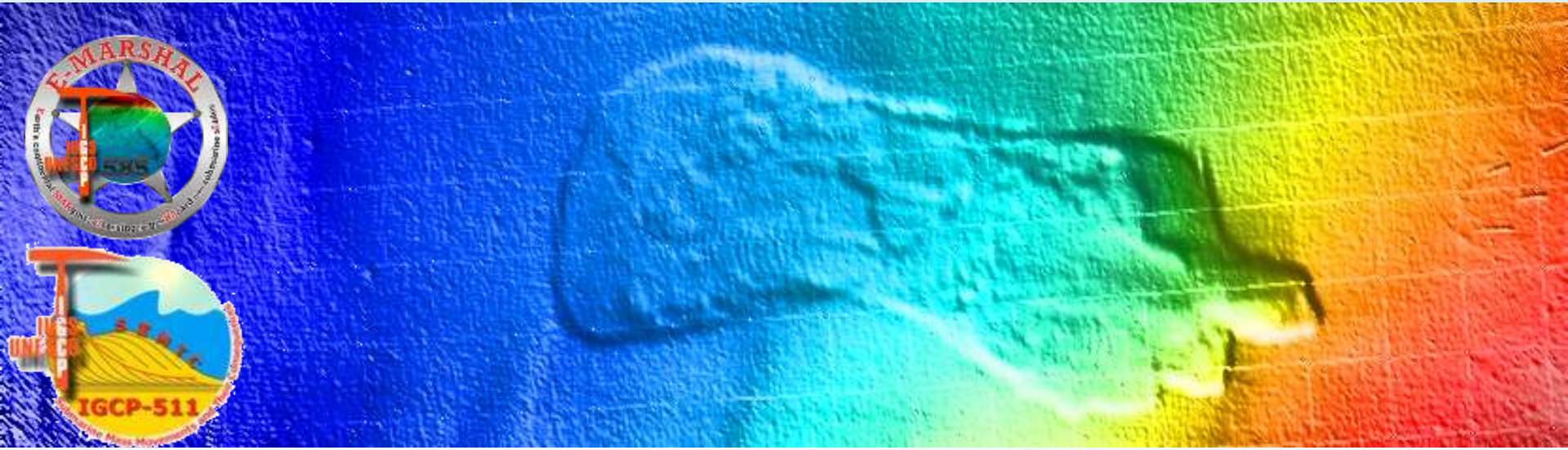
Controls, timing, and characteristics of submarine landslides in the Mediterranean area



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CSIC
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UNIVERSITAT DE BARCELONA

icrea
Institució Catalana de Recerca i Estudis Avançats

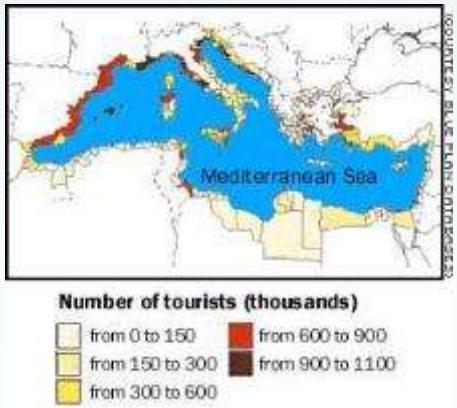
PRESENTATION STRUCTURE

- ✓ The Mediterranean Sea: a geohazard perspective
- ✓ Submarine landslides in the Mediterranean Sea
  - ✓ Areal distribution and controls on offshore failure development
    - ✓ Tectonics
    - ✓ Seismicity
    - ✓ Fluid seepage
    - ✓ Basement structure
  - ✓ Dynamic indicators: displacement and typology
  - ✓ Magnitude indicators: area, volume and scars
  - ✓ Timing of failures
  - ✓ Tsunamigenic potential
- ✓ Conclusions
- ✓ Open questions

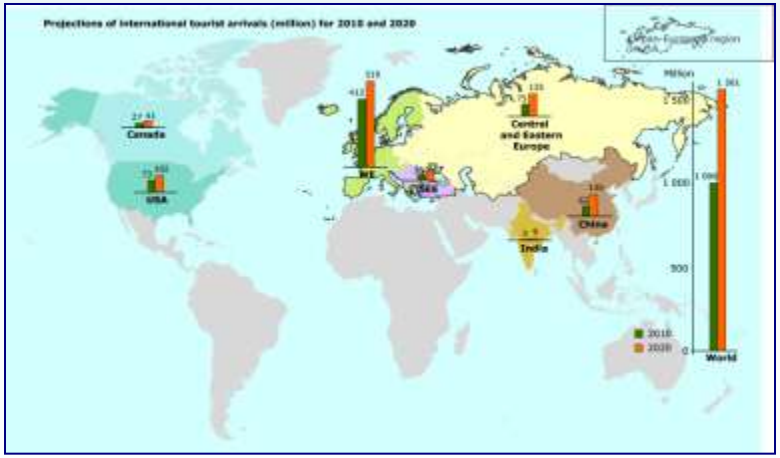
WHY THE MEDITERRANEAN SEA

- ✓ Very densely-populated coastline: 160 million inhabitants sharing 46,000 km of coastline (**3.5 inhabitants per m of coastline**).

- ✓ **World's leading holiday destination**, receiving up 30% of global tourism and an average of 135 million visitors annually; this is predicted to increase to 235-350 million tourists by year 2025 (European Environmental Agency - EEA).



"By 2025, the annual crowd will soar to anywhere from 235 to 350 million tourists, according to the EEA."



Mediterranean tourism takes its toll. By Environmental News Network (ENN) March 14, 2000; http://archives.cnn.com/2000/NATURE/03/14/mediterranean.enn/index.html

EEA web site http://www.eea.europa.eu
Copyright EEA, Copenhagen.

WHY THE MEDITERRANEAN SEA

Very high density of seafloor structures / increasing use of the seafloor:

- ✓ Infrastructures (oil, windmills, telecommunications, pipelines, ...)
- ✓ Exploitation of mineral and energy resources
- ✓ Waste disposal

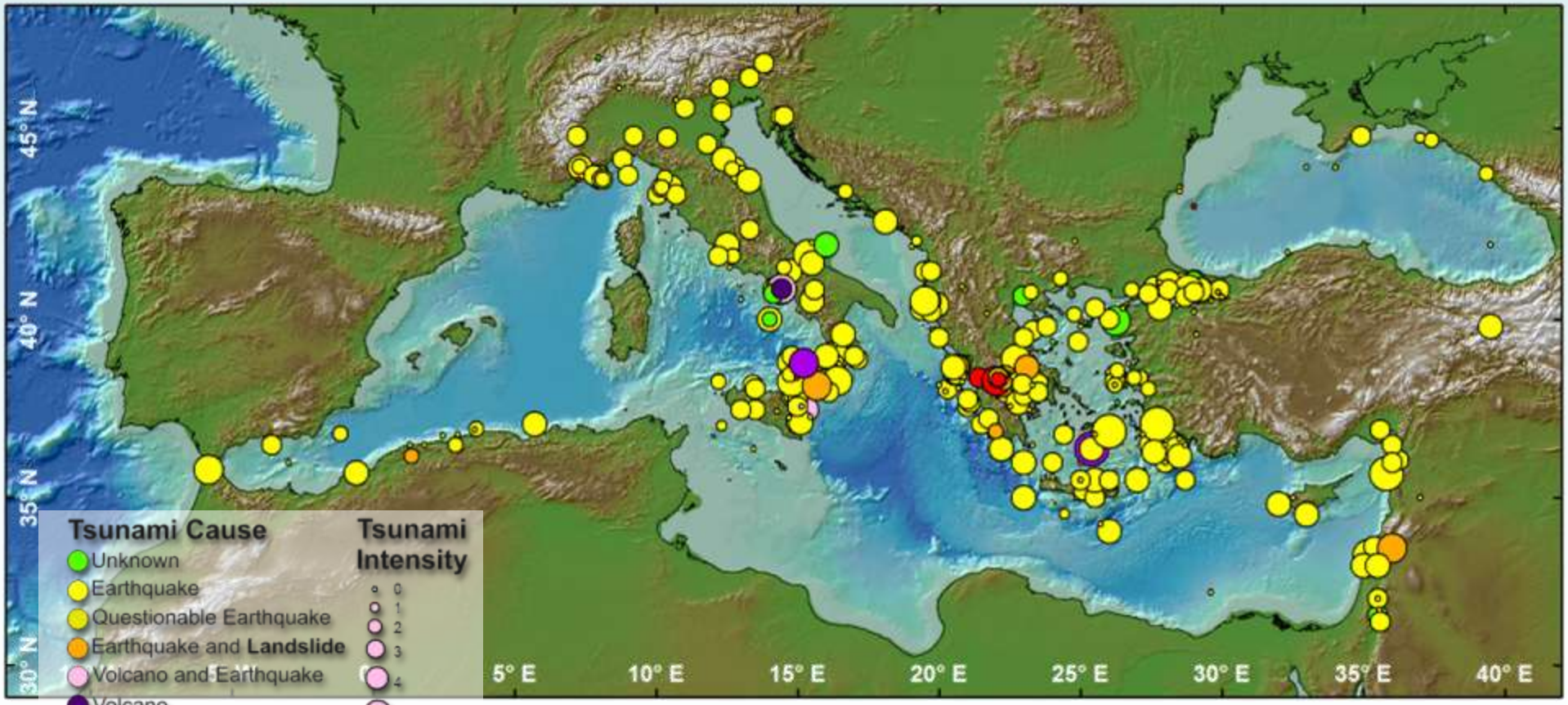
Casablanca Platform, off Spain

A study on behalf of the Submarine Cable Improvement Group shows 25% of all faults are caused by **natural hazards such submarine earthquakes, density currents and extreme weather.**

Mediterranean Fibre Cable Cut - a RIPE NCC Analysis http://www.ripe.net/
Analysis by the RIPE NCC Science Group with contributions from Roma Tre University. Editors: Rene Wilhelm, Chris Buckridge

WHY THE MEDITERRANEAN SEA

- Rich record of historical tsunamis

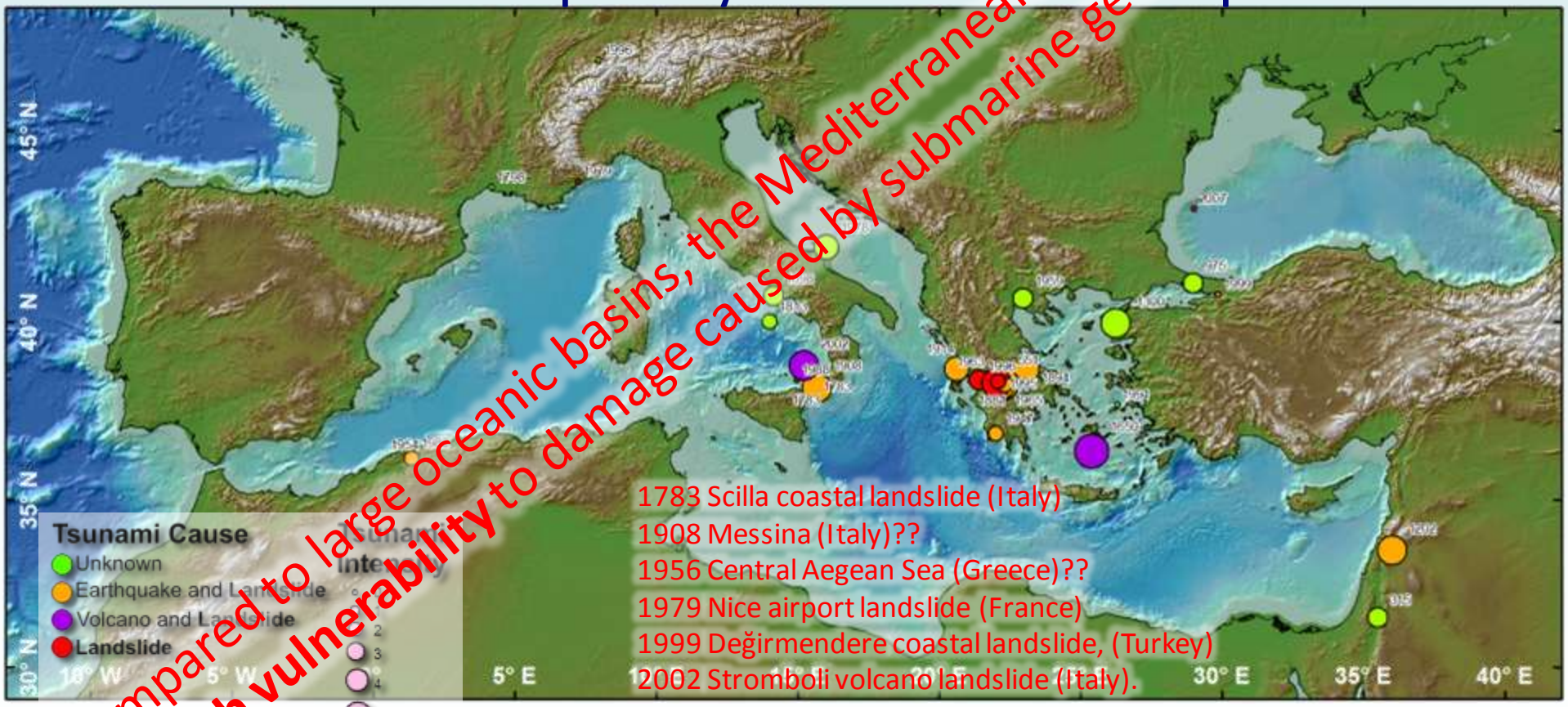


National Geophysical Data Center / World Data Center (NGDC/WDC) **Historical Tsunami Database**, Boulder, CO, USA. (Available at http://www.ngdc.noaa.gov/hazard/tsu_db.shtml)

WHY THE MEDITERRANEAN SEA

- Some tsunamis related to submarine landslides (up to 15%)
- Small dimensions → **close proximity of tsunami sources and impact areas.**

Compared to large oceanic basins, the Mediterranean Sea has a very **high vulnerability** to damage caused by submarine geohazards

