Scenario based tsunami hazard assessment

- Assess the potential threat posed by earthquake generated tsunamis on the coastlines.

- Compilation a database of potentially tsunamigenic earthquake faults, to be used as input in the definition of scenarios.

- Each Source Zone includes an active tectonic structure with a Maximum Credible Earthquake and a typical fault.

- Provide information of the expected tsunami impact (e.g. height and arrival times) onto the target coastline; it can be progressively updated as knowledge of earthquake source advances.

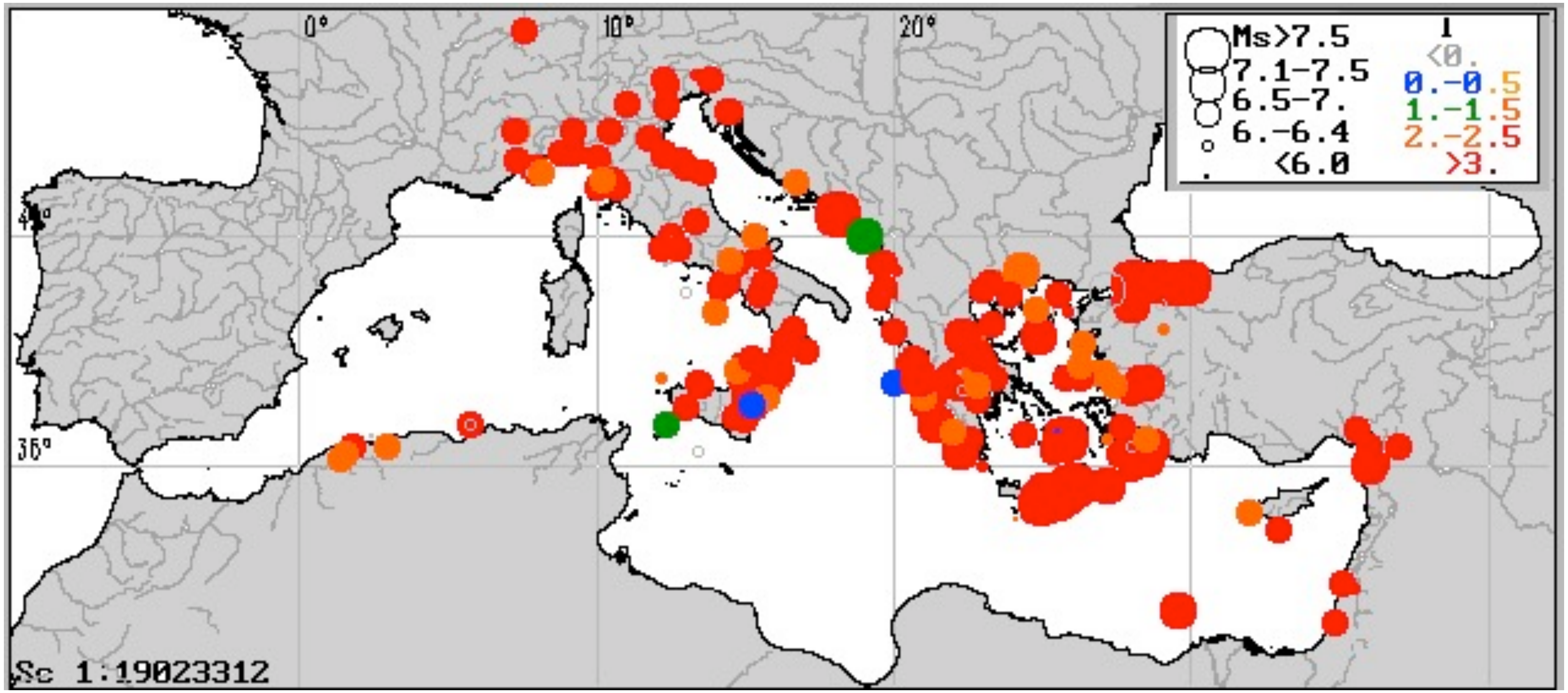
Worst Credible Tsunami Scenario approach

- Identification of credible sources capable of producing the most significant tsunamis in the target area
- Simulation the propagation of the associated tsunamis and computation of the inundation in the target area
- Build of a unique aggregated scenario by combining together all of the computed scenarios: selection of the maximum value of a given physical variable (e.g. height)
- Subjectivity and the related uncertainties can be treated in this paper by performing a sensitivity analysis

The Mediterranean Sea and Tsunamis

http://roma2.rm.ingv.it/en/facilities/data_bases/52/catalogue_of_the_euro-mediterranean_tsunamis

The Mediterranean Sea and Tsunamis



Map of epicenters of tsunamigenic earthquakes occurred since 1380 B.C. to 1996 within the Mediterranean region. The size of circles is proportional to the event magnitude, the color to the tsunami intensity

data from: 'Mediterranean Tsunami Catalog, from 1628 B.C. to present" of the Institute of Computational Mathematics and Mathematical Geophysics (Computing Center) Siberian Division, Russian Academy of Sciences. Tsunami Laboratory

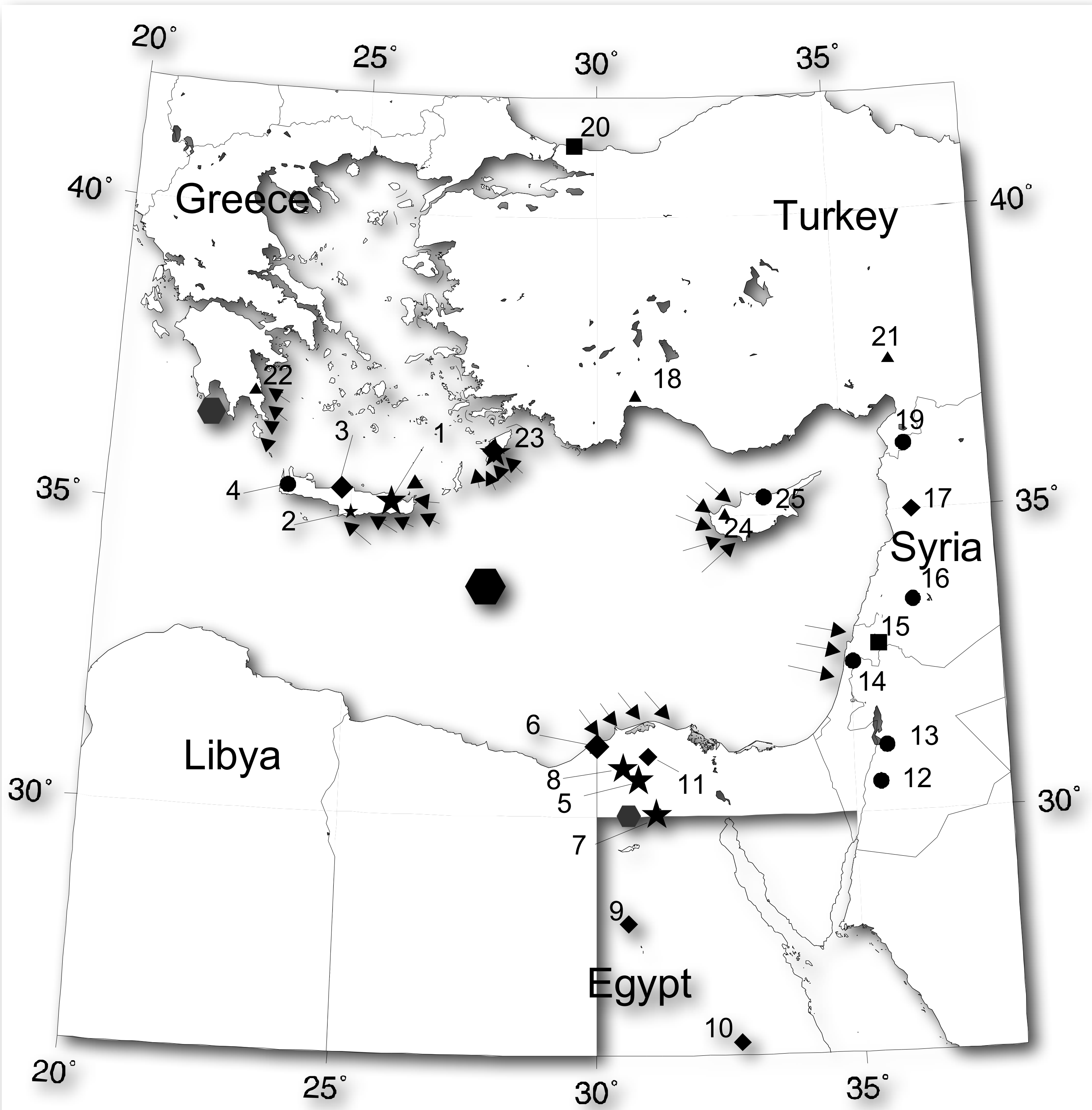
http://tsun.sscc.ru/htdbmed/

1303 Seismic activity in EM

- On 8th of August a large area of the Mediterranean region was shaken by seismic waves that caused severe damage in Crete and Egypt, moderate to minor damage in Palestine, Syria, Cyprus and Turkey.
- The distribution of damage, the duration of shaking and other associated phenomena caused by this earthquake are very different from that reported for most of the largest earthquakes felt in the area.
- Twenty-seven authors have studied the seismic activity of the 8th of August 1303 and proposed considerably different parameters (location and magnitude) for the possible seismic sources.

EL-SAYED, A., ROMANELLI, F., PANZA, G.F., 2000. Recent seismicity and realistic waveforms modeling to reduce the ambiguities about the 1303 seismic activity in Egypt, Tectonophysics, 328, 341-357.

Damaged cities and proposed locations of the event(s) of August 8, 1303



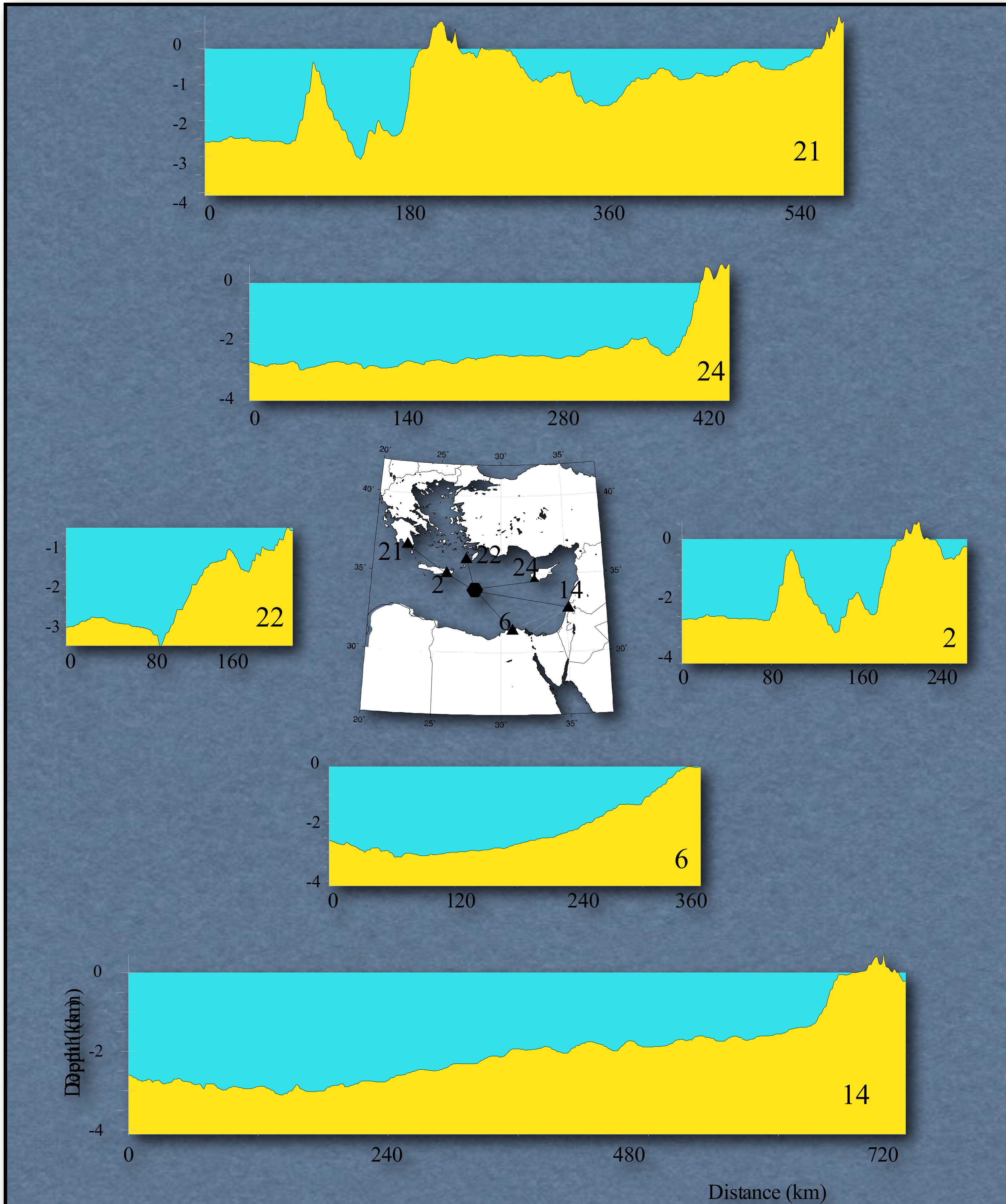
★= extensive damage or total collapse

diamond = heavy damage
circle = low damage
triangle = generic damage
square = felt

arrow = area affected by tsunami

hexagons = epicenters proposed by
Sieberg, (1932) (small),
Maamoun et al. (1984) (medium) and
Ambraseys et al. (1994) (large)

