SEA LEVEL CHANGES AND VERTICAL AND MOVEMENTS IN THE MEDITERRANEAN FROM PALEO-HISTORICAL INDICATORS, MODERN INSTRUMENTAL DATA AND MODEL PREDICTIONS

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What causes relative sea-level change?

1. Vertical land movements along the coastal zone due to:
   - regional tectonics (plate tectonics, isostasy)
   - local tectonics (earthquakes, coseismic displacements, active faults)
   - volcanism (dynamics of magma chambers i.e. uplift and subsidence)
   - other sources of local movements capable to produce subsidence or uplift

2. Change in ocean volume

We will discuss here point #1, but changes in ocean volume will also cause land movement because of change in stress state of the Earth and/or change in gravity. Thus we cannot avoid end exclude land movements, even in areas of otherwise tectonic stability.

Relative sea-level change is a complex problem, driven by a combination of climate and tectonic forcing

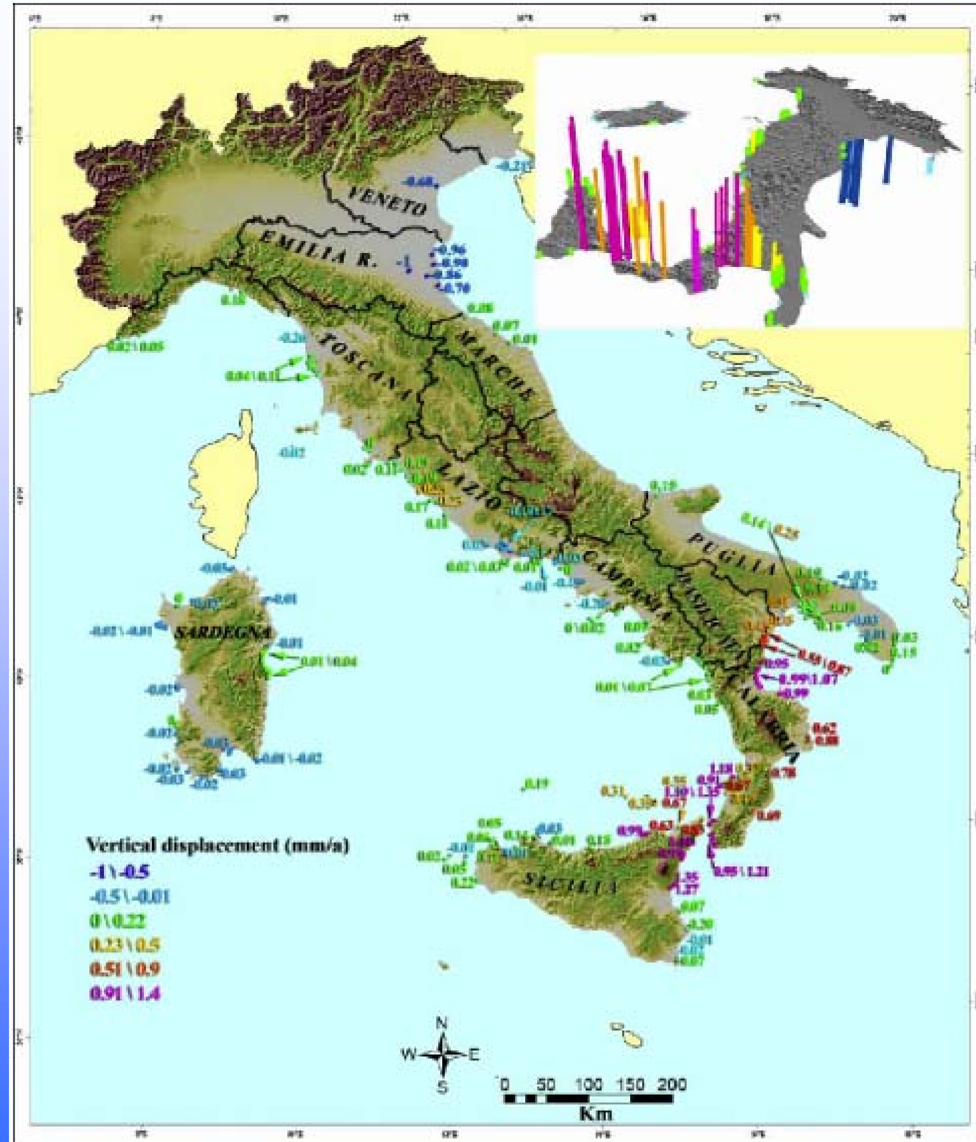
	Time Scale	Length scale	Dominant Process
Climate	Long term: 10^6 - 10^3 years	Global	Growth and decay of ice sheets.
	Intermediate: 10^3 - 10^2 years	Regional	Global change in temperature and ice volume (little ice age, medieval climate optimum).
	Short term: 10^2 - 10 years	Local	Decadal-scale climate change, wind circulation. Change in thermal state of ocean. Change in ground and surface water storage.
Tectonics	Long term: 10^6 - 10^9 years	Global	Plate tectonics and evolution of ocean basins. Ridge formation.
	Intermediate: 10^6 - 10^3(?) years	Regional	Volcanic and sediment loading changes in stress state of lithosphere.
	Short term: 10^3 - 10^2 years	Local	slow surface response to long term tectonics and volcanism
	Very short term: years – sec.	Local	Rapid surface response to tectonic and volcanism forcing.

… geological & gemorphological records of the sea level changes along the coasts (Photo: Orosei Gulf, Sardinia)

Geological evidences: MIS 5.5 (125 ka) “Tirrhenian”

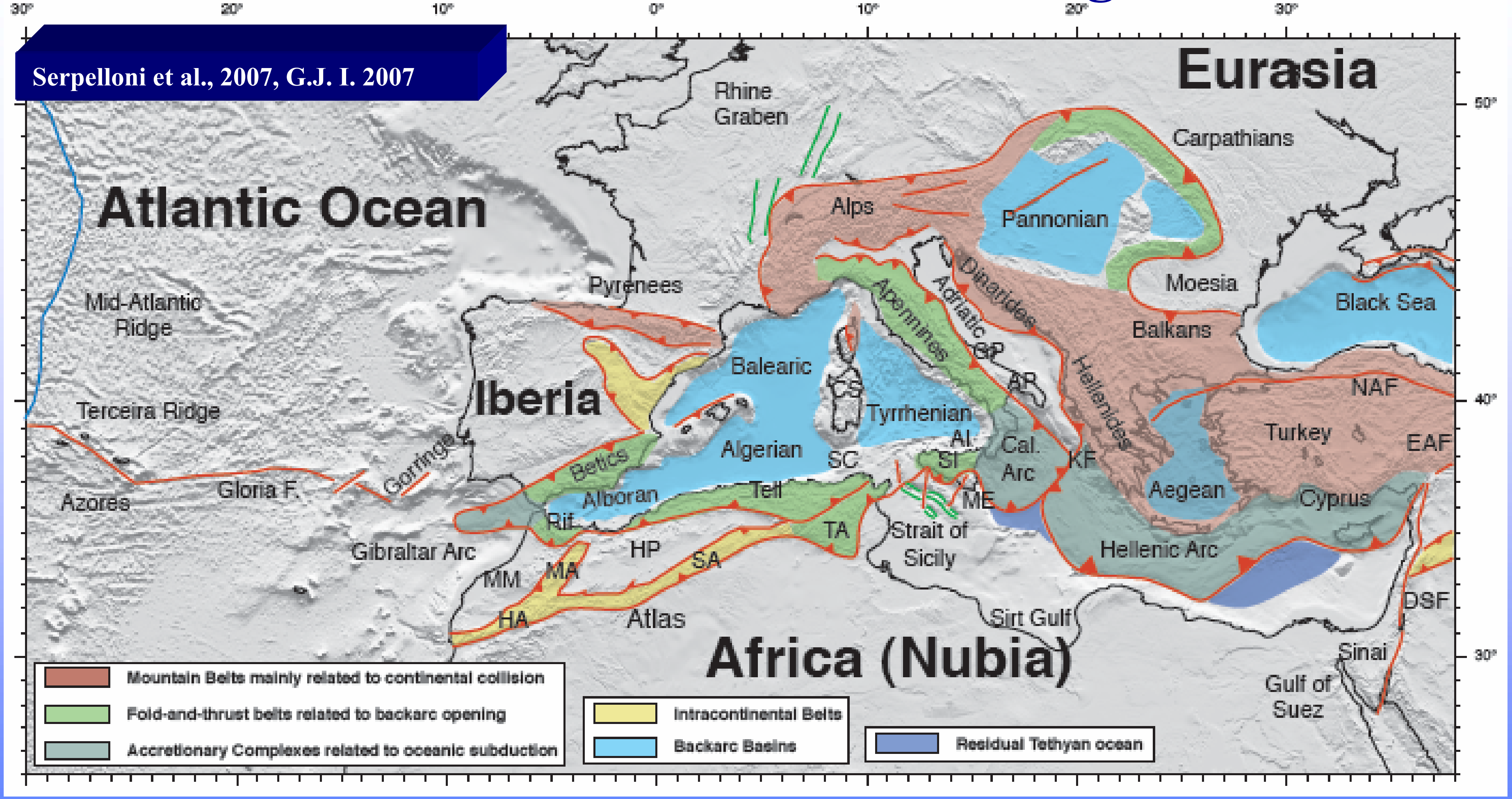
Uplifted terraces in Calabria

MIS 5.5 level



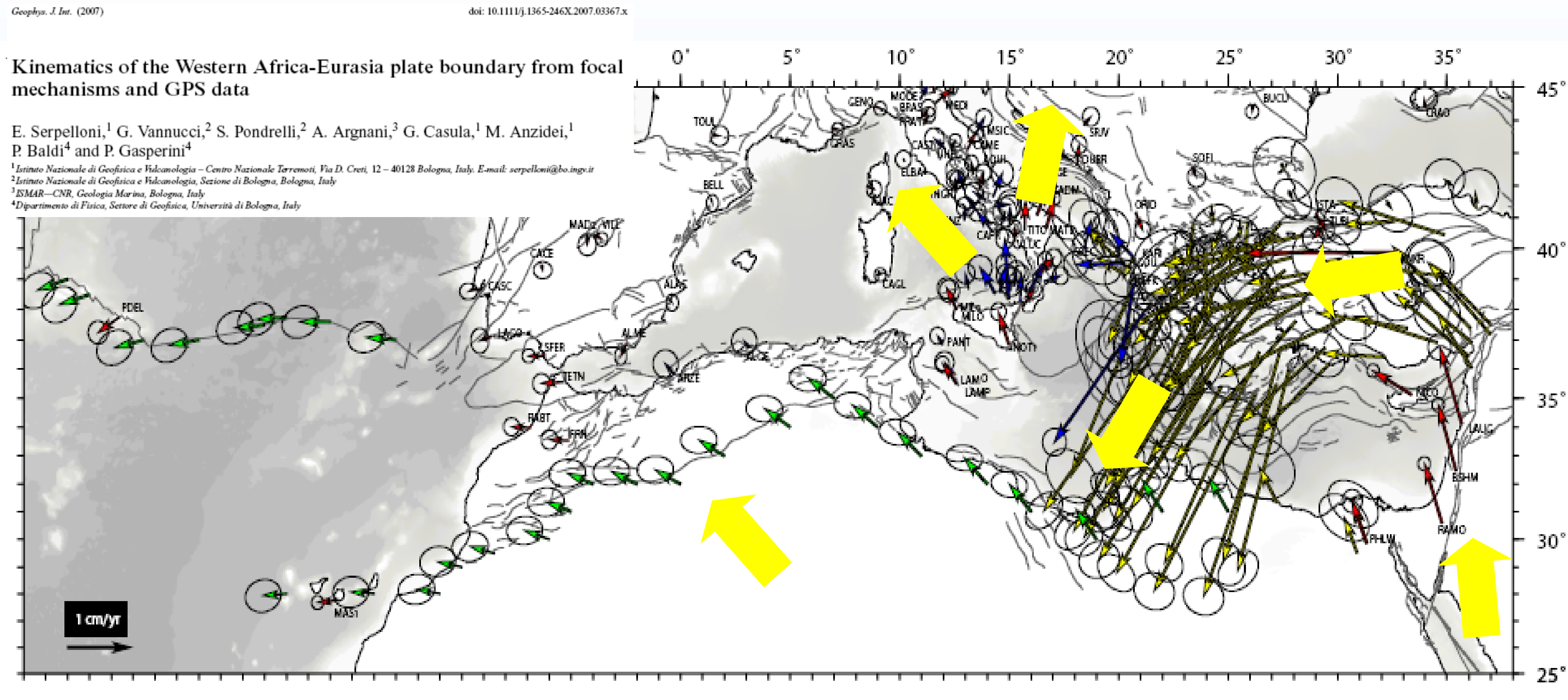
Rates of the slc (mm/yr) inferred from MIS 5.5 (125 ka) (from Ferranti et al., 2006)

