Università di Trieste
Corso di Laurea in Geologia

Anno accademico 2018 - 2019

Geologia Marina

Parte VI - ASPETTI ECONOMICI E SOCIALI

Modulo 6.2 Pericolosità dei fondali sottomarini

Docente
A. Camerlenghi

BASIC CONCEPTS

HAZARD: Is an **event** posing a threat to life, health, property or environment. Hazard assessment is the evaluation of the the **probability** of occurrence of a potentially damaging event, (where, when, how frequently, magnitude)

VULNERABILITY: is the **probability** that a community can be affected by the impact of a hazard.

RISK: is the **probability** that a specific hazard will cause harm.

Risk = Hazard x Vulnerability

Japanese Earthquake Highway Repair

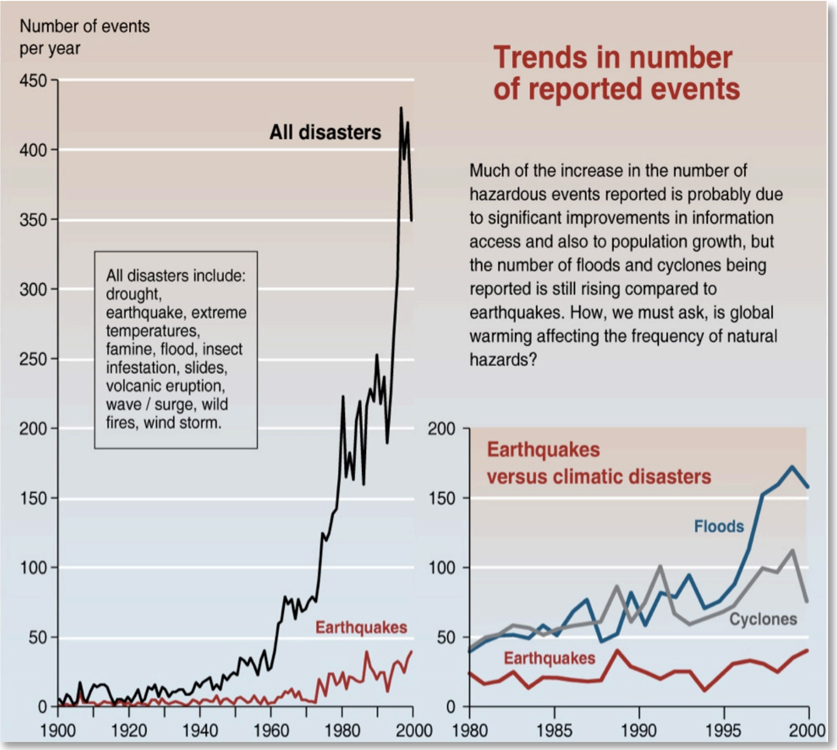
- **Earthquake: March 11 2011**
- **Repair begun: March 17 2011**
- **Road ready: March 22 2011 (six days later)**

By Mail Foreign Service, 02:01 GMT, 24 March 2011

RESILIENCE: community's capacity to cope with and recover from impacts of natural hazards.

Risk = (Hazard x Vulnerability) - Resilience

Concern for Society



Much of the increase in the number of hazardous events reported is probably due to significant improvements in information access and also to population growth, but the number of floods and cyclones being reported is still rising compared to earthquakes. How, we must ask, is global warming affecting the frequency of natural hazards?

Source: UNEP GRID Arendal
http://maps.grida.no/go/graphic/trends-in-natural-disasters

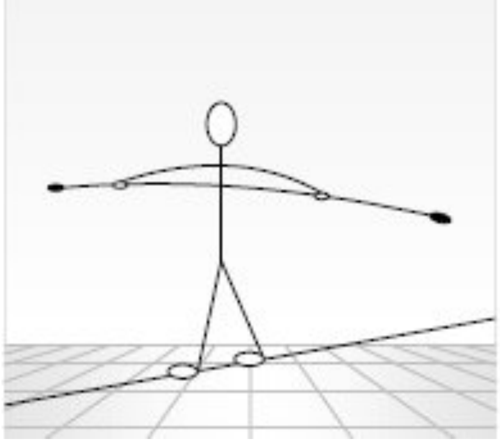
Global warming?

Anthropization
Poor planning

Preparedness of modern society

Risk = (Hazard x Vulnerability) - Resilience

Risk and Mitigation



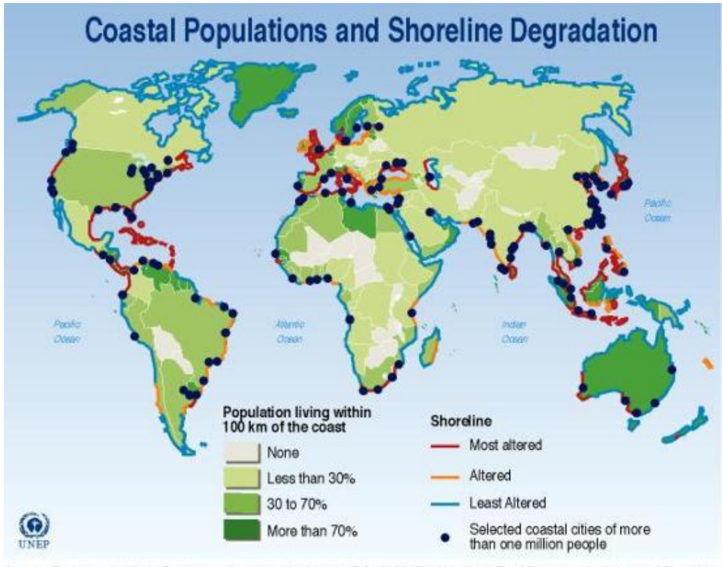
The concept of risk is illustrated by the tightrope walker. In this example, the risk to the tightrope walker is falling off and getting killed—a high-risk activity!