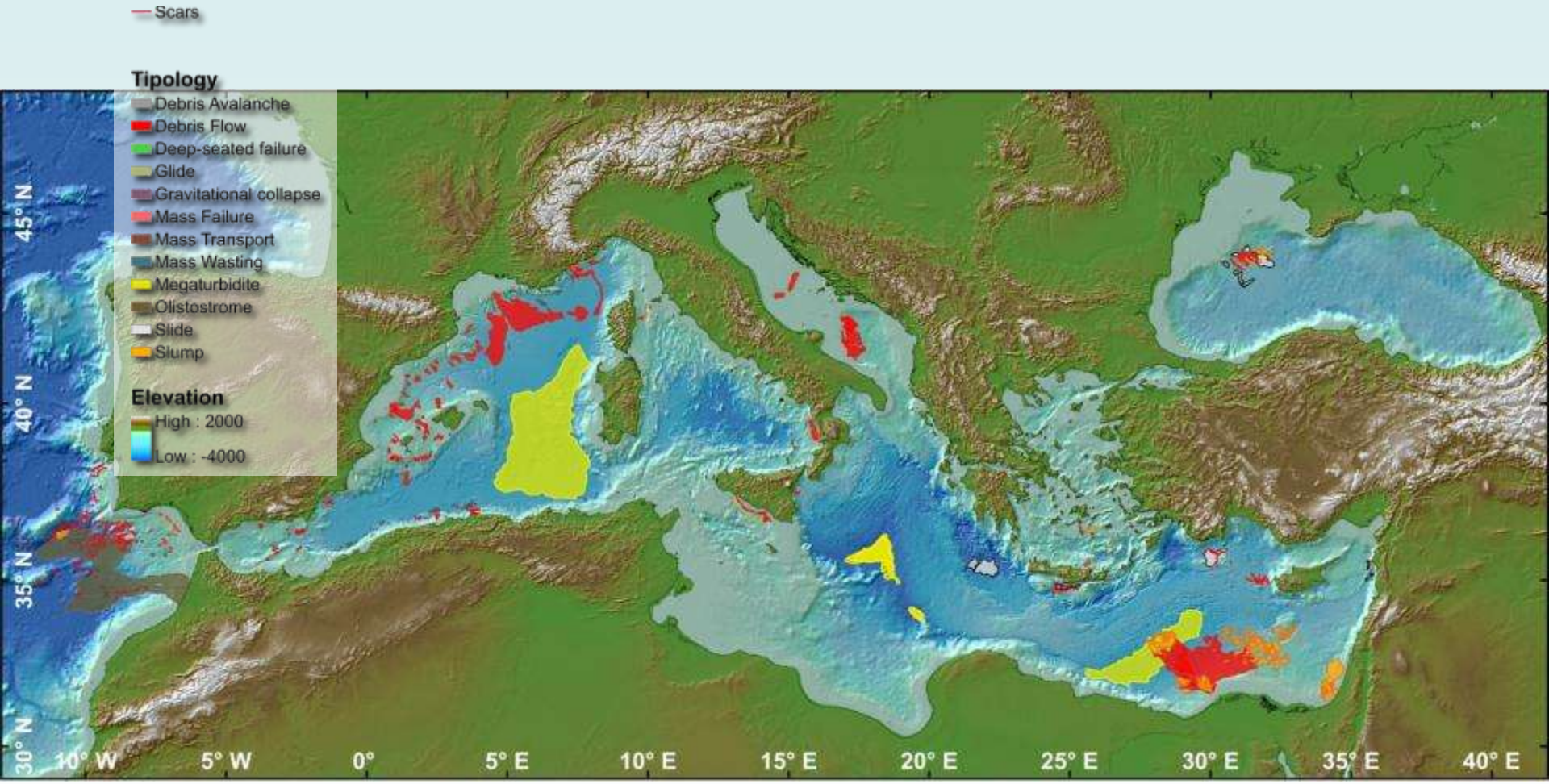


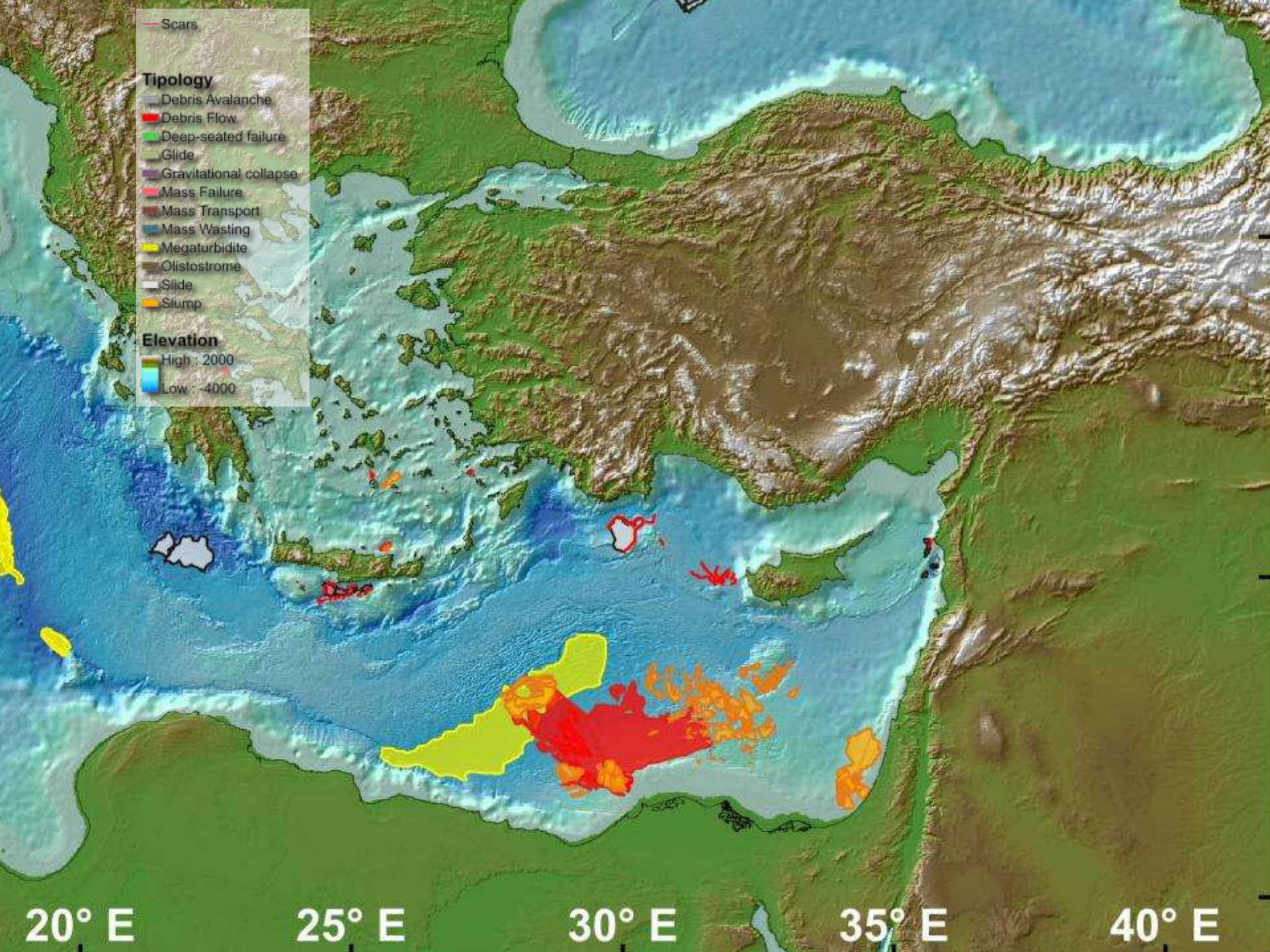
National Geophysical Data Center / World Data Center (NGDC/WDC) **Historical Tsunami Database**, Boulder, CO, USA. (Available at http://www.ngdc.noaa.gov/hazard/tsu_db.shtml)

AIMS

- ✓ Understand the magnitude, frequency and controls on submarine slope failure at the scale of a large marine basin
- ✓ Better characterize the potential for extreme geohazards in the Mediterranean

Submarine landslides in the Mediterranean Sea

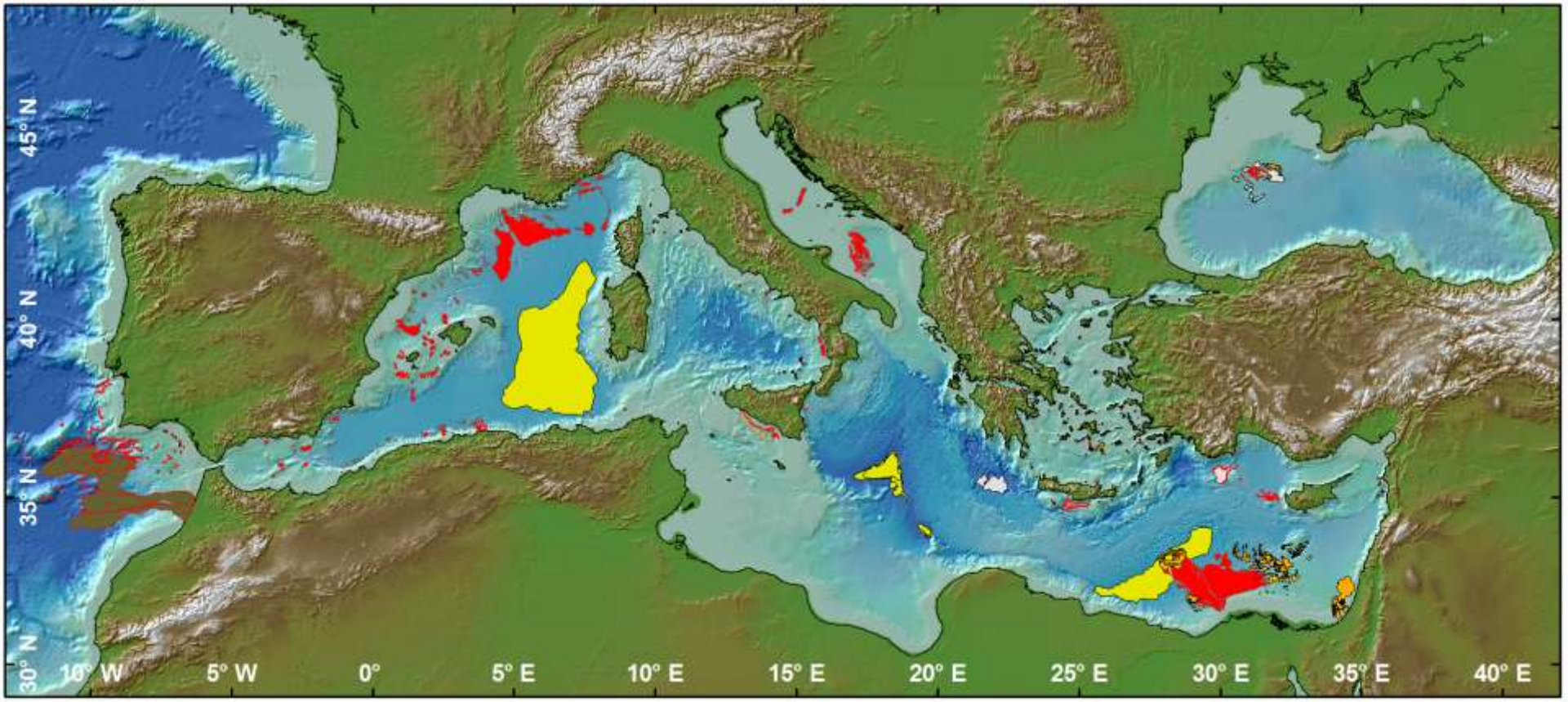



Scars
Tipology
Debris Avalanche
Debris Flow
Deep-seated failure
Glide
Gravitational collapse
Mass Failure
Mass Transport
Mass Wasting
Megaturbidite
Olistostrome
Slide
Slump
Elevation
High : 2000
Low : -4000
20° E
25° E
30° E
35° E
40° E

Areal distribution

Submarine landslides occur in very different geological settings of the Mediterranean continental margins often at depths > 1000m on slopes of < 2º

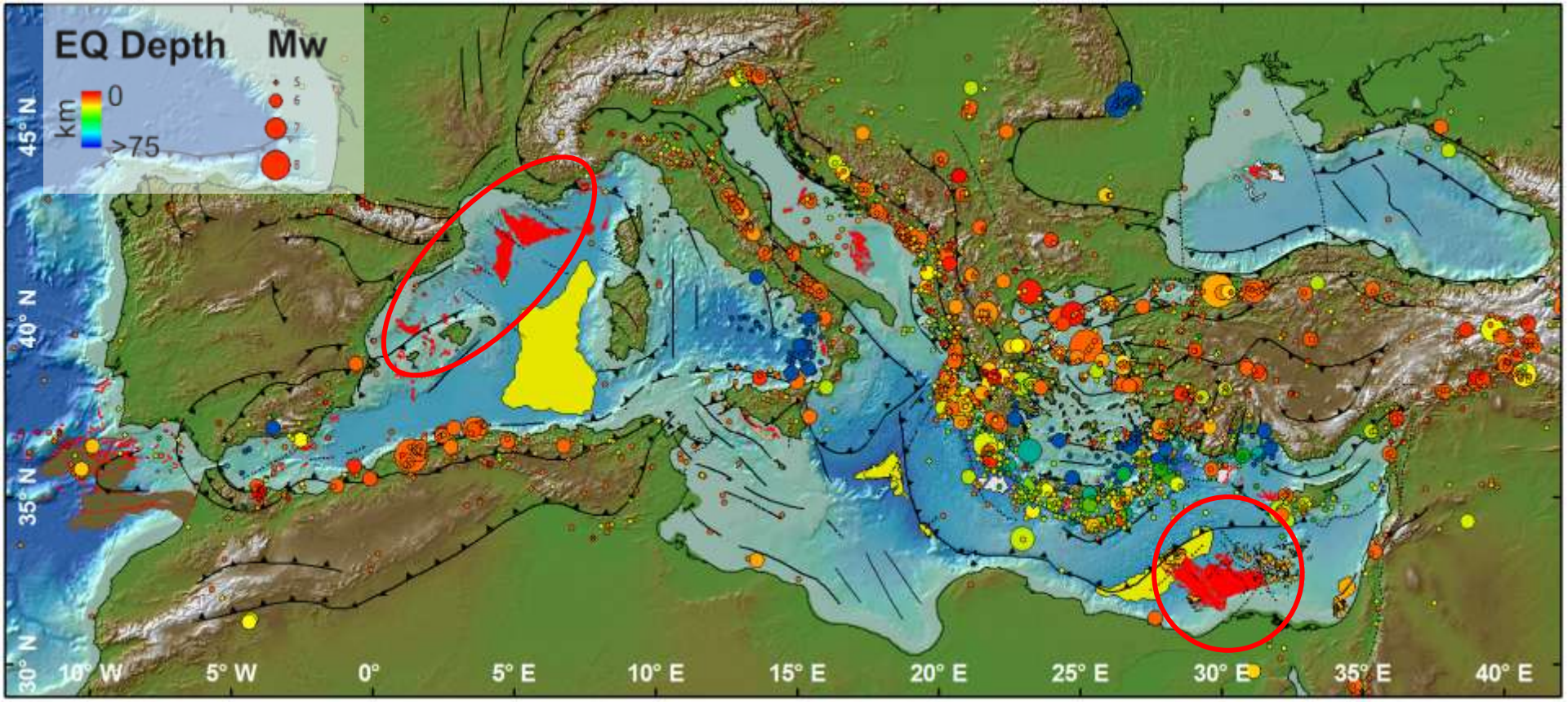
Noticeable correlation between known failure events and available high/resolution geophysical data.



The catalogue of submarine slope failures is still largely uncomplete (specially for the North-African margin).