The Mediterranean basin is an active region



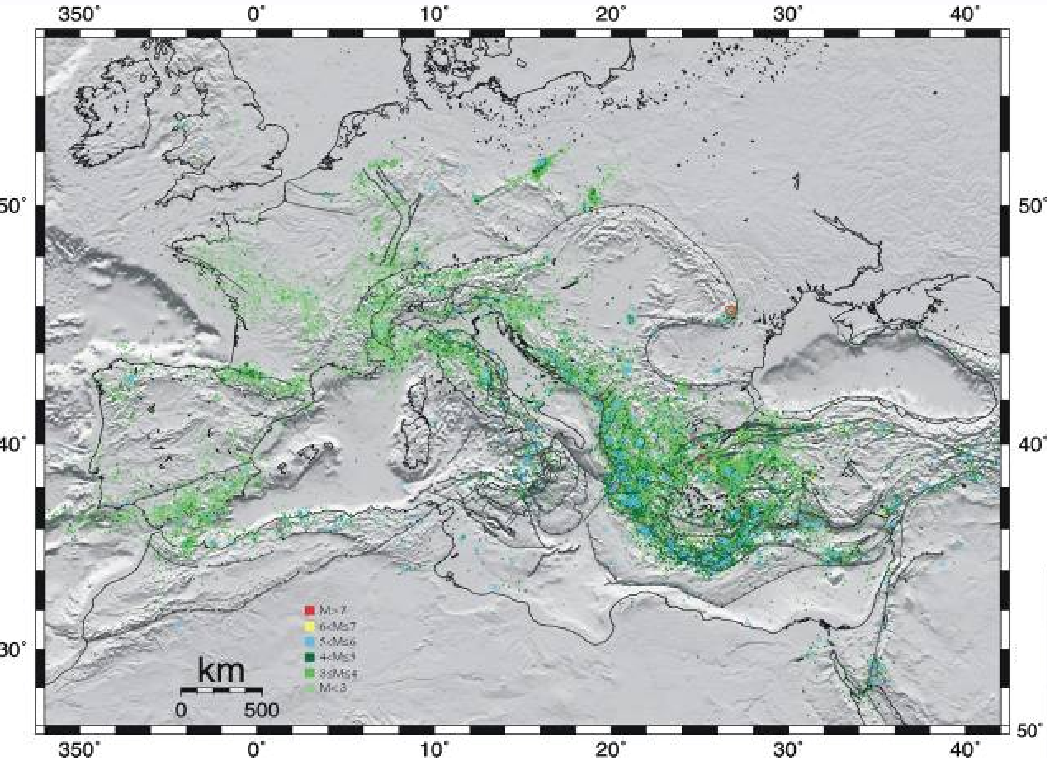
Tectonic sketch of the Mediterranean region. The grey box outlines the area studied in this work (HA: High Atlas; MM: Moroccan Meseta; MA: Mid Atlas; SA: Saharian Atlas; TA: Tunisian Atlas; HP: High Plateau; SC: Sardinia Channel; SI: Sicily; AI: Aeolian Islands; CS: Corsica-Sardinia block; AP: Apulian block; GP: Gargano Promontory; KF: Kephallinia Fault zone).

Current deformation of the Mediterranen basin

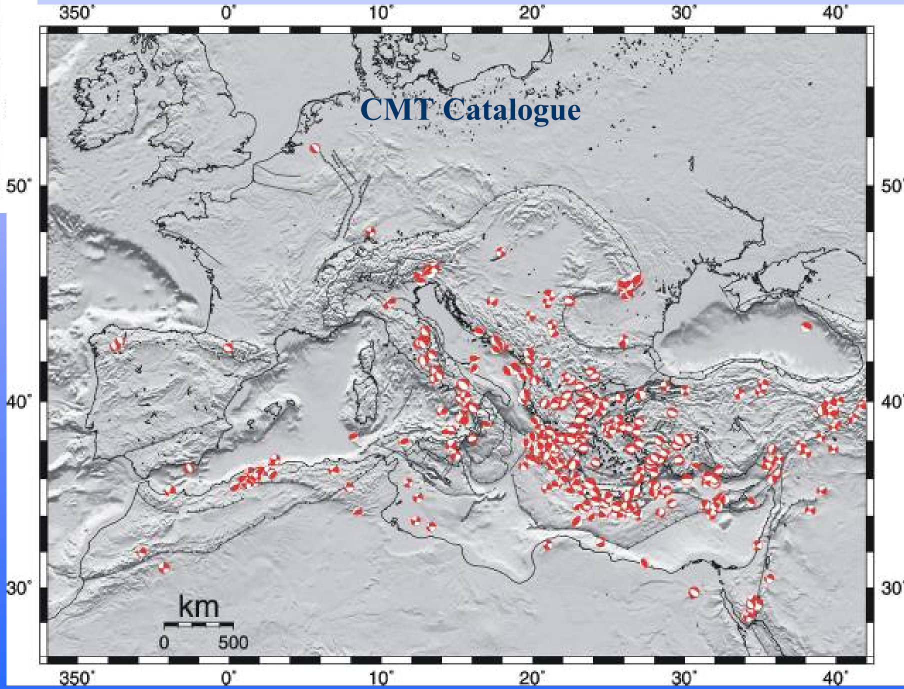


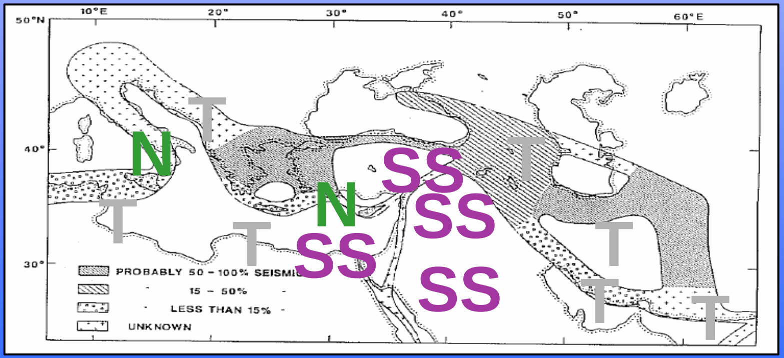
Horizontal velocities (with 95% error ellipses) given with respect to the Eurasian plate. Red arrows: permanent GPS stations; Blue arrows: non-permanent GPS stations; Yellow arrows: sub-set of McClusky et al. (2000) velocity field transformed into the Eurasian fixed frame computed in this work. Green arrows display the motion vectors of points south of the seismically active belts in northern Africa, predicted by the Nubia-Eurasia Euler vector

Seismicity of the Mediterranean basin



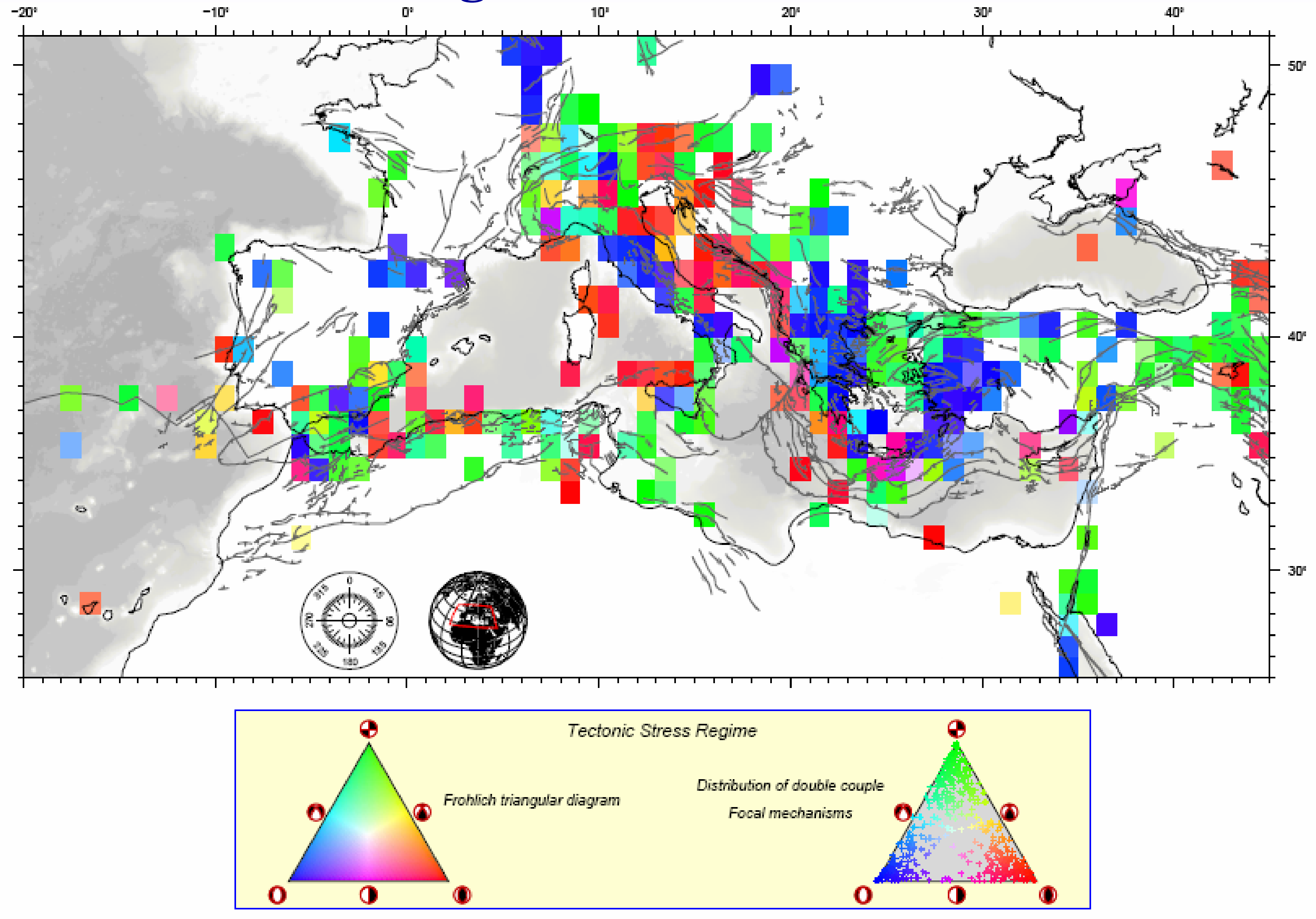
Last 30 years of instrumental seismicity CMT and RCMT.
Sismological data from ETH and IAG.





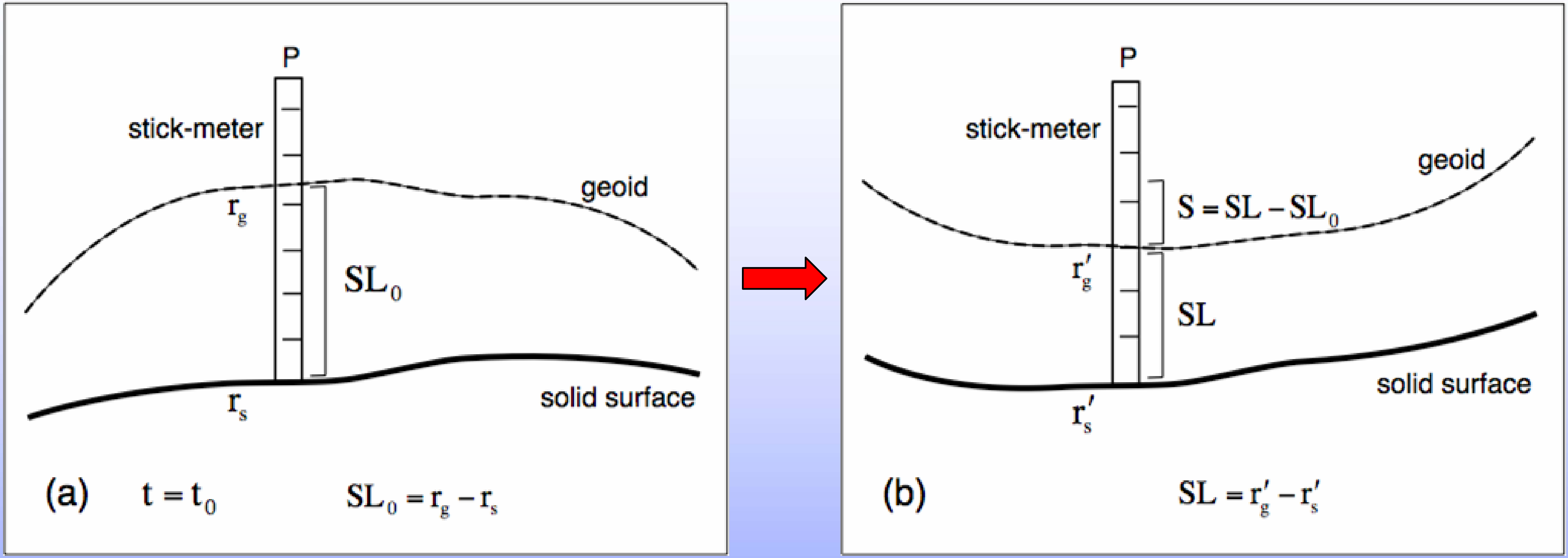
Styles of deformation inferred from seismicity

Tectonic stress regime in the Mediterranean



Last 30 years of seismicity CMT and RCMT. Sismological data from ETH and IAG. Thickness of the seismogenic layer is 25 km.

Sea level change



$$S(\omega, t) = N - U$$

where:

- $N(\omega, t) = r'_g - r_g$ = vertical geoid variation
- $U(\omega, t) = r'_s - r_s$ = vertical displacement of the Earth' crust
- ω is the position

The sea level change is defined at the Earth's crust surface because N and U act in the continents !

The natural lab

The Mediterranean basin, being settled since historical times, is a natural laboratory unique in the world, to study through coastal archaeological sites, the relative sea level change due to the vertical motion of the Earth's crust as well as the change in water volume, since the last ~22 ka BP (Cosquer cave).
Very good estimations are given by roman age sites (~2 ka BP).