Now consider that the highwire is only one metre above the ground. The falling hazard still exists and the chance of falling remains constant, but the risk is considerably different than if the person were 100 metres above the ground.

Risk is a total concept of likelihood of occurrence of a hazard and the severity of possible impacts.

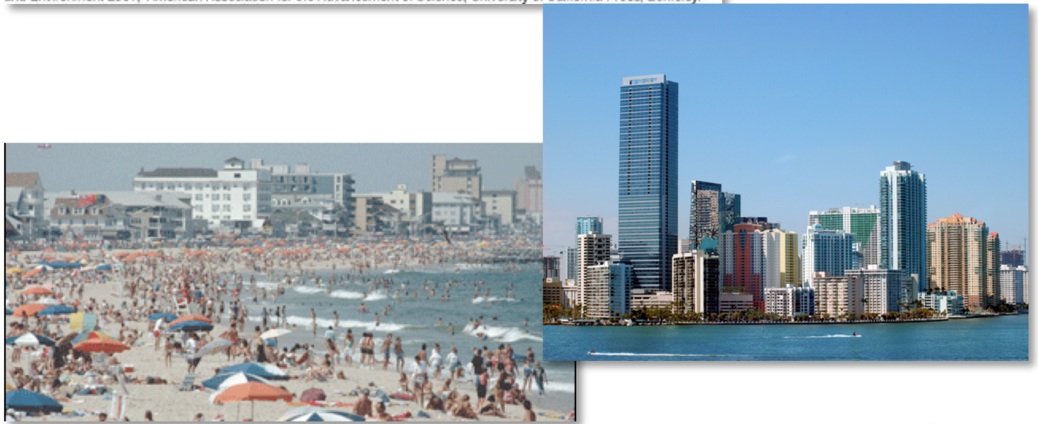
Perhaps there is a crowd below the tightrope walker vulnerable to injury. The severity of impact to the tightrope walker and the crowd can be mitigated by a safety net, the chance of falling can be reduced by special training and the extent of injury can be mitigated by emergency medical response capability.

The overwhelming bulk of humanity is concentrated along or near coasts on just 10% of the earth’s land surface



Source: Burke et al., World Resources Institute, Washington DC, 2001; Paul Harrison, Fred Pearce, *AAAS Atlas of Population and Environment 2001*, American Association for the Advancement of Science, University of California Press, Berkeley.

Coastal areas with high population densities are those with the most shoreline degradation or alteration. Densely populated areas close to seas are also the most attractive for a lot of **economic activity**.



Top Ten World Largest Cities:

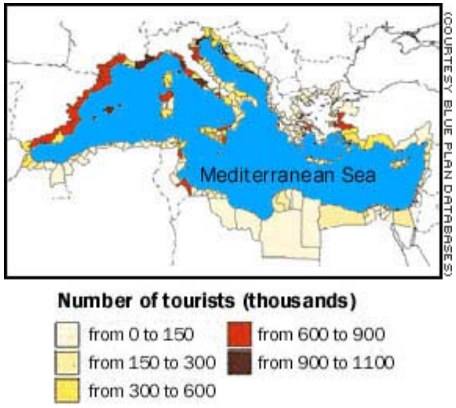
- Tokyo, Japan (coastal)
- Mexico City, Mexico
- Mumbai, India (coastal)
- Sáo Paulo, Brazil
- New York City, USA (coastal)
- Shanghai, China (coastal)
- Lagos, Nigeria (coastal)
- Los Angeles, USA (coastal)
- Calcutta, India (coastal)
- Buenos Aires, Argentina (coastal)

….we must understand submarine hazards

VULNERABILITY

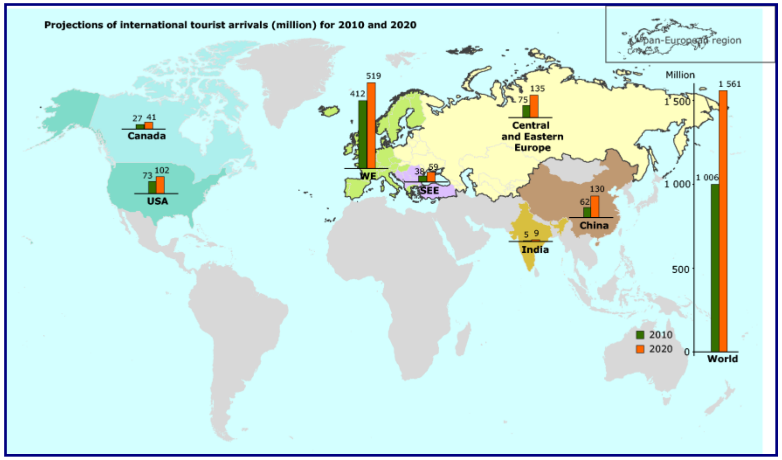
- Very densely-populated coastline: 160 million inhabitants sharing 46,000 km of coastline (**3.5 inhabitants per m of coastline**).