Relation to the geological structure

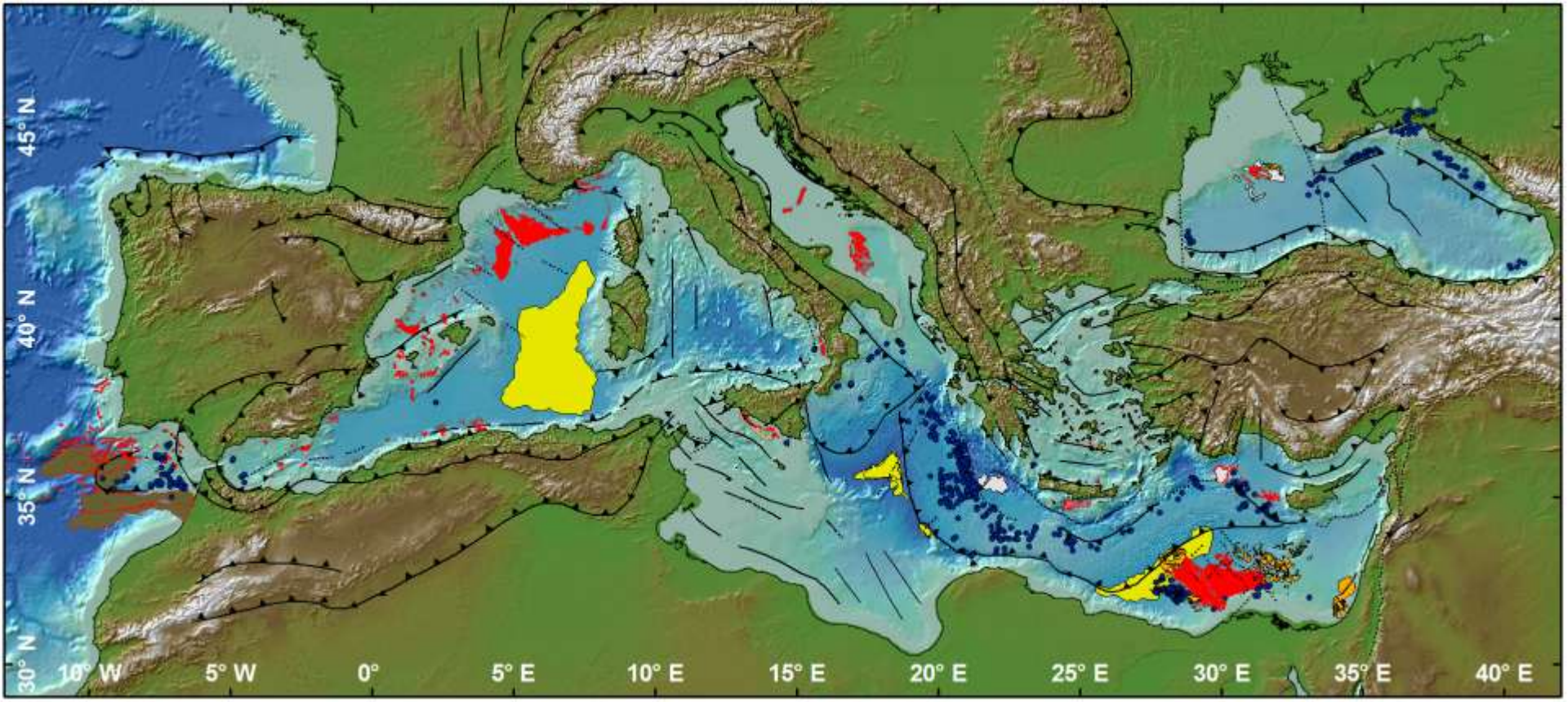
- ✓ Two clusters of know major submarine landslides → aseismic margins (Ebro, Rhone, Nile).
- ✓ The most tectonically active area (The Hellenic Arc) has a relatively low density of known events.
- ✓ The deformation fronts of the Mediterranean and Calabrian ridges host few submarine landslides.



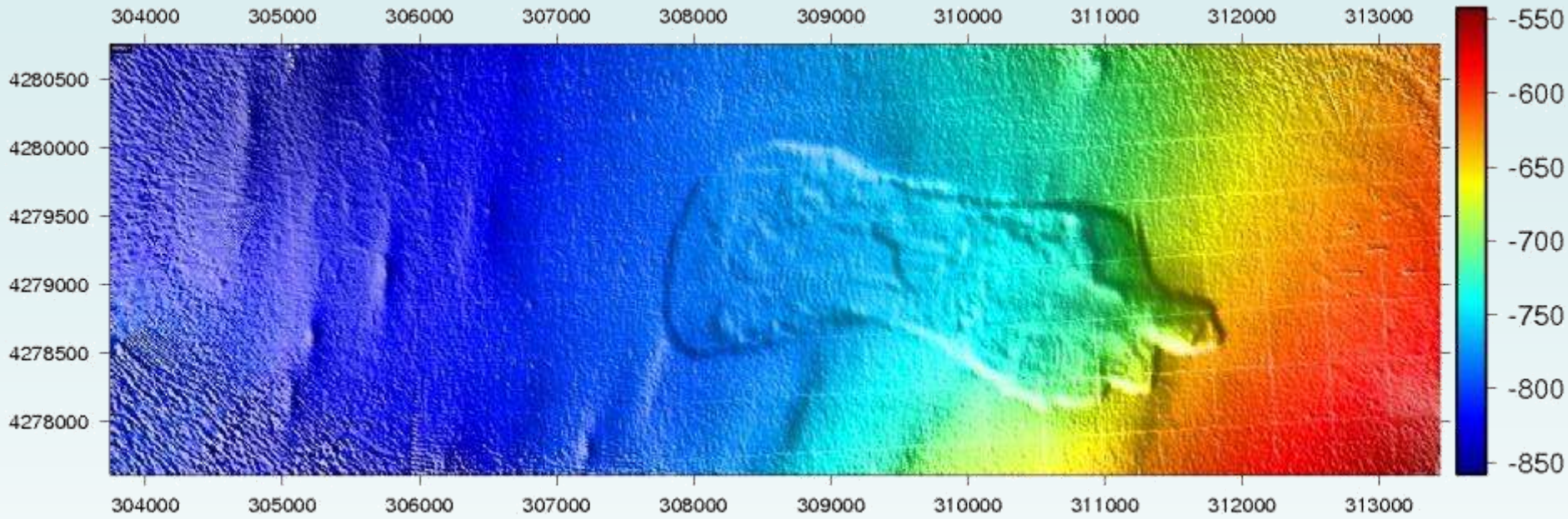
Earthquakes 1973-2011 USGS/NEIC (PDE) catalog

Relation to the margin hydrogeology

- ✓ Active fluid seepage structures often related to tectonics
- ✓ Large landslides occur in areas of active fluid seeping and Messinian salt tectonics.

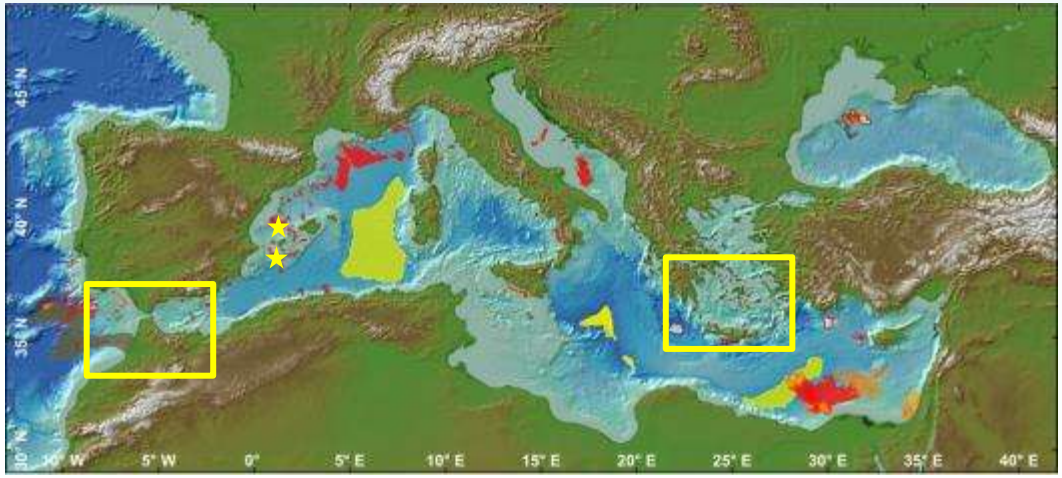


Relation to the margin hydrogeology

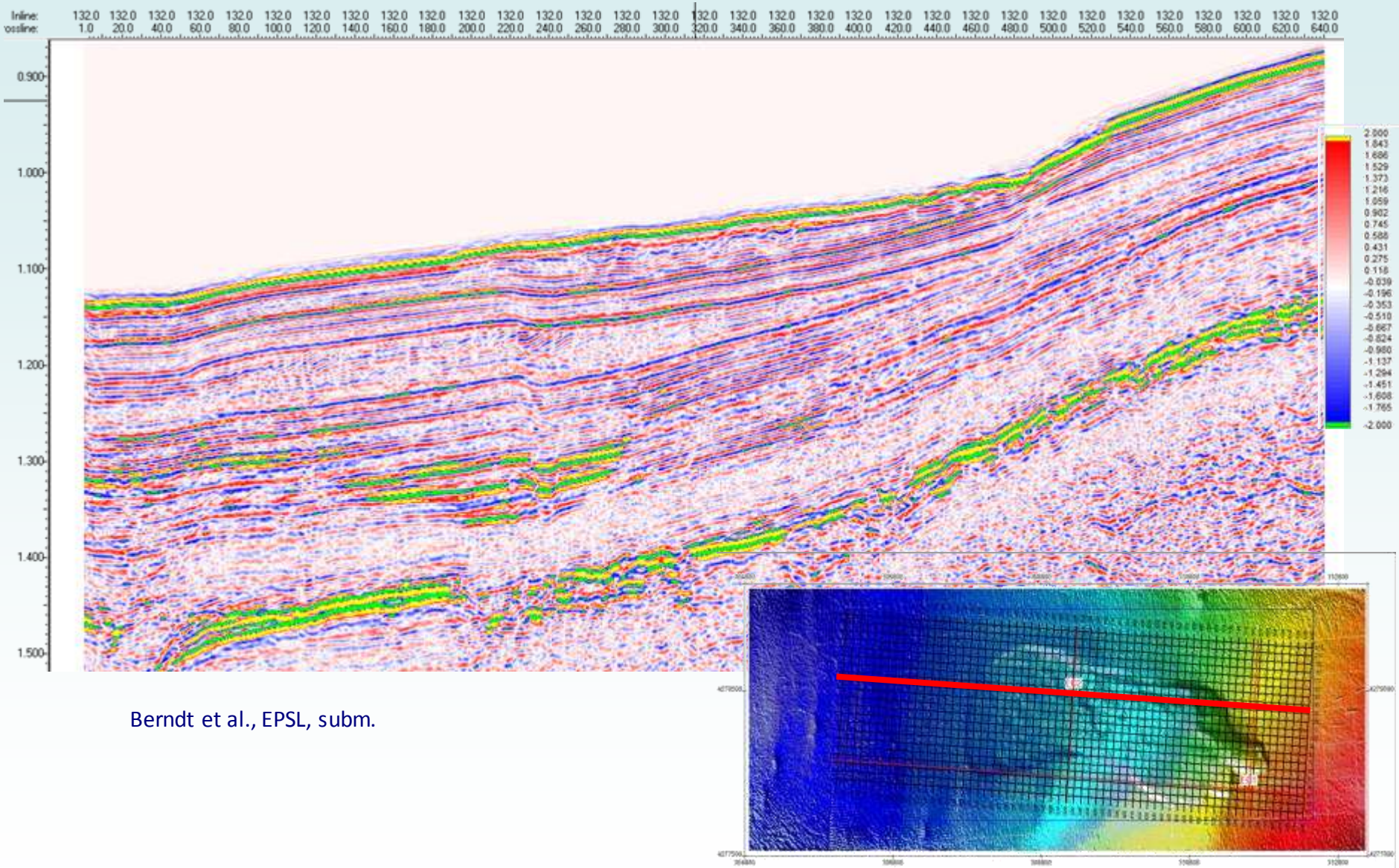


Ana slide (0.14 km^3 → 3.5 x 1.5 km), Holocene

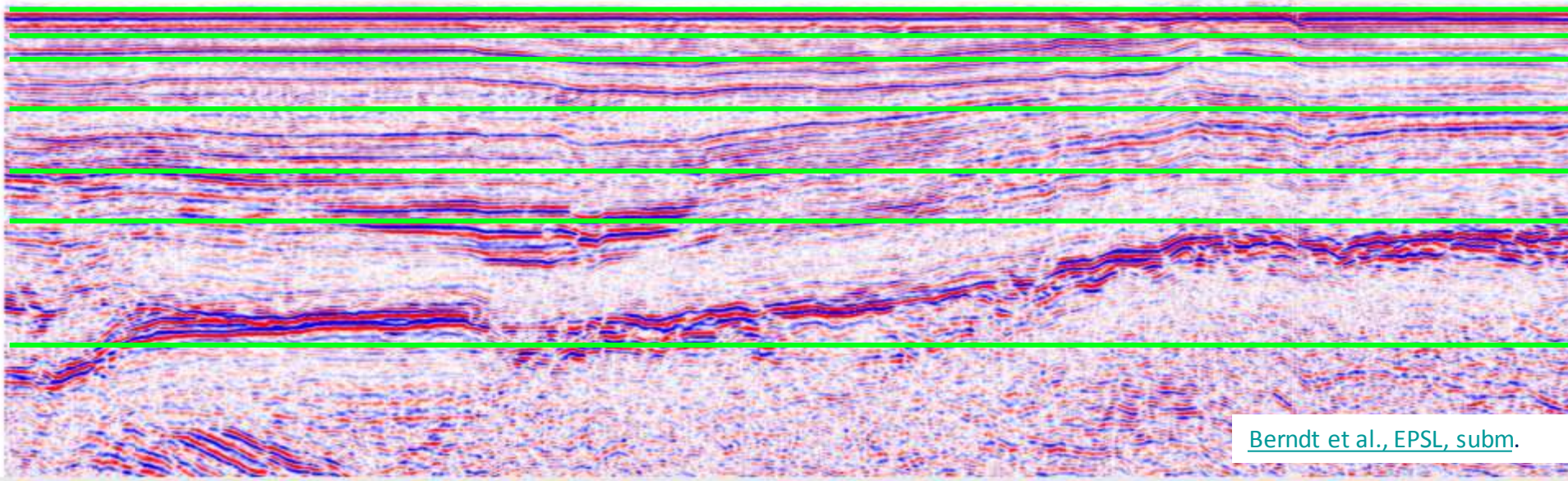
Importance of fluid flow systems and overpressure generation
→ common observation



Relation to the margin hydrogeology

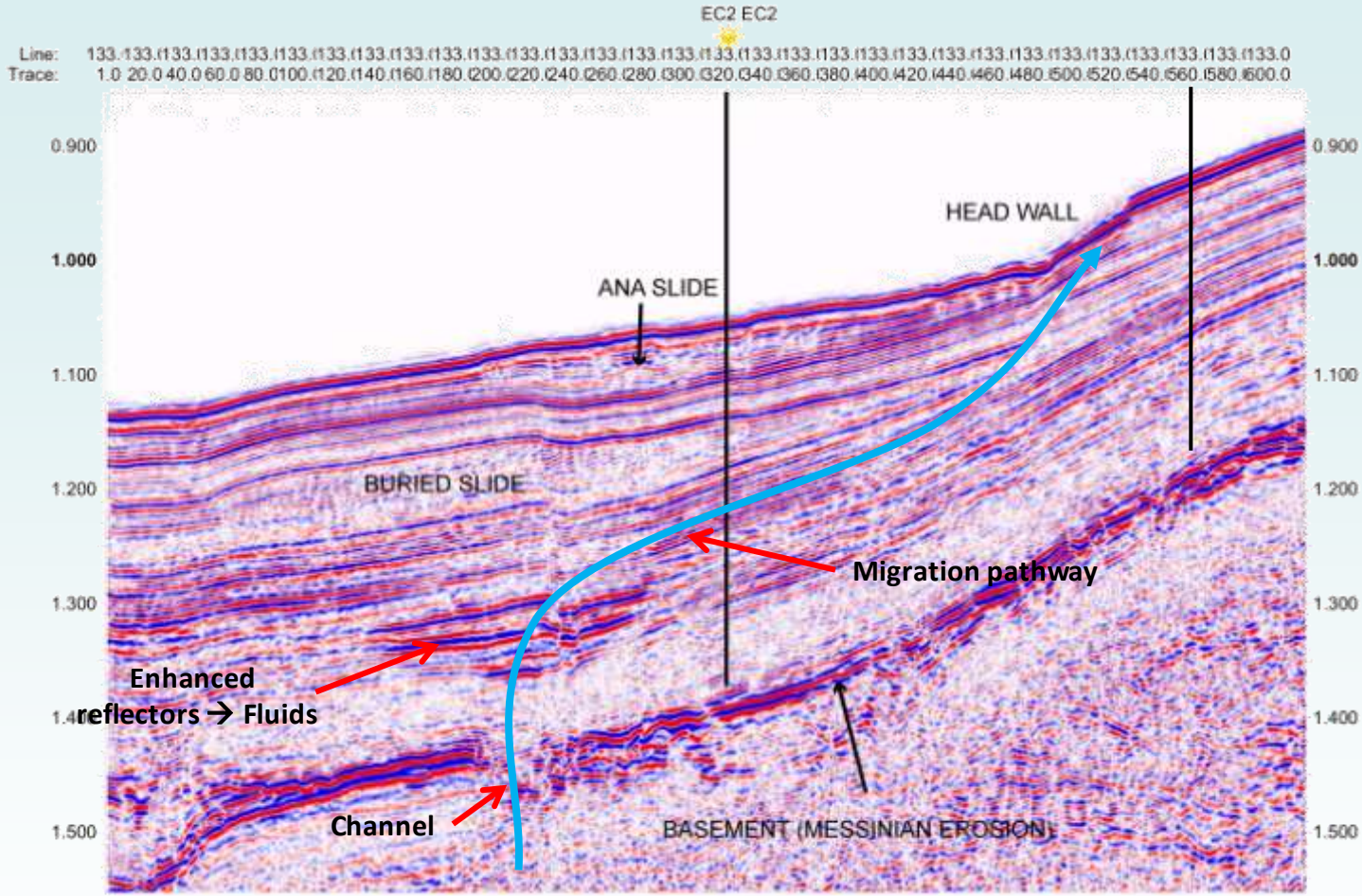


Berndt et al., EPSL, subm.