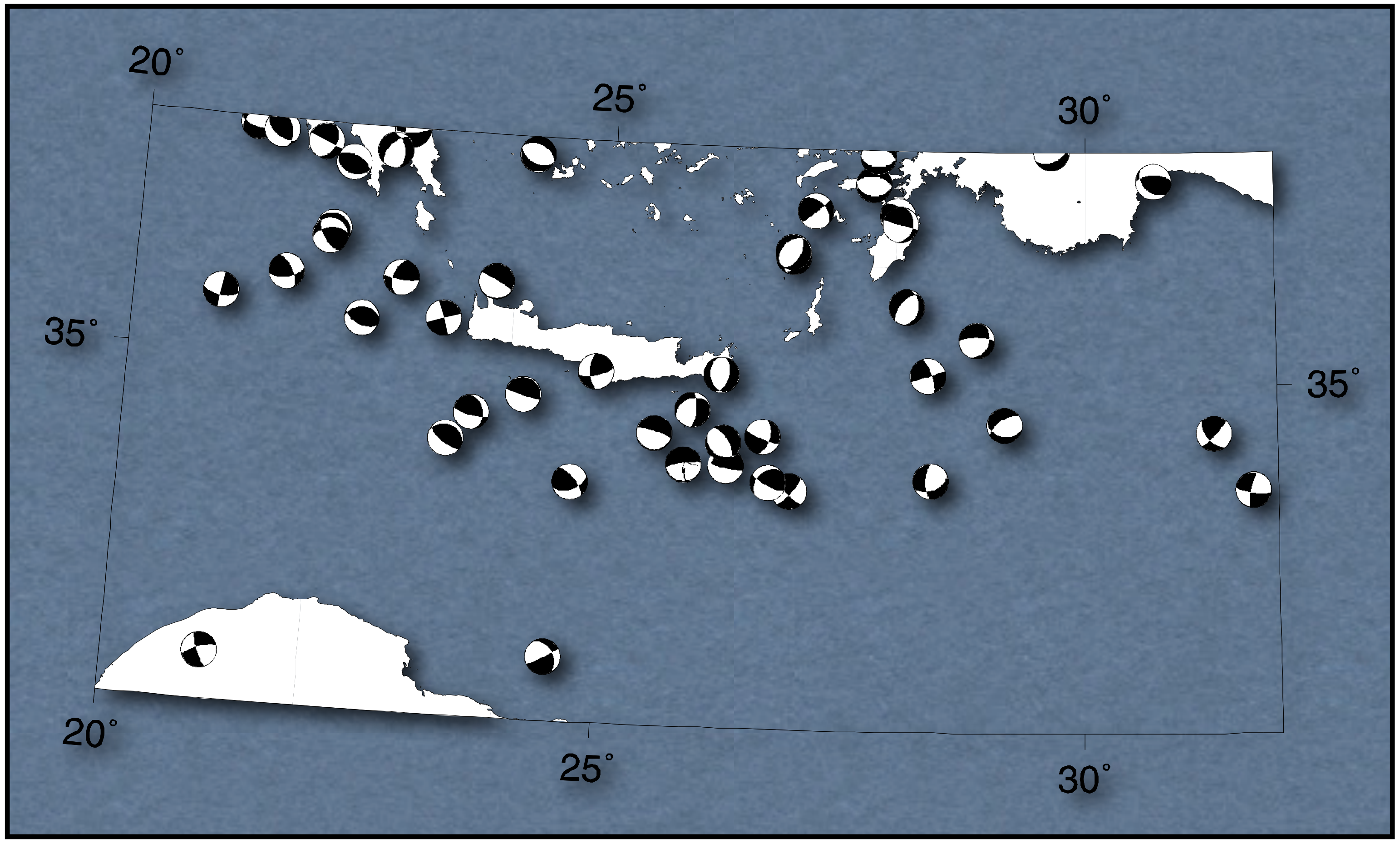
The reported tsunamis strongly support that the seismic activity occurred at sea, i.e. in the Hellenic arc or south of the Peleponnese. To identify a plausible location, tsunami motion is calculated theoretically in the sites that, according to the available information, have experienced strong tsunamis.



The input that is necessary is:

(1) the lithosphere and bathymetery models from the source area to the site of interest, and

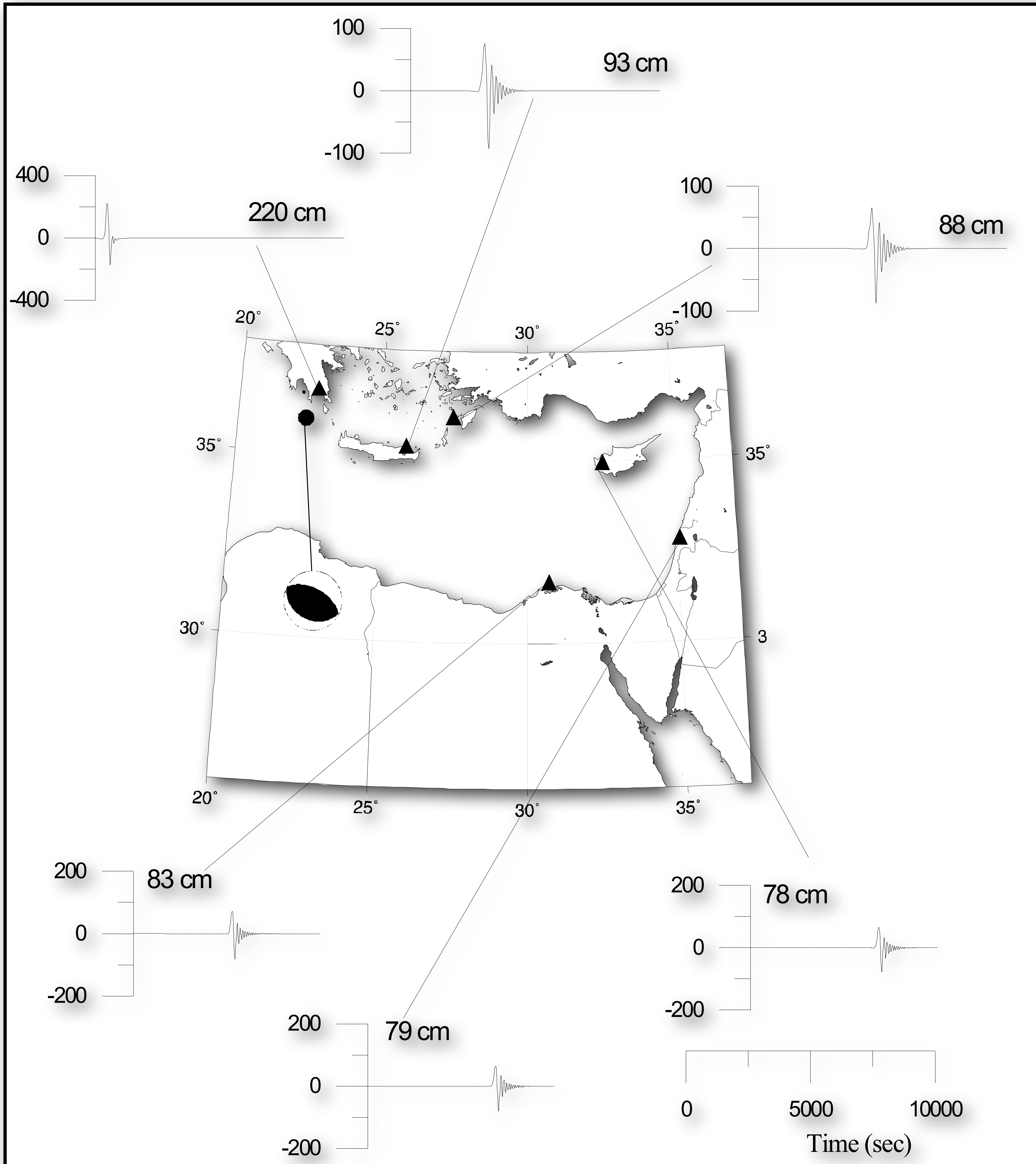
(2) the fault parameters - magnitude, depth and focal mechanism - for the assumed seismic source.



Generally, earthquakes occur in the Hellenic arc at shallow-intermediate depth and have focal mechanisms varying from normal, reverse to strike slip , as it is typical for a subduction zone. We assume that all events in the suggested areas had or will have one of these mechanisms.

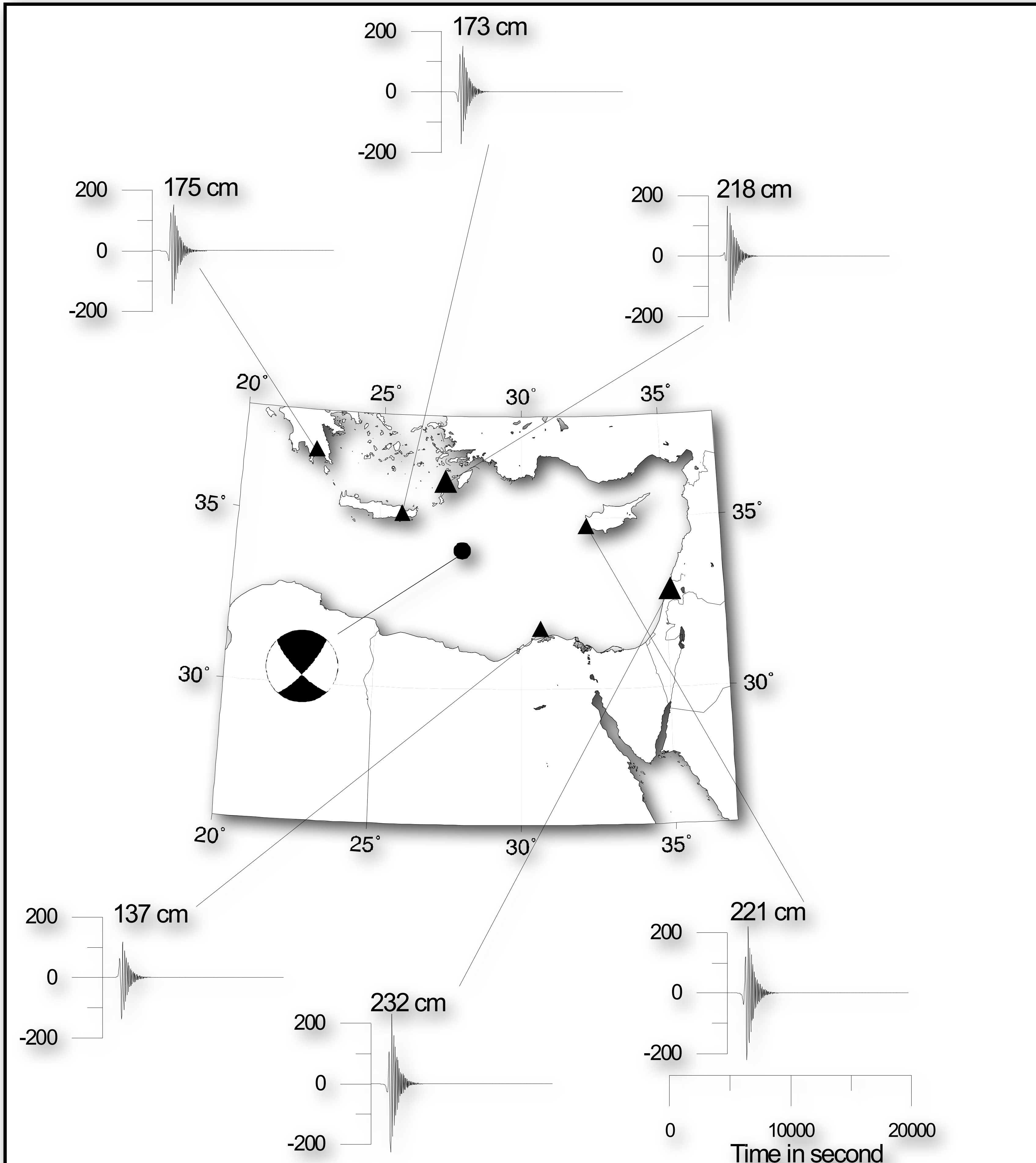
Out of the twenty-seven authors, nine report magnitude with values that vary from 6.5 to 8.0. Therefore, different calculations have been carried out assuming different source sizes, depths and mechanisms consistent with the present tectonics of the proposed epicentral area.

Tsunami computed using Maamoun et al. (1984) location



Fault parameters:
Strike = 289º
Dip = 22º
Slip = 75º

Depth =10 km
Magnitude = 7.0



Tsunami computed using Ambraseys et al. (1994) location

Fault parameters:

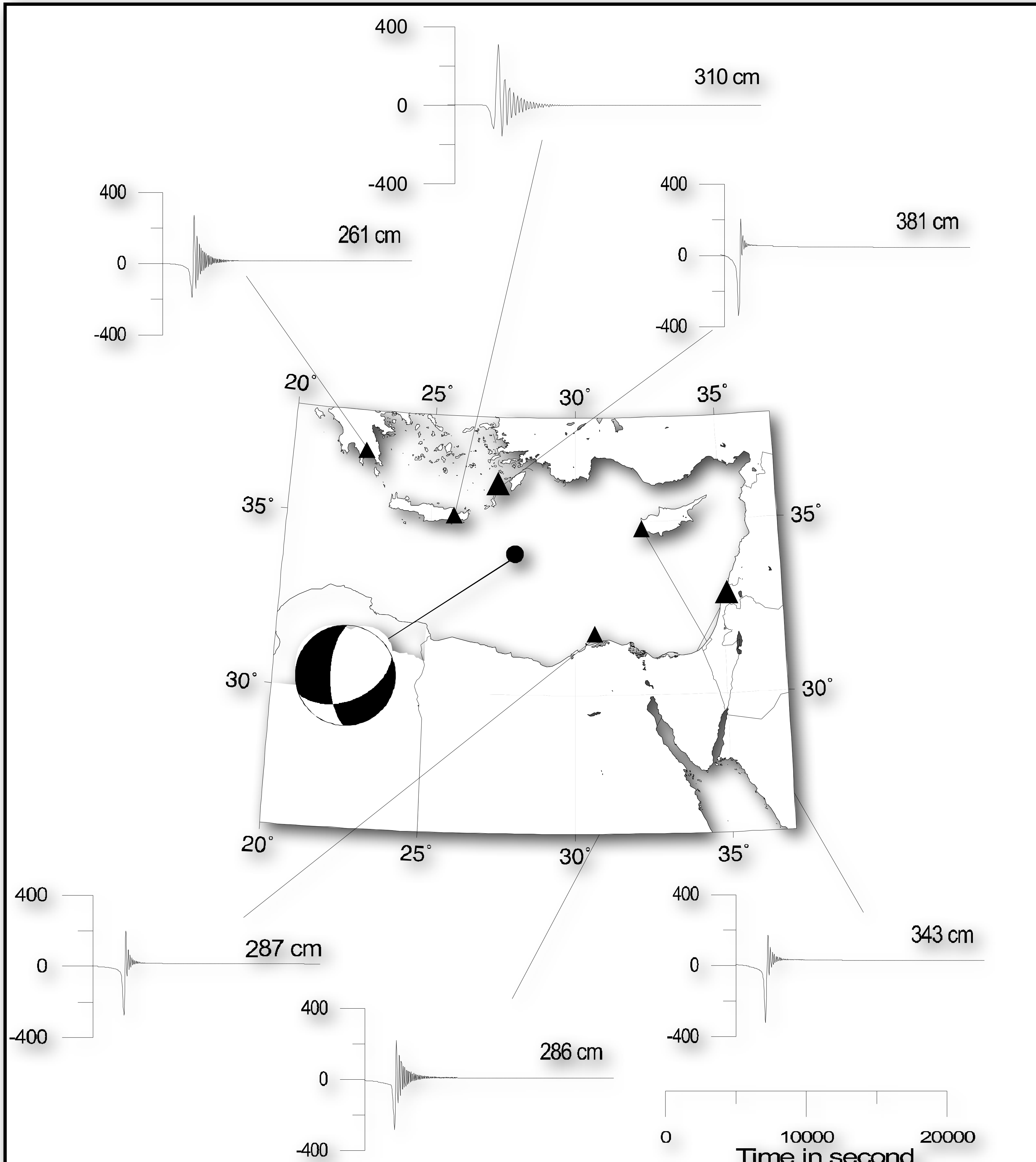
Strike = 135°

Dip = 76°

Slip = 13°

Depth =20 km

Magnitude = 7.8



Tsunami computed using Ambraseys et al. (1994) location - 2

Fault parameters:

