partial \eta}{\partial t} + \dfrac{\partial}{\partial x}\left[(\eta + H - B)u\right] + \dfrac{\partial}{\partial y}\left[(\eta + H - B)v\right] = \dfrac{\partial B}{\partial t} \end{cases}$$

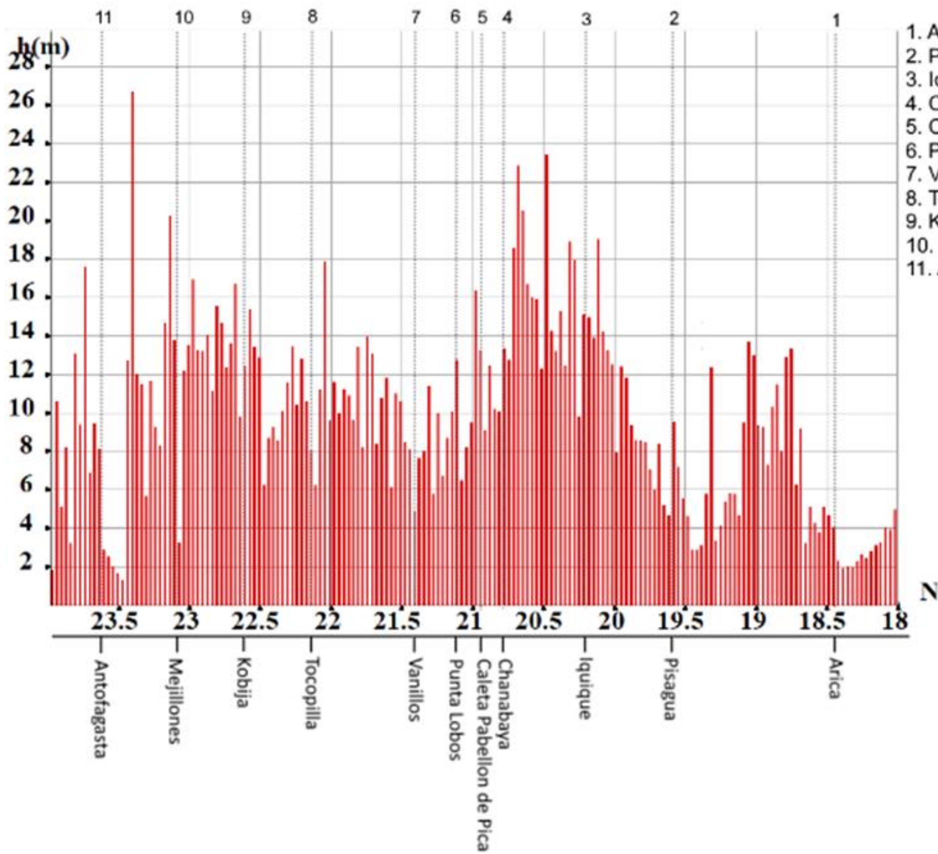


η(x,y,t) **is the perturbation of free water surface relative to its undisturbed level,** ***H*** **is the maximum depth of basin,** ***B(x,y,t)*** **is the change of the basin bottom (taking into account the dynamical seismic source characteristics).**

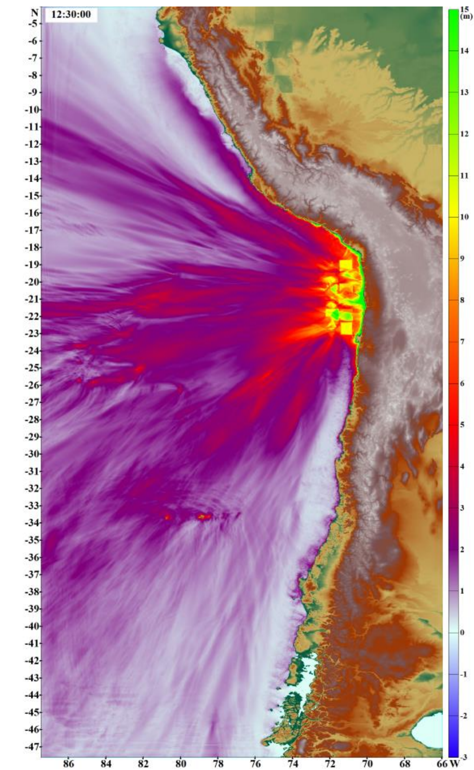
Of the variety of difference schemes approximating equations, we chose the scheme proposed in [*Marchuk et al.,* 1983] because of its high algorithmic versatility. The scheme is based on a divided difference and, in conjunction with the central difference approximation of spatial derivatives, simplifies the numerical implementation of boundary conditions, *sh is the* roughness coefficient.