- **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



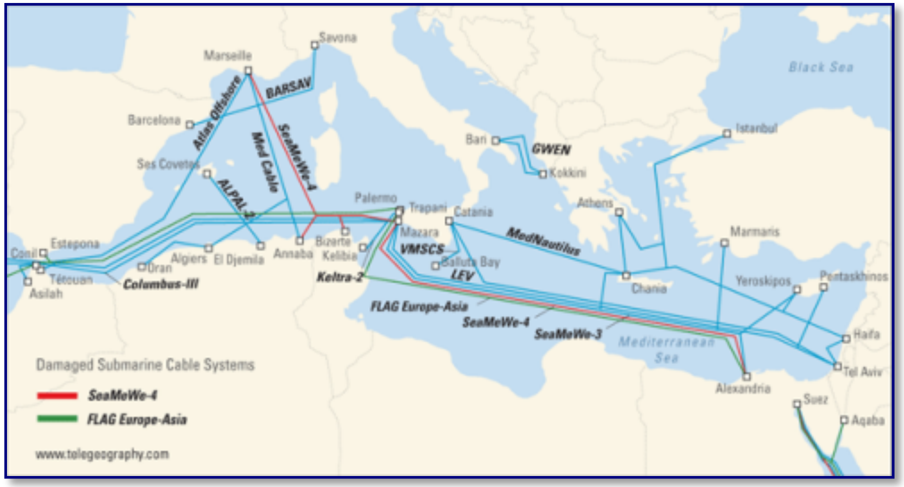
EEA web site http://www.eea.europa.eu
Copyright EEA, Copenhagen.

VULNERABILITY

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

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

Casablanca Platform, off Spain



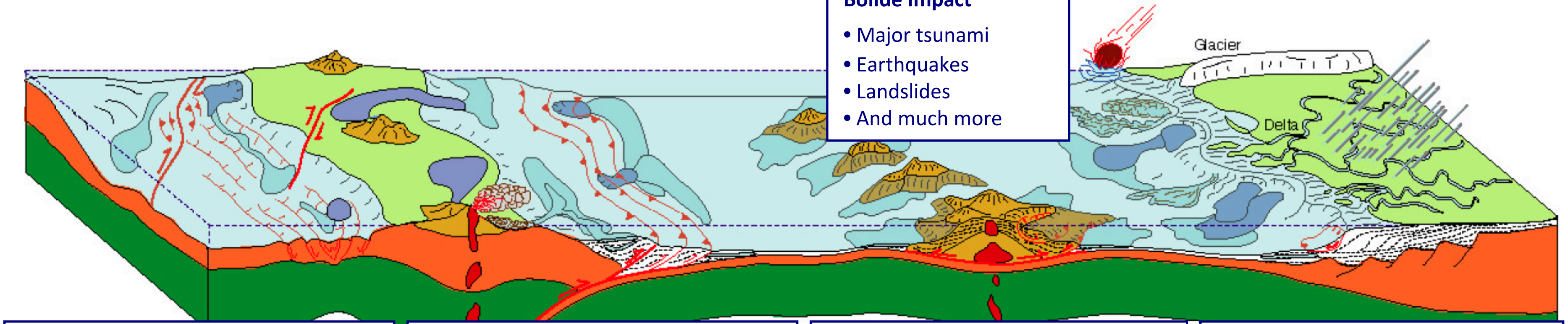
A study on behalf of the Submarine Cable Improvement Group shows 25% of all faults are caused by **natural hazards such submarine earthquakes, density currents and extreme weather.**

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

SUBMARINE GEOHAZARDS

- **EARTHQUAKES** originated below the sea floor
- **VOLCANIC ISLAND ERUPTIONS** and **FLANK COLLAPSE**
- **SUBMARINE LANDSLIDES** and sediment mass movements (turbidity currents, debris flows, slumps)
- **TSUNAMIS** (originated by the above)
- **METHANE EMISSIONS**
- **METEORITE IMPACTS in the OCEANS**

SUBMARINE GEOHAZARDS OCCUR IN ALL OCEANIC ENVIRONMENTS
but
THEY CONCENTRATE ON CONTINENTAL MARGINS



Bolide Impact

- Major tsunami
- Earthquakes
- Landslides
- And much more

Rift & Transform Margins

- Moderate earthquakes
- Submarine/subaerial landslides
- Debris flows, turbidity currents
- Tsunamis
- Methane emissions

Subduction Margins

- Large earthquakes
- Submarine/subaereal landslides
- Explosive eruptions, lahrs
- Debris flows, turbidity currents
- Tsunamis
- Methane emissions

Oceanic Volcanoes

- Submarine/subaerial landslides
- Debris flows, turbidity currents
- Volcanic eruptions
- Earthquakes
- Tsunamis
- Methane emissions