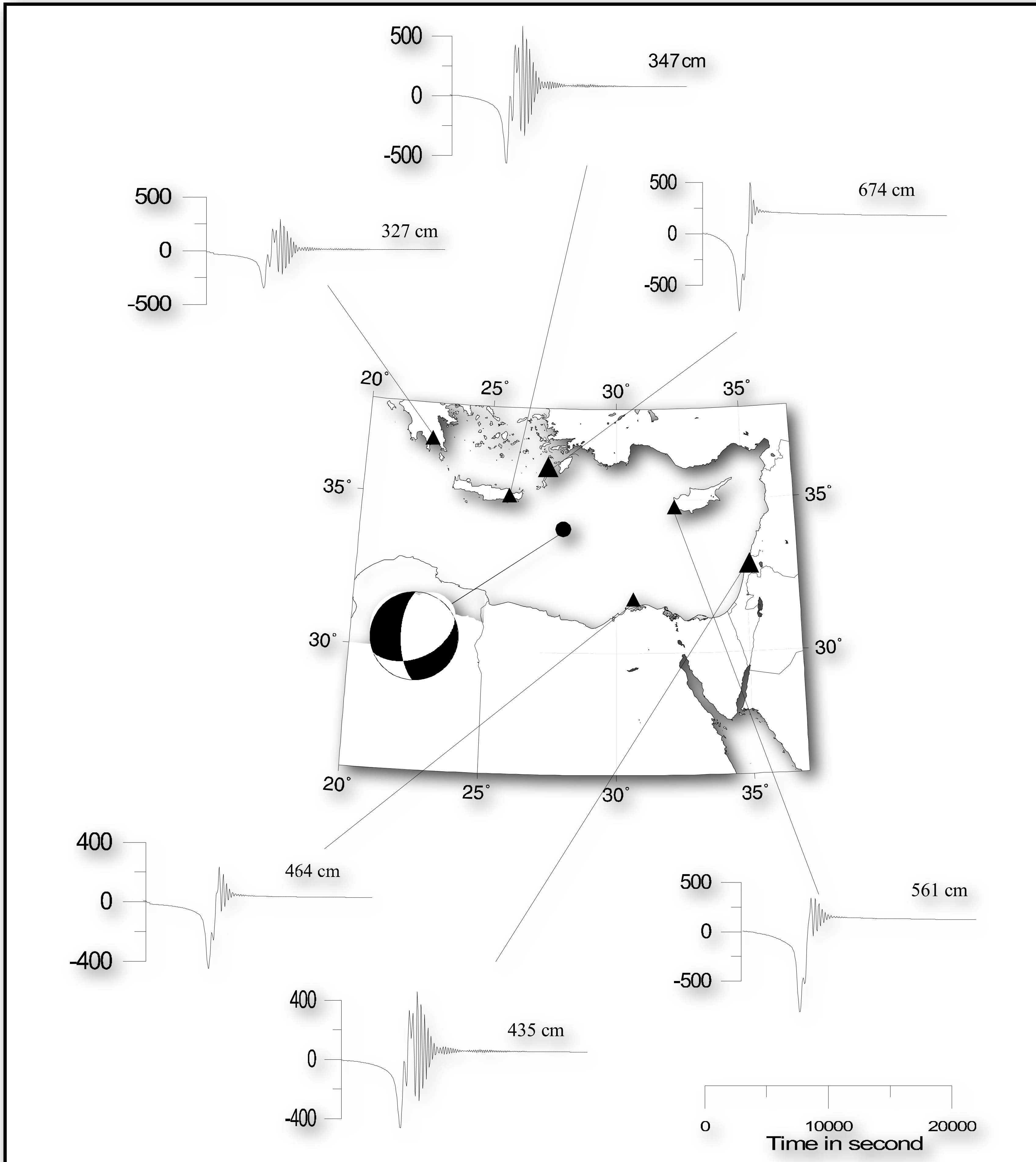
Strike = 67°

Dip = 48°

Slip = 345°

Depth =15 km

Magnitude = 7.3



Tsunami computed using Ambraseys et al. (1994) location - 2 multiple event

Fault parameters:

Strike = 67°

Dip = 48°

Slip = 345°

Depth =15 km

Magnitude = 7.3

Tsunami parametric study

Calculated horizontal tsunami motion peak values at Alexandria, corresponding to Ambraseys location (lat. = 34°N and long. = 28°E), assuming different magnitudes, focal mechanisms and depths; R, N, S denote reverse (strike = 227°, dip = 37° and slip = 24°), normal (67, 48 and −34°) and strike slip fault mechanism (135, 76 and 13°); Tsunami peaks (in meter) are calculated for three different focal depths; the three focal mechanisms considered correspond to the mechanisms of the events of July 22, 1985 (mb = 5.4), September 27, 1985 (mb = 5.5) and May 22, 1986 (mb = 5.1) located at latitude 34.16°N longitude 28.40°E, 34.05°N–26.97°E and 34.12°N–26.72°E, respectively; sites are shown in Fig. 2; bold numbers in the table indicate the values that can be supported by the reported description (Ambraseys et al., 1994; Guidoboni and Comastri, 1997)

Magnitude				Mechanism			Tsunami (m) at site (6)			Tsunami (m) at site (14)			Tsunami (m) at site (24)			Tsunami (m) at site (22)			Tsunami (m) at site (2)			Tsunami (m) at site (21)		
8.0	7.5	7.3	7.0	R	N	S	10	15	20	10	15	20	10	15	20	10	15	20	10	15	20	10	15	20
X				X			21.73	20.45	7.69	21.28	24.76	11.79	25.35	27.41	12.01	41.82	43.95	18.00	28.30	26.15	9.79	14.16	13.62	5.15
X					X		32.45	20.84	12.38	26.71	13.68	7.59	31.95	34.17	14.03	53.51	54.55	22.16	42.71	33.69	18.67	19.68	17.83	10.48
X						X	10.23	12.09	5.44	7.45	6.37	5.43	13.56	11.40	8.54	24.02	17.84	12.47	12.18	13.30	5.25	5.73	5.91	3.01
	X			**X**			**3.87**	**3.64**	**1.38**	**3.79**	**4.41**	**2.10**	**4.52**	**4.89**	**2.14**	**7.50**	**7.87**	**3.22**	**5.05**	**4.66**	**1.74**	**2.52**	**2.42**	**0.92**
	X				**X**		**5.79**	**5.69**	**2.21**	**4.25**	**4.76**	**2.08**	**5.71**	**6.10**	**2.50**	**9.57**	**9.75**	**3.96**	**7.70**	**6.06**	**3.34**	**3.53**	**3.19**	**1.87**
	X					**X**	**1.84**	**2.16**	**0.98**	**1.33**	**1.14**	**0.97**	**2.43**	**2.04**	**1.52**	**4.34**	**3.20**	**2.23**	**2.26**	**2.38**	**0.94**	**1.03**	**1.05**	**0.53**
		X		**X**			**1.94**	**1.82**	**0.69**	**1.90**	**2.21**	**1.05**	**2.27**	**2.45**	**1.07**	**3.76**	**3.95**	**1.62**	**2.53**	**2.34**	**0.88**	**1.26**	**1.21**	**0.46**
		X			**X**		**2.91**	**2.85**	**1.10**	**2.13**	**2.39**	**1.04**	**2.86**	**3.06**	**1.25**	**4.80**	**4.89**	**1.99**	**3.87**	**3.04**	**1.68**	**1.77**	**1.60**	**0.94**
		X				**X**	**0.92**	**1.08**	**0.49**	**0.67**	**0.57**	**0.48**	**0.48**	**1.52**	**1.02**	**2.17**	**1.61**	**1.12**	**1.13**	**1.19**	**0.47**	**0.52**	**0.53**	**0.27**
			X	X			0.69	0.64	0.24	0.68	0.78	0.37	0.81	0.87	0.38	1.33	1.40	0.57	0.89	0.83	0.31	0.44	0.43	0.16
			X		X		1.03	1.01	0.39	0.75	0.85	0.37	1.01	1.08	0.44	1.70	1.73	0.71	1.37	1.08	0.59	0.62	0.56	0.33
			X			X	0.33	0.38	0.17	0.23	0.20	0.17	0.43	0.36	0.27	0.77	0.57	0.39	0.40	0.42	0.16	0.18	0.17	0.07

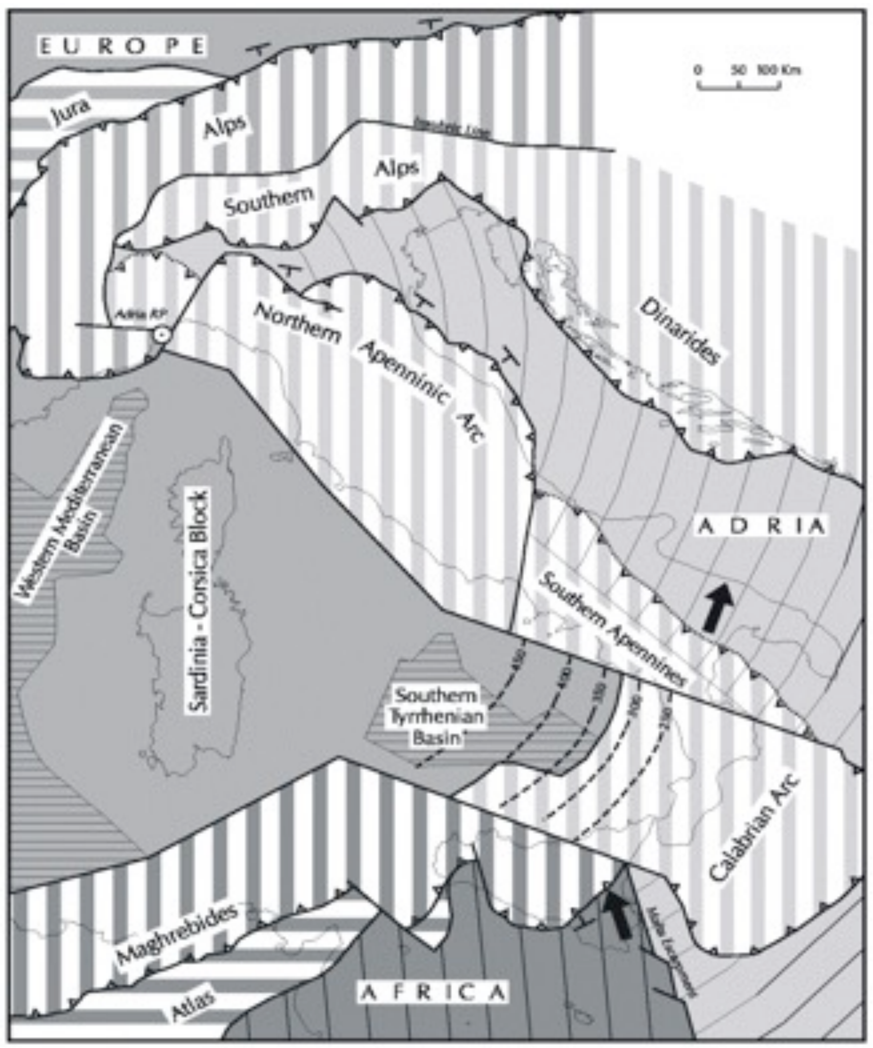
Conclusions

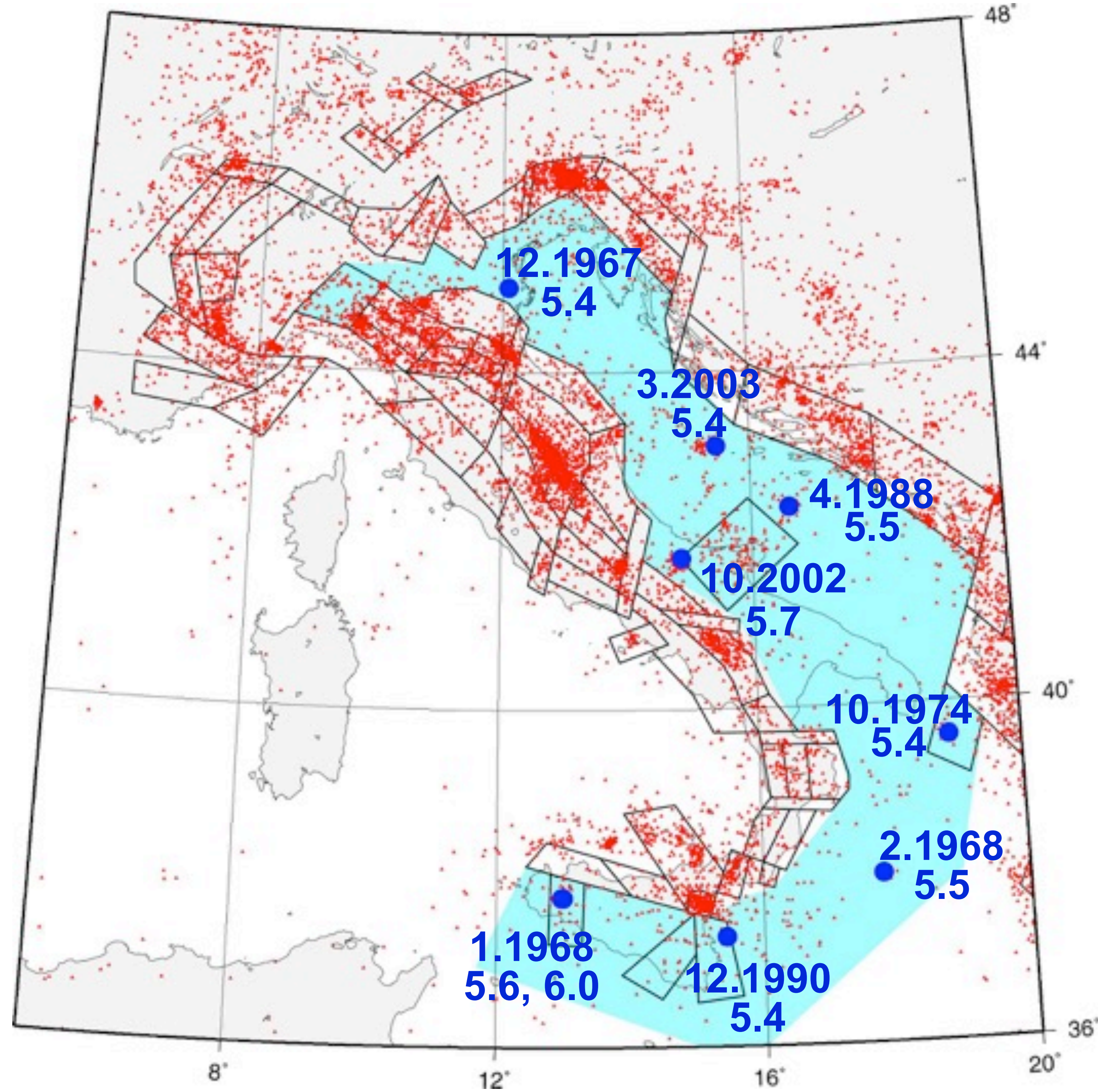
- The 1303 reported tsunami in the Eastern Mediterranean is more likely due to a relatively large (M~7.5), complex and shallow (h<20km) earthquake in the Hellenic arc. This event could explain the severe damage in Crete, and Rhodes, Alexandria as well as the low damage in Palestine, Jordan, Syria, Turkey and Cyprus.