Coastal archaeological sites in the Mediterranean can provide good data for relative sea level change measure since the last ~3.5 ka due to change in water volume, as well as for the estimation of the Earth's crust deformation

HOW ?

Geodetic approach ! Specific architectural features of these sites, can be considered unconventional levelling benchmarks or "archaegeodetic benchmarks" which have recorded the intermediate (~10^3 to $3x10^3$ yr) to very short term (~10^2 yr to seconds) land movements (tectonics, isostasy, seismicity and volcanism).

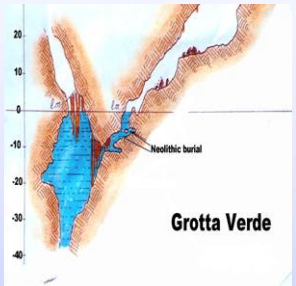
WHY ?

Because they were built w.r.t. the mean sea level (tidal zone) at a location, thus with respect to the geoid. The latter is the reference surface usually used to measure the topographic elevation of points placed above or below the mean sea level.

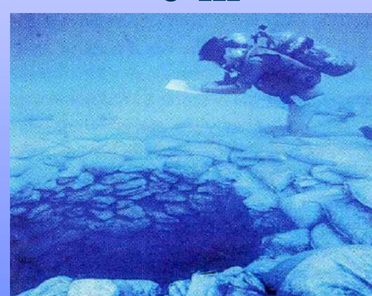
Evidences of the relative sea level changes in the Mediterranean since the last interglacial

-120 m

-8.5 m



-6 m

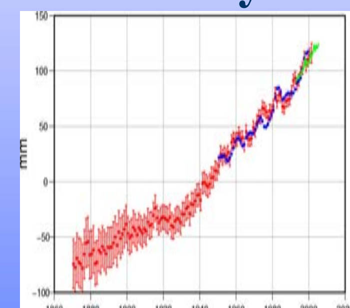


-2.5 m

-1.35 m

-0.5 m

1-2 mm/yr



~22 ka
Cosquer (France)

~8-6 ka
Wells (Israel)
Grotta Verde (Sardinia)

~8 ka
Broze age Sites (Israel)

~2.5ka
Greek age Sites (Med)

~2ka
Roman age Sites (Med)

~0.5ka
Bizanthyne Sites (Med)

Present time

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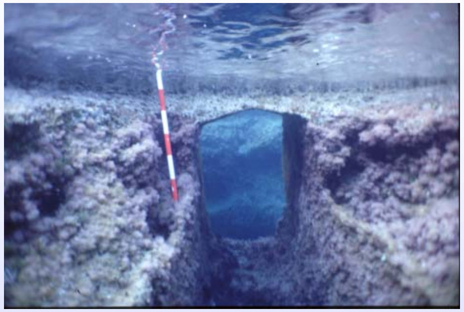
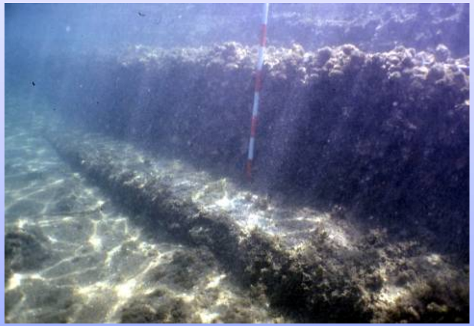
time

~2ka archaeogeodetic benchmarks (functional elevations)



Fish thanks

- channels, sluice gates, sliding posts,
- lower crepidine
- thresholds of channels



Harbours

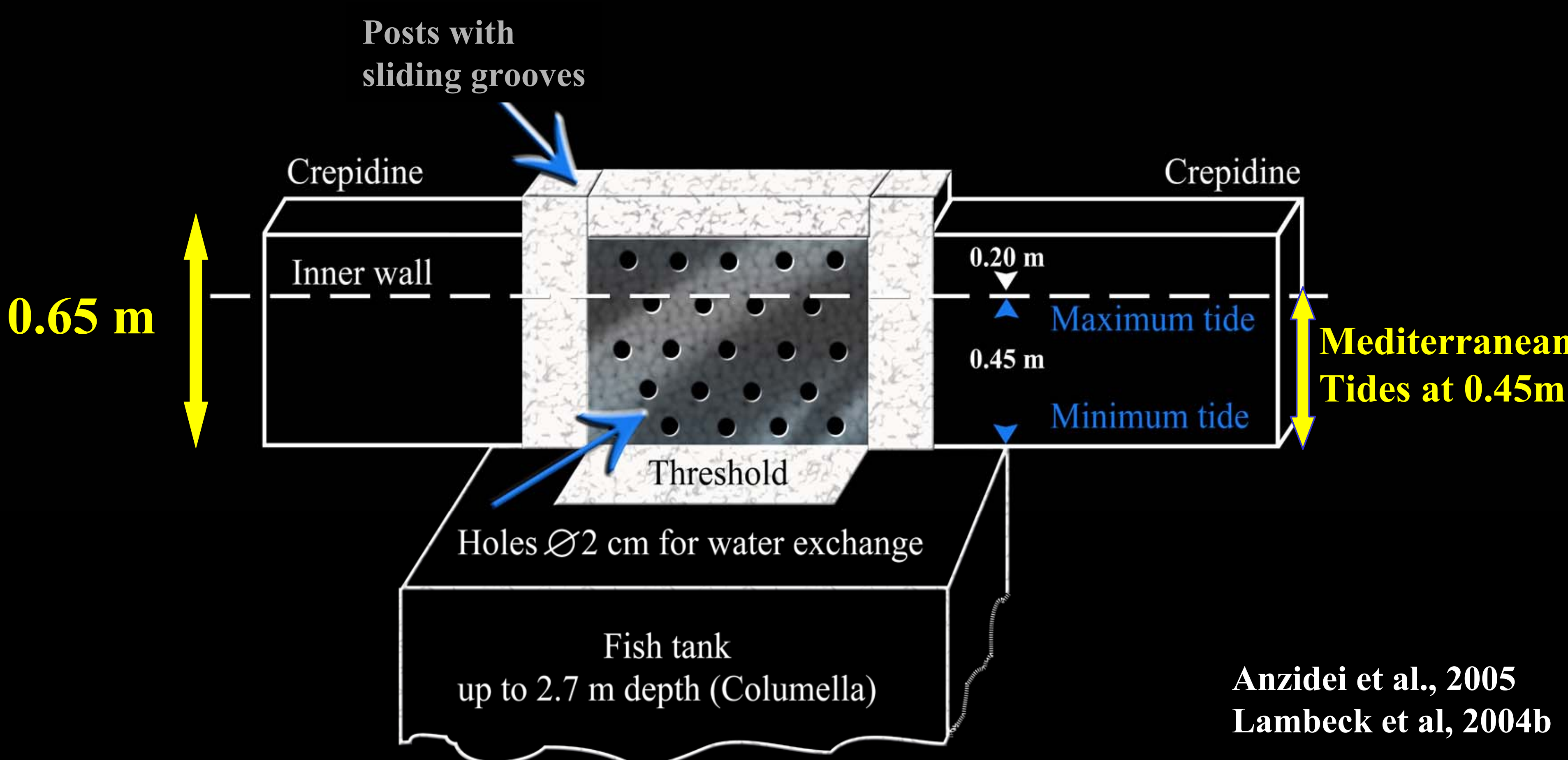
- Bollards
- lower crepidine
- channels
- stairs, piers, docks
- slipways

Quarries

- lower cuttings

Sluice gates: the precise ~2ka benchmark

Sketch of a sluice gate for the water exchange in a Roman Fish tank



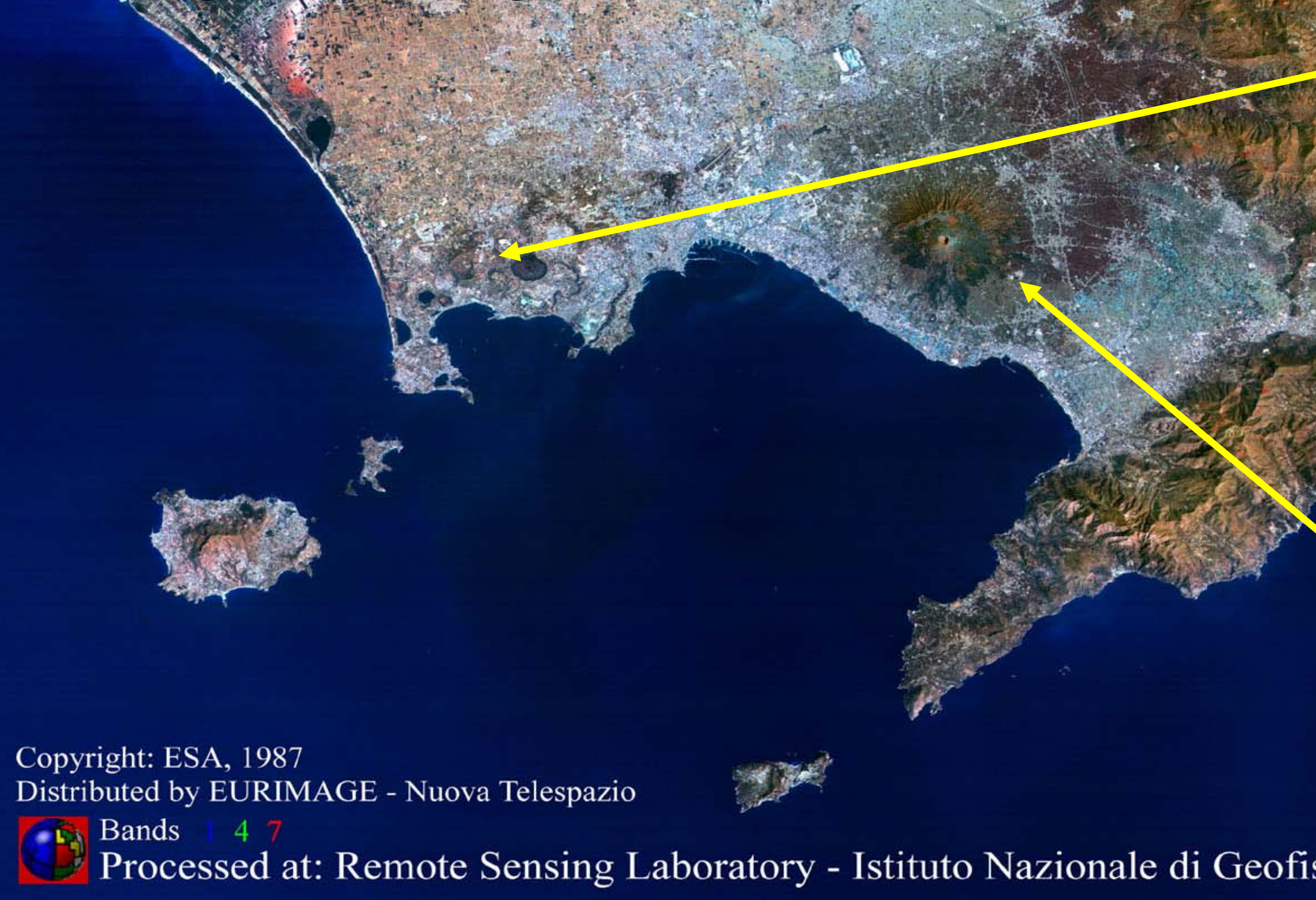
Anzidei et al., 2005
Lambeck et al, 2004b

The top of the sluice gate coincides with the elevation of the lowest level foot-walk (crepidine), to a position above the highest tide level.

Some examples from coastal archaeological sites in the Mediterranean

Phlaegrean Fields, Naples, Italy

Evidences of different values of vertical deformation inferred from the elevations at Serapeo and at the submerged sites in the gulf of Baia (-5.5 m).