$$f_1 = \frac{-C_h}{H+\eta} u\sqrt{u^2+v^2}\ , \quad f_2 = \frac{-C_h}{H+\eta} v\sqrt{u^2+v^2}\ , \text{ где } \quad Ch = \frac{(H+\eta-B)^{0.4}}{sh}$$

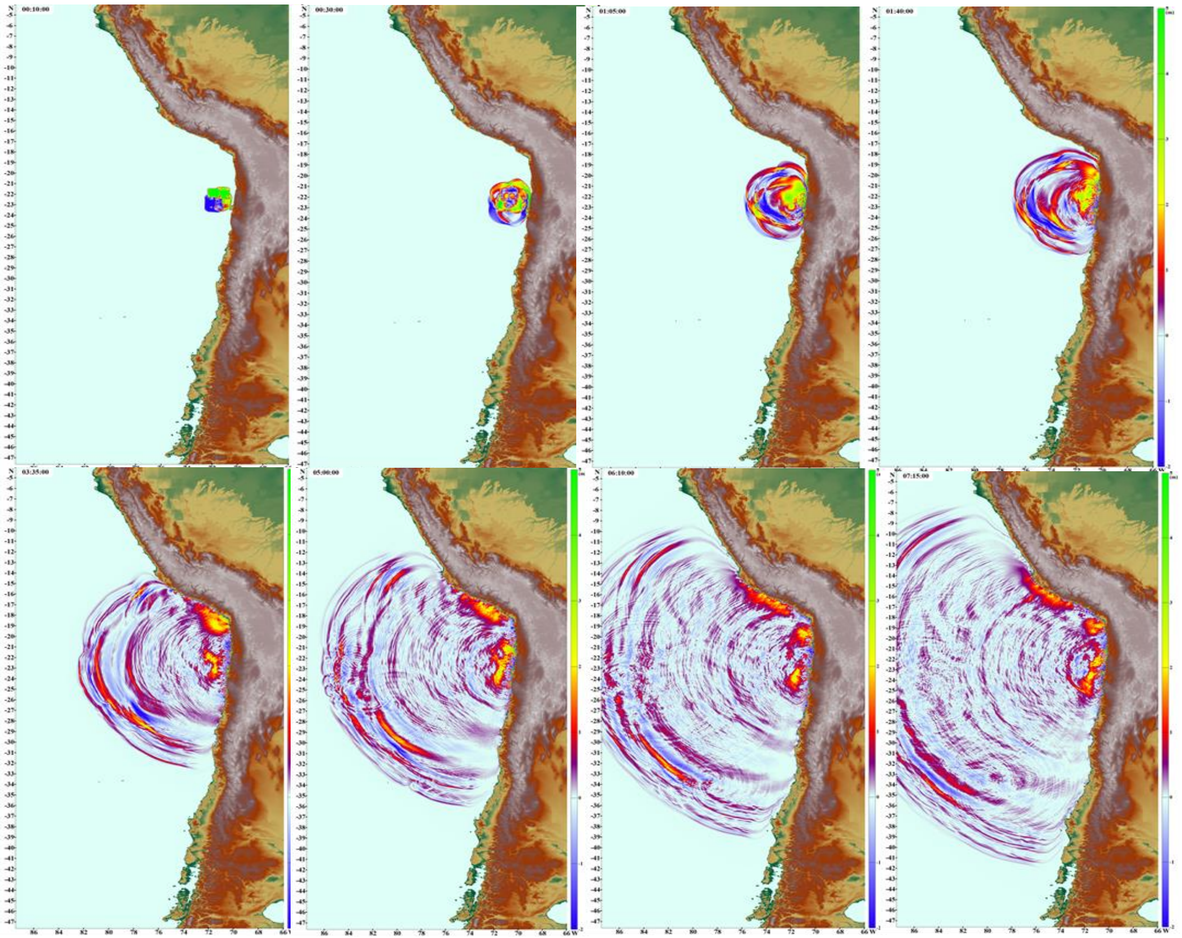
Numerical simulation of the generation and propagation of tsunami waves for scenario 10