- At the same time strong events in the Hellenic arc can hardly cause complete damage at distances of about to 500-600 km but are expected to generate long period motion in Egypt, which may explain the partial collapses (the lighthouse, Minaret, people walking with difficulties).

- A two-events scenario is suggested by our computations: another moderate event very likely occurred to the south of Cairo, beneath the Nile valley. The strong water oscillation, short period effect, and extensive damage in Cairo and along the Nile valley can be explained by this event, whose focal depth (between 15-20 km) and mechanism could have been similar to the earthquake of 1992.

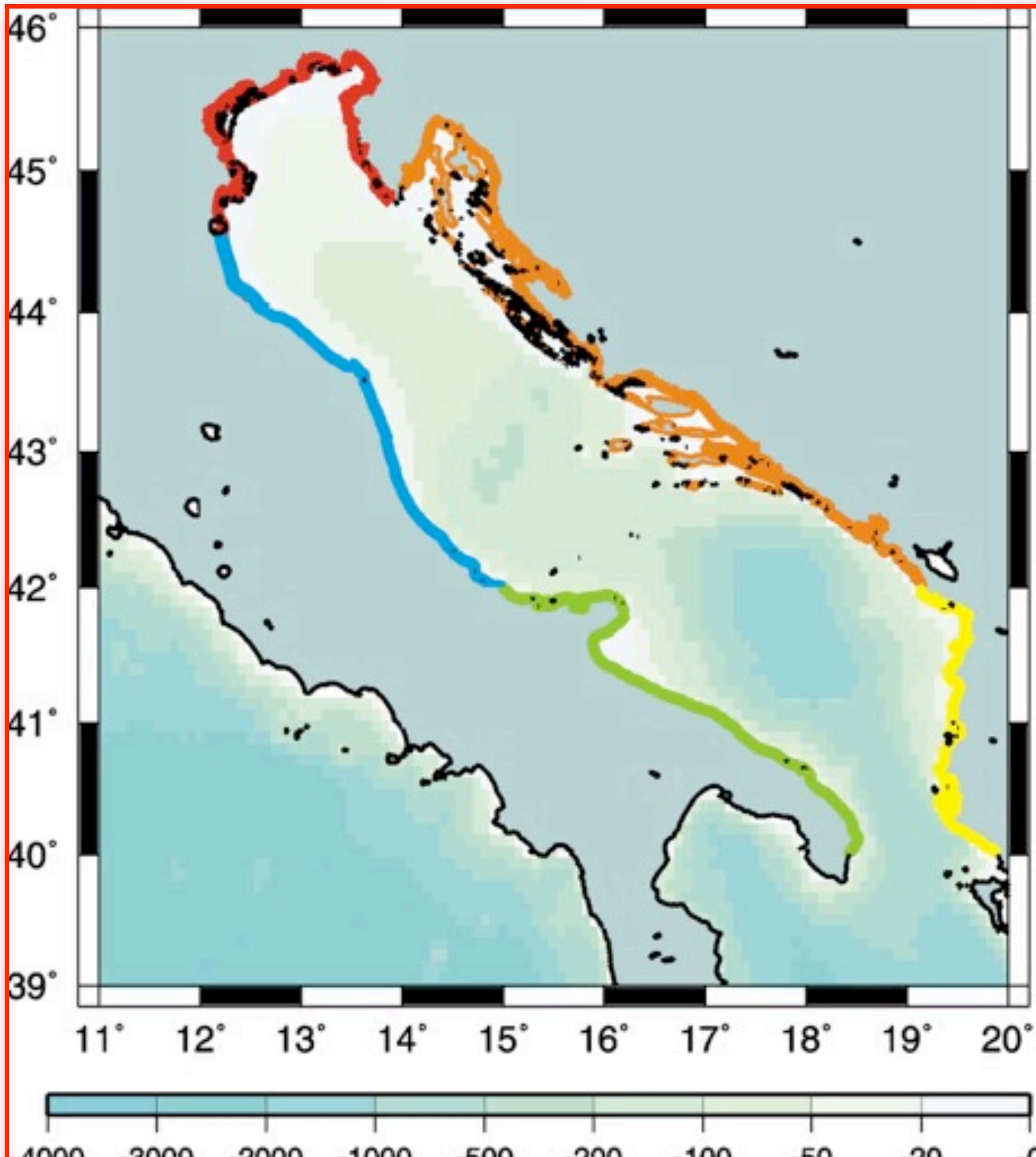
Seismicity in the Adriatic basin





Earthquakes with M≥5.4 (1964-2004)

Historical tsunami in the Adriatic basin

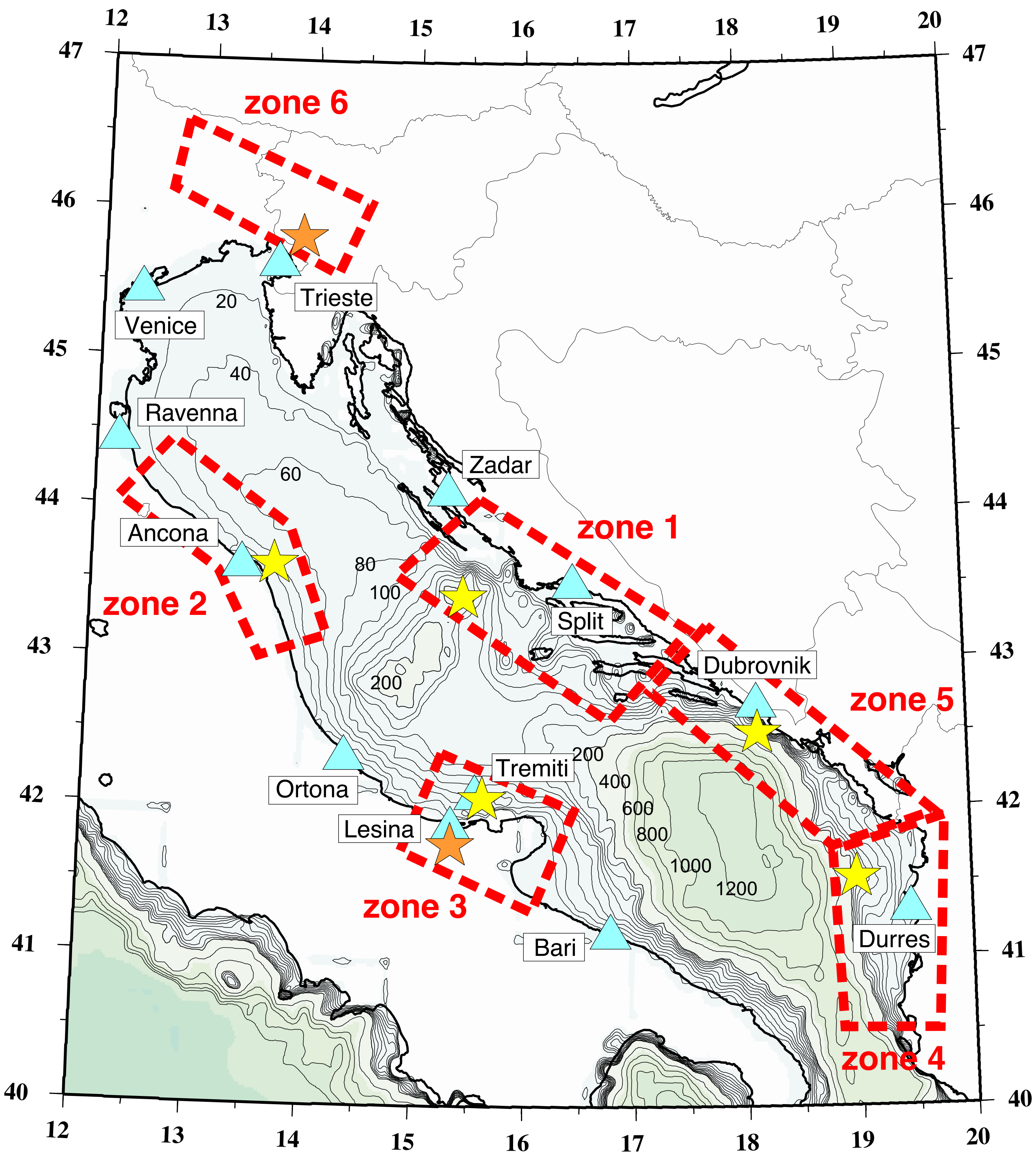


Tsunami reported in
ICTP Technical Report 2005:

CATALOGUE OF REPORTED
TSUNAMI EVENTS IN THE
ADRIATIC SEA
(from 58 B.C. to 1979 A.D.)

10	North-Adriatic coasts
14	Central-Adriatic Italian coasts
11	South-Adriatic Italian coasts
10	Croatian, Serbian and Montenegro coasts
13	Albanian coasts

Hazard scenarios for the Adriatic basin

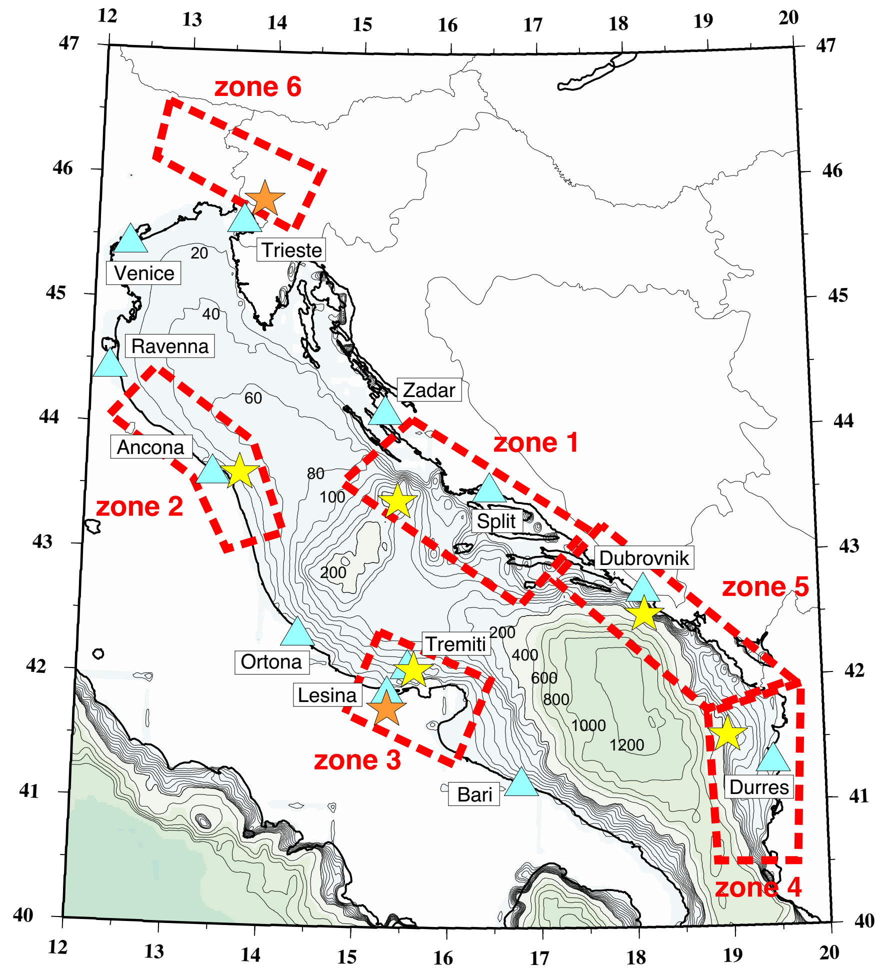


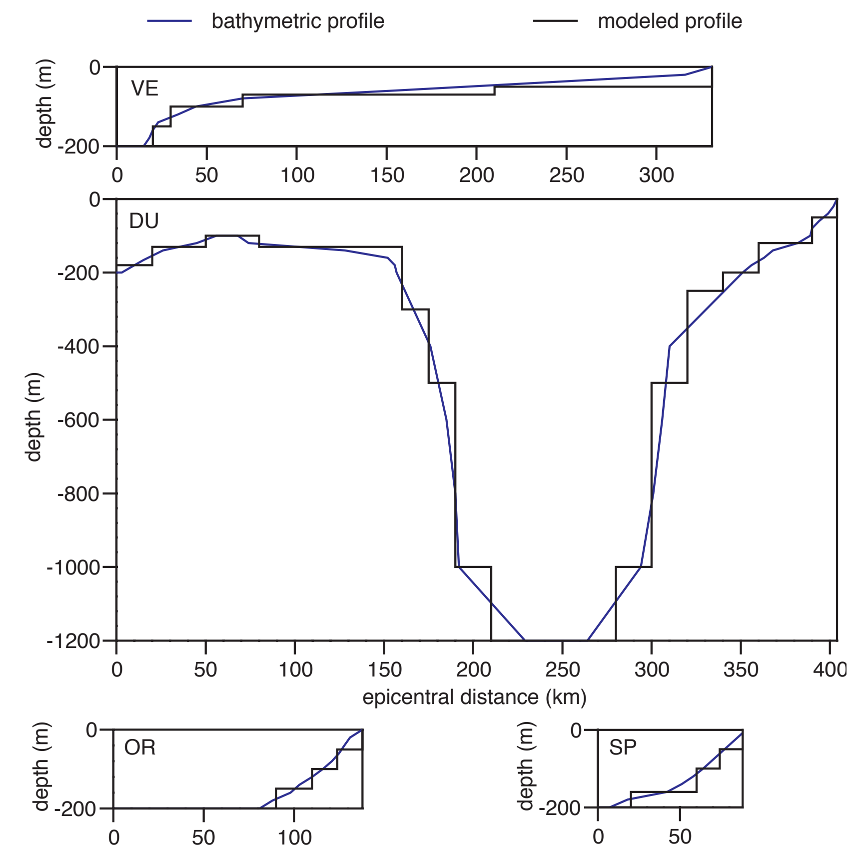
Bathymetric map of the Adriatic Sea. The bathymetric contours are drawn with a step of 20 m in the range from 0 to –200 m and with a step of 200 m in the range from –200 m to –1200 m.