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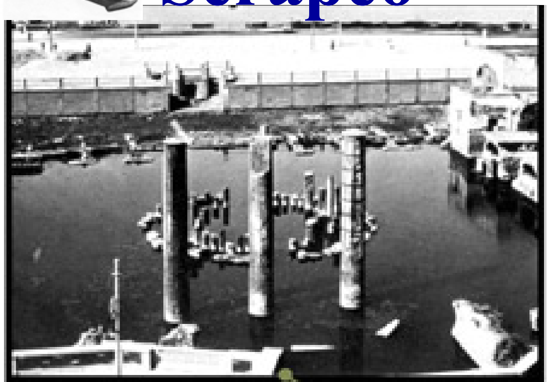
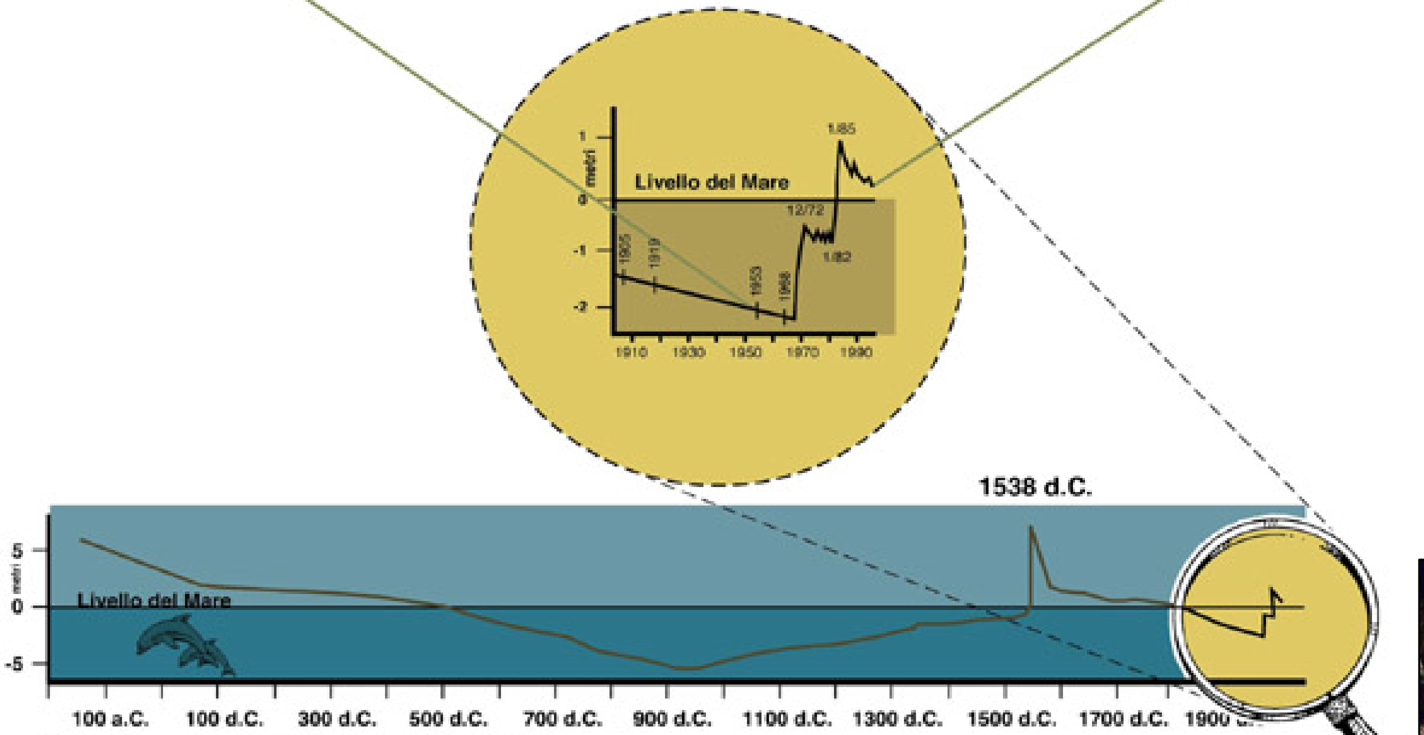
The long term records of the bradiseism at Serapeo





Movimento del Suolo al Serapeo

Ricostruito sulla base di dati geologici, documenti storici e, dal 1905, dati di livellazioni di precisione.

The repeated episodes of uplift and subsidence have been recorded by the Serapeo, the ancient market of Puteoli. S.L. up to +7 m (Morhange et al., 2006)


Baia
-5.5 m b.s.l.
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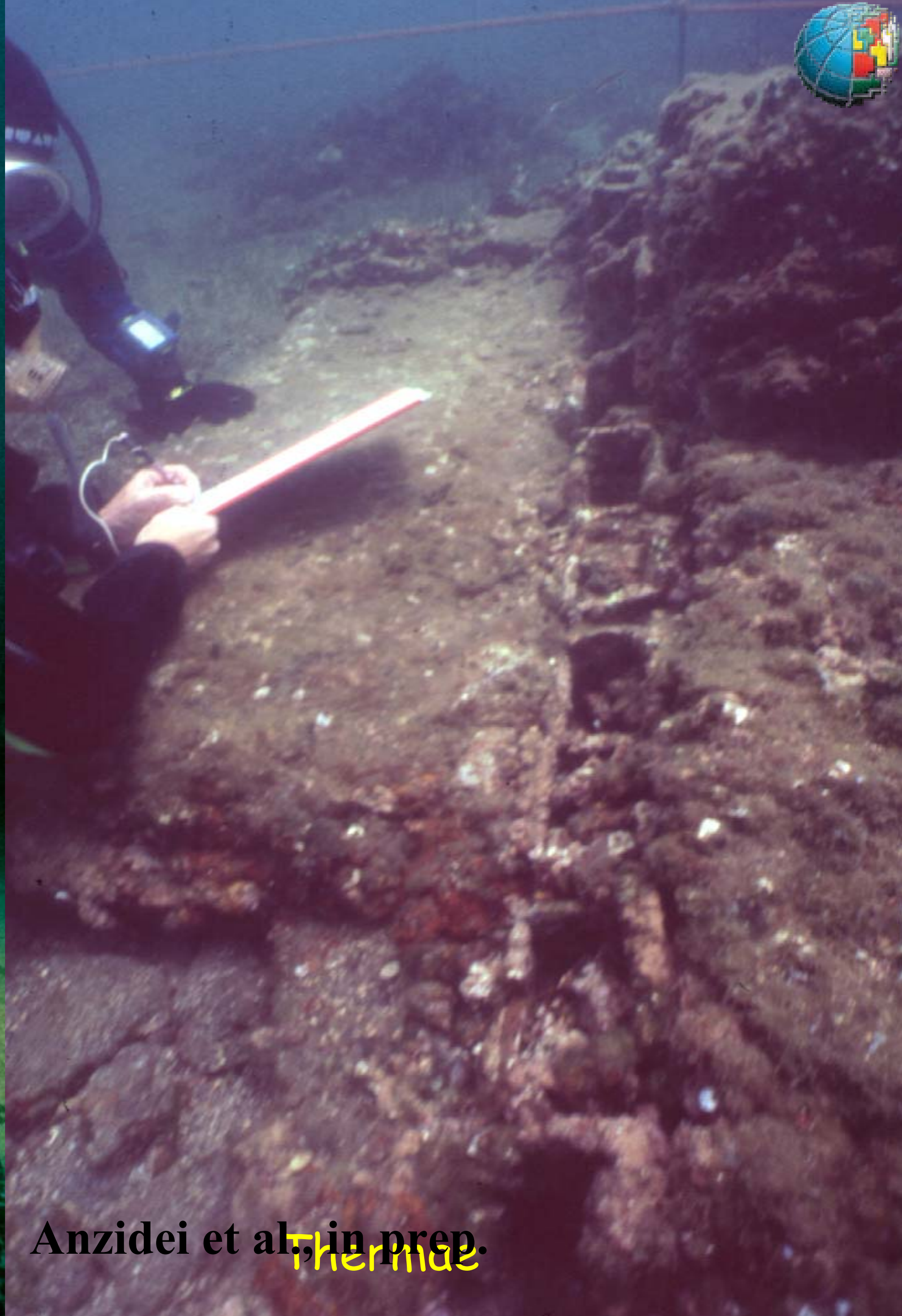
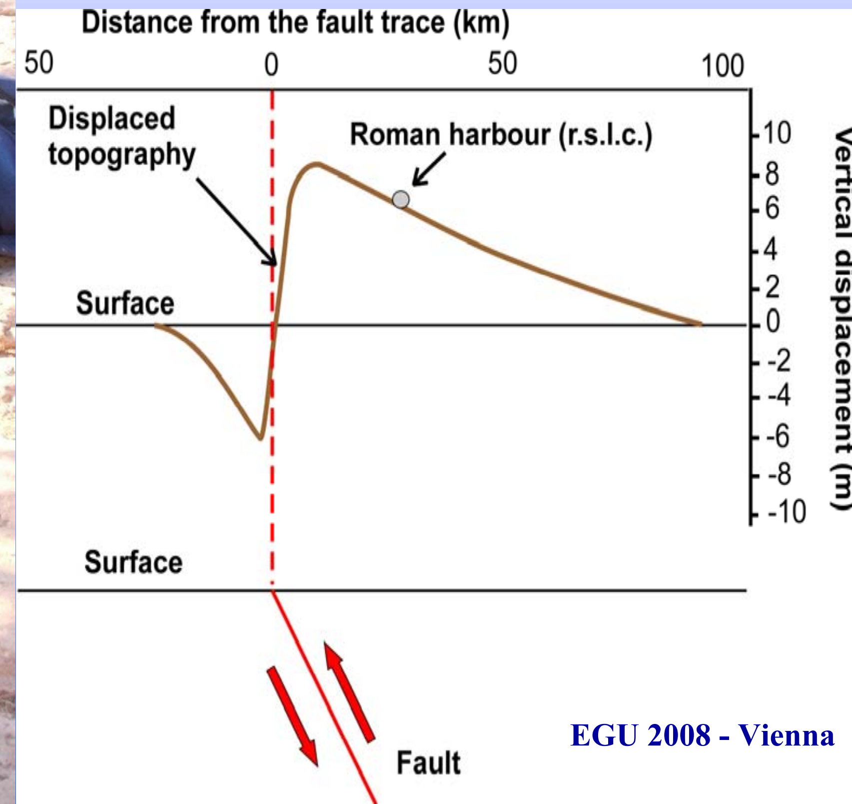

Anzidei et al., in prep.
Thermae

Crete island – seismic region

Roman harbour of Phalasarna, Creta: 6.5 m of coseismic uplift during the AD 360 earthquake (Stiros and Drakos, 2006; R.Basili p.c. 2007). Fault parameters and Mmax can be estimated.

Roman harbour of Phalasarna, Crete

Harbour location



Okada model of the 365 a.D. fault, Crete earthquake (M ≥ 8.5). (from Stiros and Drakos, 2006, modified)

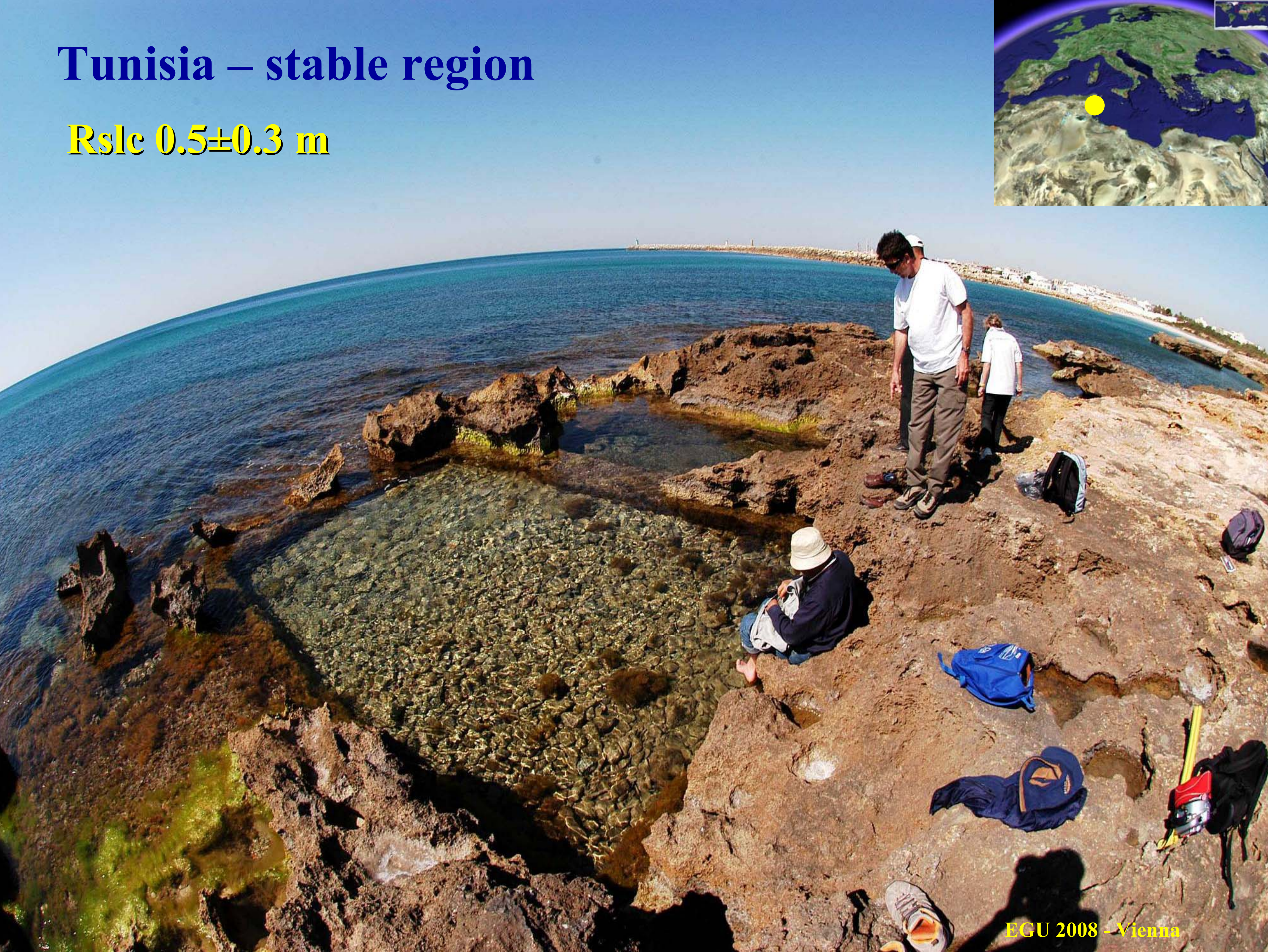
Photo, courtesy of R.Basili, INGV

SW Turkey – seismic region

Cleopatra's bath
Twelve islands

See the movie

Kekova
The Lycian tombs


Tunisia – stable region
Rslc 0.5±0.3 m
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Israel – stable region

Pool Haifa

New preliminary observations show an rslc at ~0.0±0.2 m (2ka). Stable region.