Points	Real data
1. Arica	20 m; 9 m
2. Pisagua	5 m
3. Iquique	9 m; 6 m
4. Chanabaya	10 m
5. Caleta Pabellon de Pica	10 m
6. Punta Lobos	10 m
7. Vanillos	14 m
8. Tocopilla	24 m
9. Kobija	12 m; 9 m
10. Mejillones	12 m; 21 m
11. Antofagasta	7 m; 6 m



Numerical simulation of the generation and propagation of tsunami waves for scenario 10

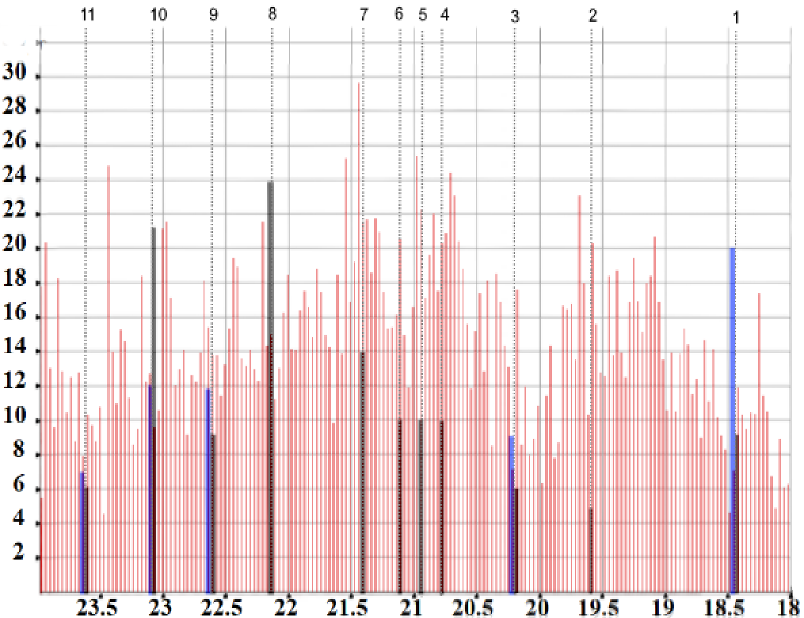


Tsunami wave propagation for 8 time moments of scenario 10

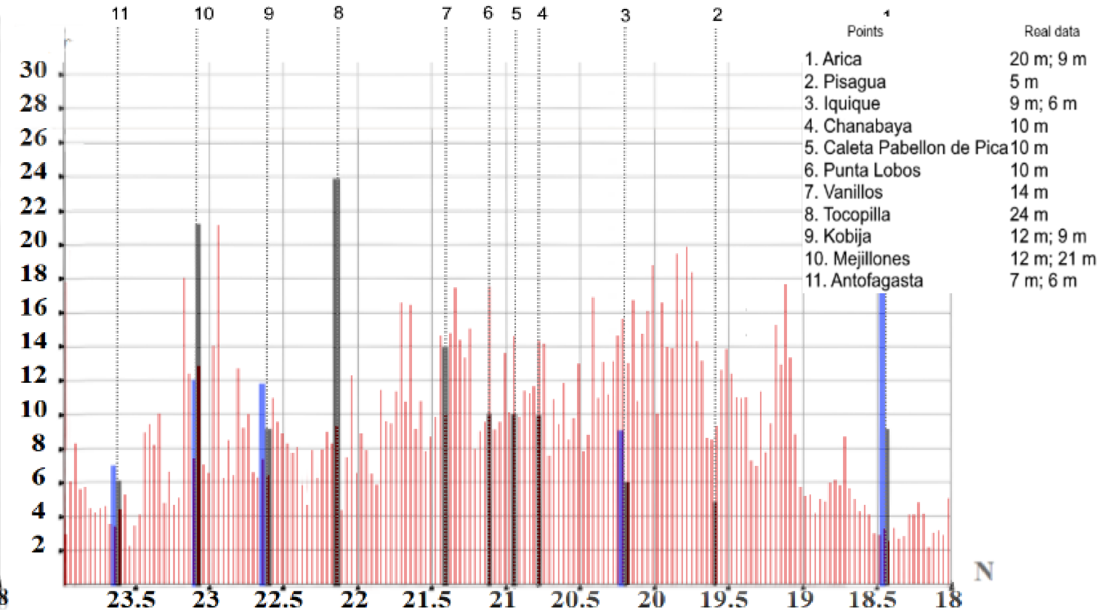
Catastrophic earthquake in Chile on May 9, 1877