Berndt et al., EPSL, subm.


305900
310900
305900
310900

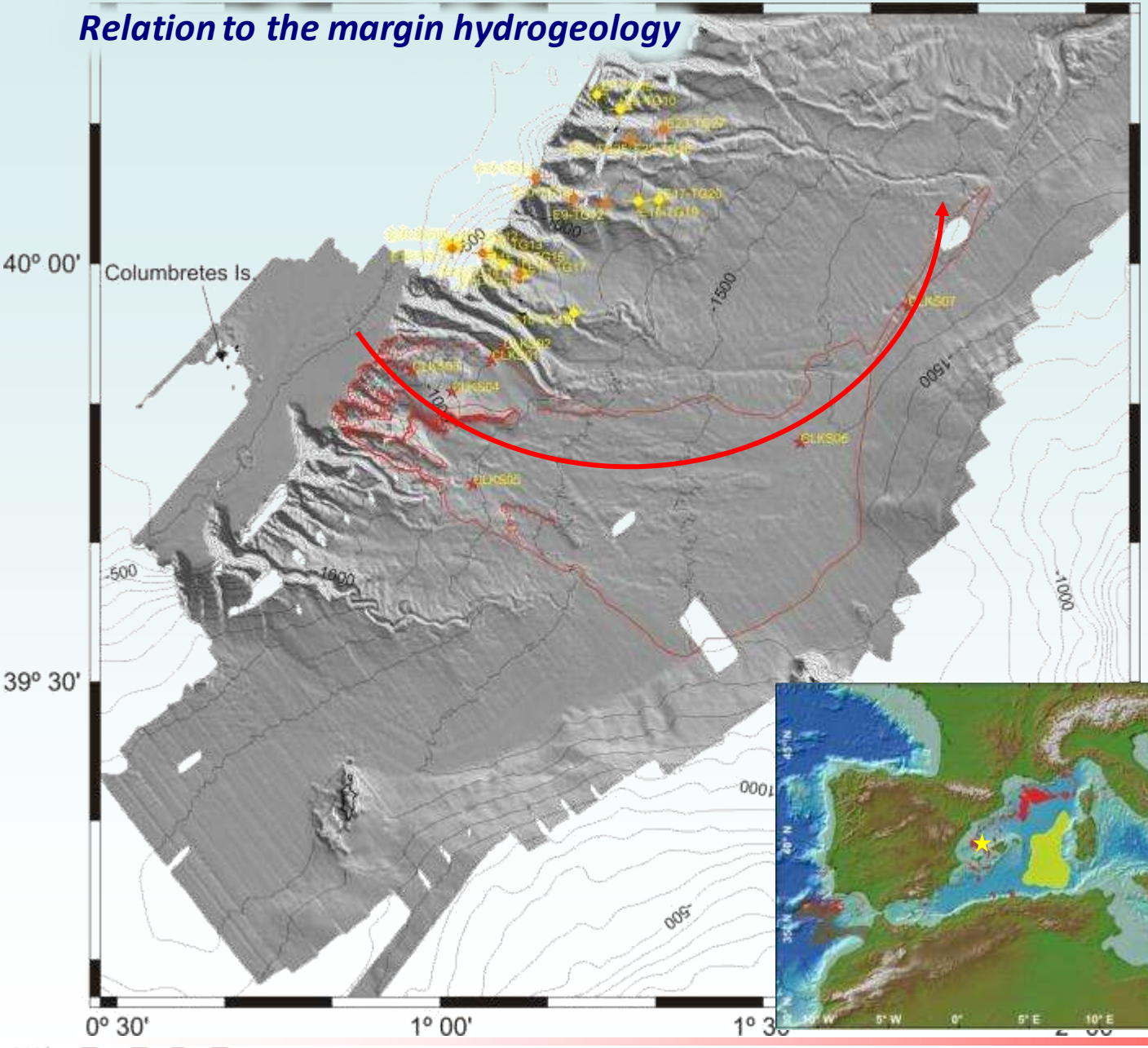
Relation to the margin hydrogeology



Berndt et al., EPSL, subm.

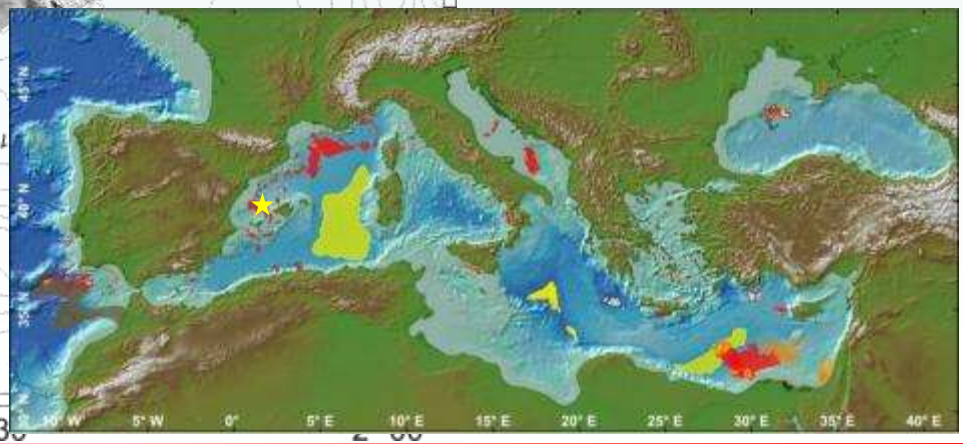
- ✓ Fluid escape through erosional features on MES
- ✓ Fluid pathway controlled by permeability layering and tectonics
- ✓ Overpressure develops at shallow depth due gas saturation ¿and reduction in total stress? (gas exsolution)

Relation to the margin hydrogeology

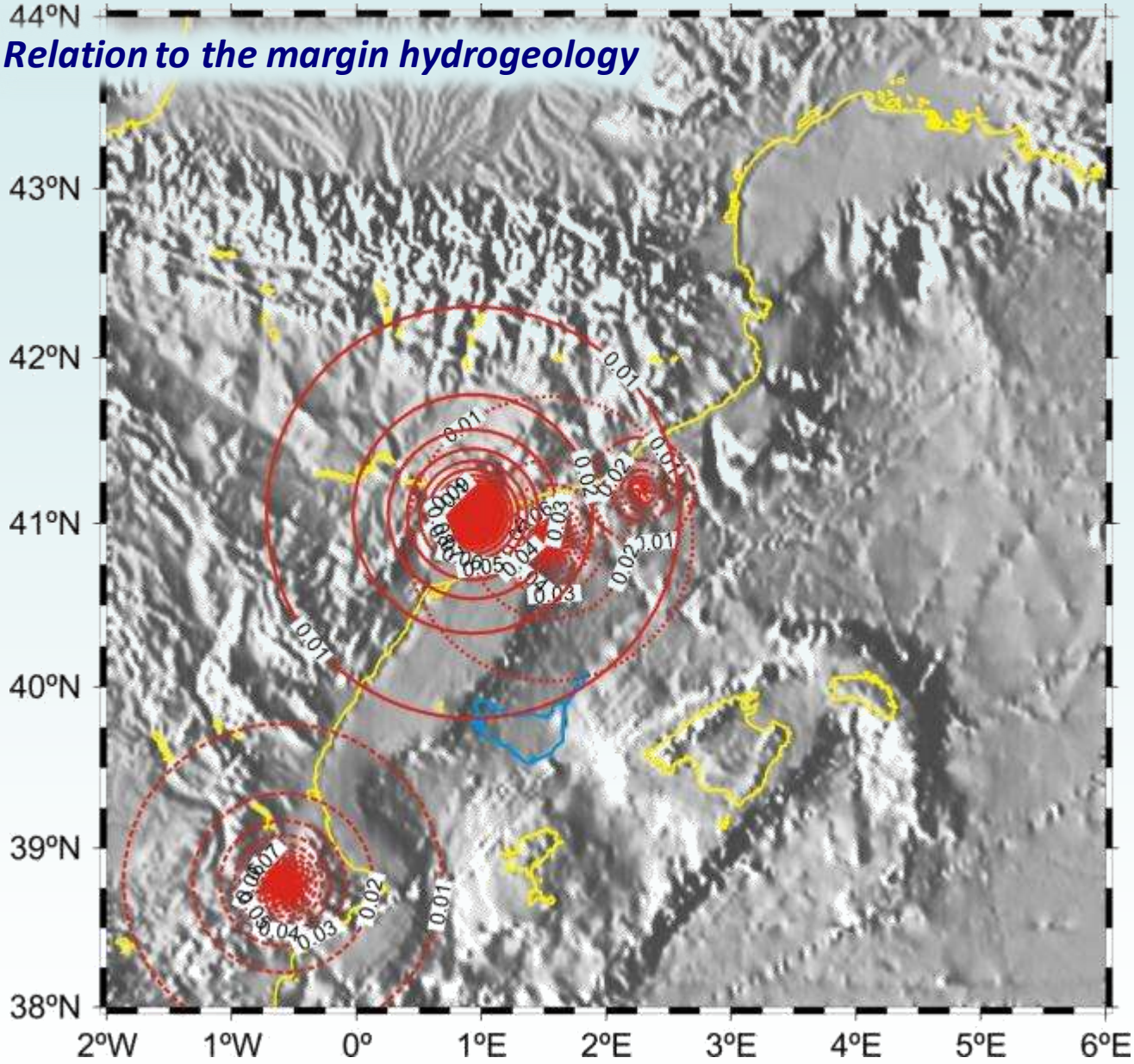


Swath bathymetry of the BIG'95 debris flow area with location of the landslide boundaries.

- ★ our study.
- ⌖ ⌖ Baraza et al. (1990).