Harbour of Cesarea

Crusader's Jetty


Briatico (Italy, Calabria) – active region
Relative sea level change
at 0.0 ±0.2 m from the
Fish tanks
Briatico, Calabria: equilibrium
between tectonic uplift, s.l.c. and
isostasy of ~ 1.4 m (in absence of
known coseismic movements).
Same results at Alicante (Spain) !
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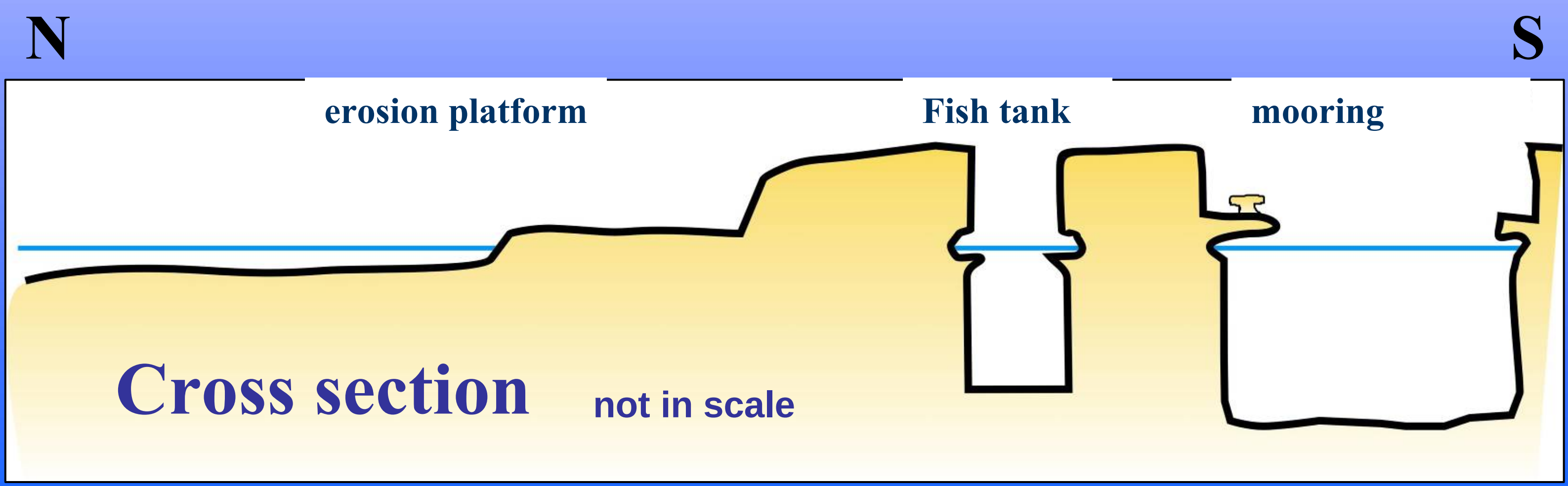
Briatico (Calabria) – active region

The elevation between the archaeological and morphological indicators show that the relative sea level has not changed since the last 1806 ± 50 years.
Balance betwwen tectonic uplift and the glacio-hydro-isostatic signal at 0.7 mm/yr. Agreement with geological data (5e level). (Anzidei et al., 2006)



Archaeogeodetic data vs predicted sea level curves, tide gauge and GPS data

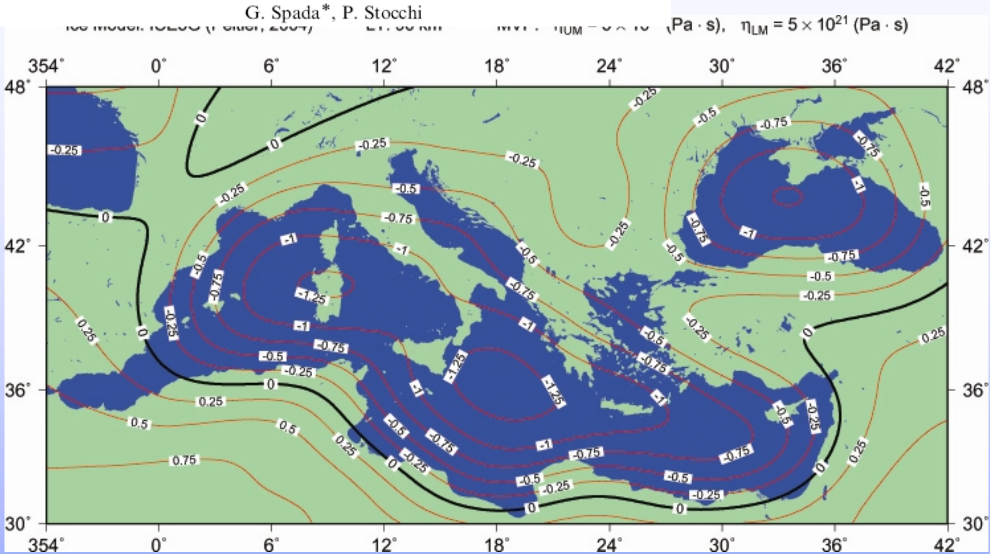
Some examples and work in progress

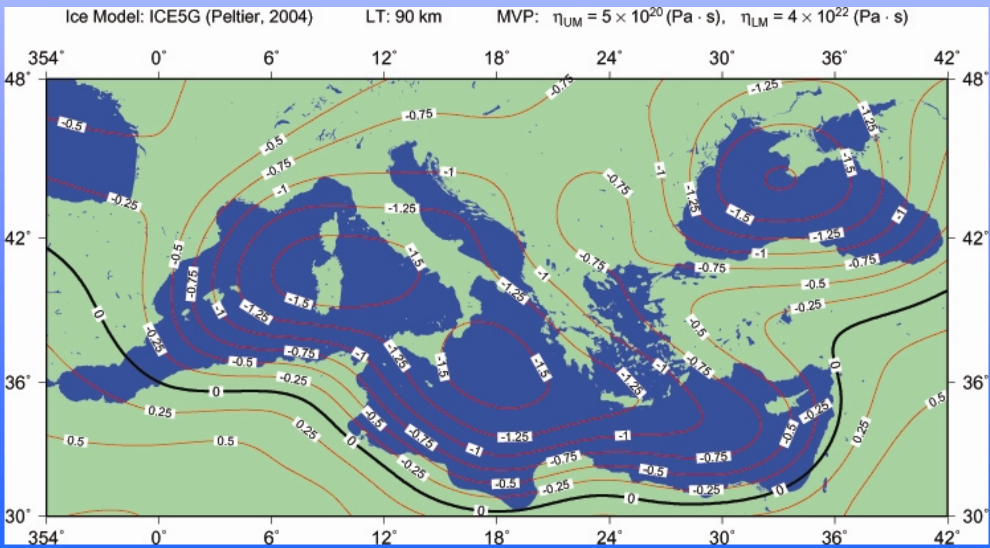
Sea level models at 2ka

ELSEVIER
Computers & Geosciences 33 (2007) 538–562
COMPUTERS & GEOSCIENCES
www.elsevier.com/locate/cageo

SELEN: A Fortran 90 program for solving the "sea-level equation"☆

G. Spada*, P. Stocchi

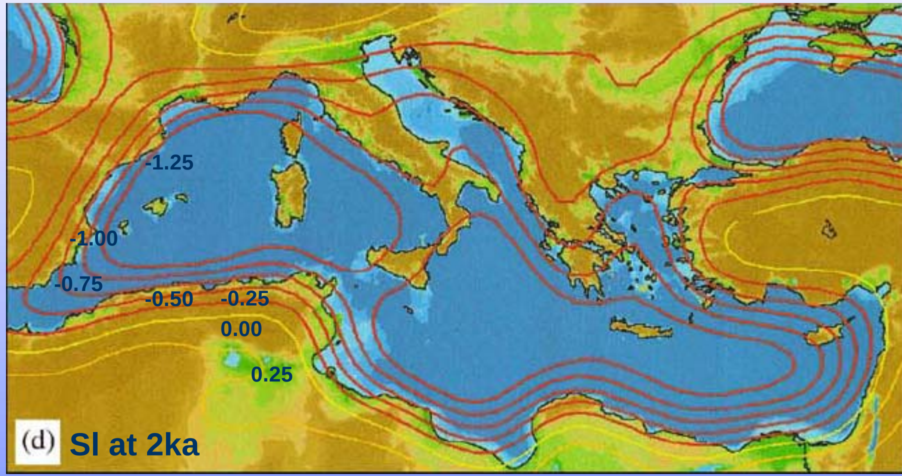




ELSEVIER
Quaternary Science Reviews 24 (2005) 1969–1988
QSR

Sea-level change in the Mediterranean Sea since the LGM: model predictions for tectonically stable areas

Kurt Lambeck*, Anthony Purcell
Research School of Earth Sciences, Australian National University, Canberra ACT 0200, Australia

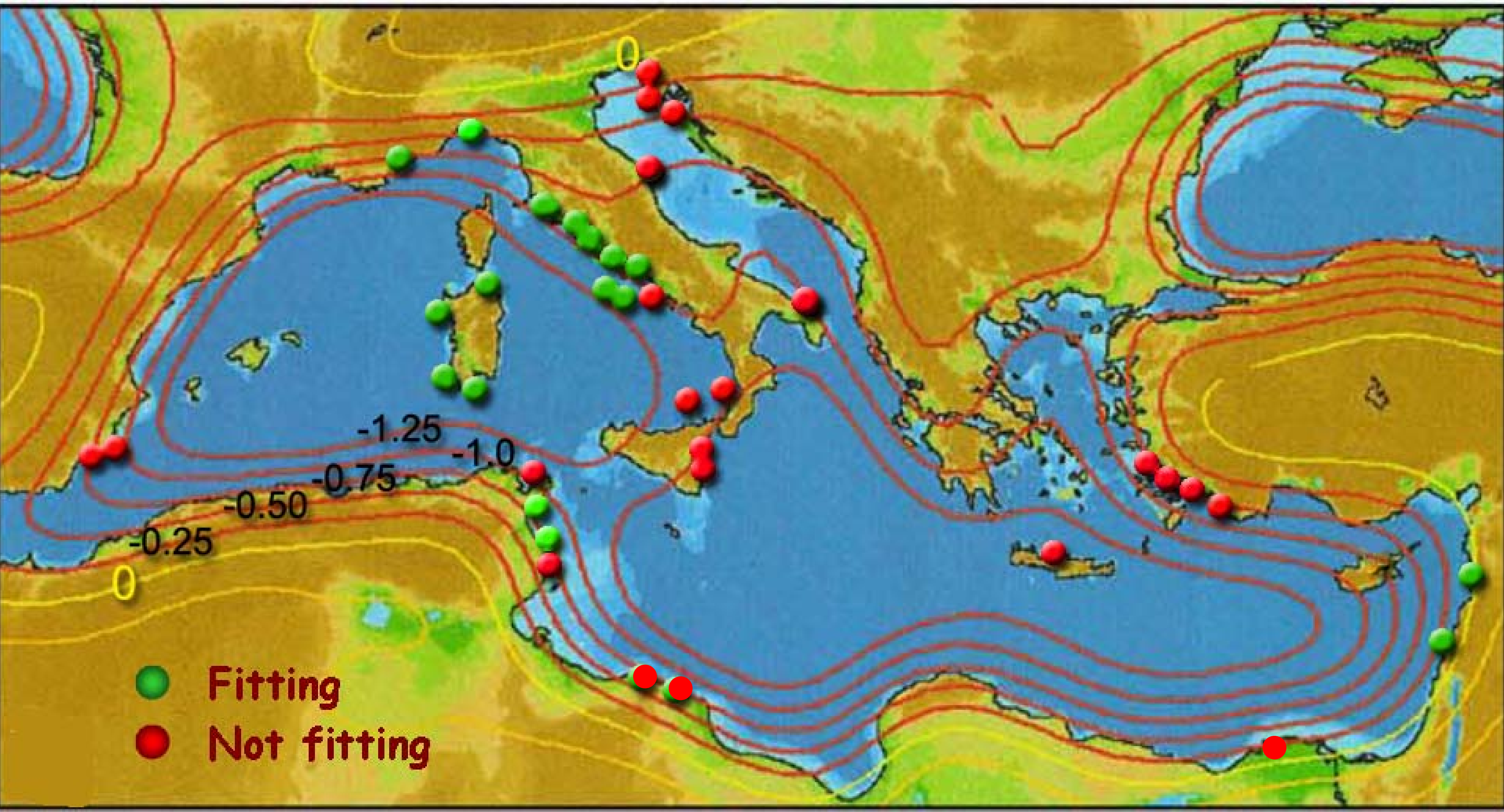


Predicted sea level change at 2ka. Ice model ICE5G (Peltier, 2004).