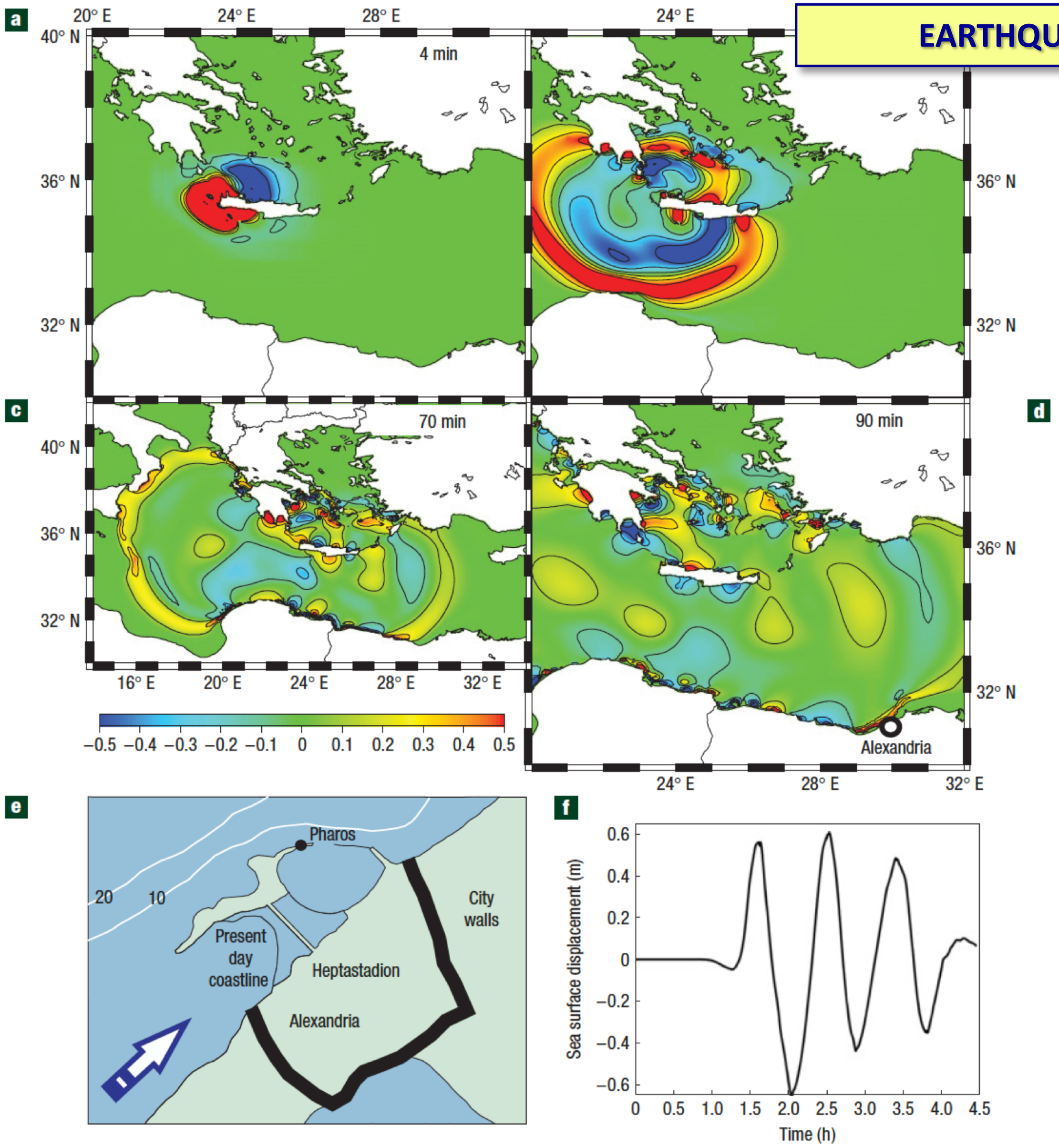
Passive Margins

- Submarine landslides
- Debris flows, turbidity currents
- Modest earthquakes
- Tsunamis
- Methane emissions

Adapted from Morgan et al., 2009. *Scientific Drilling*, available at: http://www.iodp.org/geohazards/

SUBMARINE GEO-HAZARDS

EARTHQUAKES originated below the sea floor



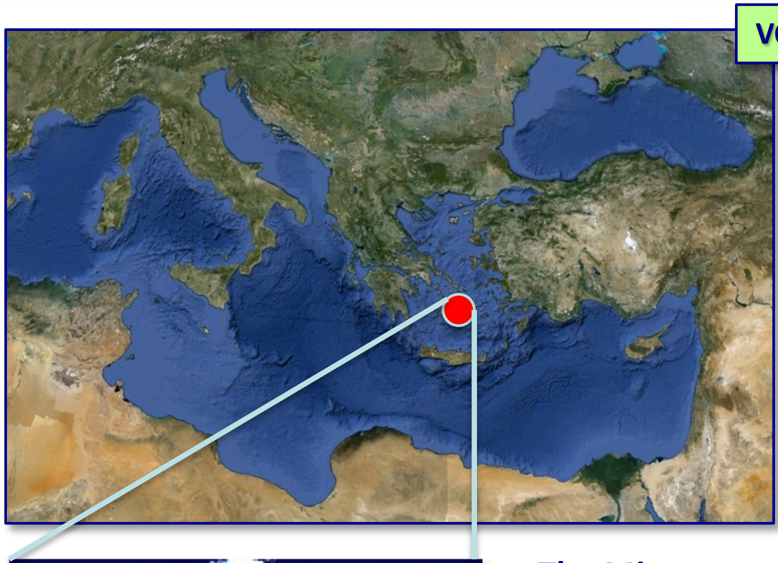
Eastern Mediterranean tectonics and tsunami inferred from the AD 365 earthquake

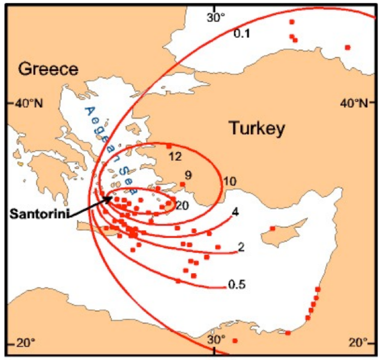
Shaw et al., 2008. Nature

AMMIANI
MARCELLINI
RERUM GESTARUM
LIBRI XVIII.
ITEM
OMNIA
NUNC RECOGNITA
AB
JACOBO GRONOVIO.

Marcellinus, A. (390)
Res Gestae, Vol. II,
(26) 15-19.

VOLCANIC ISLAND ERUPTIONS and **FLANK COLLAPSE**



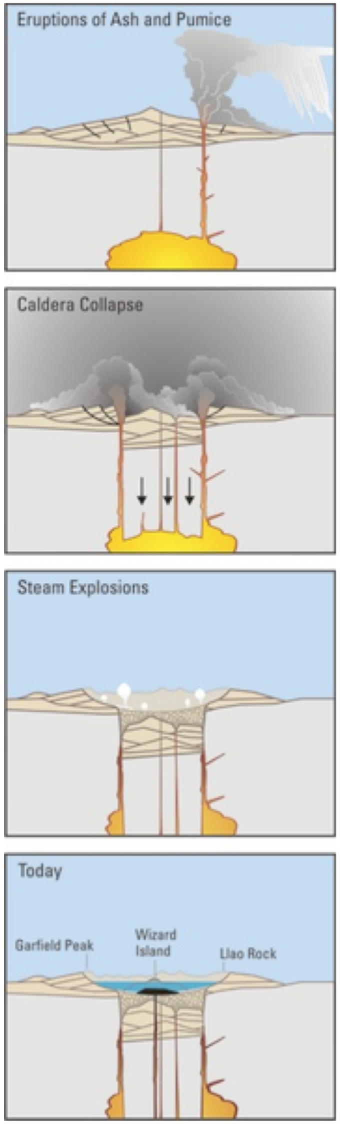


Ash from the Minoan eruption (in cm)