However, a large number of scenarios considered by us with such a localization of the epicenter of the earthquake did not yield any results that were close to real data. So, on the histograms you can see the distribution of the maximum wave heights along the coast.

Scenario 11



Scenario 13

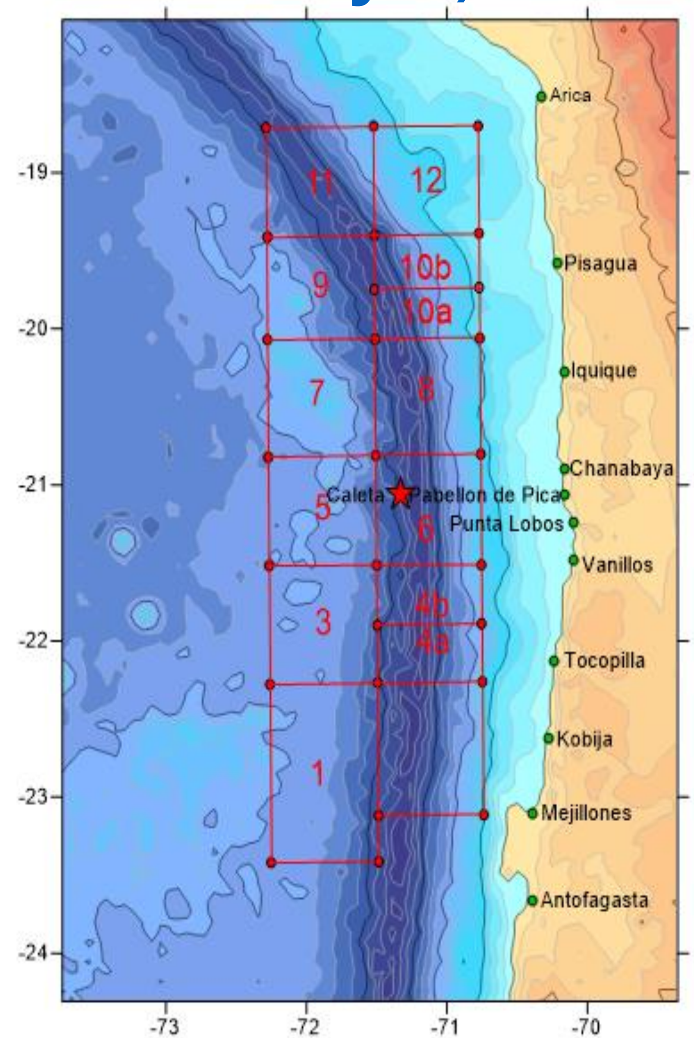


Red — calculated histogram; gray - data on Soloviev; blue - data from the work of the Chilean tsunamists (Diana Comte and Mario Pardo, 1991; Diaz, J., 1992; Barrientos, S., Ward, S.N. , 2009, Ward, S.N. ,2009; *Jorge Van Den Bosch F., Gustavo Oses A.)*