Earth model parameters:

- **Lithospehric thickness 90 km**
- **upper mantle viscosity**
  5×10^{20} P; 5×10^{21} Pa s
- **lower mantle viscosity**
  4×10^{22} Pa s (Spada and Stocchi, 2006)

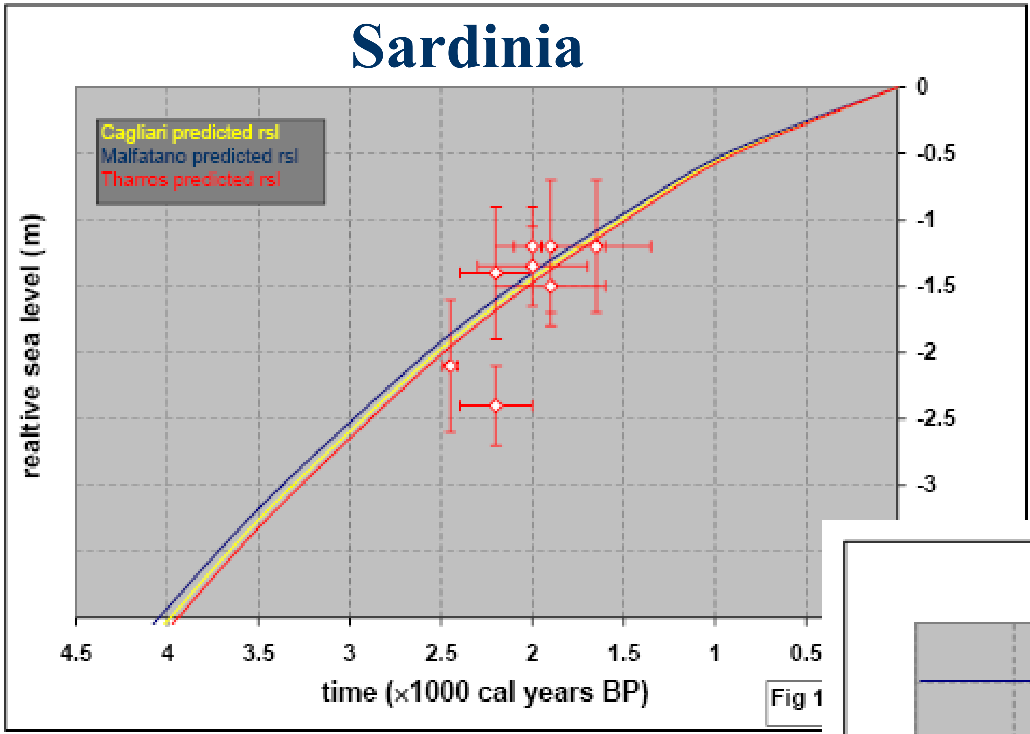
Archaeological data and rslc geophysical model at 2ka

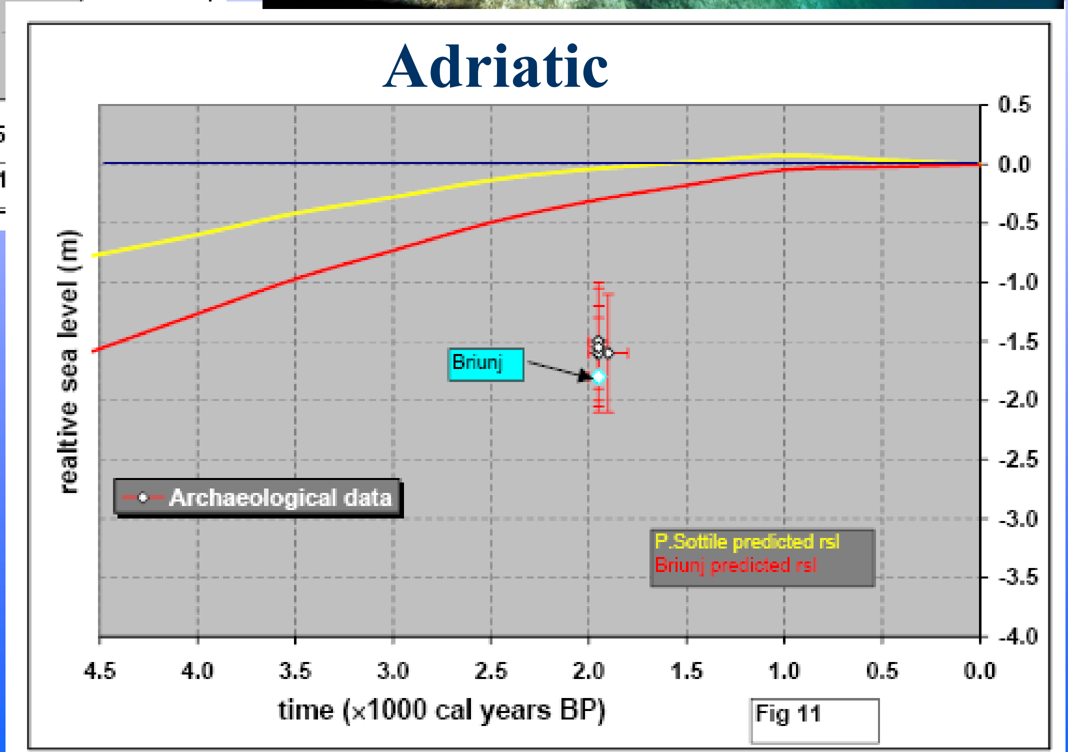


Model from Lambeck & Purcell, 2005. Predicted relative sea levels at 2 ka. Red are negative values, orange positive values, yellow is zero change.

Observations from Tallarico et al., 2003, Sivan et al., 2004, Lambeck et al, 2004, Marrinier et al., 2005, Anzidei et al., 2005, Morhange et al., 2006, Antonioli et al, 2007, Anzidei et al., this meeting

Sardinia & Adriatic: example of GIA & tectonics



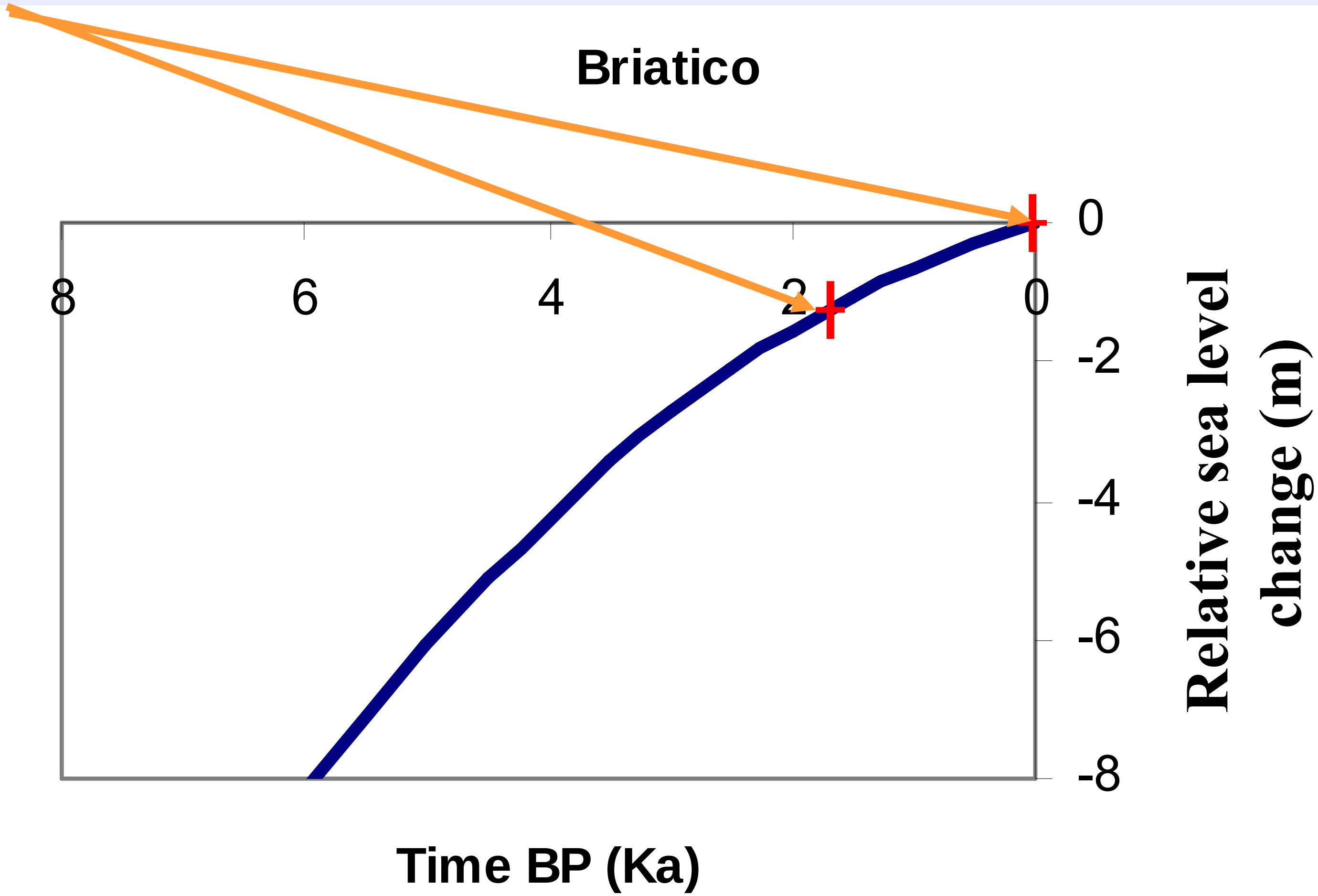


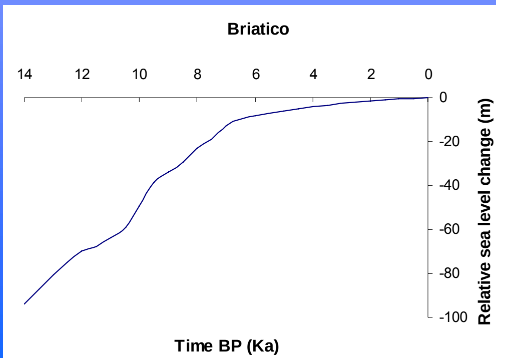
Sea level curves can be estimated from isostatic rheological models of the Earth's crust: three-layer, lithosphere thickness ~ 65 km, seismic discontinuity at 670 km, viscosity $3x10^{20}$ Pas, lower mantle average viscosity ~ 10^{22} Pas (earth model m3)

(Lambeck and Purcell, 2005)

Sea level curve at Briatico: balance between tectonics, slc and GIA

The archaeogeodetic benchmark
follows the sea level curve since its construction (1806±50 yr BP).
(curve from Lambeck and Purcell, 2005) .

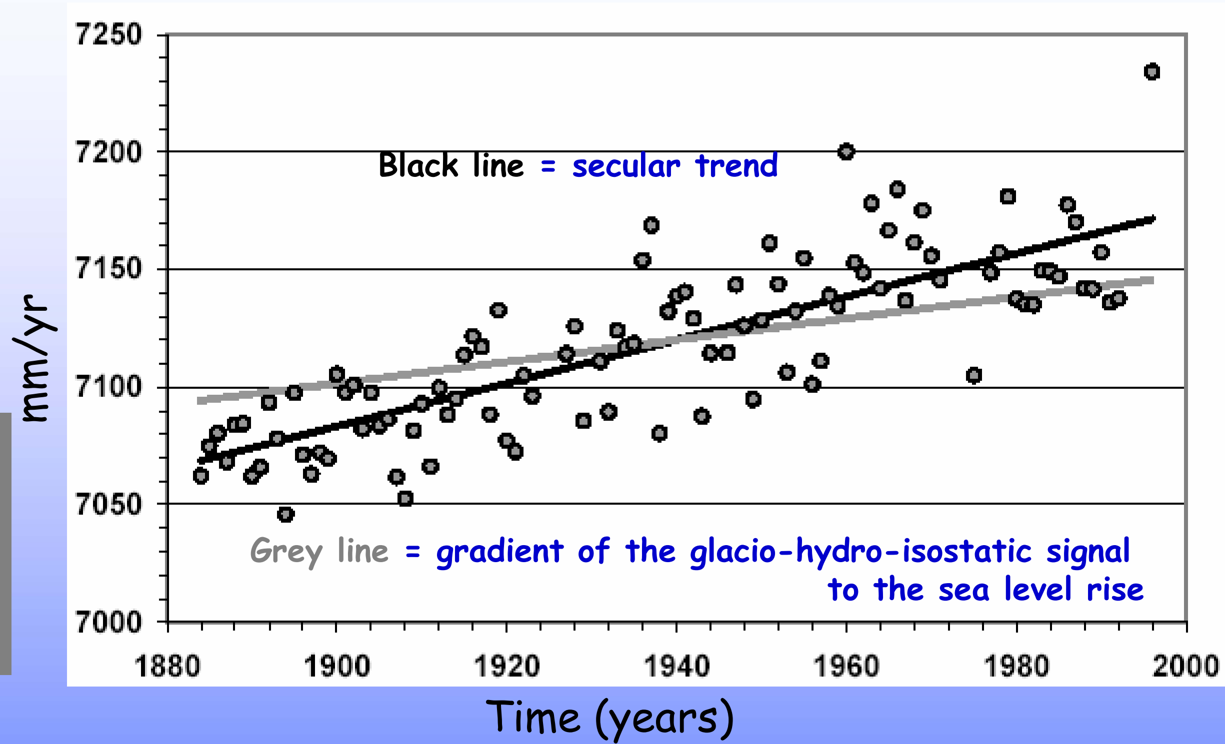




Tide gauge data and archaeological sites

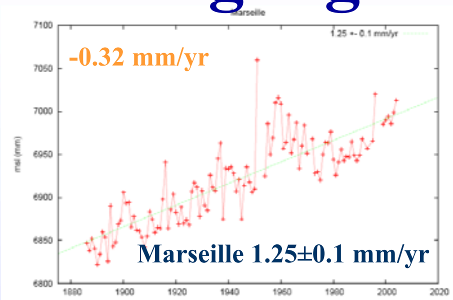
Tide gauge data reducted to the Torre Astura site (stable), corrected for the differential glacio-hydro-isostatic signal.