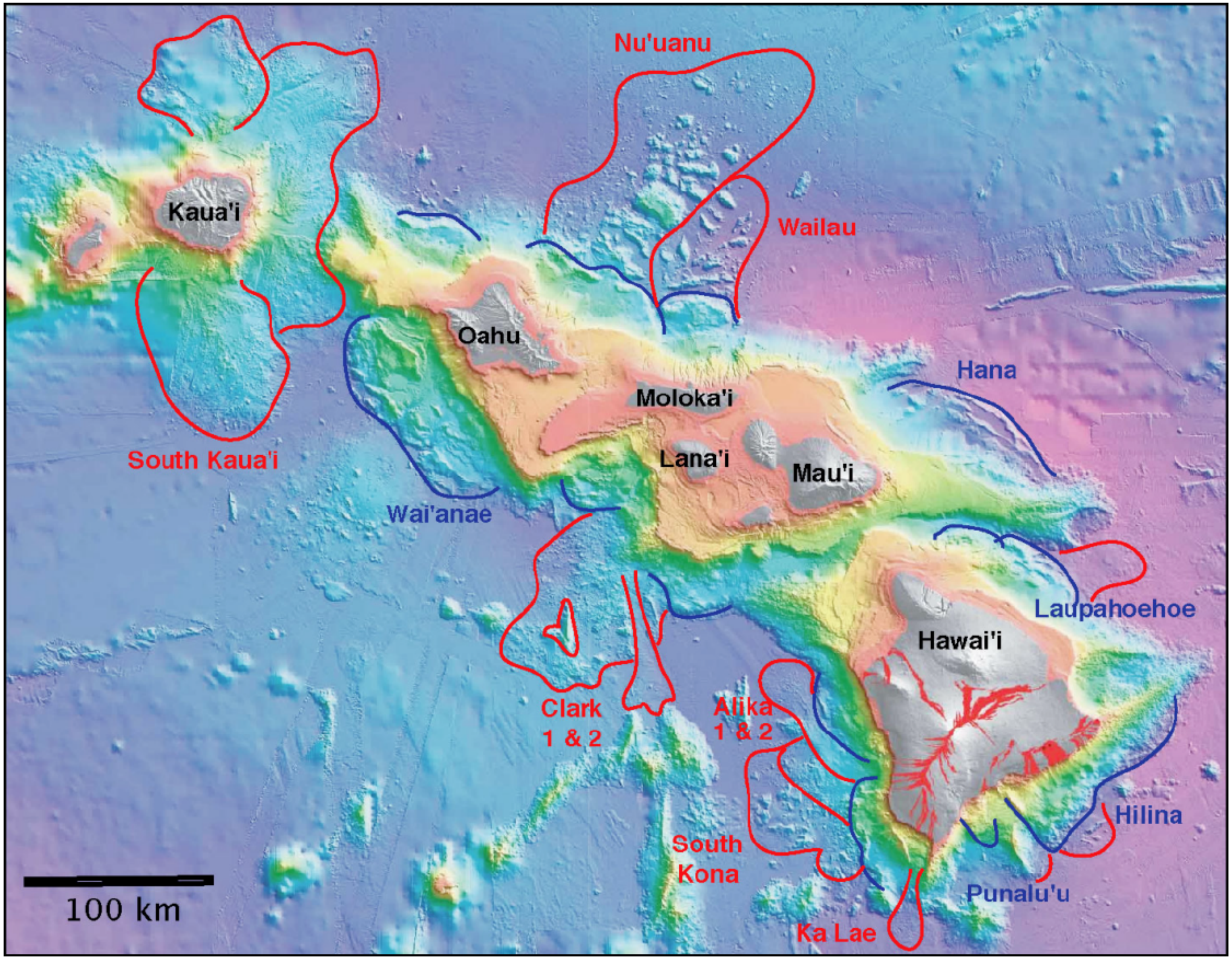
Friedrich (1994)

The Minoan eruption of Santorini happened around 1645 BC in the Late Bronze Age.