The contours of the six tsunamigenic zones are shown in red, the blue triangles correspond to the 12 receiver sites, the stars correspond to the epicenters of the considered events (yellow: offshore, orange: inland).

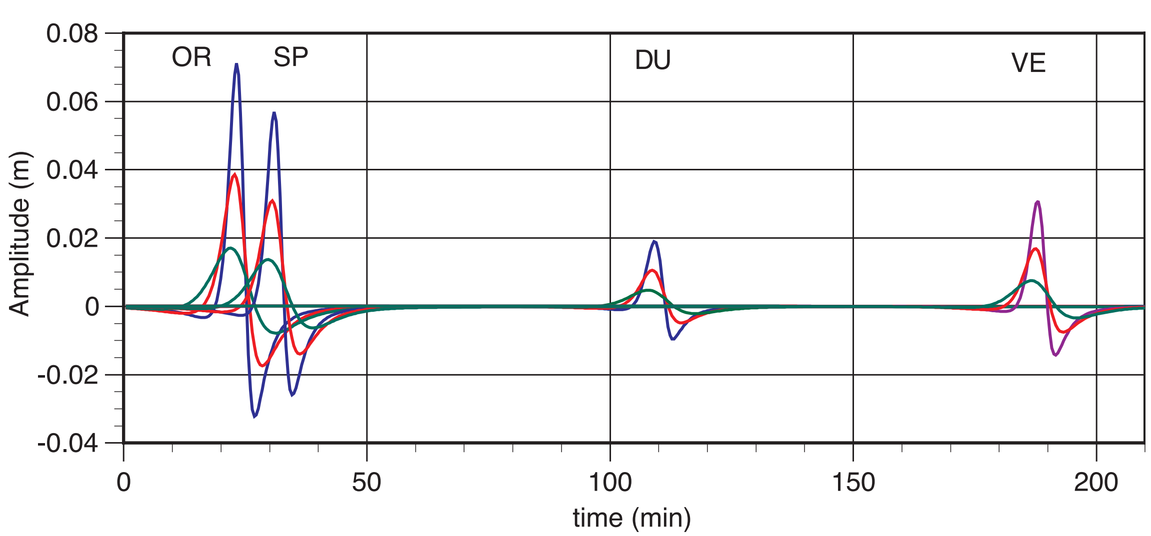
Paulatto M., Pinat T., Romanelli F. , 2007. Tsunami hazard scenarios in the Adriatic Sea domain". Natural Hazards And Earth System Sciences (on line), vol. 7, pp. 309-325.

Tsunami scenarios in Adriatic Sea - Zone I





Bathymetric profiles to (from top) Venice (VE), Durres (DU), Ortona (OR) and Split (SP)

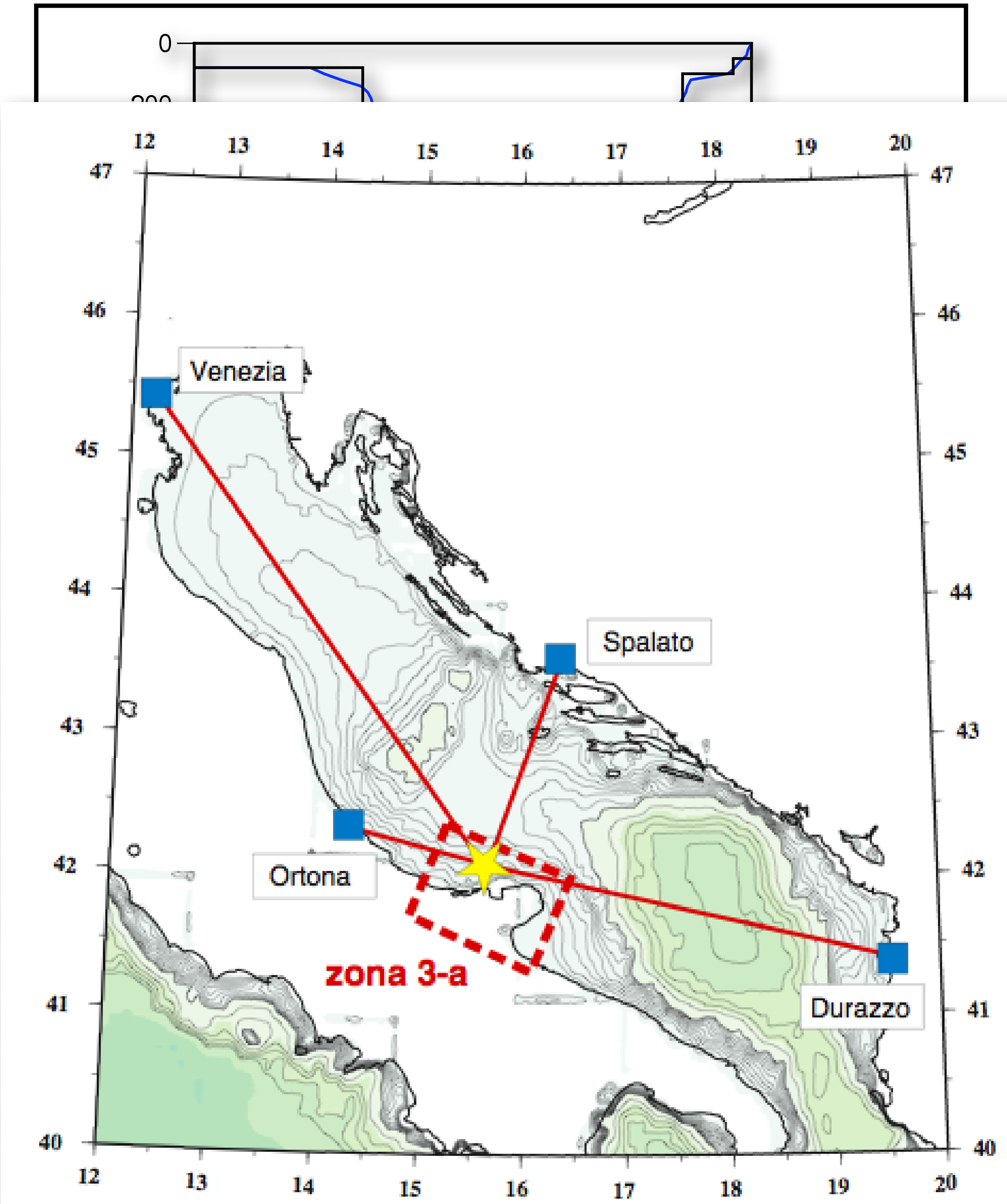


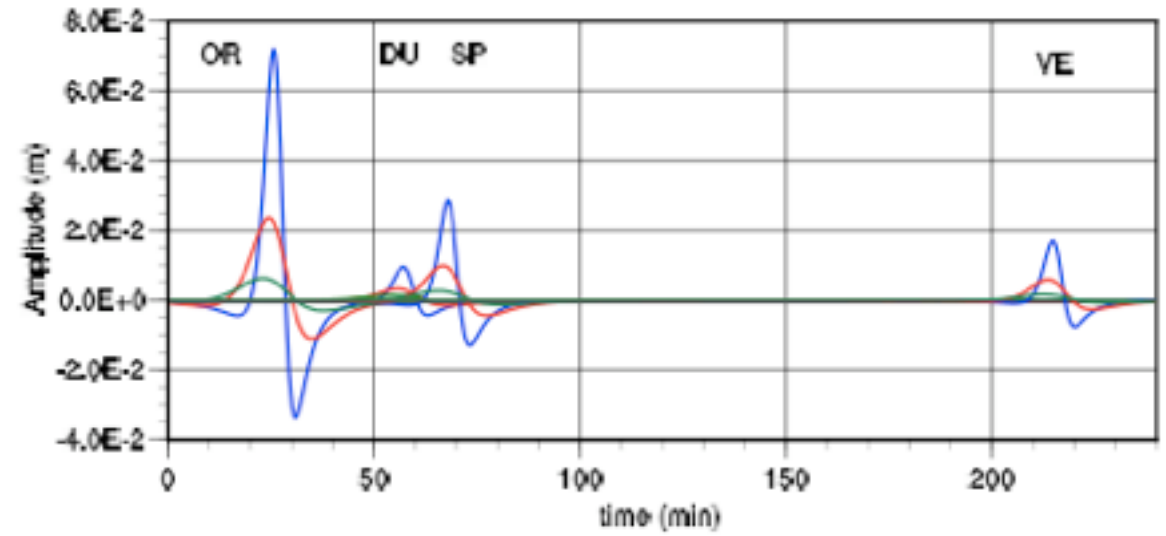
Synthetic mareograms for H =10 km (blue), 15 km (red), 25 km (green). Magnitude: M =6.5.

M	6.5			7.0			7.5			*Travel*
H (km)	10	15	25	10	15	25	10	15	25	*time (min)*
Durres	0.02	0.01	<0.01	0.11	0.06	0.03	0.60	0.33	0.15	*109*
Ortona	0.07	0.04	0.02	0.40	0.22	0.10	**2.25**	**1.22**	0.54	*23*
Split	0.06	0.03	0.01	0.32	0.17	0.08	**1.80**	0.98	0.43	*31*
Venice	0.03	0.02	0.01	0.17	0.09	0.04	0.97	0.53	0.24	*188*

Maximum amplitudes and related arrival times for different depths and magnitude

Tsunami scenarios in Adriatic Sea - Zone I





Synthetic mareograms for Zone 3-a. Focal depth: 10 km (blue), 20 km (green), 30 km (red). Magnitude: 6.5.

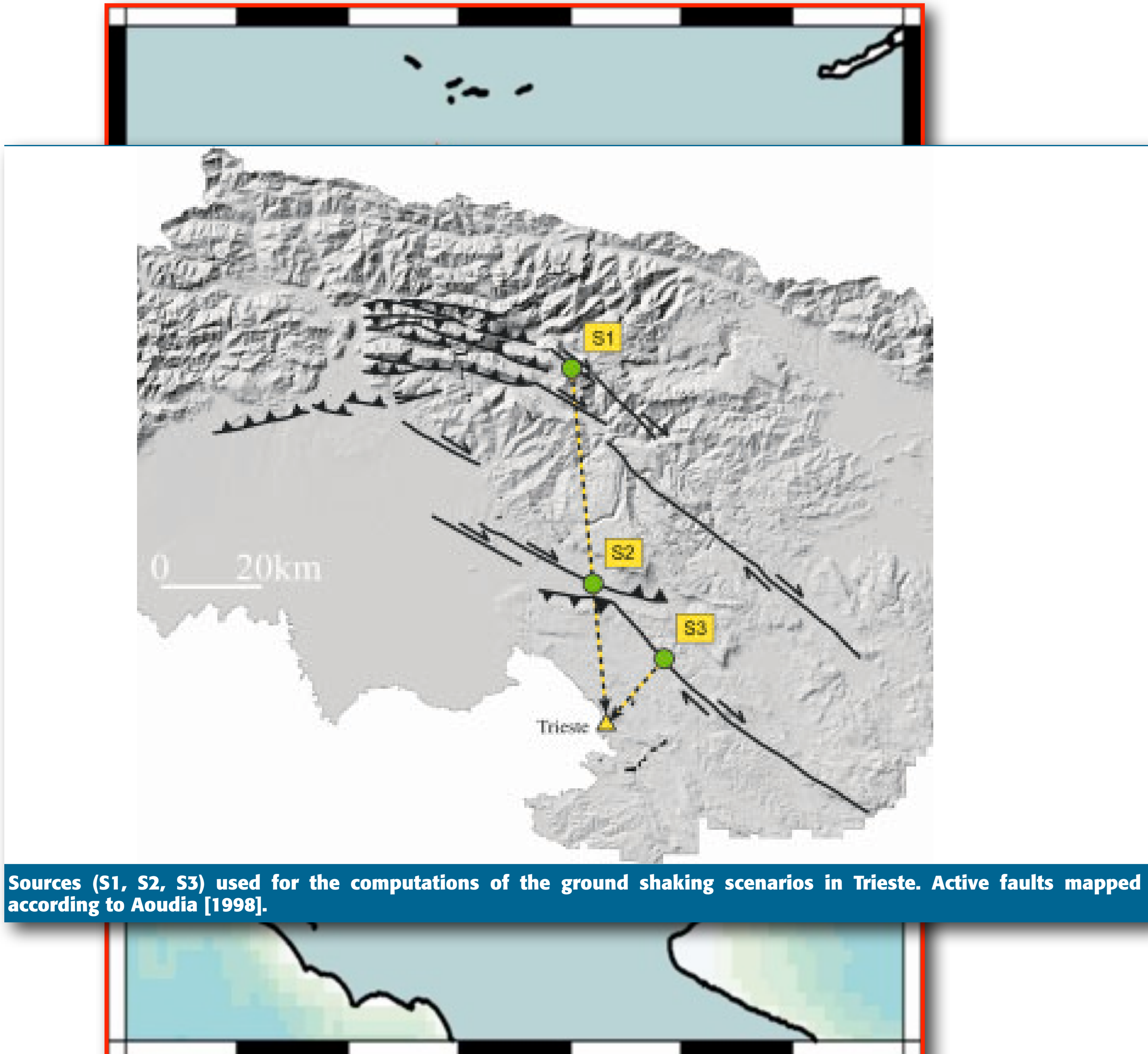
Zone boundaries (in red), the representative epicenter (yellow star), the four receivers (blue boxes) and their source-receiver paths (in red) are shown.