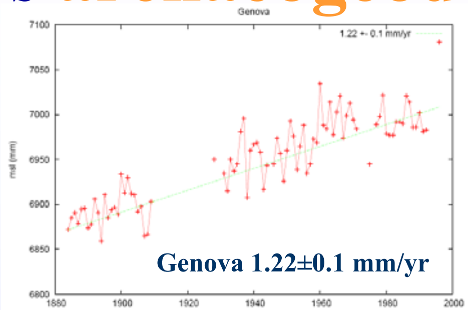
Eustatic signal at
1.02±0.21 mm/a for the last 100 yr
Isostatic correction at
0.54±0.03 mm/yr

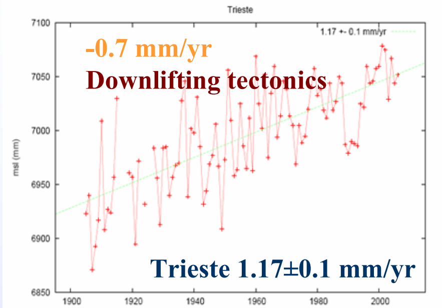


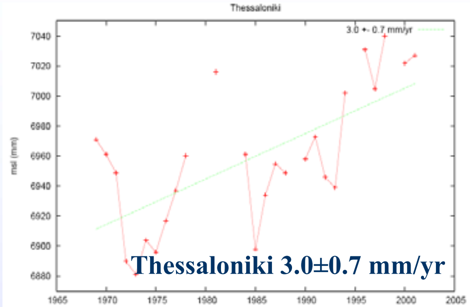
The rate of the modern sea level rise cannot be extrapolated far back in time to the roman age because this not consistent with the elevation of the archaeogeodetic benchmarks. Archaeological data as well as those of the tide gauge data, are consistent with a sea level rise started at the end of the XIX century or at the beginning of the XX century (100±53 years BP).

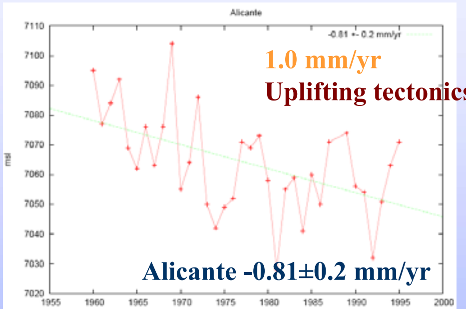
Tide gauges vs archaeogeodetic indicators

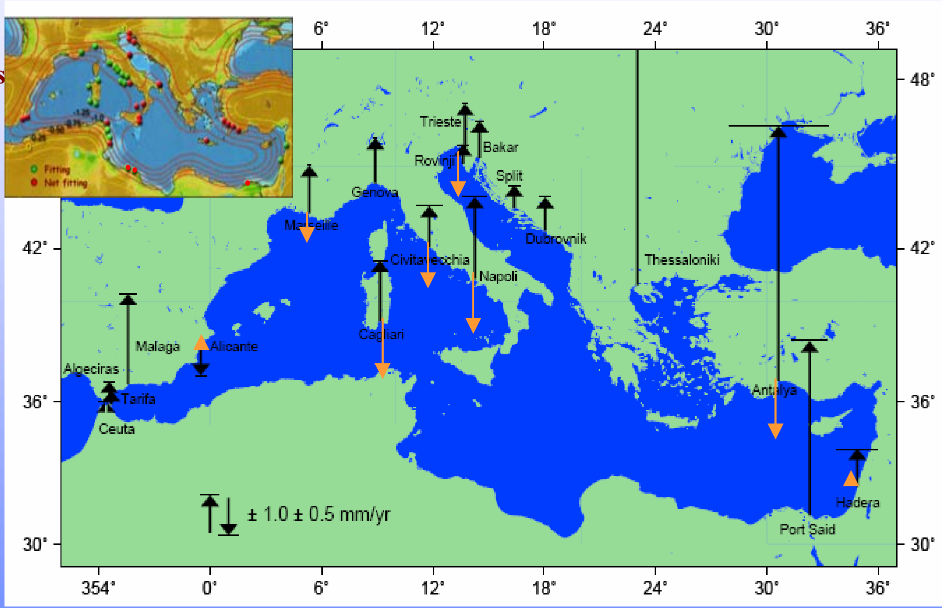


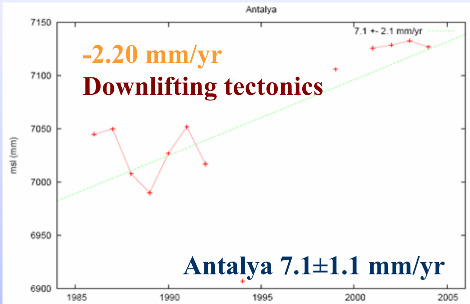


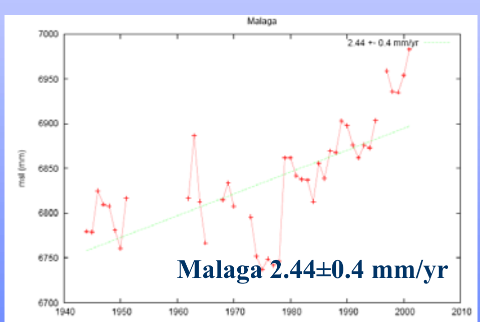


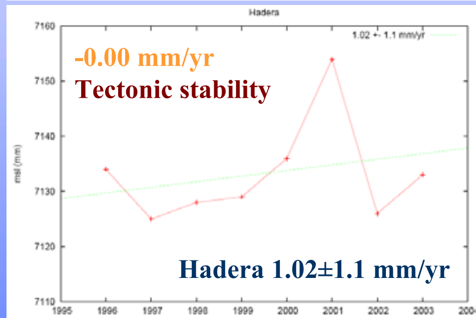


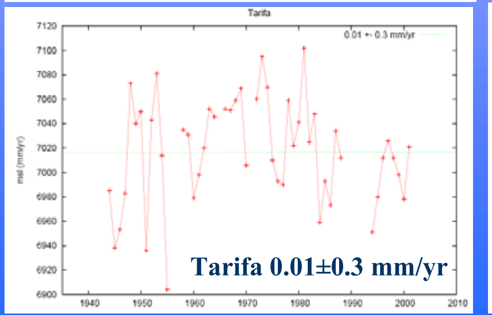


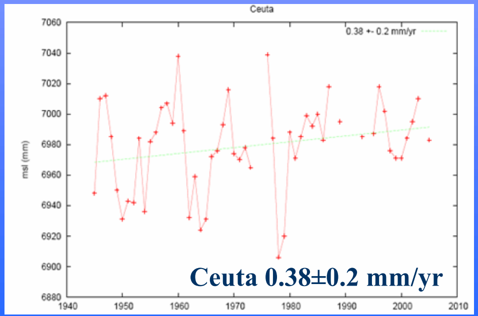


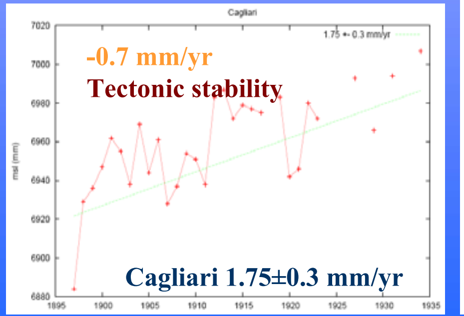


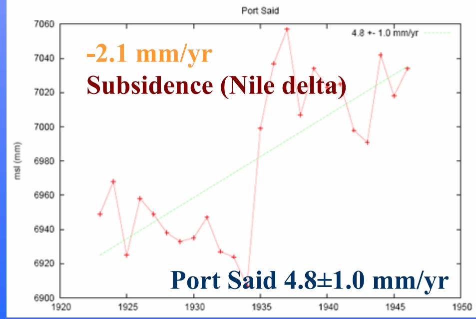






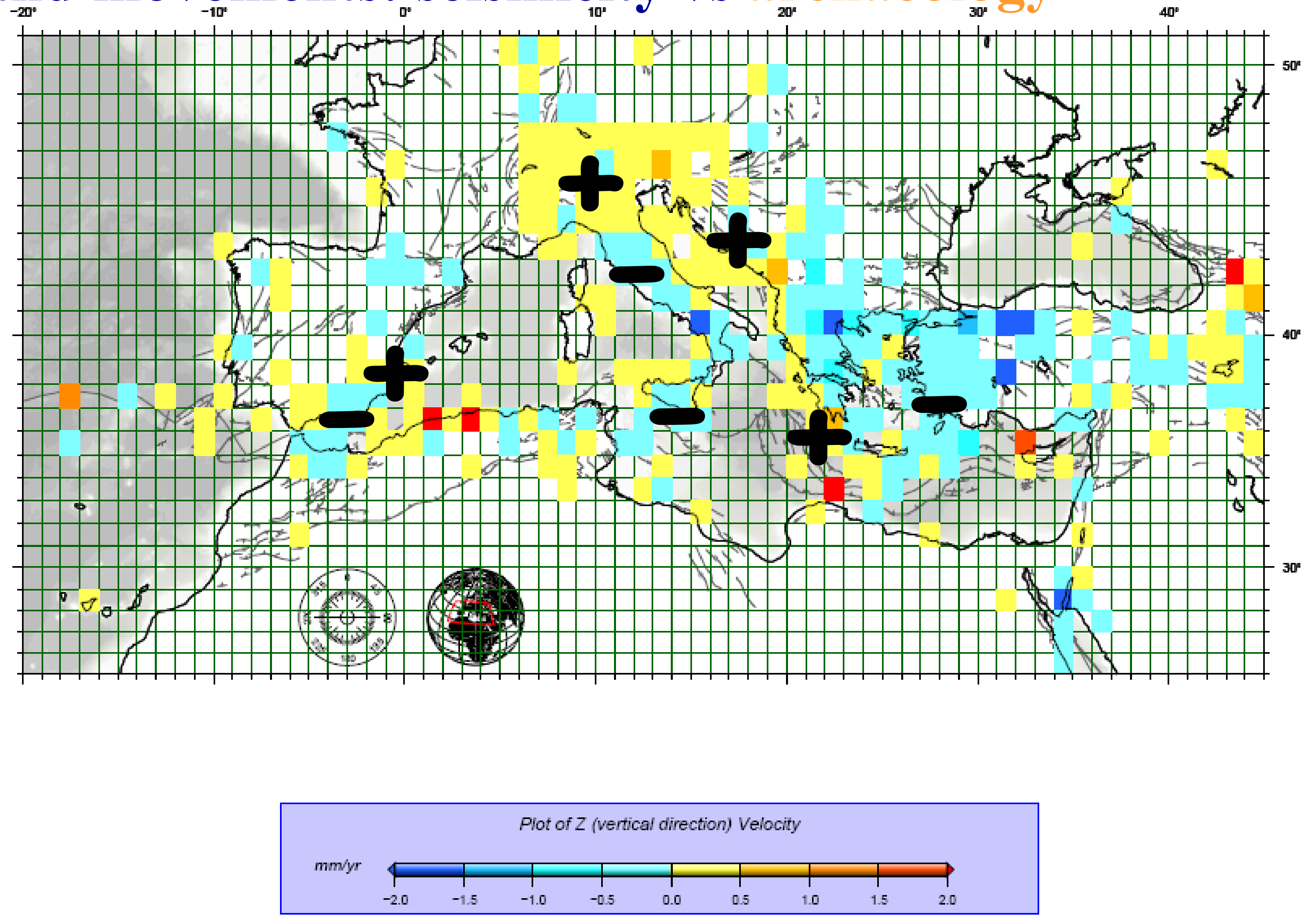






Trends in agreement with archeogeodetic sites !

Land movements: seismicity vs archaeology



Vertical deformation inferred from seimic moment tensor of last 30 years of seismicity (CMT and RCMT). Sismological data from ETH and IAG. Tickness of the seismogenic layer is 25 km.