Akrotiri remains

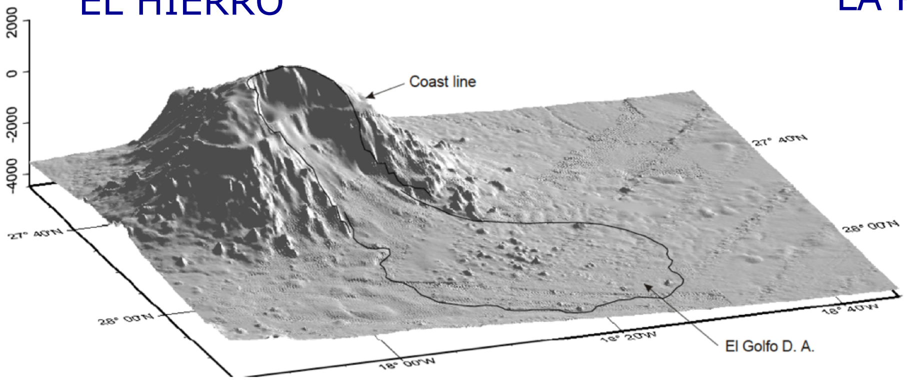


http://pubs.usgs.gov/fs/2002/fs092-02/

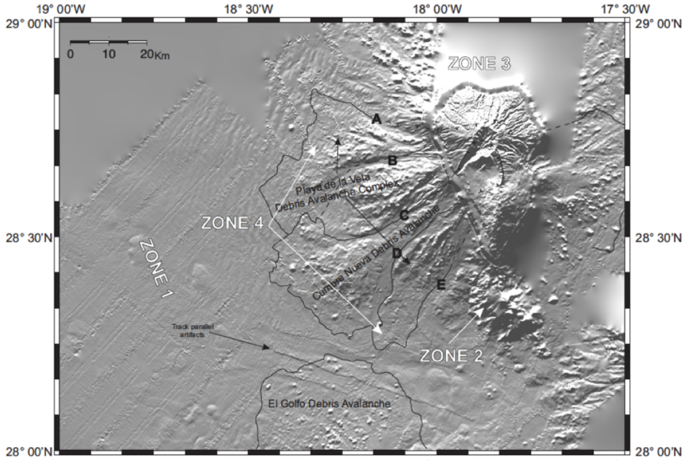


Morgan et al., 2009. Scientific Drilling

EL HIERRO

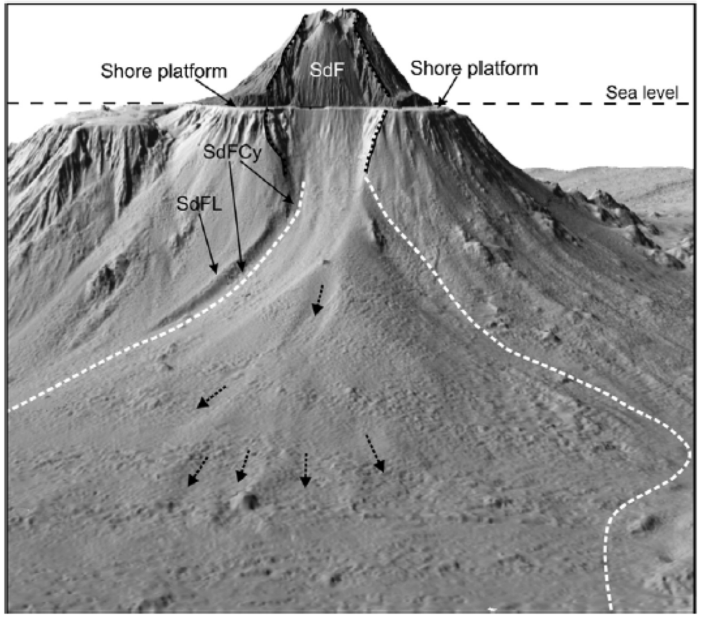


LA PALMA



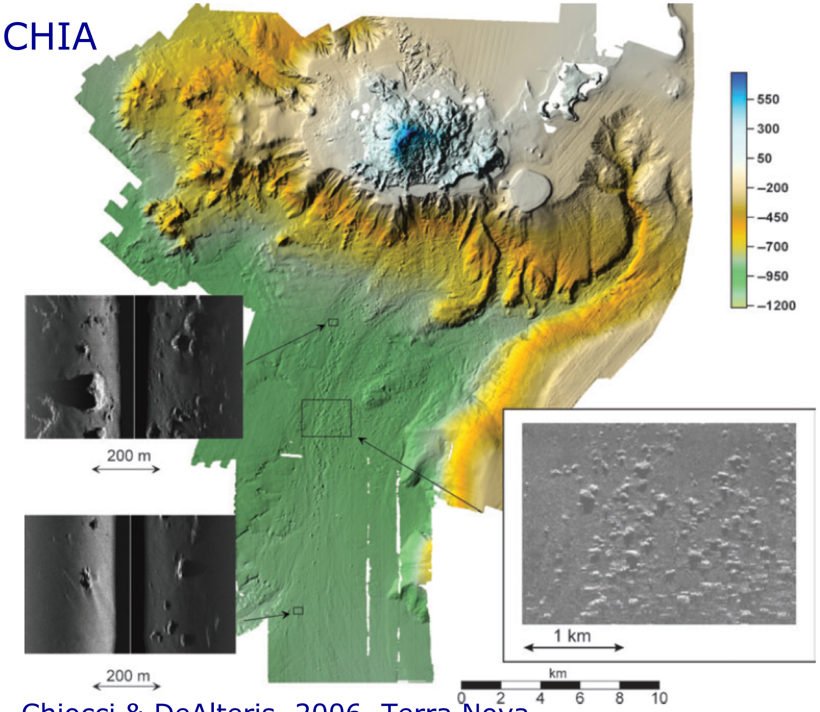
Urgeles et al., 1999. JGR

STROMBOLI