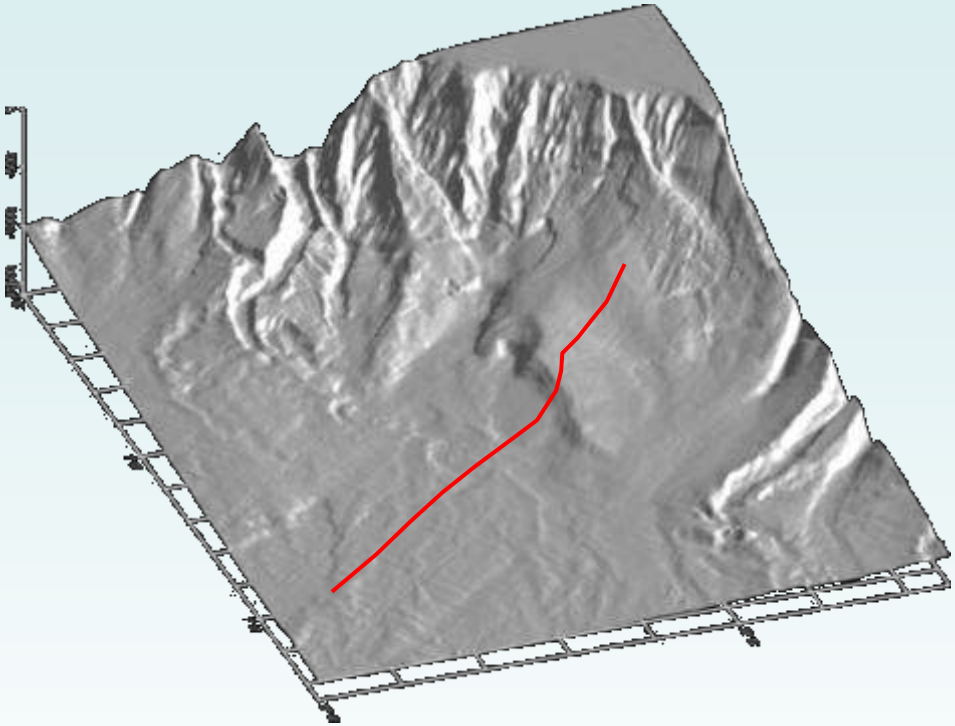


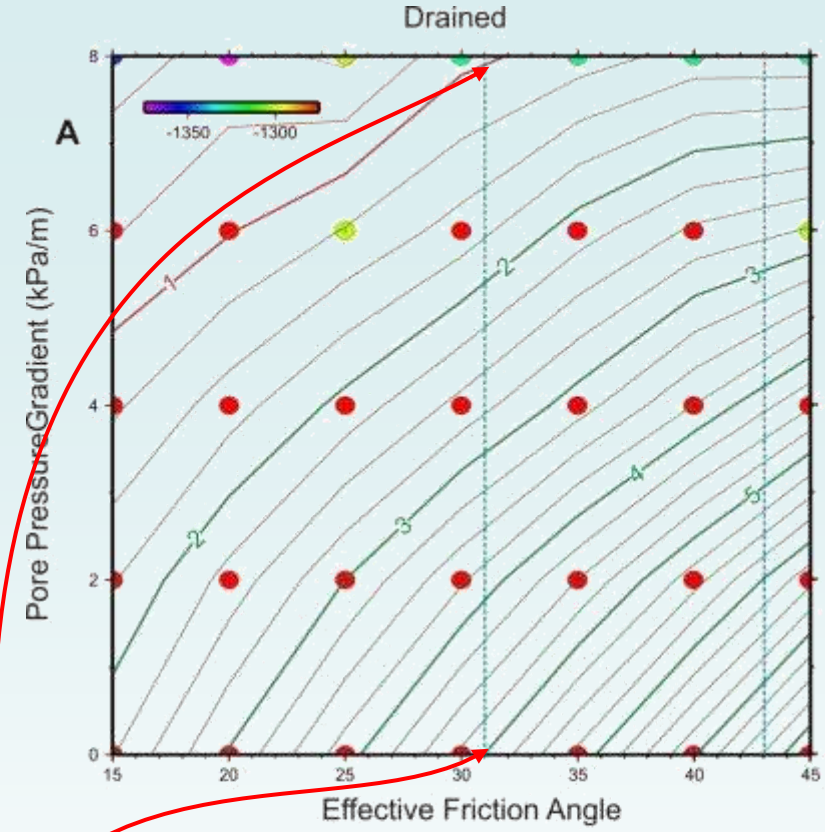
Relation to the margin hydrogeology

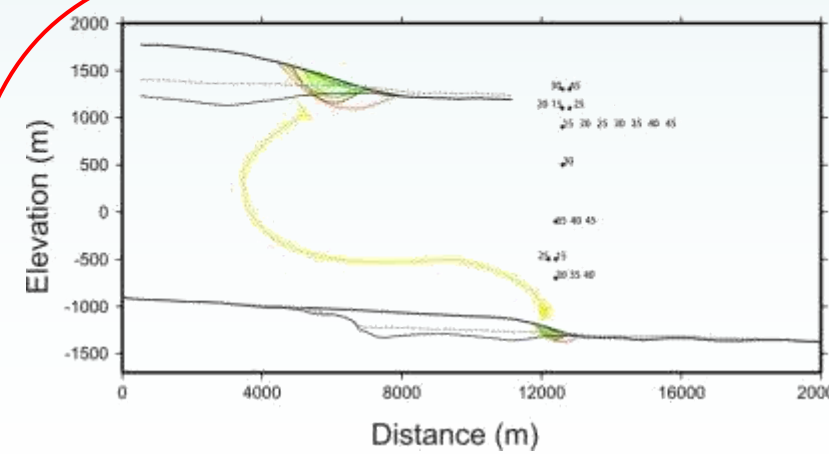


PGA according to published strong ground motion – attenuation relations

Relation to the margin hydrogeology

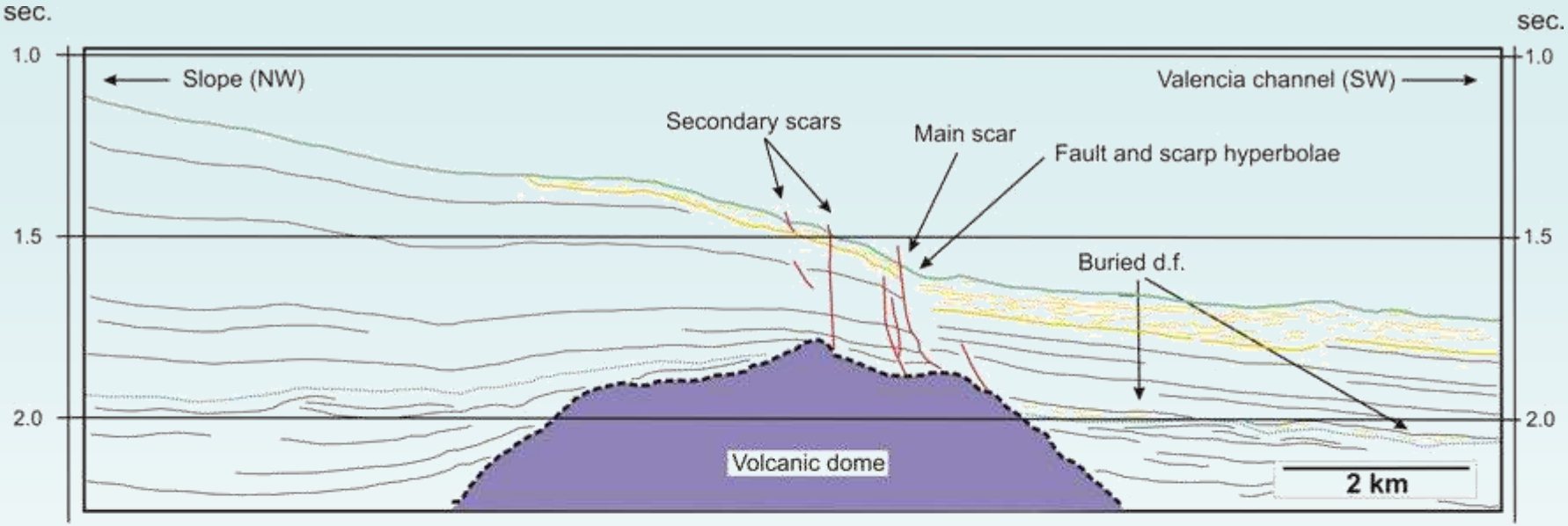


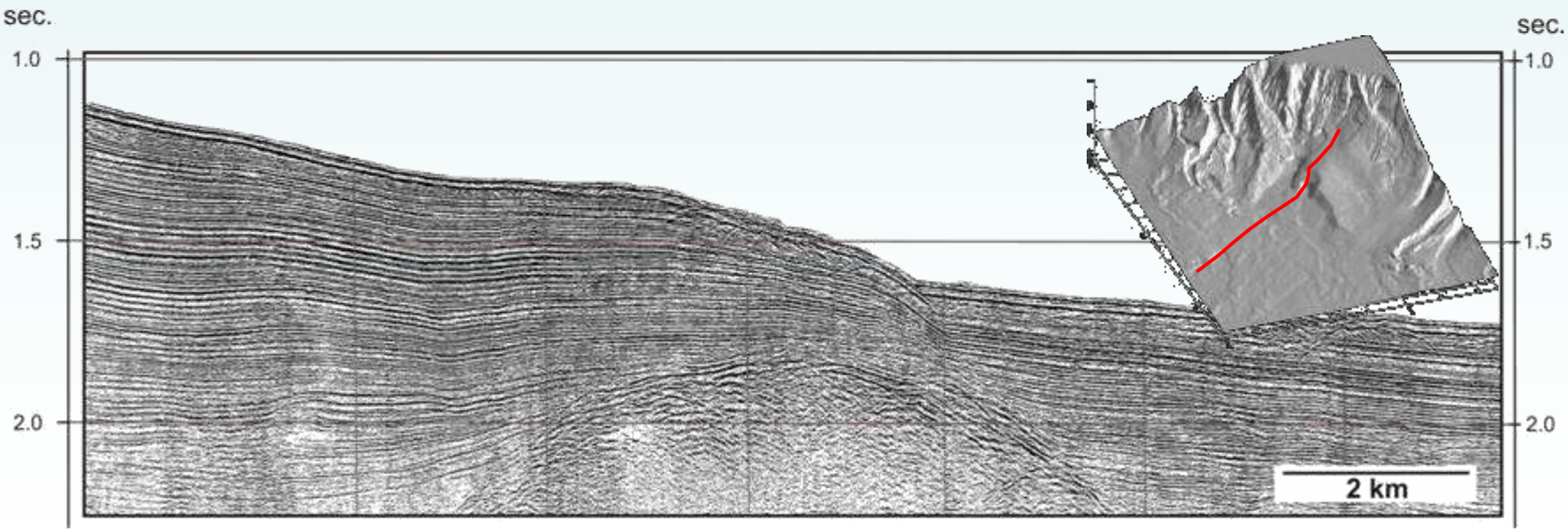




Drained back-analysis:
FS hydrostatic: 5.01
→ Pressure gradient: ~8 kPa/m (R_u=0.7)