Catastrophic earthquake in Chile on May 9, 1877

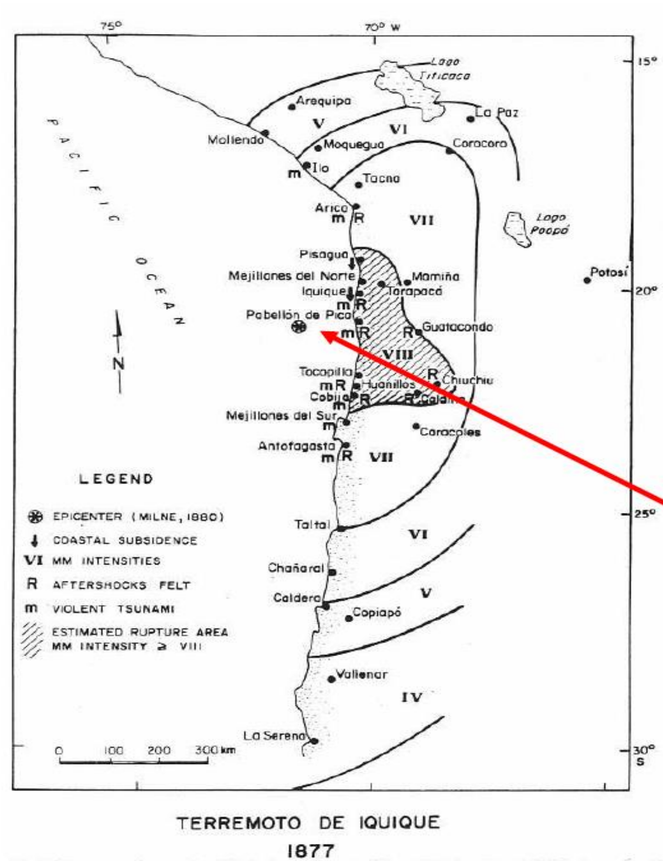
New hypothesis

An additional analysis of the available data on the implementation of this earthquake led us to the conclusion about erroneous information on the localization of the epicenter of the earthquake on May 9, 1877. By changing the localization of the epicenter and forming a more complex seismic focus, taking into account the movement of aftershocks, both towards the north, to Arica, and towards the south, to Antofagasta, we obtained the most adequate distribution of the maximum wave heights along the considered section of the Chilean coast.



The center of the earthquake with an epicenter in p. Caleta Pabellon de Pica. Colored dots indicate virtual tide gauges.

Catastrophic earthquake in Chile on May 9, 1877

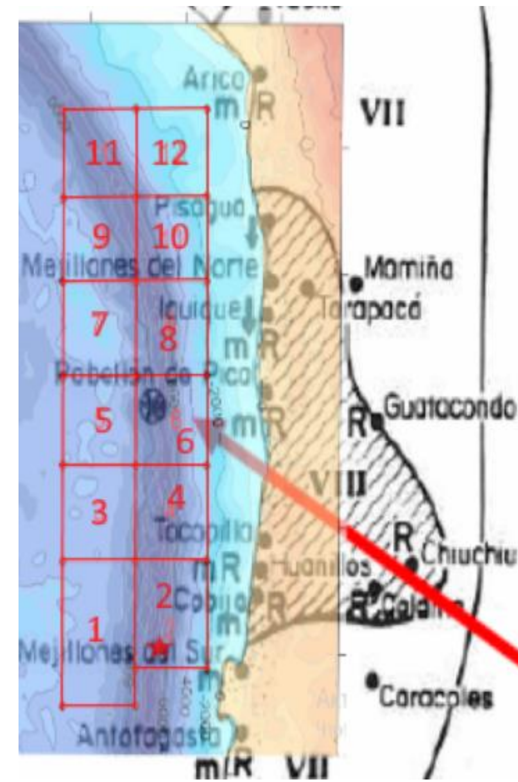


Hypothesis confirmation

Kausel and Campos, 1992. proposed hypocenter from tsunami damage and flooding on the other hand, Diana Compte and Mario Pardo 1991 (Natural Hazards) proposed Epicenter in "reappraisal of great historical earthquake in the northern Chile and southern Peru seismic gap" proposed for 1877 epicenter the coordinates 21.0 lat. S. and 70.3 Long. W. and 8.8º Ms, 8.7º mL. magnitude, 420 Km Length of the breaking zone.