Romagnoli et al., 2009. Marine Geology

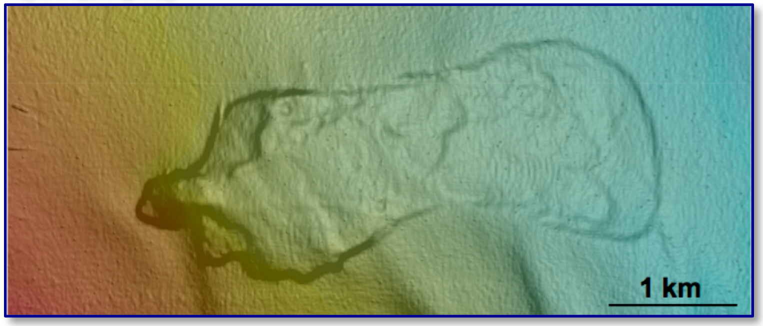
ISCHIA



Chiocci & DeAlteris, 2006. Terra Nova

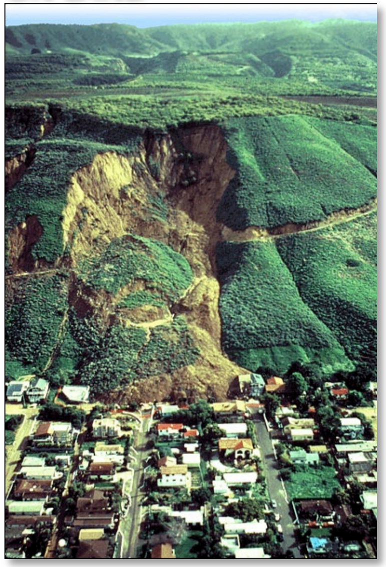
SUBMARINE LANDSLIDES

OFFSHORE

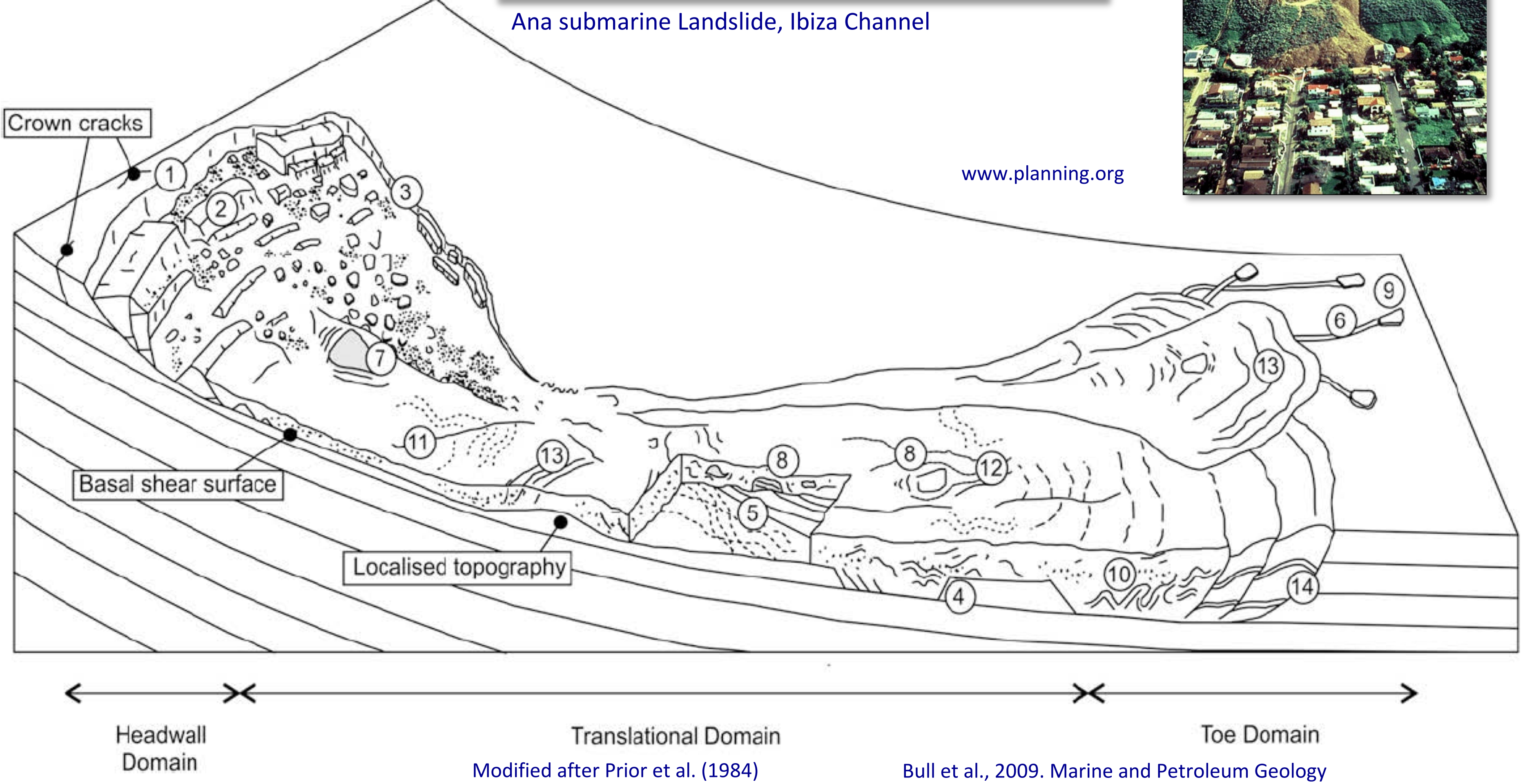


Ana submarine Landslide, Ibiza Channel

ON LAND



www.planning.org



Modified after Prior et al. (1984)