of Zone 3, offshore source case. Scenarios are calculated for three values
10, 15, 25 km. Amplitudes are reported in meters. Amplitudes exceeding

M	6.0			6.5			7.0			*Travel*
H (km)	10	15	25	10	15	25	10	15	25	*time (min)*
Durazzo	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	0.05	0.02	0.01	57
Ortona	0.01	<0.01	<0.01	0.07	0.02	0.01	0.41	0.13	0.04	26
Spalato	0.01	<0.01	<0.01	0.03	0.01	<0.01	0.16	0.06	0.02	68
Venezia	<0.01	<0.01	<0.01	0.02	0.01	<0.01	0.10	0.03	0.01	215

Source 2 scenario

Inland source ⇒ Green-function approach

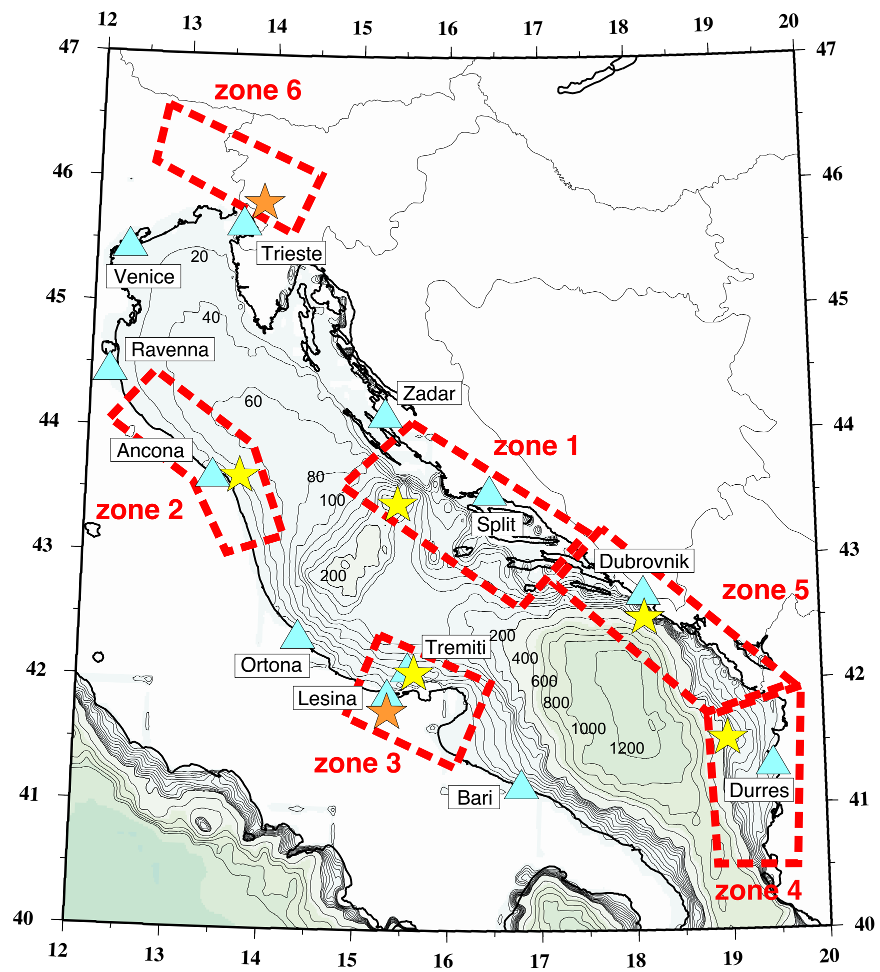


Sources (S1, S2, S3) used for the computations of the ground shaking scenarios in Trieste. Active faults mapped according to Aoudia [1998].

The recent re-evaluation of the 1511 earthquake by Fitzko, P. Suhadolc, A. Aoudia and G. F. Panza (2005) is consistent with a 6.9 magnitude single event rupturing 50 km of the Idrija right-lateral strike-slip fault with bilateral rupture propagation. This part of the Idrija fault stands 40 km far from the coastline.

Another seismogenic structure that needs to be considered is the the Rasa-Cividale right lateral-strike slip (Aoudia, 1998), that stands at 16 km from the coastline.

Tsunami scenarios in Adriatic Sea - Zone 6

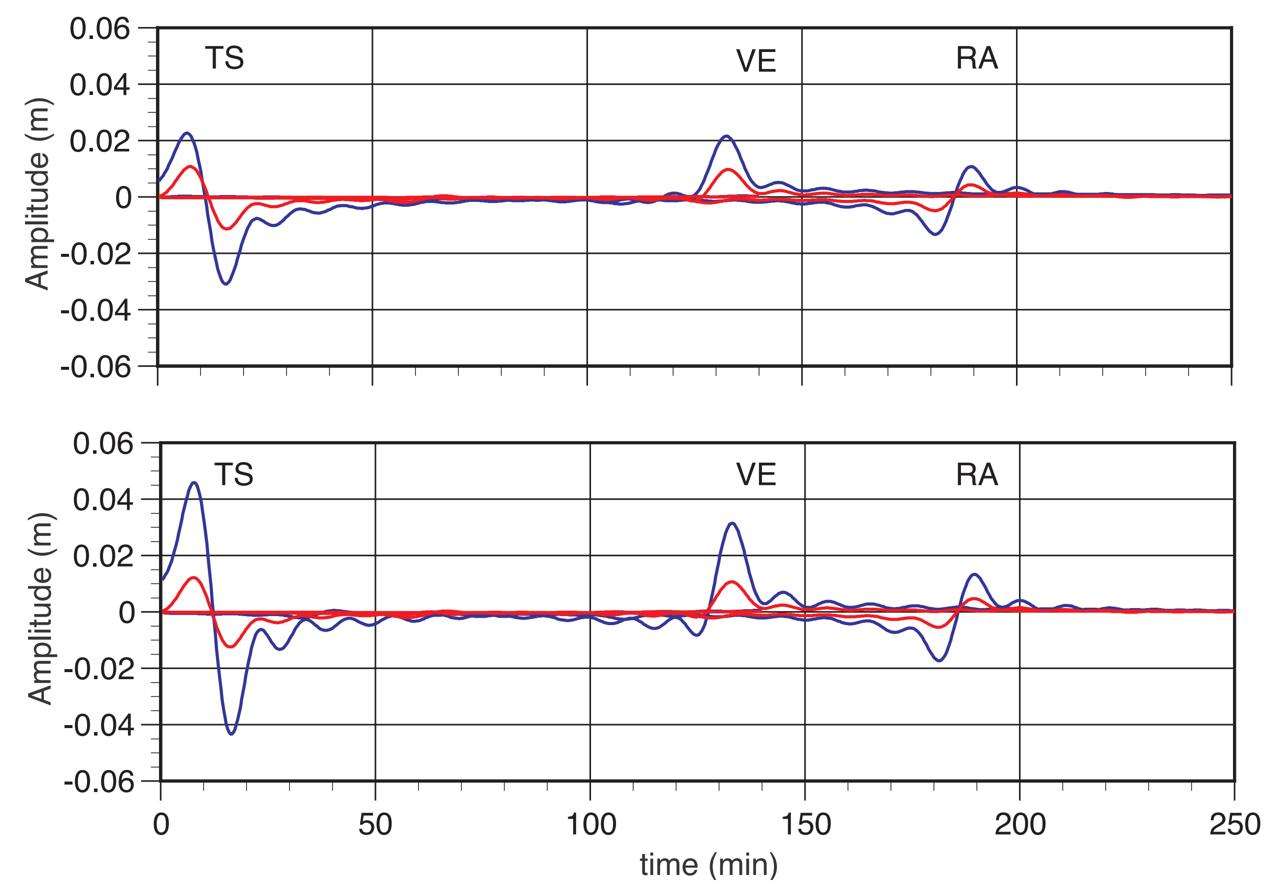


M / d (km)	6.5 / 20	6.5 / 40	7.0 / 20	7.0 / 40	*Travel time (min)*
Trieste, dip = 45°	<0.01	<0.01	0.02	0.01	*7*
Trieste, dip = 30°	<0.01	<0.01	0.05	0.01	*8*
Venice, dip = 45°	<0.01	<0.01	0.02	0.01	*132*
Venice, dip = 30°	<0.01	<0.01	0.03	0.01	*133*
Ravenna, dip = 45°	<0.01	<0.01	0.01	<0.01	*189*
Ravenna, dip = 30°	<0.01	<0.01	0.01	<0.01	*189*

Maximum amplitudes and related arrival times for different depths and magnitude

Table 7. Main parameters identifying the three sites of Zone 6.

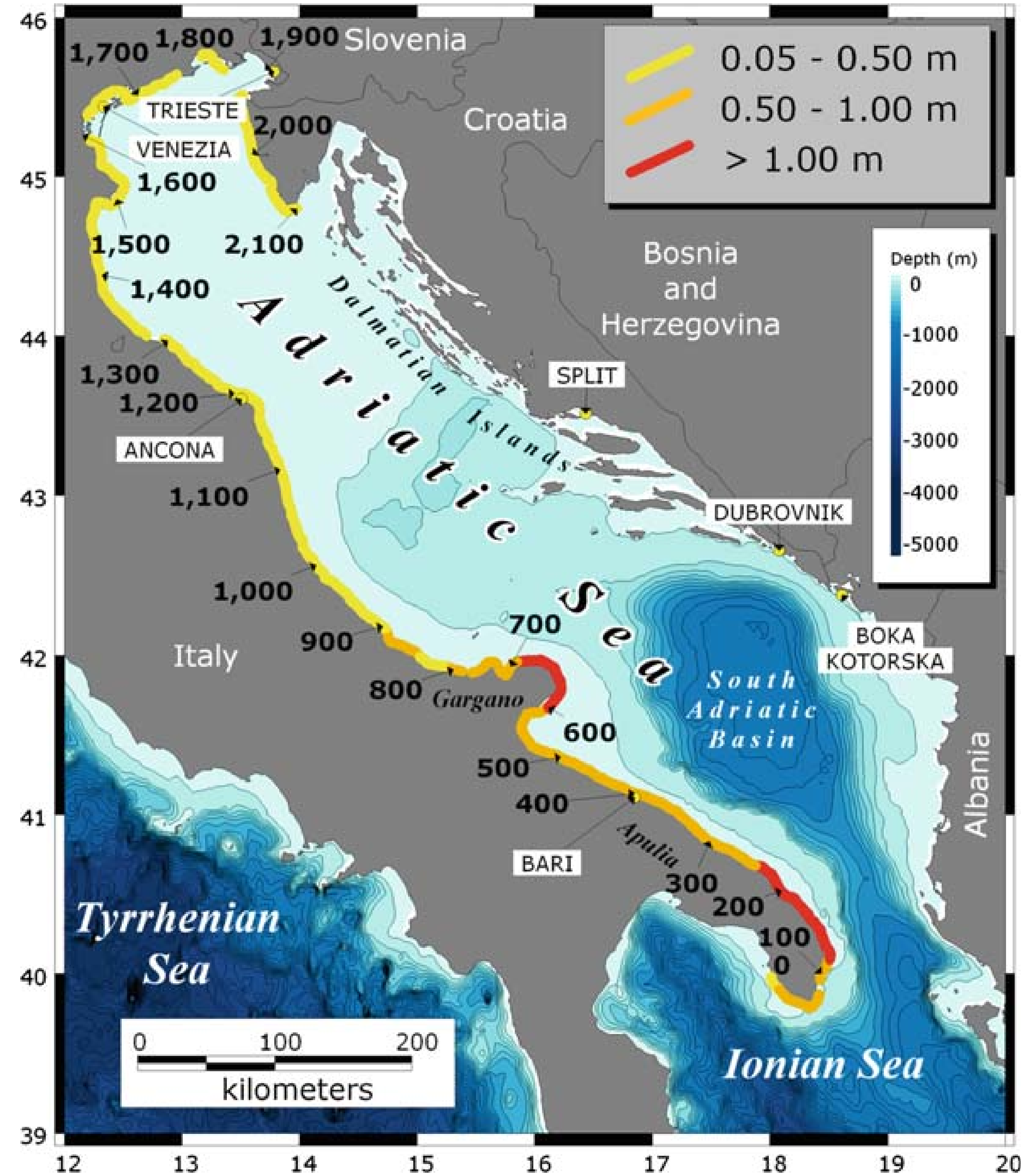
Site	Latitude	Longitude	Epicentral dist. R
Trieste (TS)	45.67° N	13.77° E	30 km, 50 km
Venice (VE)	45.45° N	12.35° E	130 km, 150 km
Ravenna (RA)	44.42° N	12.20° E	210 km, 230 km



Synthetic mareograms for Zone 6, magnitude, M=7.0. Above: dip angle=45°; below: dip angle=30°. Blue line, d=20 km; red line, d=40 km.

Updating...