The two groups of Chilean seismologists agree with data by Soloviev, we believe that they are more consistent in their analysis, therefore it is better to accept epicenter at approximately 21º latitude.

(*Jorge Van Den Bosch F., Gustavo Oses A., Chile)*



The location of the source with the new localization of the epicenter (6 block)

Catastrophic earthquake in Chile on May 9, 1877

The movement of key-blocks in the virtual center of the earthquake Scenario 23

Driving order	Block numbers	1	2	3	4a	4b	5	6	7	8	9	10 a	10 b	11	12
1	Heights (m)	-3.5	2	5.5	3.5	3	0	-3	1	-1	1	1.5	-3	2	4
	Block lift start time (s)	90	75	60	30	30		15	0	0	45	45	45	120	105
	Block lift completion time (s)	105	90	75	45	45		30	15	15	60	60	60	135	120
2	Heights (m)	3			1.5					0				1.5	
	Block lift start time (s)	165			150					150				135	
	Block lift completion time (s)	180			165					165				150	

Comparison of numerical simulations of the generation and propagation of tsunami waves for a number of scenarios

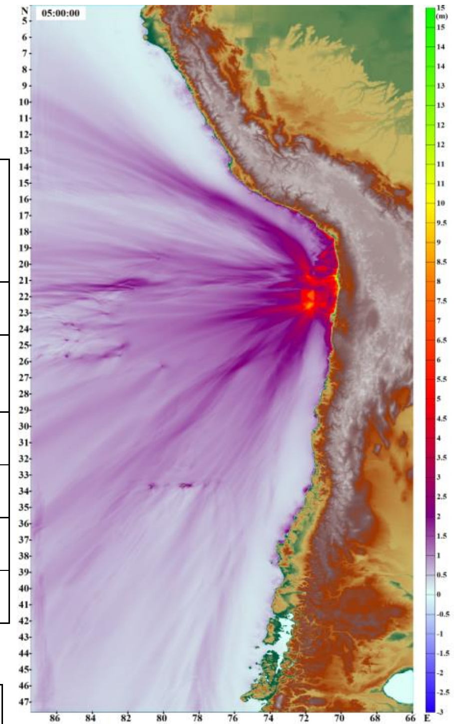
Scenario 13, 17, 18, 20, and 23

Tabl.1

Points	Arica	Pisagua	Iquique	Chanabaya	Caleta Pabellon de Pica	Punta Lobos	Vanillos	Tocopilla	Kobija	Mejillones	Antofagasta
Real data	9 (20)	5	6 (9)	10	10	10	14	24	9 (12)	21 (12)	6(7)
Scenario 13	5	9	16	14	15	18	10	10	6	8	4
Scenario 17	9	21	10	12	13	12	15	12	18	18	5
Scenario 18	13	21	10	9	10	10	8	10	8	14	5
Scenario 20	10	18	8	10	8	10	11	6	10	13	6
Scenario 23	7	**12**	**13**	**8**	**8**	**12**	**11**	**11**	**12**	**10**	**12**