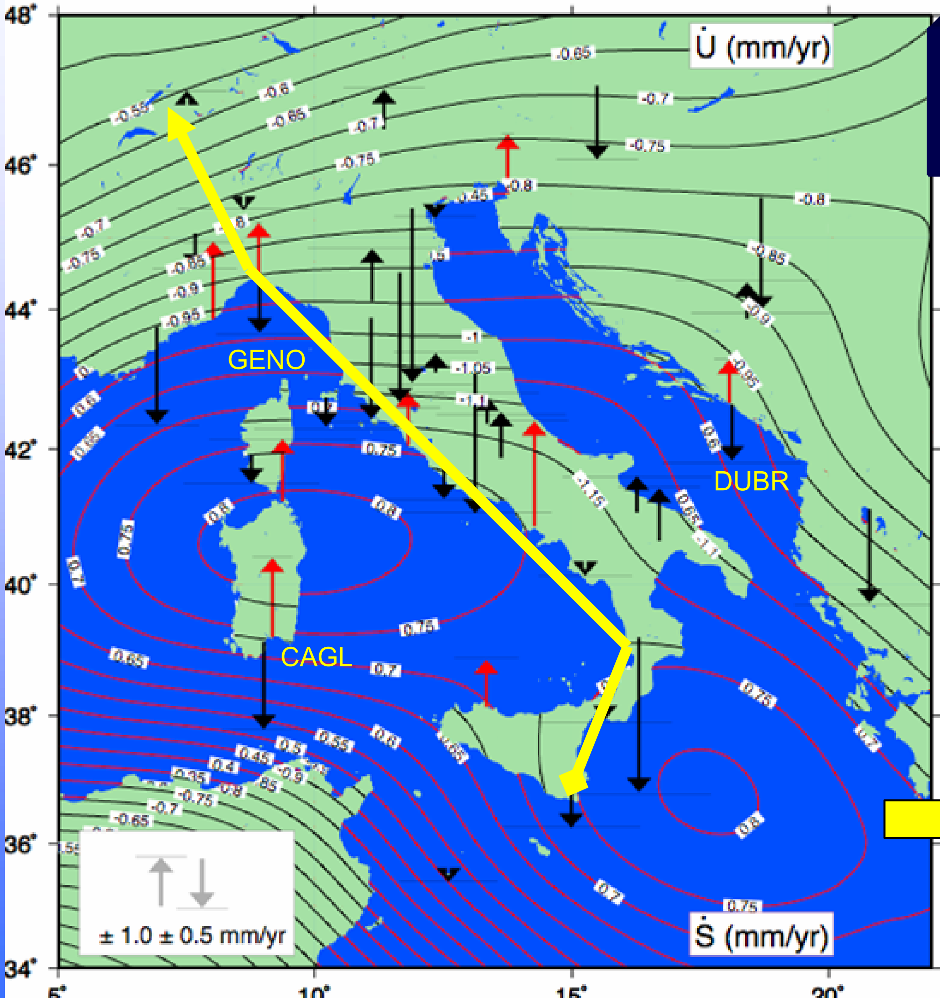
Models vs GPS & tide gauges

ICE5G,
LT = 90 km,
VSP = HVC

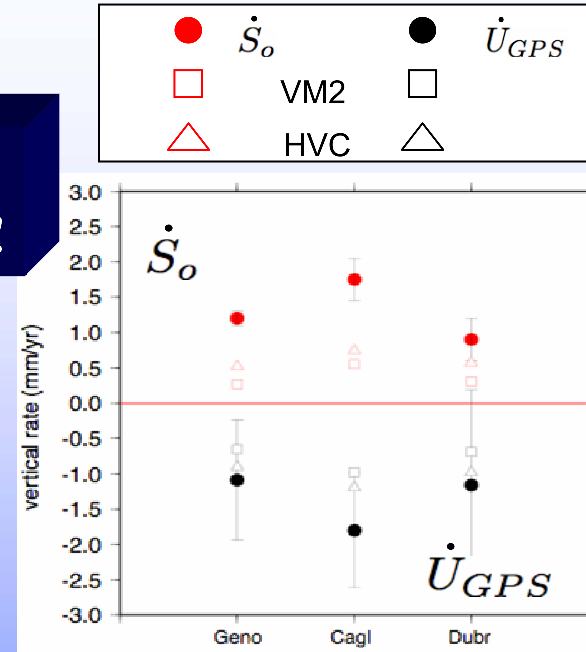
$\dot{U}_{GPS}$ (GPS rate from Serpelloni et al., 2006)

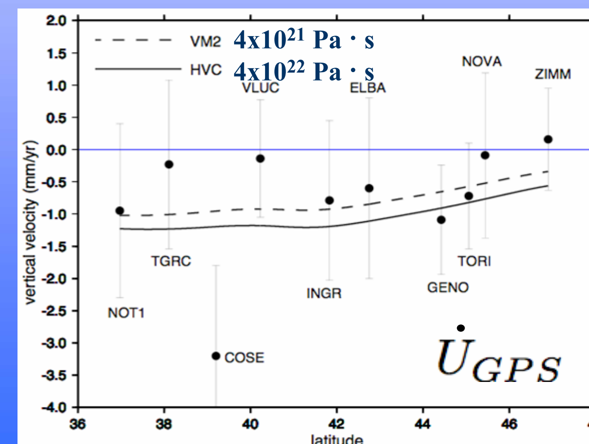
$\dot{S}_o$ (sea level rate from PSMSL data base)

from Stocchi et al., 2007 submitted



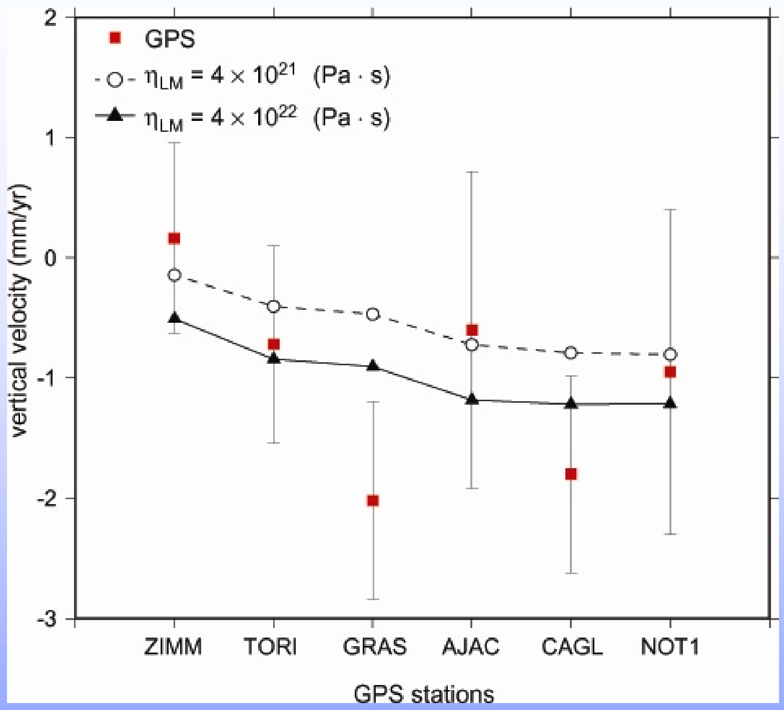
Work in progress !



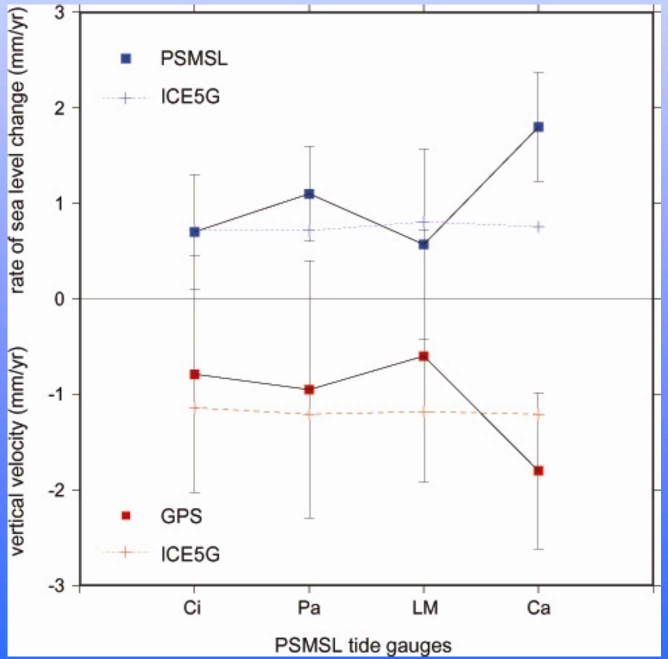


Vertical velocities predicted from the glacio-hydro-isostatic model (two viscosity values of the mantle) vs vertical GPS velocities computed across a N-S section from ZIMM (Germany) to NOT1 (Siciliy). Model ICE5G

GPS vs tide gauges & models in the Mediterranean

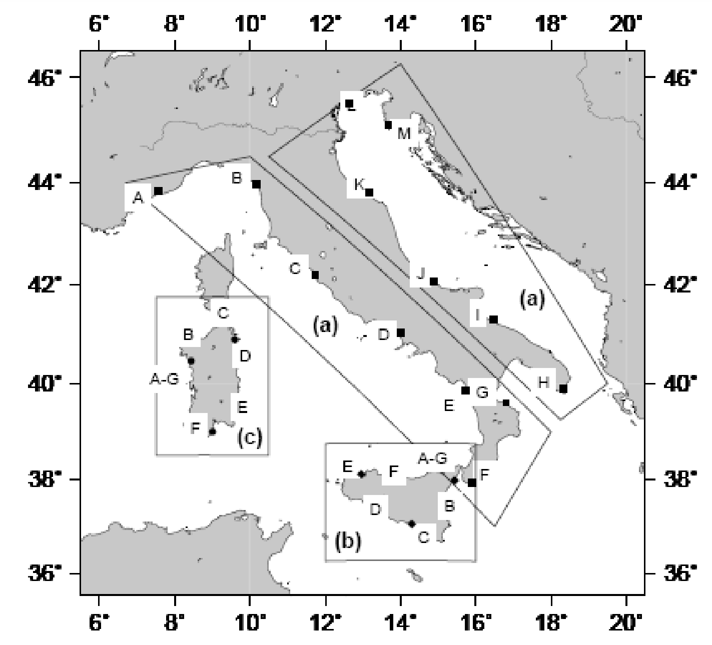


Vertical velocities predicted from the glacio-hydro-isostatic model (for two viscosity values of the mantle) versus vertical GPS velocities computed at selected stations across a N-S section from ZIMM (Germany) to NOT1 (Siciliy). Model ICE5G (GPS data from Serpelloni et al., 2006 Annals of Geophysics and model from Spada and Stocchi, 2007)

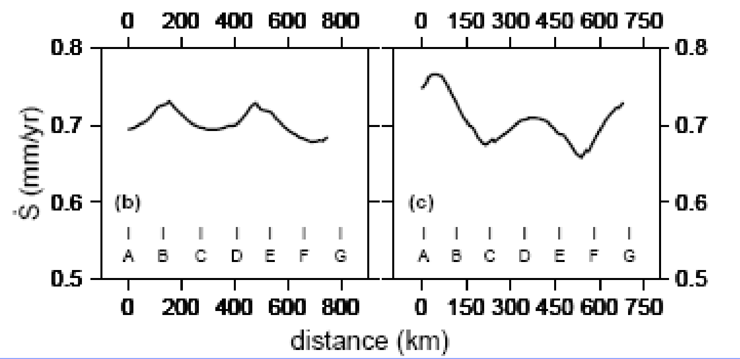


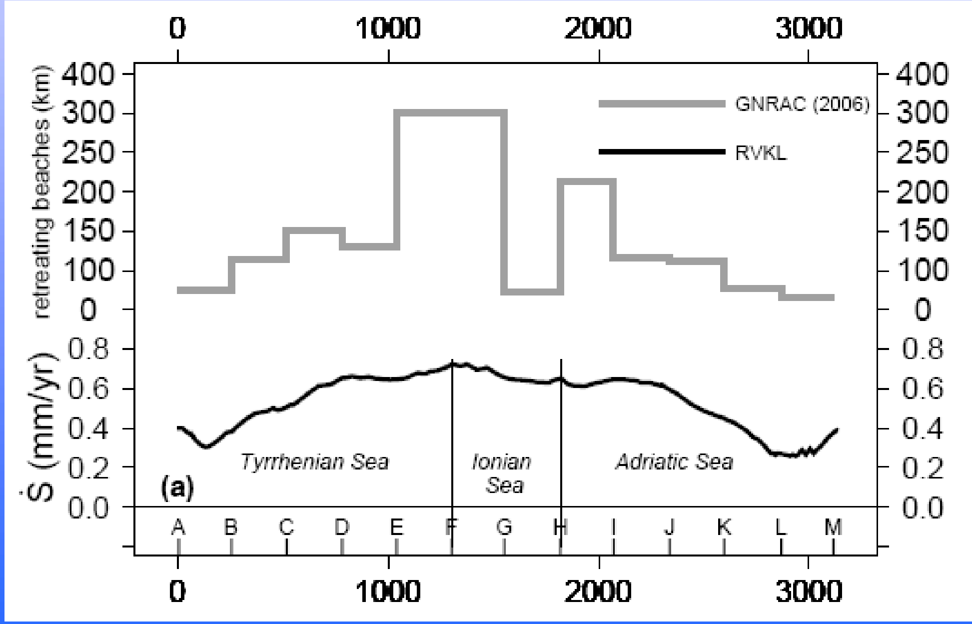
Slc rates from tide gauges versus GPS vertical velocities. Model ICE5G (GPS data from Serpelloni et al., 2006 Annals of Geophysics and model from Spada and Stocchi, 2007)

Work in progress



Predicted ˙S for ICE5G(RVKL) and estimated length of retreating beaches according to GNRAC (2006), relative to the Italian peninsula (a), Sicily (b), and Sardinia (c).





CONCLUSIONS

- The rslc since ~2ka along the coastlines of the Mediterranean region displays different values at different locations. It is dominated by the effect of the GIA as well as by tectonics (i.e. uplift at Briatico and Alicante; coseismic uplift. of 6.5 m at Phalasarna, Crete) and volcanism (i.e. Aeolian islands and Baia).

- coastal archaeological allow the estimation of level change rates since since ~3.5 ka due to ii) vertical isostatic movements of the Earth's crust, iii) local vertical movements due to tectonics and volcanism. Rates mm yr^{-1} of 0.8 for Sardinia, 1.1 for northern Adriatic (but with tectonics of 0.8 mm yr^{-1}) 0.7 for Tyrrhenian sea, 0.7 at Alicante, 2.2 in SW Turkey 0.25 in North Africa,

- timing of the 2ka sea level rise. Instrumental rate cannot be extrapolated far back in time to roman age, being it is not consistent with the elevation of the archaeogeodetic benchmarks. It started 100±53 years BP. Calibration of slc models

- Current GPS vertical velocities in Italy, w.r.t. stable Sardinia records a general subsidence due to GIA which modulates the long–wavelength pattern of vertical deformation along the coasts of Italy, but still cannot explain GPS observations across the Apennines Description of the glacio-hydro-isostatic model in this active tectonic area, requires constraints based on RSL, geomorphological, archaeological, tide guges and GPS data.

THE END