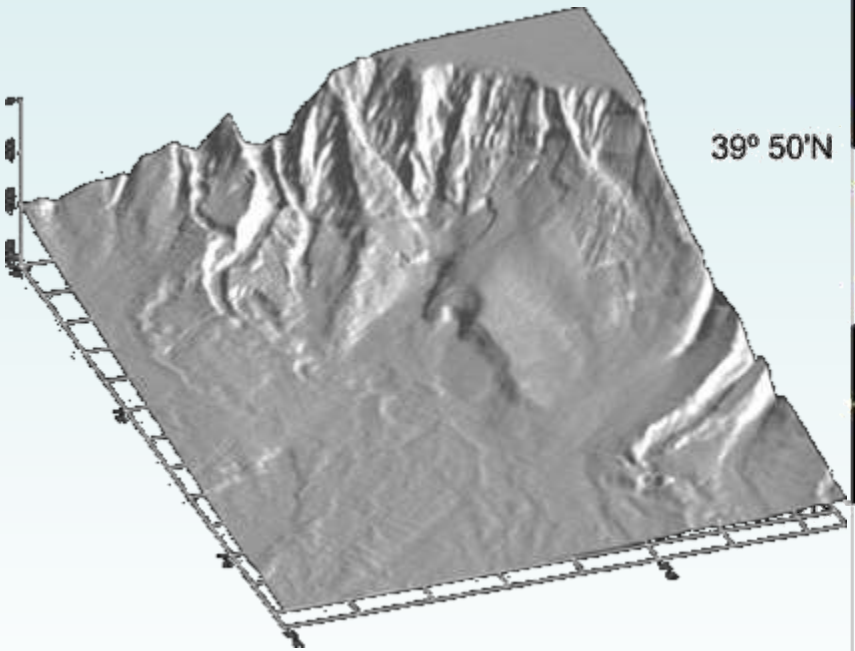
Relation to basement structure



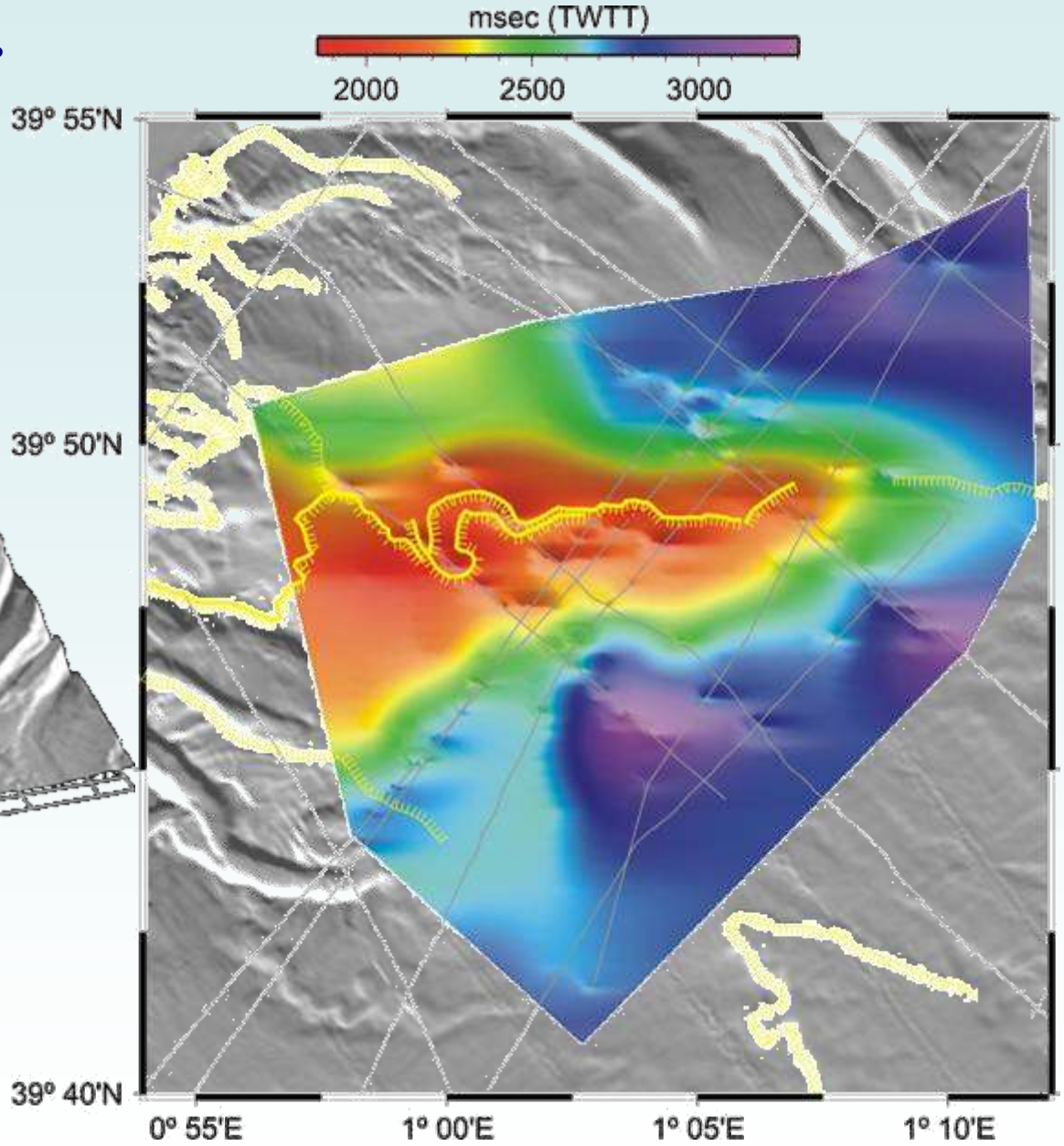


Relation to basement structure

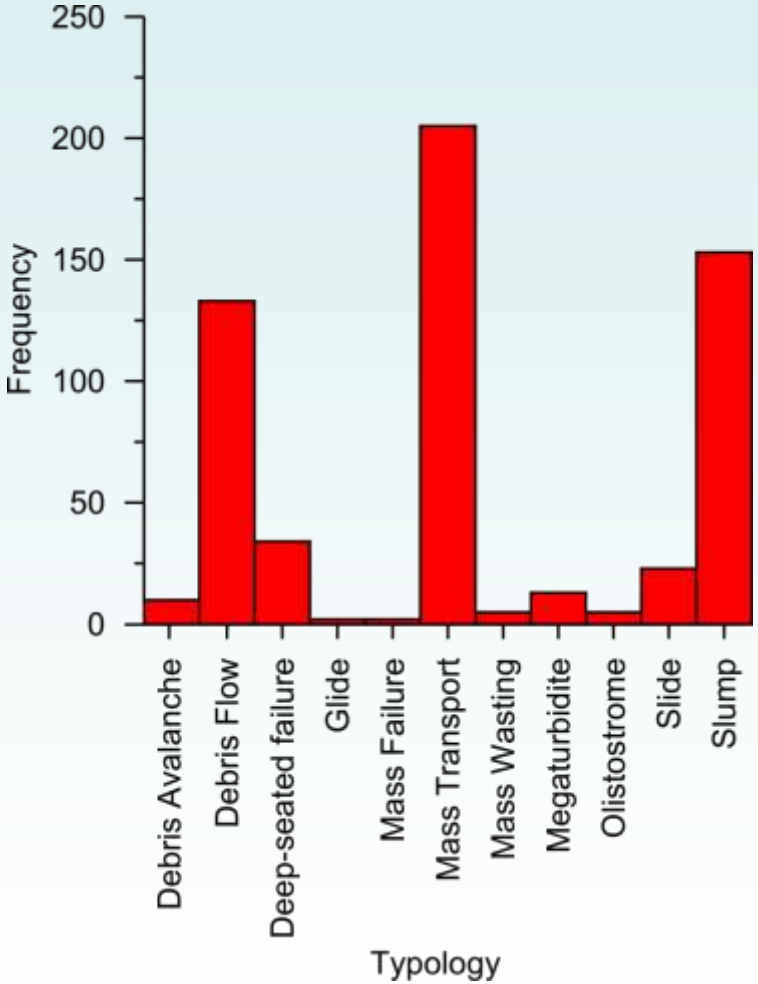
Structure map of the volcanic dome

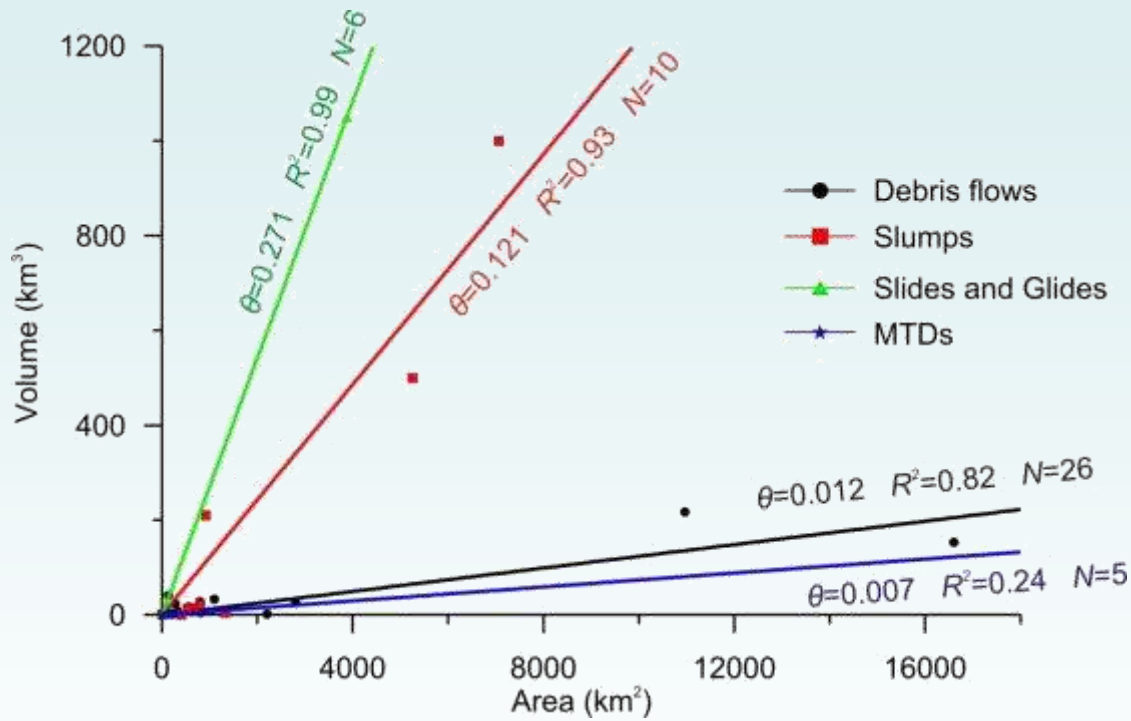


Seismic reflection profiles

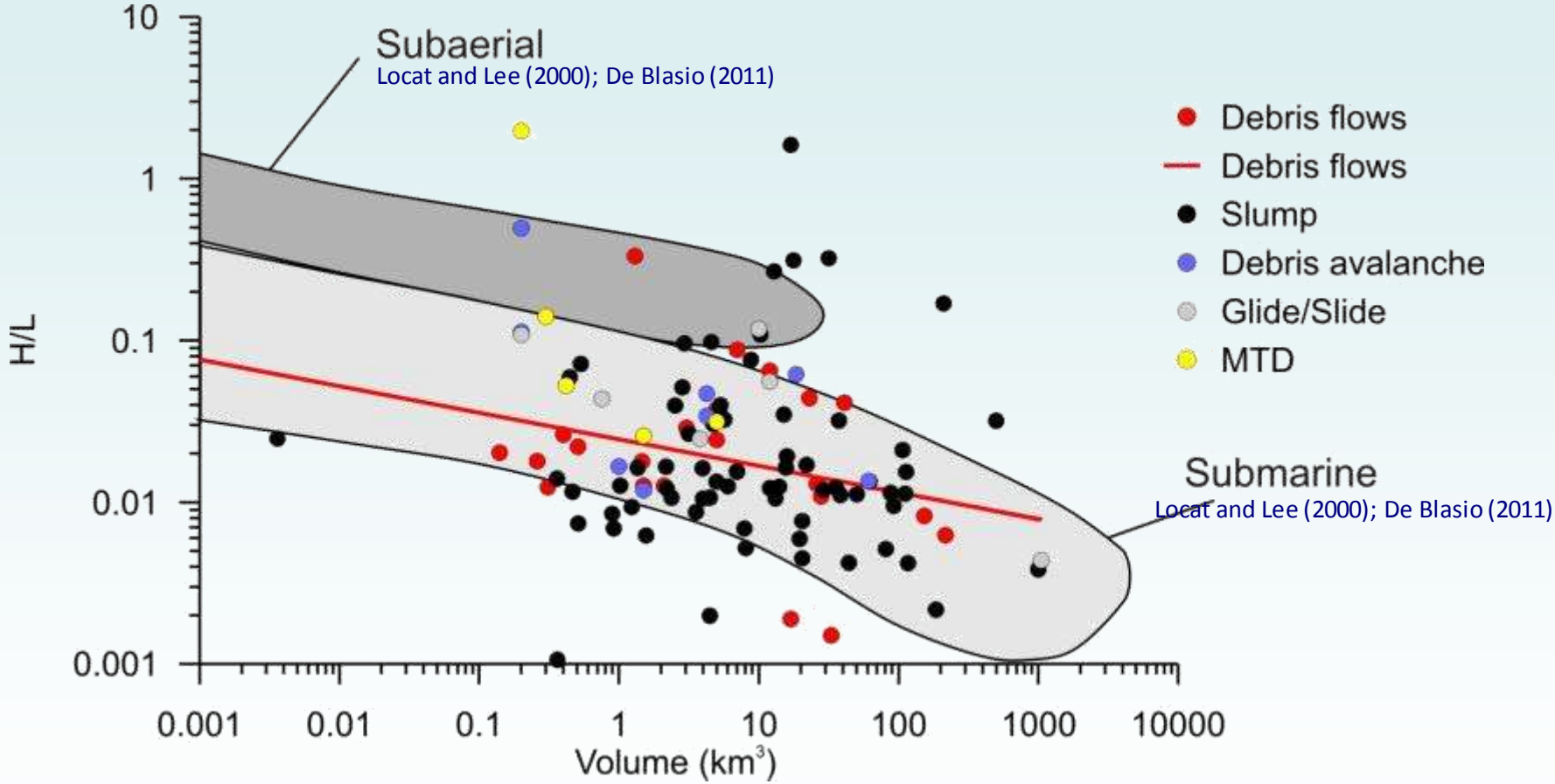


Dynamic charcteristics: typology





Dynamic charcteristics: typology

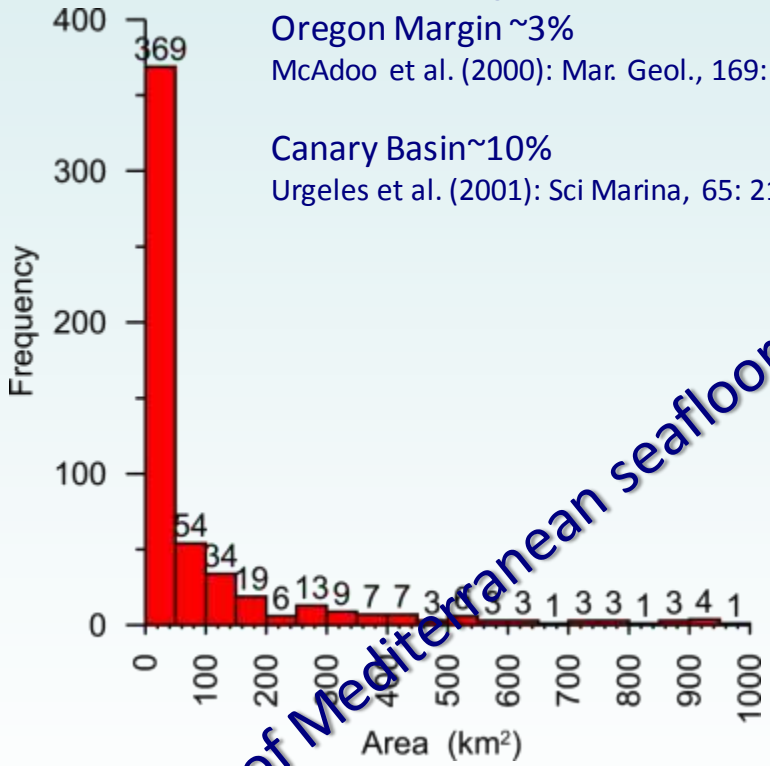


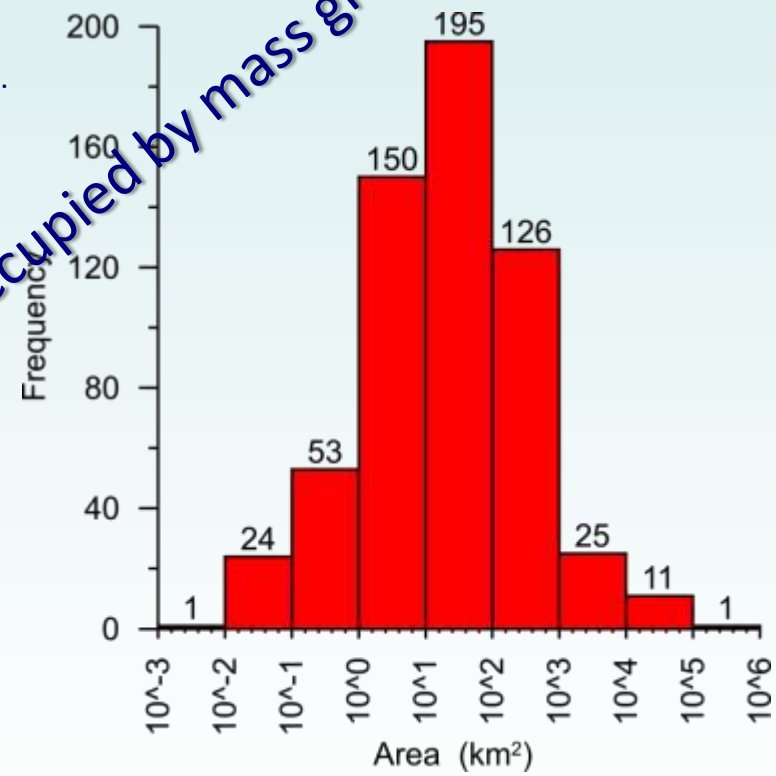
The ratio H/R of submarine landslides of the same volume exhibit an apparent friction coefficient some 10 times lower → Hydroplanning

Magnitude charcteristics: area

Gulf of Mexico ~27%
New Jersey Margin~9.5
California Margin ~7%
Oregon Margin ~3%
McAdoo et al. (2000): Mar. Geol., 169: 103-136.

Canary Basin~10%
Urgeles et al. (2001): Sci Marina, 65: 21-32

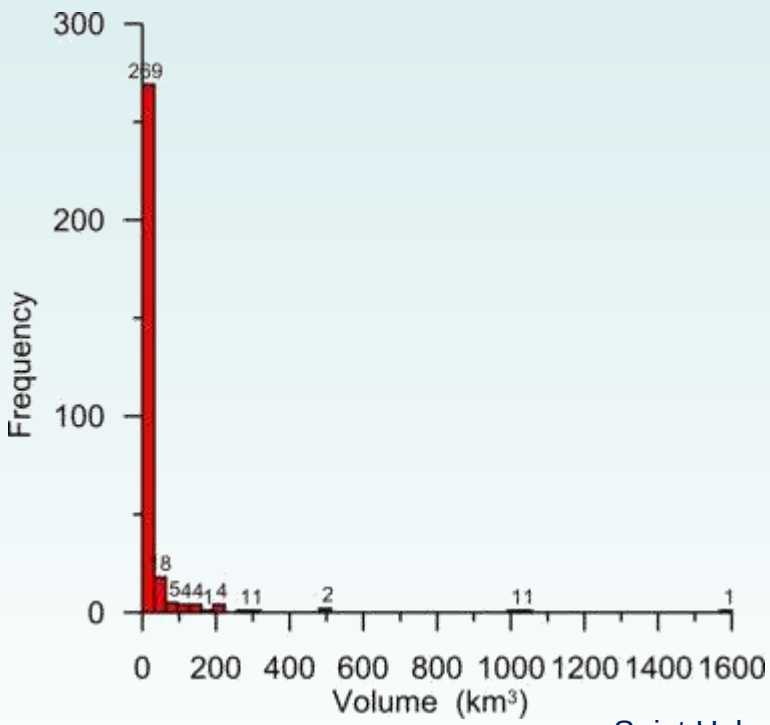


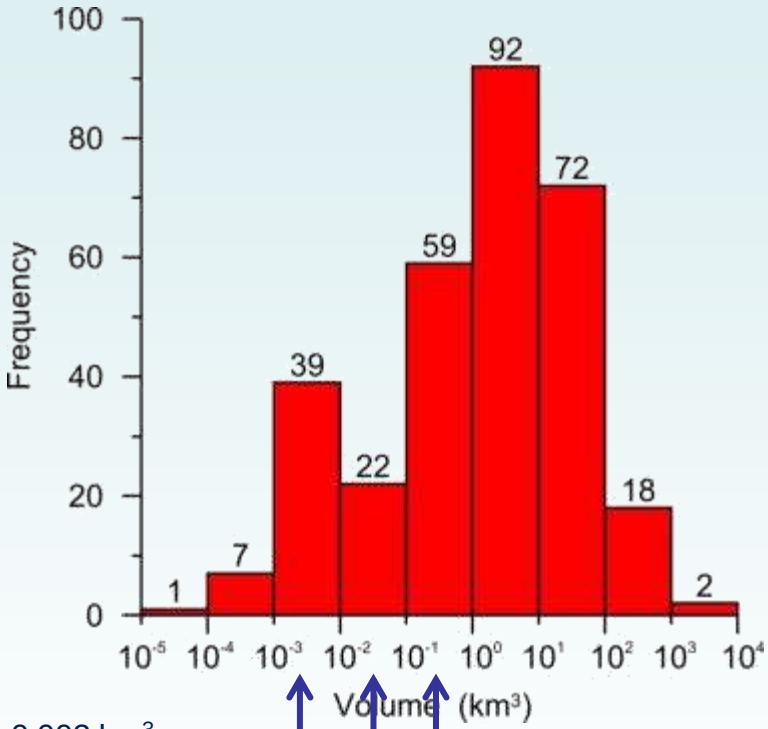


18% of Mediterranean seafloor is occupied by mass gravity-flows

- **Area** ranging from a few squared km to about 1000 km²
- Little erosion, wide-spread slope hydrological conditions → large failures

Magnitude charcteristics: volume





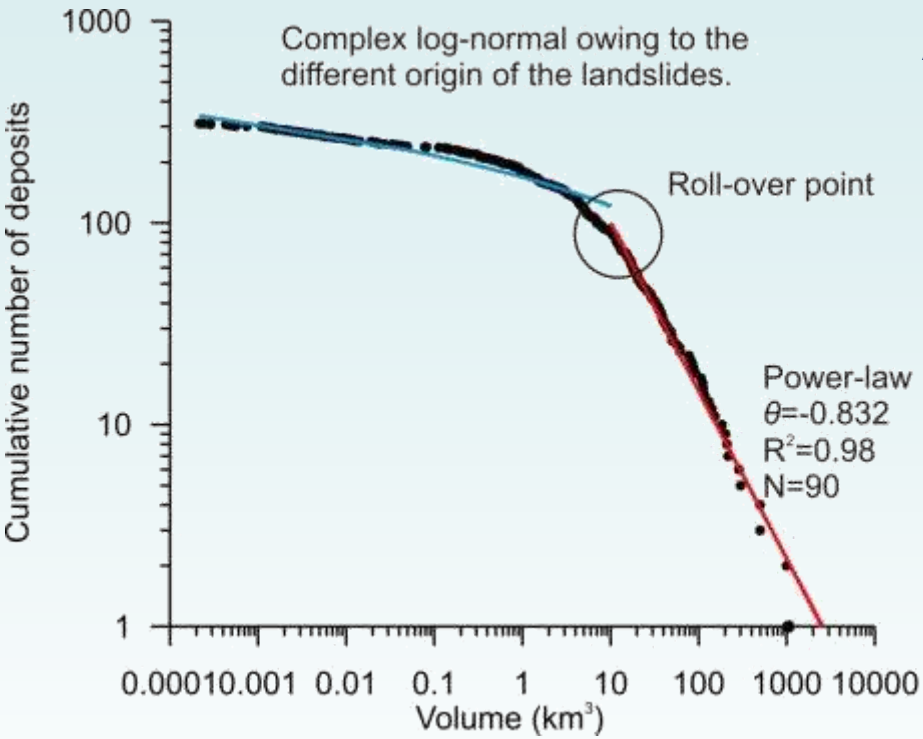
Saint Helens, WA, 0.003 km^3
Saint-Jean-Vianney, QC, 0.007 km^3
Usoi, TJ, 0.002 km^3