Tabl. 2. Name of points and numbers of corresponding blocks

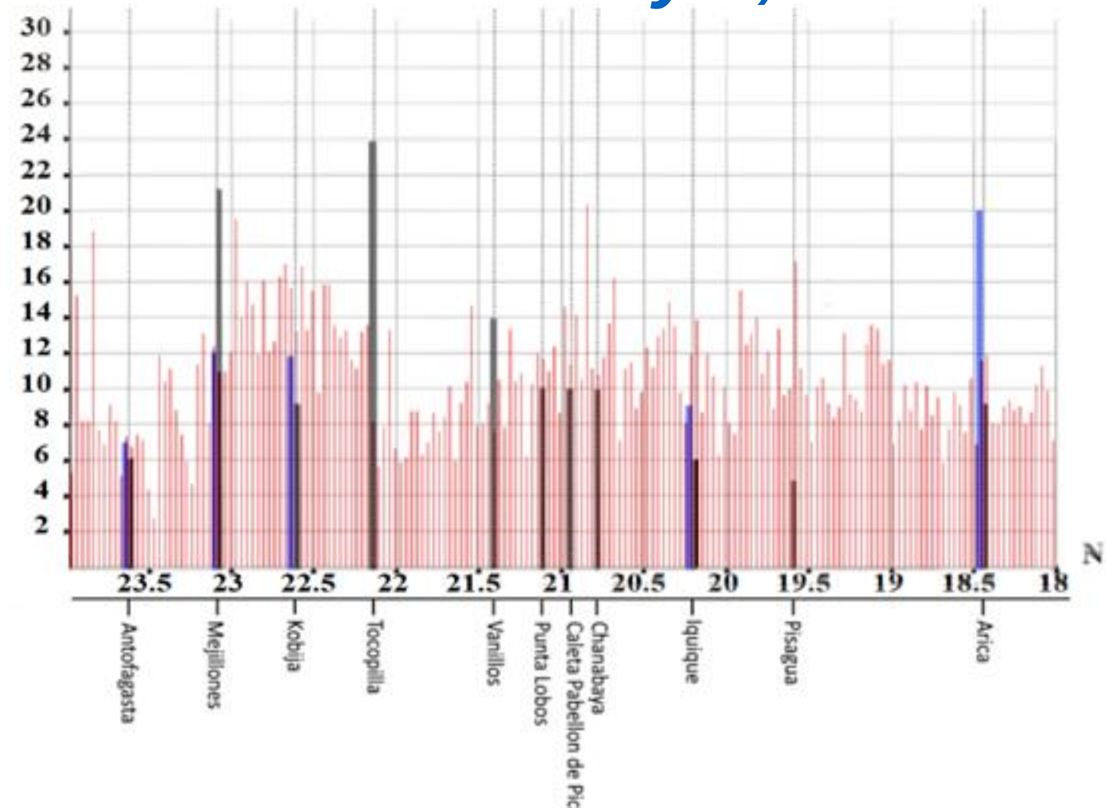
Points	Arica	Pisagua	Iquique	Chanabaya	Caleta Pabellon de Pica	Punta Lobos	Vanillos	Tocopilla	Kobija	Mejillones	Antofagasta
Blocks	To the north 11-12	9-10	7-8	5-6-7-8	5-6	5-6	3-4-5-6	3-4	1-2	1-2	South of 1
Real data	9 (20)	5	6 (9)	10	10	10	14	24	9 (12)	21 (12)	6(7)



Distribution of maximum wave heights in the computation water area for scenario 23

Catastrophic earthquake in Chile on May 9, 1877

In the numerical simulation of the earthquake of 1877, 26 scenarios of the implementation of the movements of keyblocks in the center of the earthquake were carried out. The figure shows a histogram that most closely describes the distribution of the maximum wave heights along the section of the coast of Chile under consideration for the earthquake of May 9, 1877.



A histogram of the distribution of the maximum tsunami wave heights (Scenario 23) along the coastal section under consideration for the 1877 earthquake. Red — calculated histogram; gray - data on Soloviev; blue - data from the work of the Chilean tsunamists(Diana Comte and Mario Pardo, 1991; Diaz, J., 1992; Barrientos, S., Ward, S.N. , 2009, Ward, S.N. ,2009;

Conclusion

There are many numerical complexes for estimating the maximum wave heights on the coasts. A number of them takes into account the dynamics of the Earth's crust in the center of the earthquake during the seismic process. However, when, according to seismologists, the gaps in adjacent segments can be quite small and amount to about less than 100 km. At the same time, the existing complexes are not able to adequately reflect such dynamics. This was also encountered by the Chilean tsunamists, who for a long time tried to obtain data at a number of coastal points close to those available in the literature by numerically simulating the earthquake of May 9, 1877. It should be noted that the inconsistency of the available field data from different authors seriously complicates the analysis of the possible realization of the dynamics in the source of the earthquake. However, when applying the keyboard block- model of the earthquake source, confirmed now geodetic observations, we were able to come closest to solving this problem.


Thank you very much