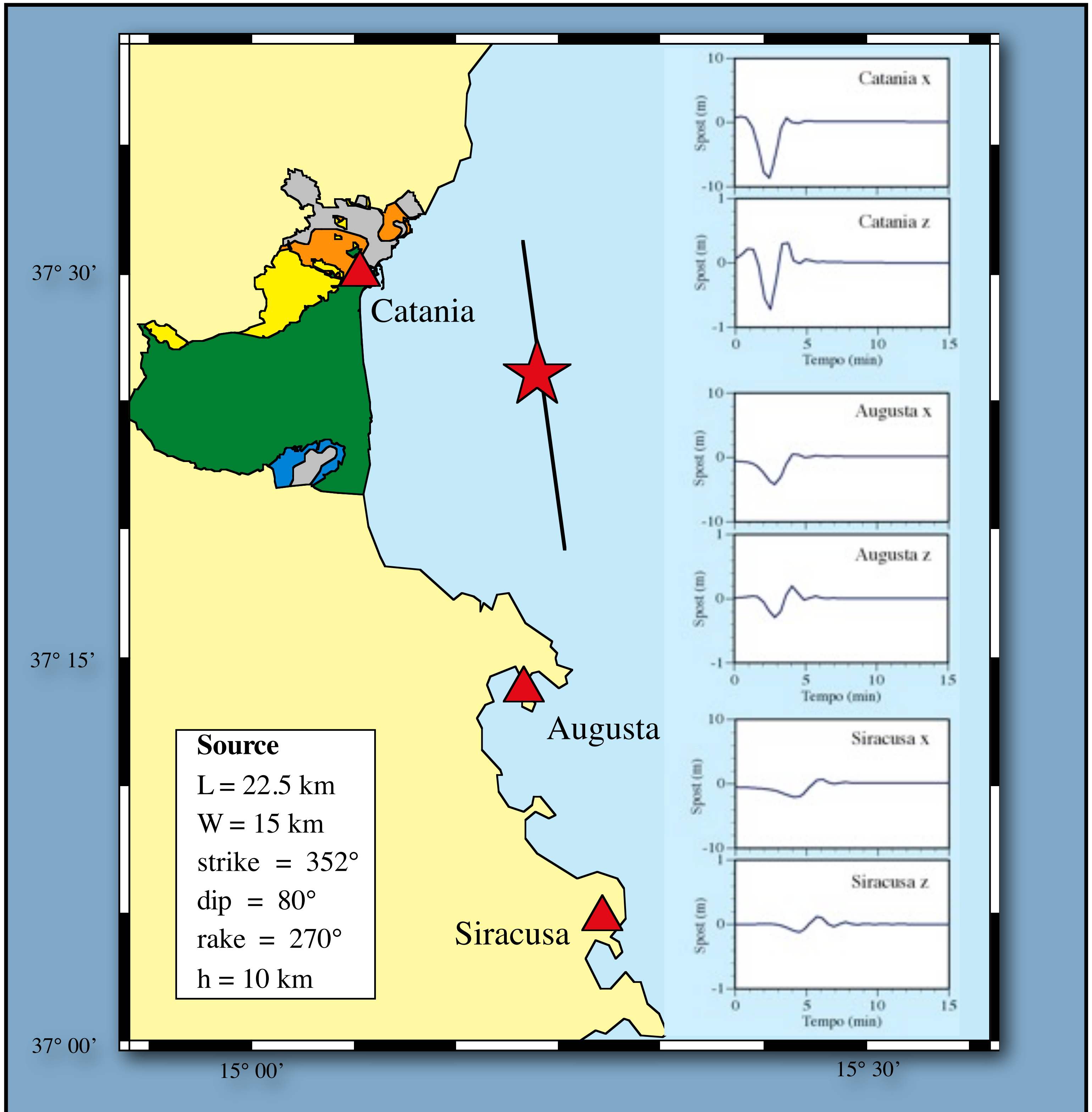
Tectonic sketch map of the Adriatic basin.



Combined threat levels posed by all SZs

Tiberti et al., 2009. Scenarios of Earthquake-Generated Tsunamis for the Italian Coast of the Adriatic Sea, Pageoph, 165, 2117–2142.

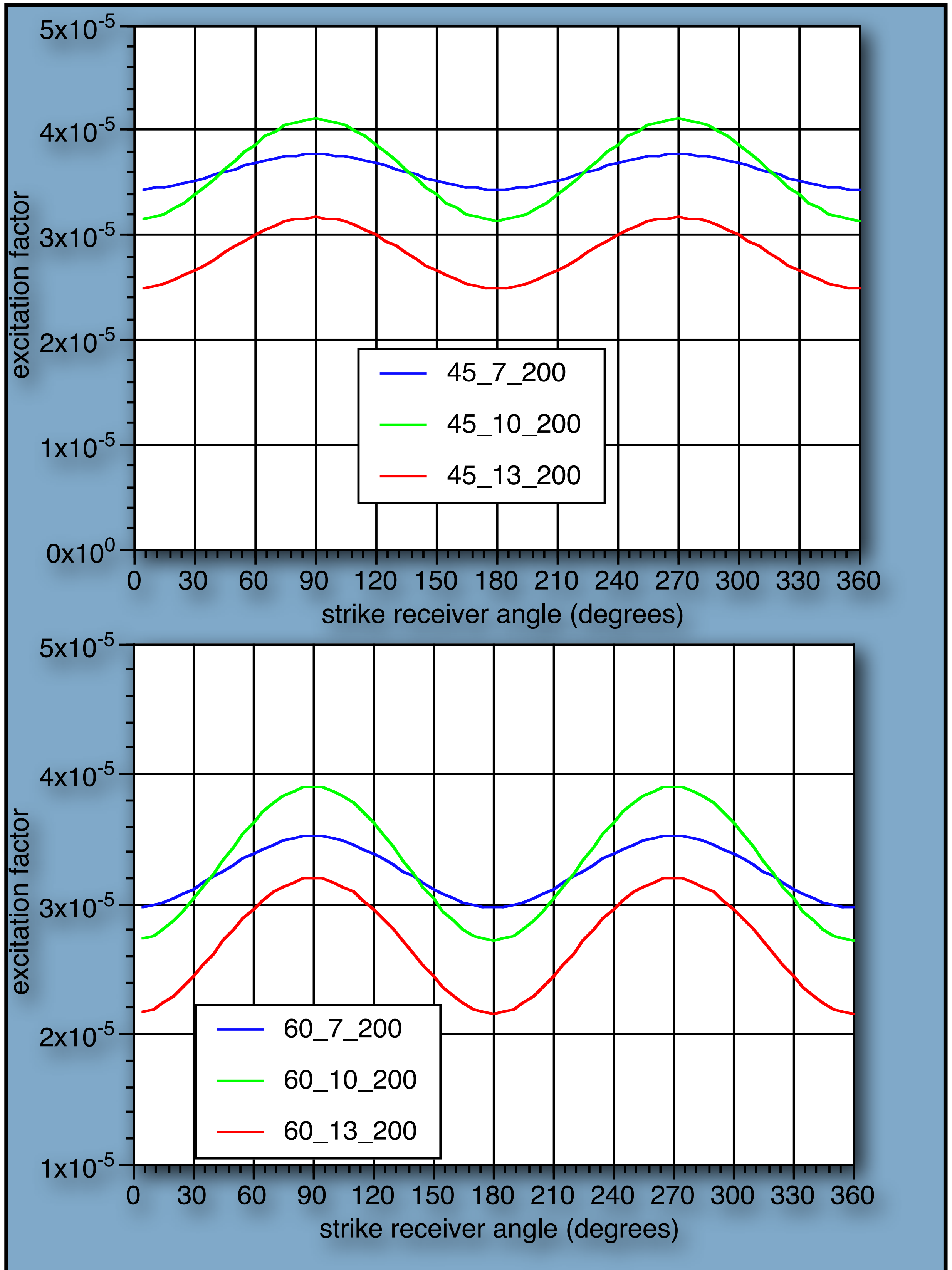
Eastern Sicily



Catania Area
and the
seismic source
considered for the
scenario earthquake
(Hyblean fault)

and related
tsunami scenario

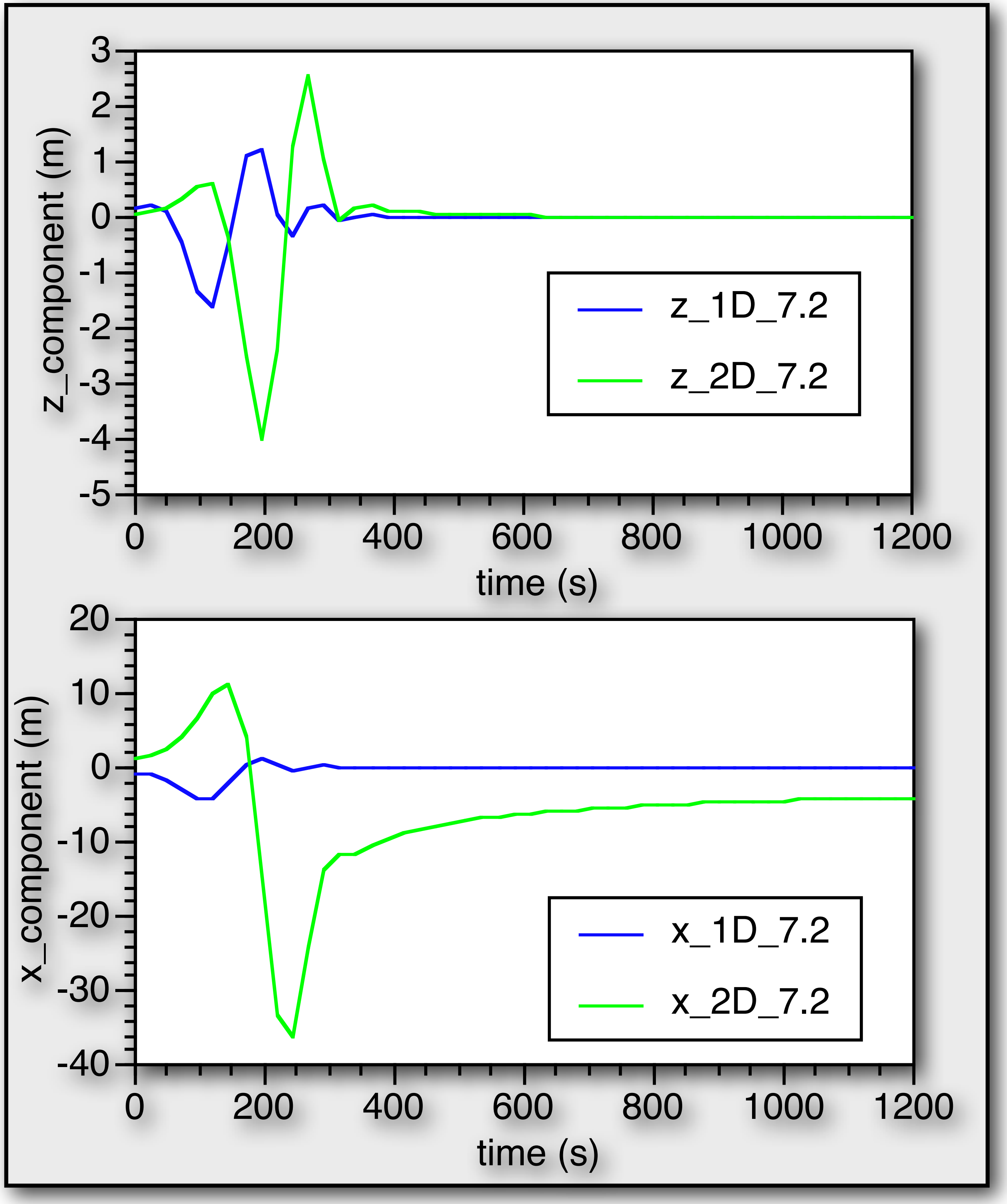
Parametric studies



Excitation factors for different values of:

strike,
dip,
focal depth

Near real time estimate in Augusta



Synthetic mareograms for a laterally homogeneous oceanic model (1D), with a 3 km thick fluid layer, and a laterally heterogeneous one (2D) [from 3km to 0.2km]

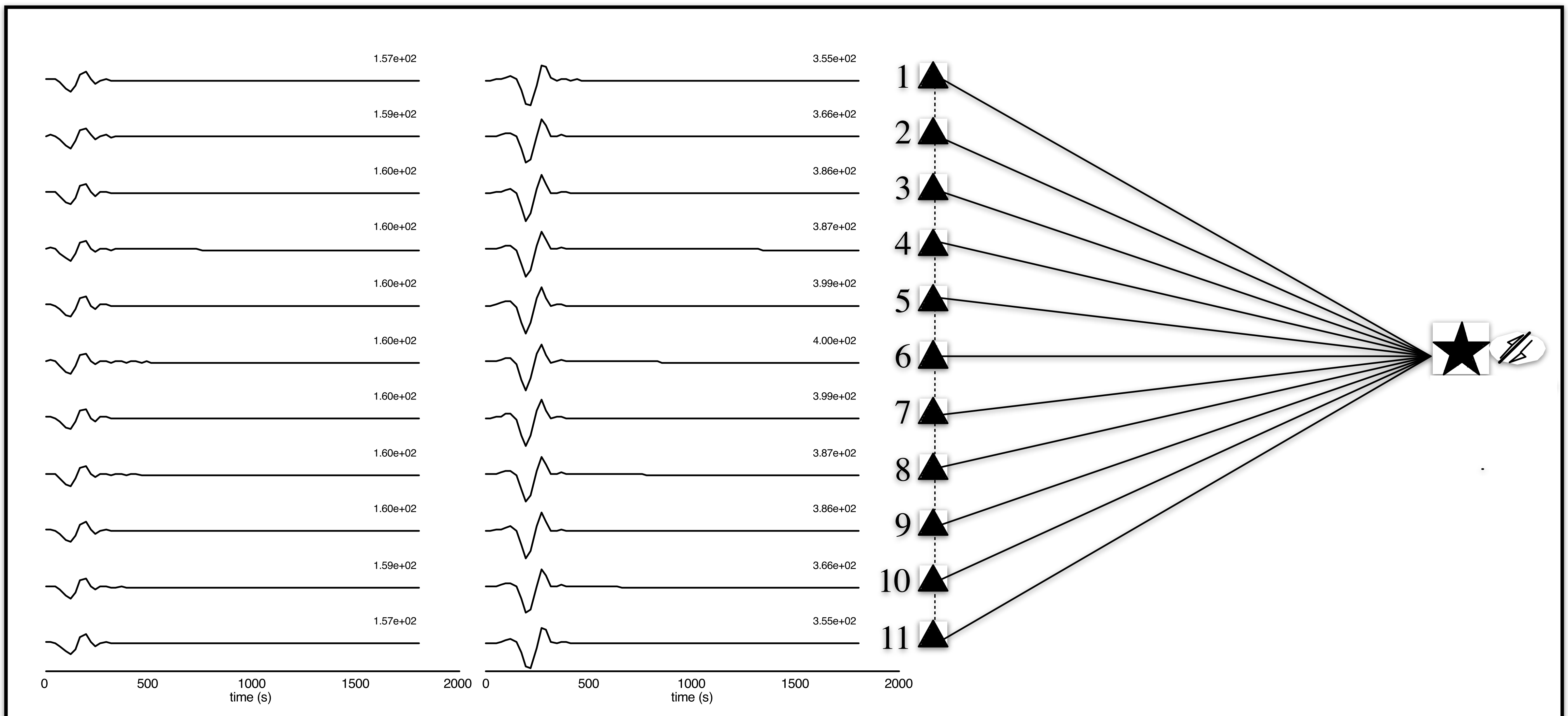
Input for an hybrid method

The realistic calculation of the effect of tsunami on the coastline can be done with an efficient **hybrid approach** (analytical+numerical), that allows to propagate the tsunami wavefield from the closure depth (about 100 m) of the analytical model till the coastline, taking into account realistic 3D bathymetries.