- **Volume** up to 1000 km^3

Frank Slide, BC, 0.03 km^3
Hope Slide, BC 0.047 km^3

Pufu, CH, 0.45 km^3
Vajont, IT, 0.27 km^3

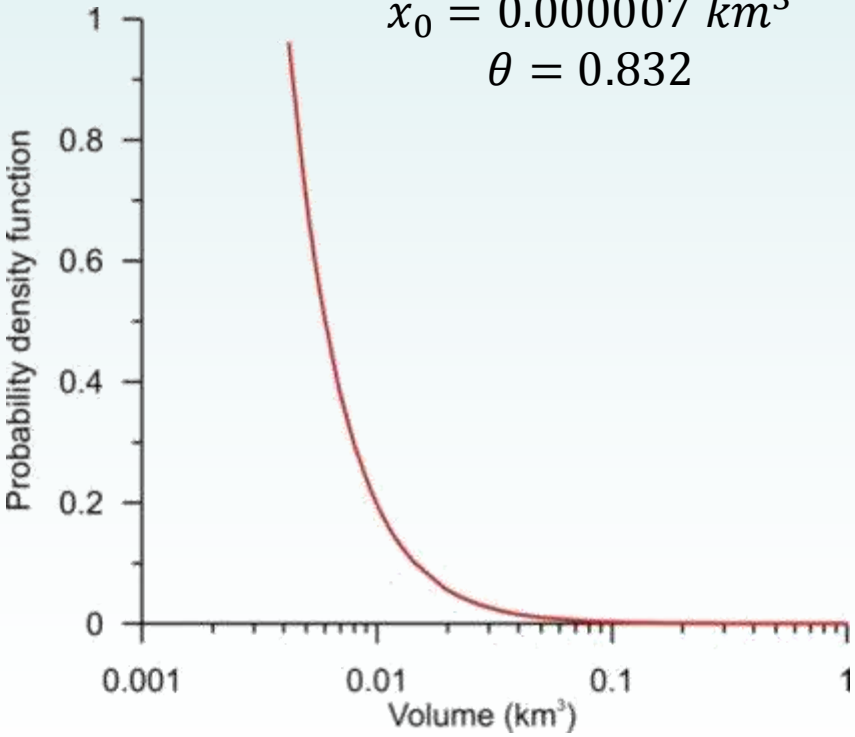
Magnitude charcteristics: volume



Assuming that the cumulative-volume data conforms to a Pareto distribution

$$F(x) = prob(x) = \frac{\theta {x_0}^{\theta}}{x^{\theta+1}}$$

$$x_0 = 0.000007\ km^3$$
$$\theta = 0.832$$

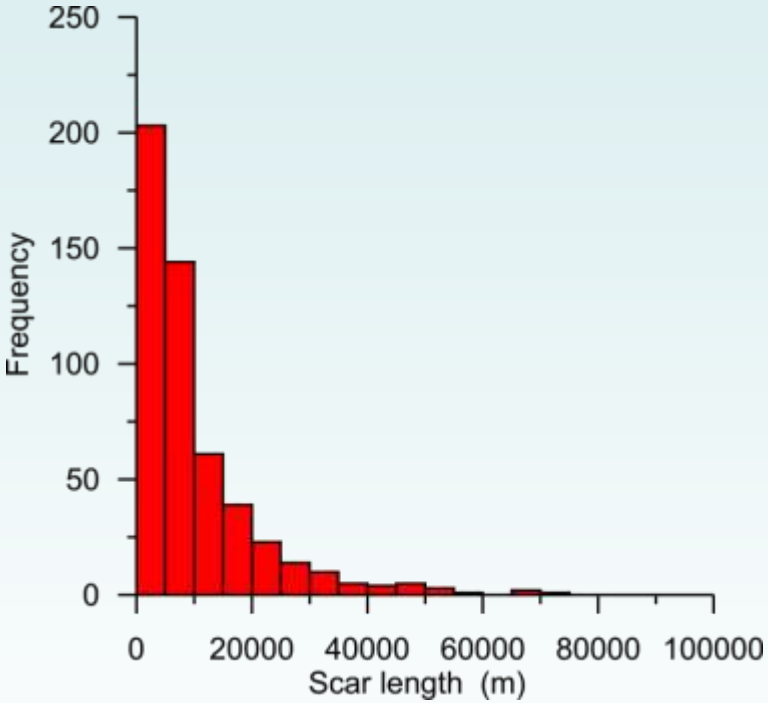


Landslide with probability of observation of:

10%	0.0145 km³
25%	0.0088 km³
50%	0.0060 km³
75%	0.0048 km³

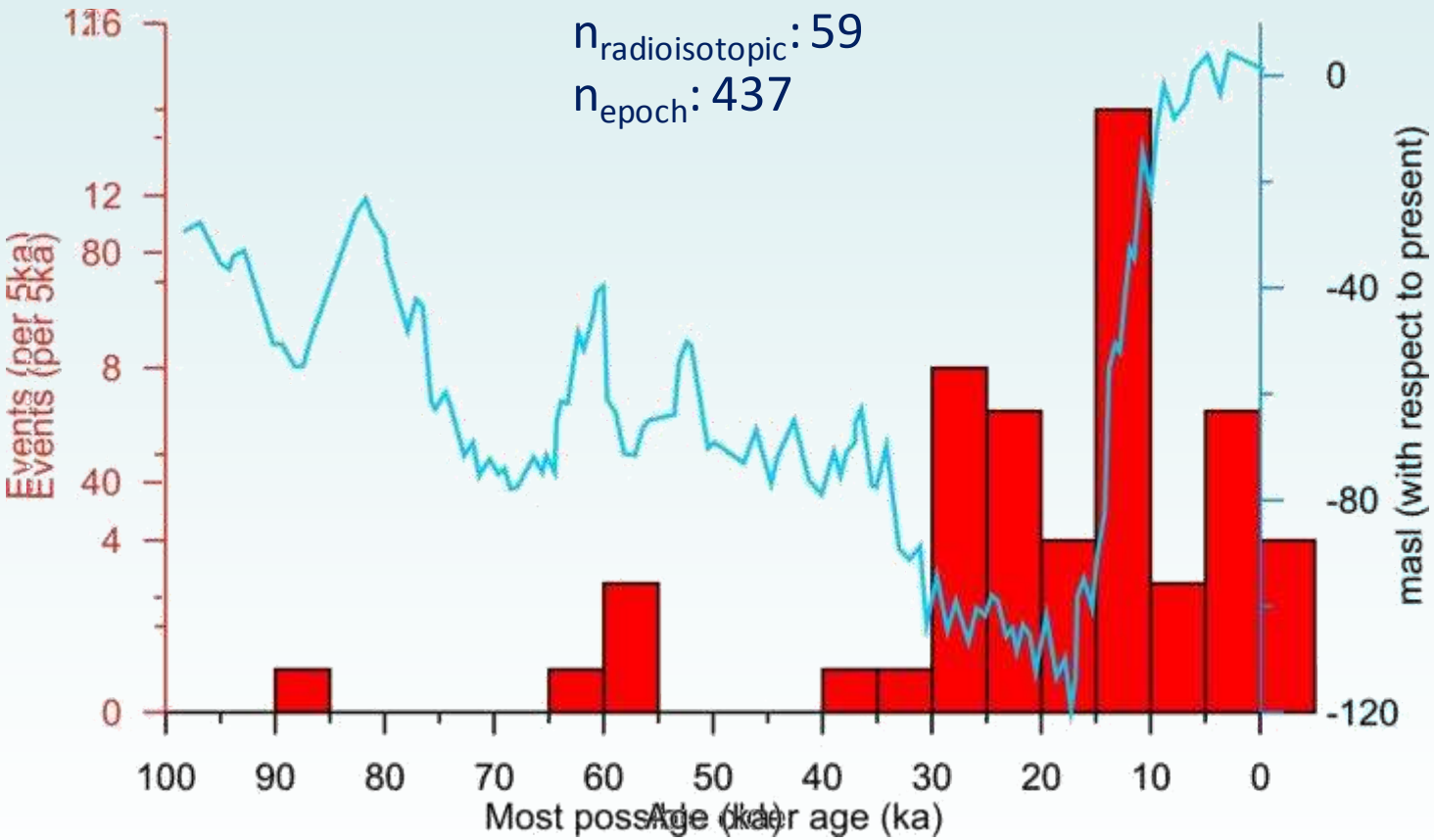
A landslide of 1 km³ has a probability of observation of 4.2×10^{-3}

Magnitude charcteristics : scars



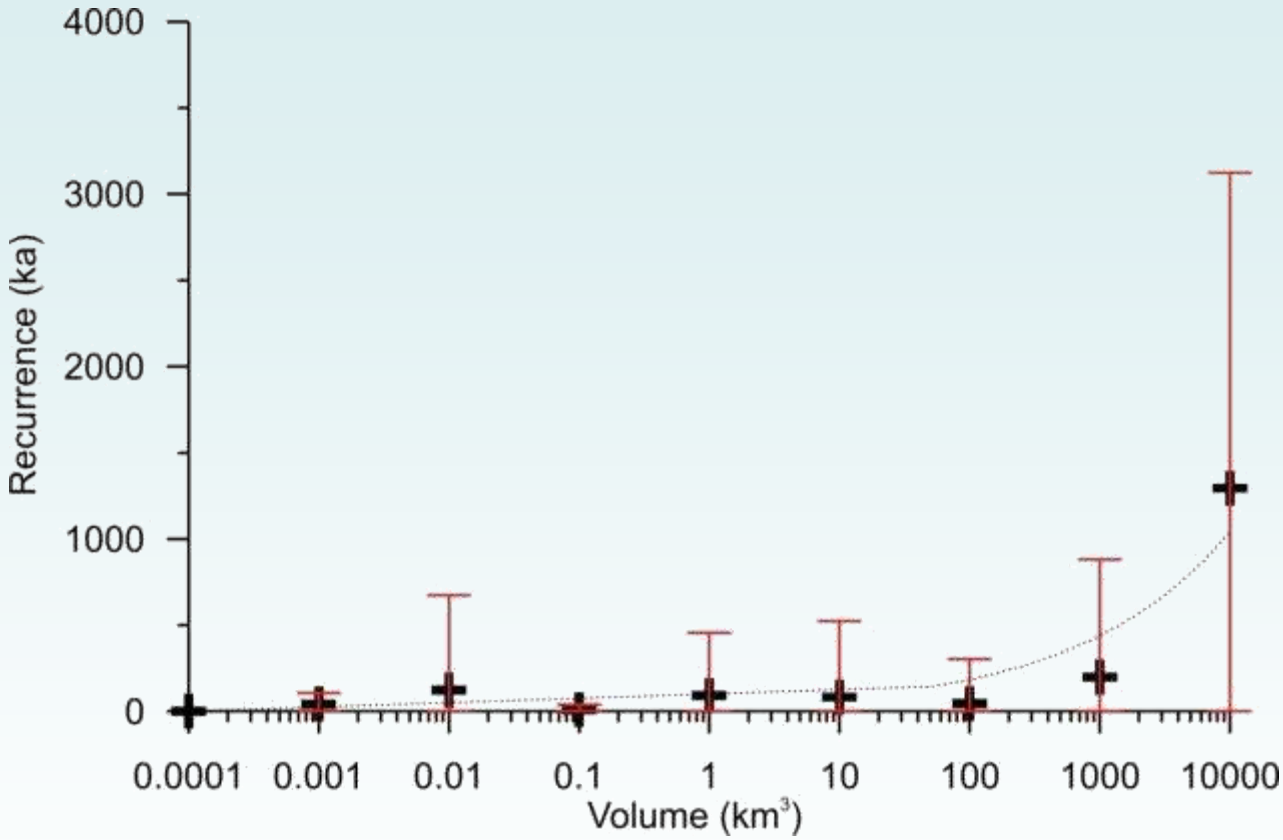
Headwalls are generally less than 20 km long, but may reach 75 km and are involve sequences up to 300 m thick

Timing of failure



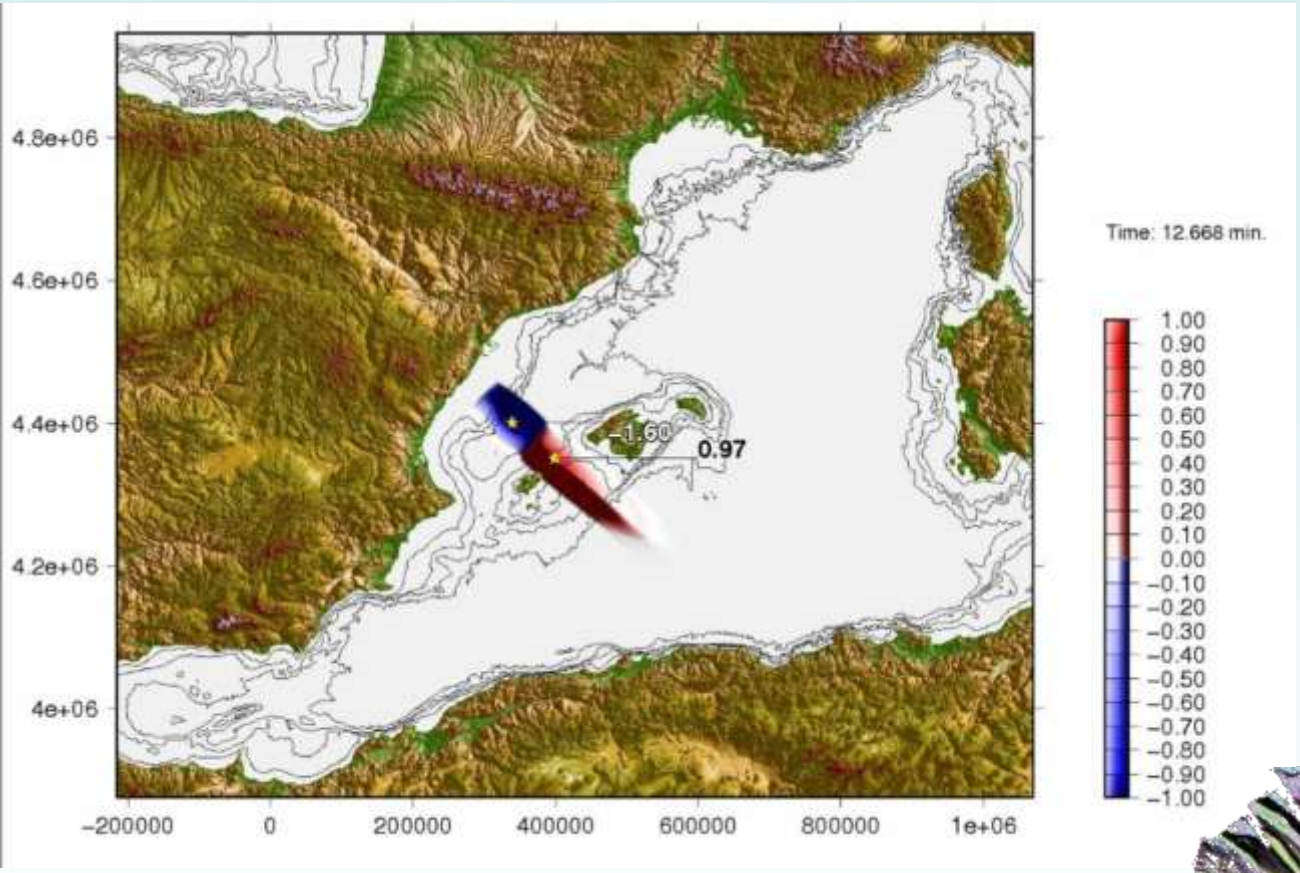
Landslide emplacement during the last de-glaciation