Thus, using the modal approach, the synthetic mareograms have been calculated in a series of points that represents the borderline (in the water) of the grid for the numerical computations, where the boundary conditions for the numerical method (e.g. finite differences) are applied.

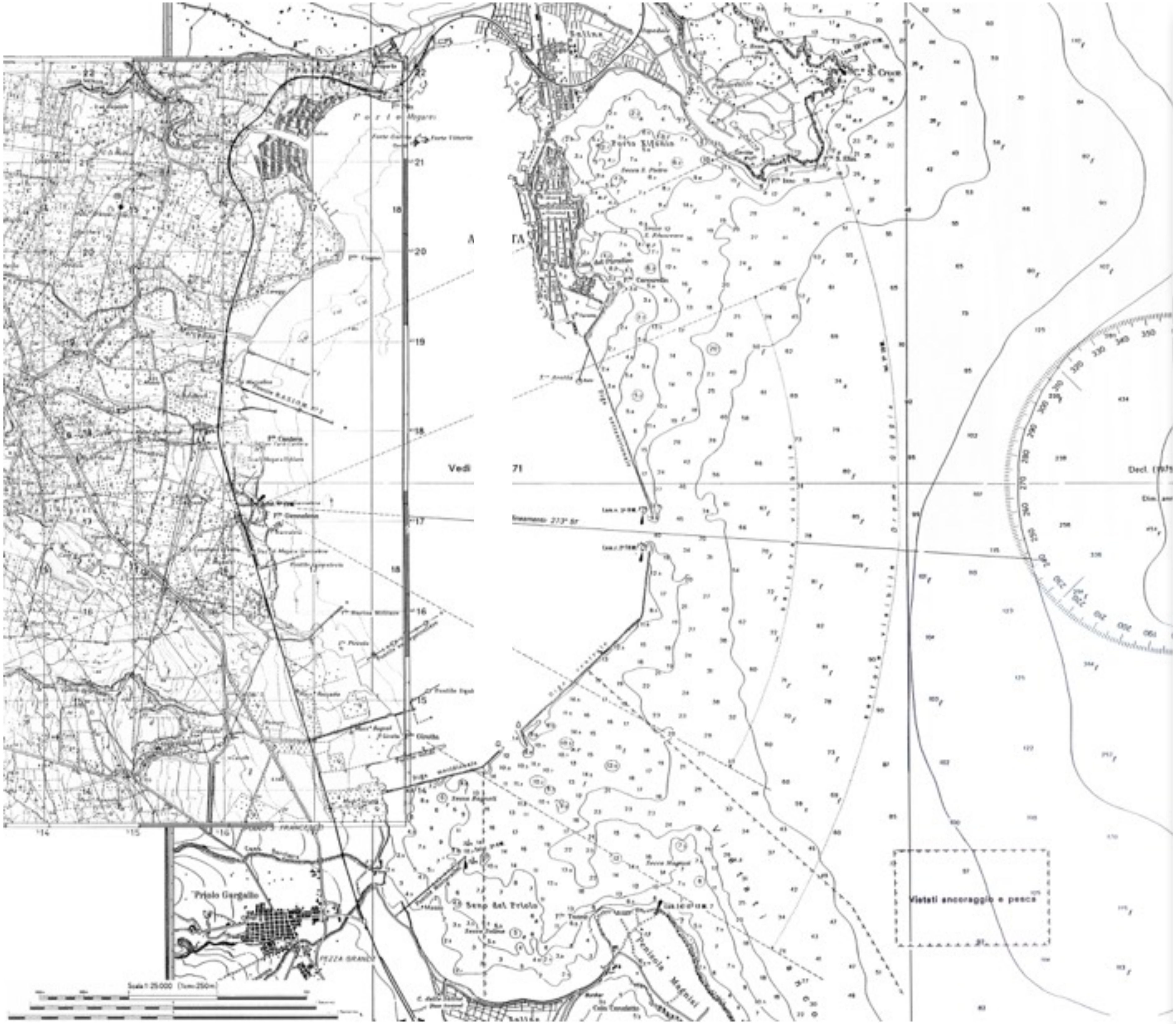
Input for an hybrid method

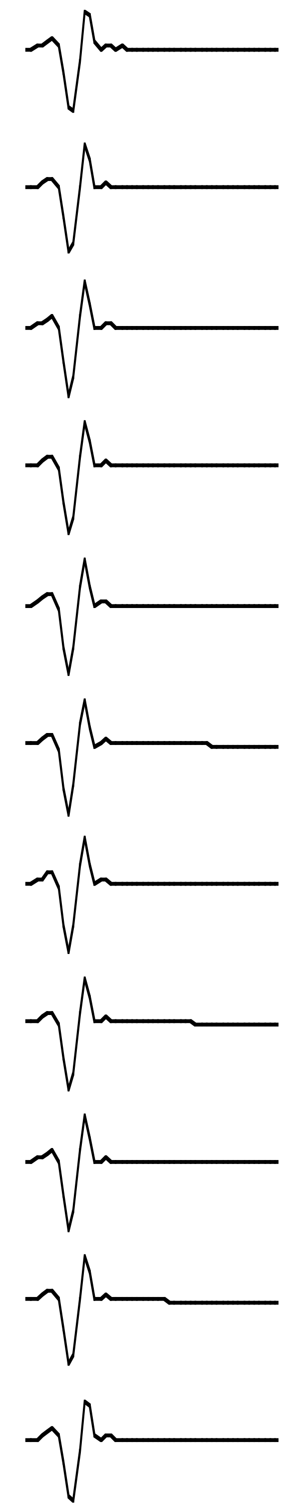
Synthetic mareograms (vertical component) calculated as boundary conditions for the numerical grid:
spacing is about 1 km, final depth of the oceanic layer is 50m.



homogeneous model (A) heterogeneous model (B)

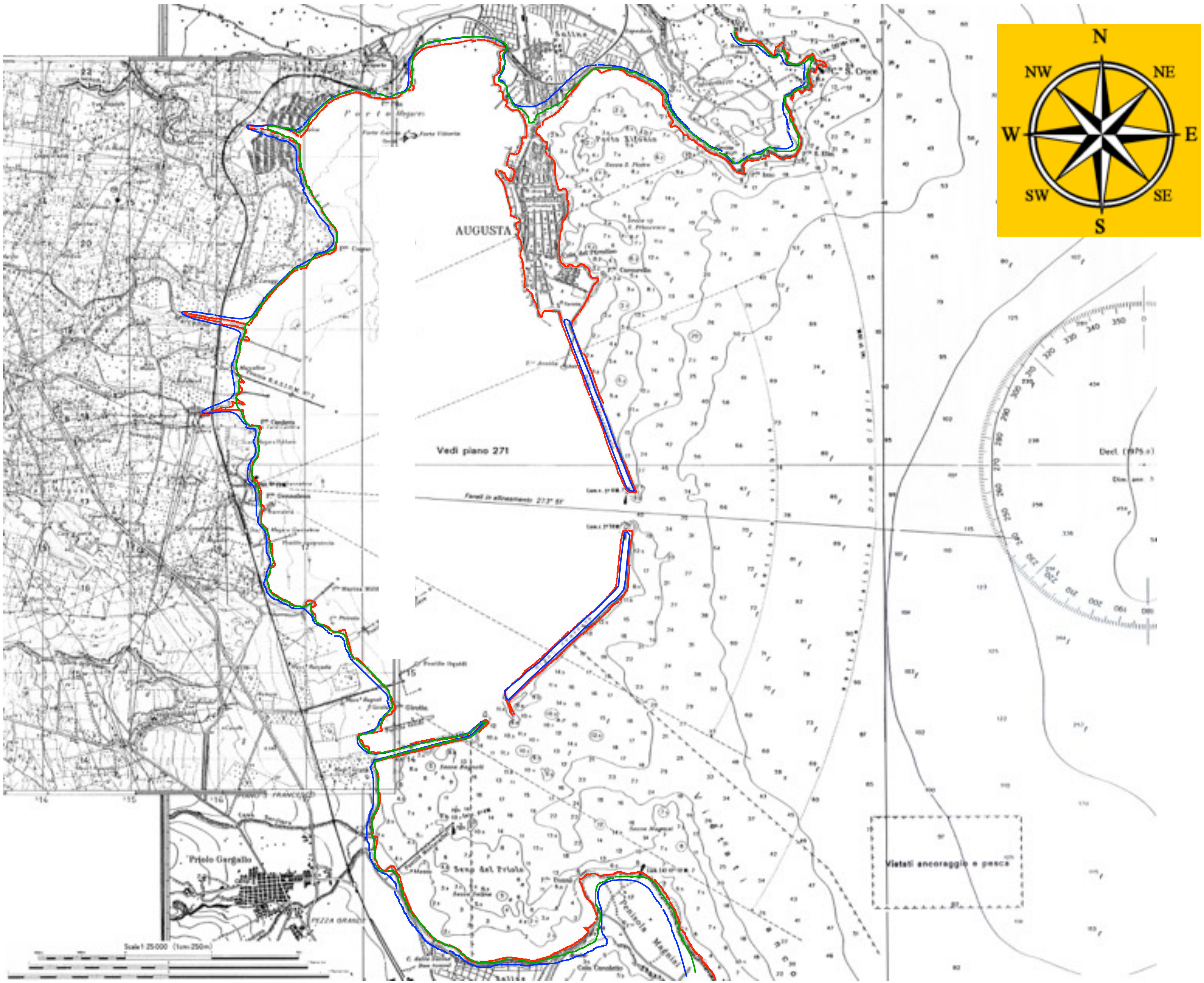
Hybrid method (Bathymetry)





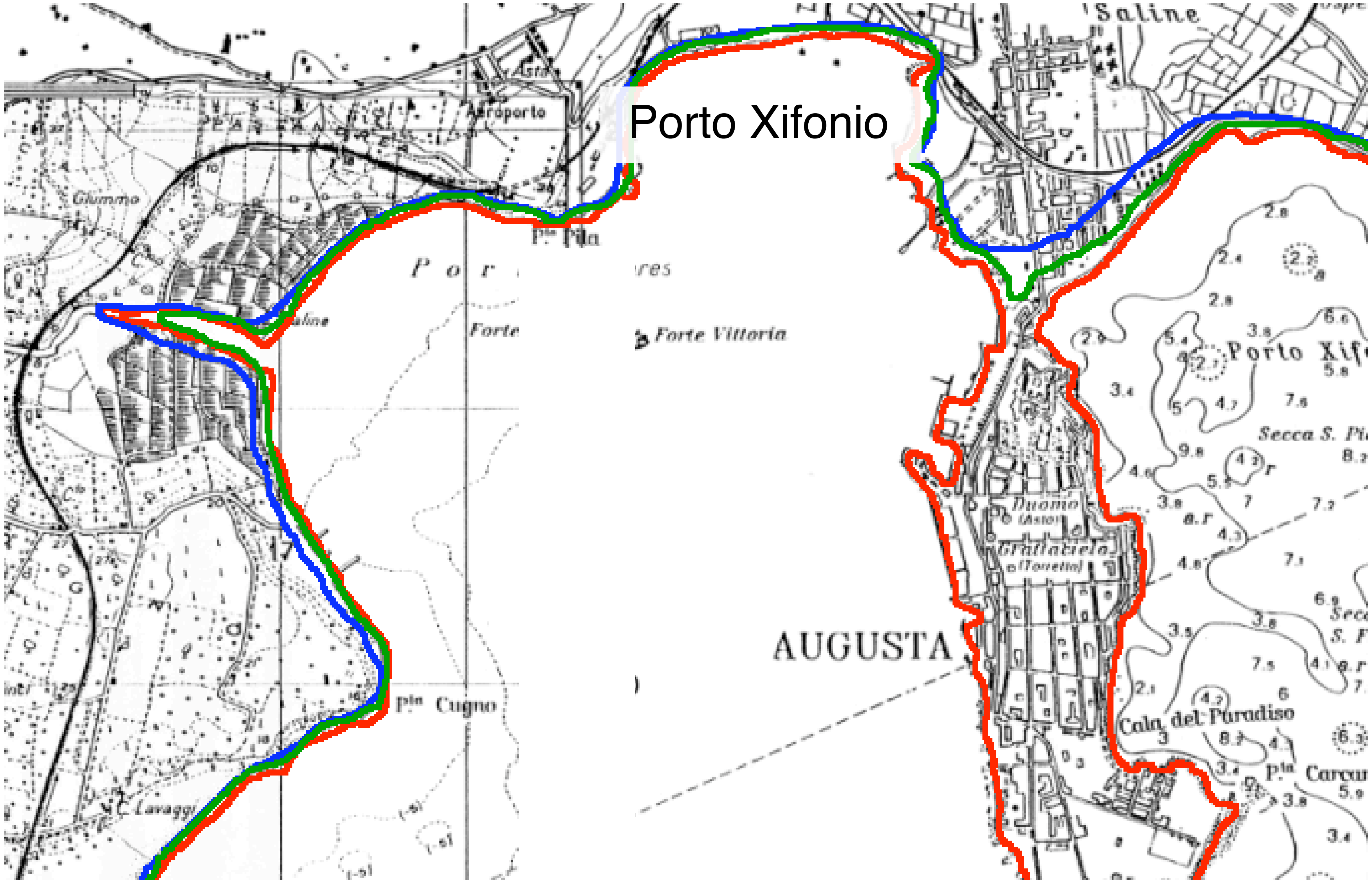
The proper boundary conditions allow the numerical scheme to find the solutions of the equations for shallow water, using the detailed bathymetry.

For the interaction of the tsunami with the coastlines of the bay of Augusta it is necessary to take into consideration also the topography of the merged areas.



Expected tsunami inundation distance in Augusta

comparison between the coastline at the equilibrium and maximum inundation distance for A and B.



Expected tsunami inundation distance in Augusta

Confronto tra la linea di costa in condizioni di quiete e le linee di massima penetrazione dei maremoti innescati dai maremoti di scenario considerati. Le aree inondate sono sensibilmente coincidenti per i diversi maremoti (a meno di una maggiore penetrazione alle spalle del porto Xifonio). Pertanto, sotto l'ipotesi di impermeabilità, resistenza e non tracimabilità delle difese esterne, la costa interna della rada è sensibilmente al riparo da grandi danni. Al contrario, l'isola di Augusta risulta estremamente esposta; nel primo scenario (maremoto A) sull'isola si ha la risalita di un'onda di ampiezza pari a circa 1.5m mentre nel secondo scenario (maremoto B) si ha la risalita di un'onda di ampiezza pari a circa 3m. Dunque, l'energia distruttiva che impatta Augusta cambia notevolmente nei due scenari.