Timing of failure



Recurrence
(oldest event within a volume bin / # dated events within the same volume bin)

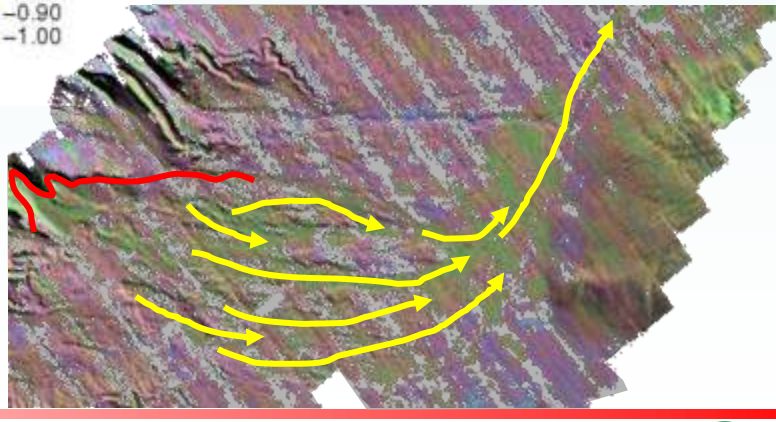
Consequences



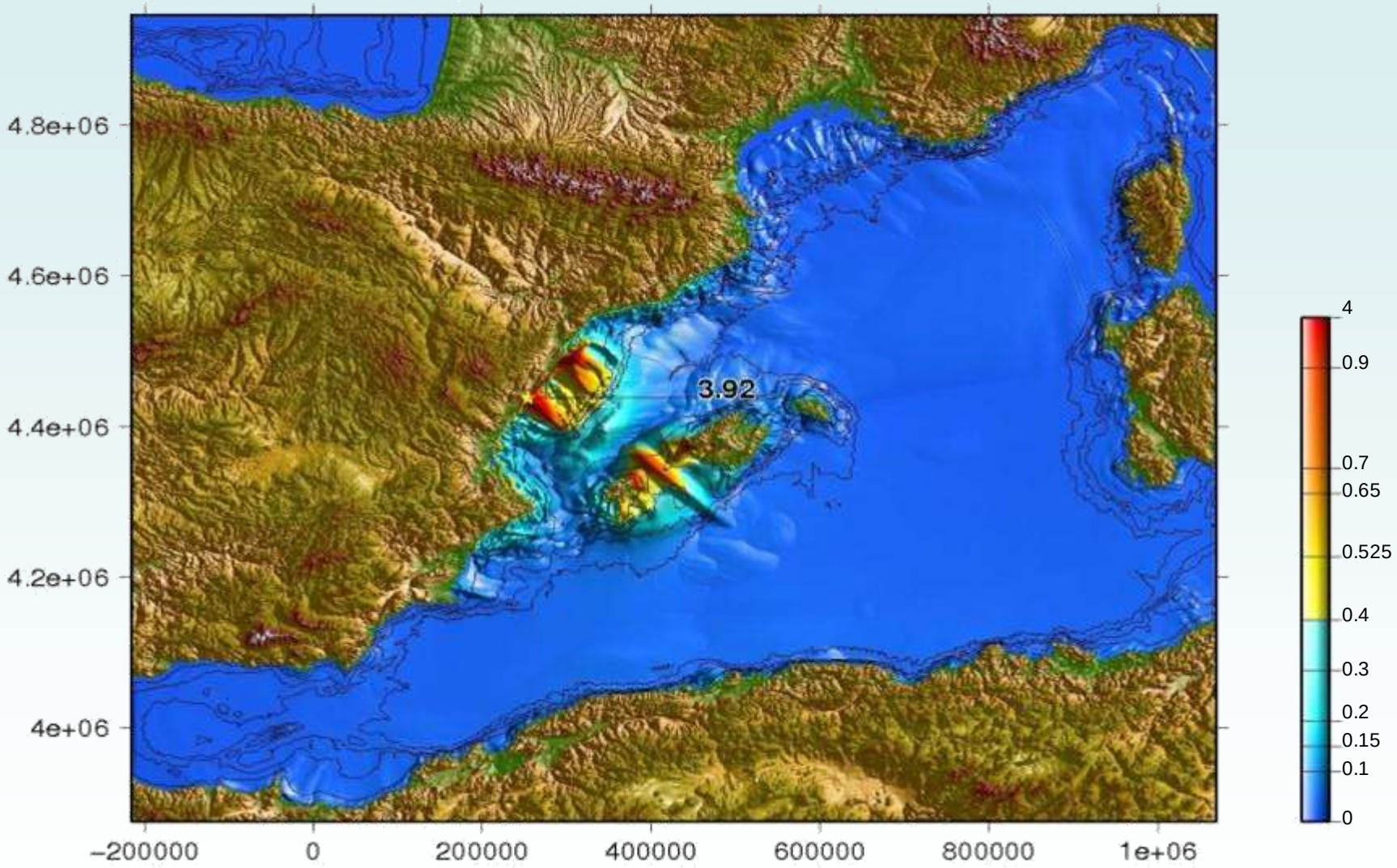
BIG'95 mid-size 26 km³ slide

Mean z_0	1275 m
Mean angle	1.5º
Length	8.8 km
Thickness	250 m
Width	11.1 km
Bulk density	1.7 g/cm^3
a_0	0.0636 m/s^2
Terminal velocity	48.348 m/s
Characteristic motion	37 km
Characteristic time	760 s
Tsunami wavelength	8,5 km
Distance traveled in t_0	16 km
Max. Froude number	0.43

- ✓ Slide motion → Watts and Grilli (2002)
- ✓ Tsunami generation and propagation → Geowave
  - ✓ TOPICS initial free surface elevation and water velocities derived from multivariate, semi-empirical curve fits
  - ✓ FUNWAVE long wave propagation model based on the Boussinesq approximation of wave dynamics (Wei et al., 1995; Wei and Kirby, 1995).



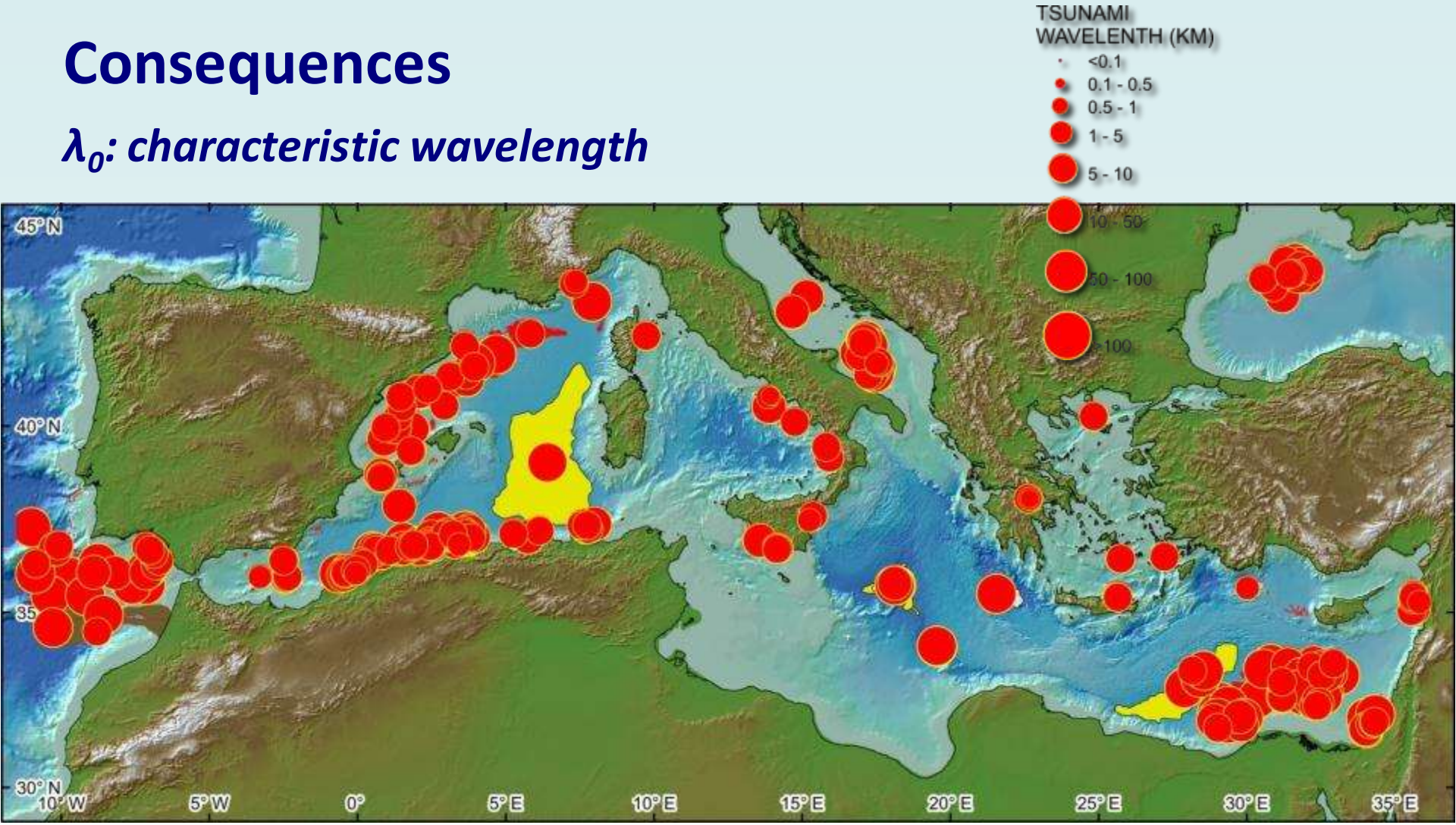
Consequences



BIG'95 mid-size 26 km³ slide → max. Sea surface elevation

Consequences

λ_0: characteristic wavelength

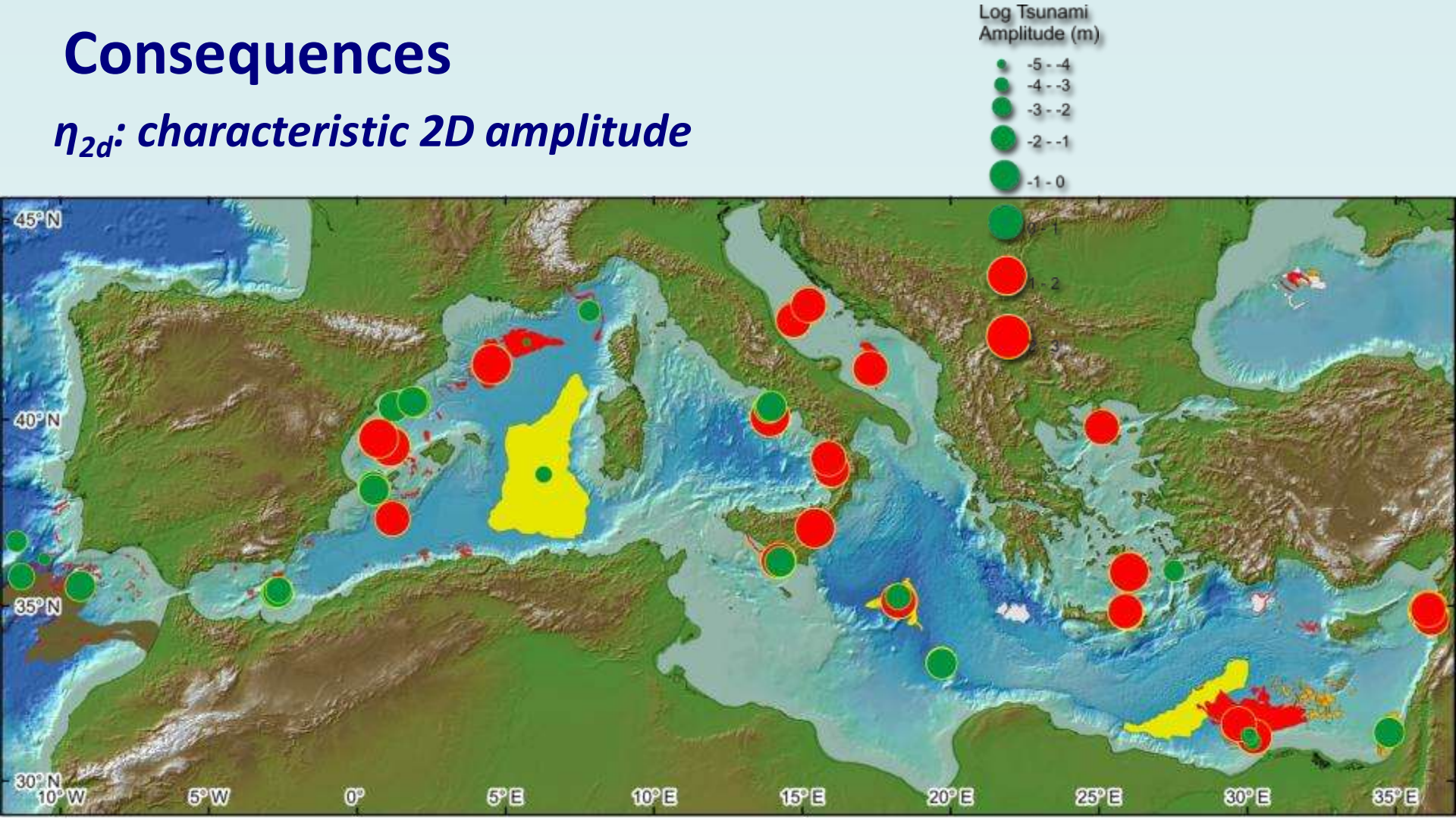


Tsunami Wavemaker model (Watts et al. 2003: NHESS)

$$\lambda_o \equiv t_o \sqrt{g\,d} \cong 3.87 \sqrt{\frac{b\,d}{\sin\theta}}$$

Consequences

η_{2d}: characteristic 2D amplitude



Tsunami Wavemaker model (Watts et al. 2003: NHESS)

$$\eta_{2d} \cong 0.2139\, T \left(1 - 0.7458 \sin\theta + 0.1704 \sin^2\theta\right) \left(\frac{b \sin\theta}{d}\right)^{1.25}$$

CONCLUSIONS:

- ✓ Incomplete catalogue!!
- ✓ Need to standardize the information being published
- ✓ Tectonically active margins → numerous but small failures.
- ✓ Passive margins with large sediment supply →larger slope failures; large overpressure necessary for failure; unfrequent process
- ✓ Landslides originate in water depths exceeding 1000 m on slopes of 2º.
  - ✓ Continental rise is a place of high slope instability
- ✓ Highly mobile events, many structures can be put at risk along their path
- ✓ Little is known for age of the failure events
  - ✓ 47/532 ~ accurate age determinations.
  - ✓ 437 reported with an epoch (difficult relation trigger - environmental factors)
  - ✓ Large amount of Holocene events → climate induced stress changes (sedimentary load, sea level, bottom temperature effect on fluid flow, gas hydrate and gas systems)
- ✓ MES and salt distribution → major condition for fluid migration pathways
- ✓ Basement structure and consolidation couple to control location of slope failure
- ✓ Tsunamis → major consequence and potential geohazard
  - ✓ Active margins → freq., small landslide tsunamis
  - ✓ Passive margins → unfreq., large landslide tsunamis (preparedness, resilience)

Thanks!