Bull et al., 2009. Marine and Petroleum Geology

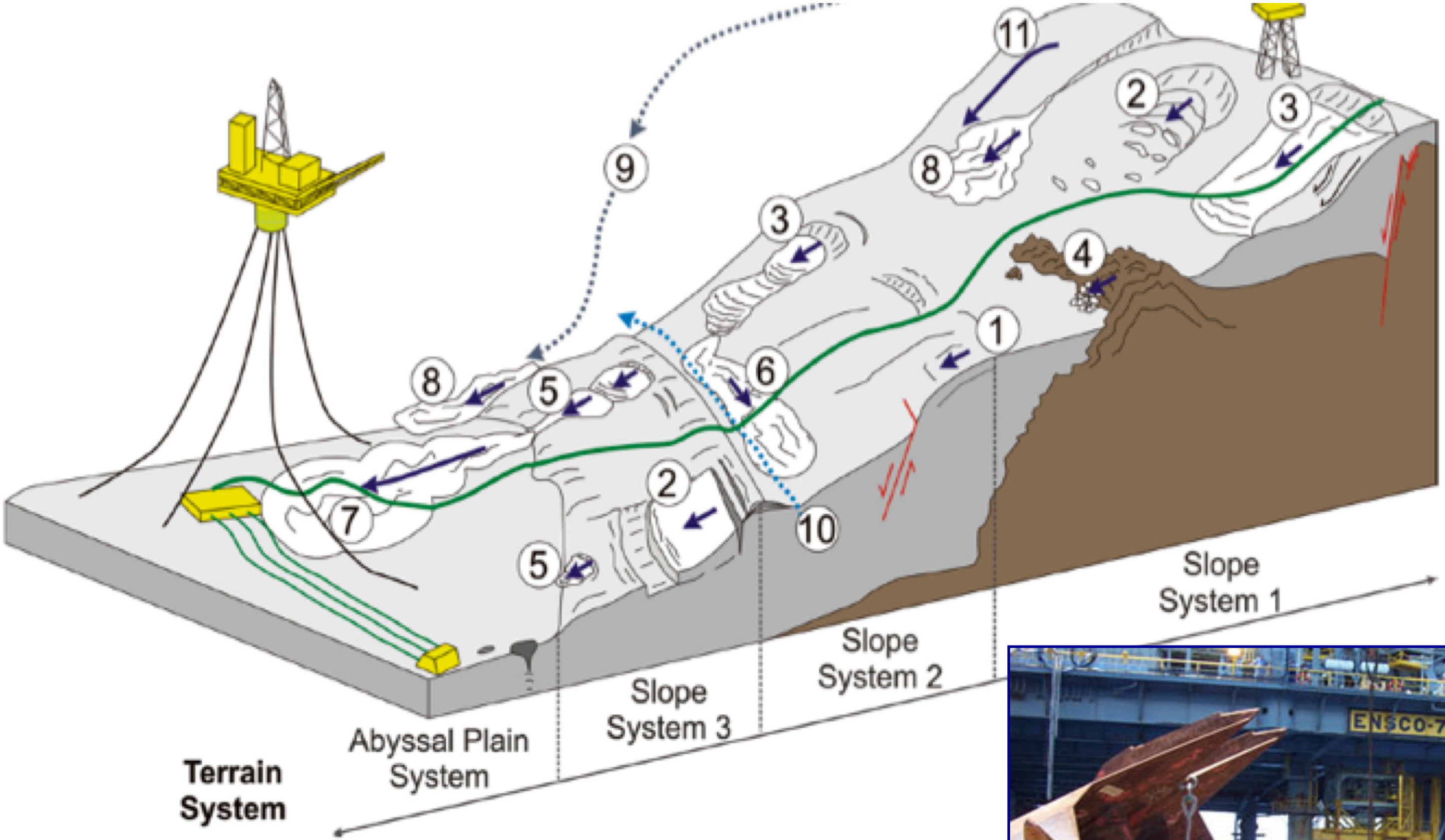
DEFINITIONS

- **Submarine landslides** are one of the main agents through which sediments are transferred across the continental slope to the deep ocean.

- They are **ubiquitous** features of submarine slopes in all geological settings and at all water depths.

- **Hazards** related to such landslides range from destruction of offshore facilities to collapse of coastal facilities and the generation of tsunamis.

Concern for safety of economic activity (energy, communications)



Mosher, 2010.

R. Craig Shipp, Shell International E&P Inc. IODP Geohazard Workshop, Portland 2008

Approaches to the study of submarine landslides

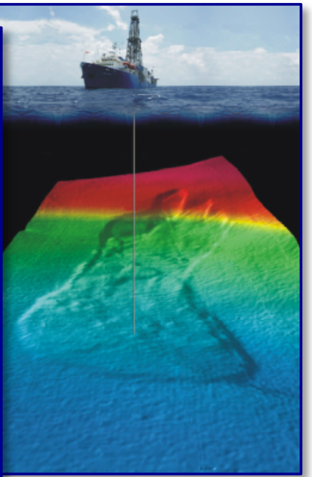
- **CHARACTERIZATION**
(morphology, geometry, structure)

- **PRECONDITIONING FACTORS**
(sedimentology, fluid flow regime, tectonic history…)

- **TRIGGERS**
(external stimulus that initiates the process)

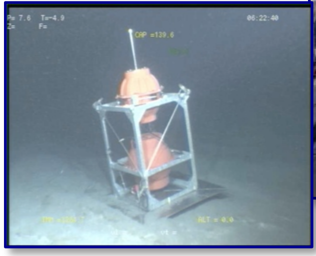
- **TRANSPORT MECHANISMS**
(flow mechanics)

- **FREQUENCY**
(Stratigraphic analysis and ^{14}C dating)



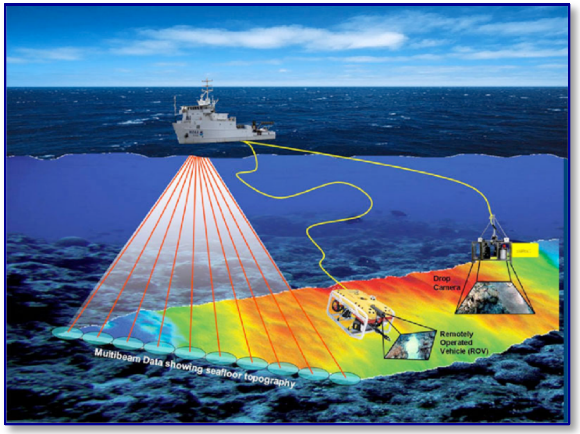
Drilling

In Situ geotechnical merasurements (IFREMER Penfeld Penetrometer)



Mid-term temperature/pore pressure lance (SAPPI)

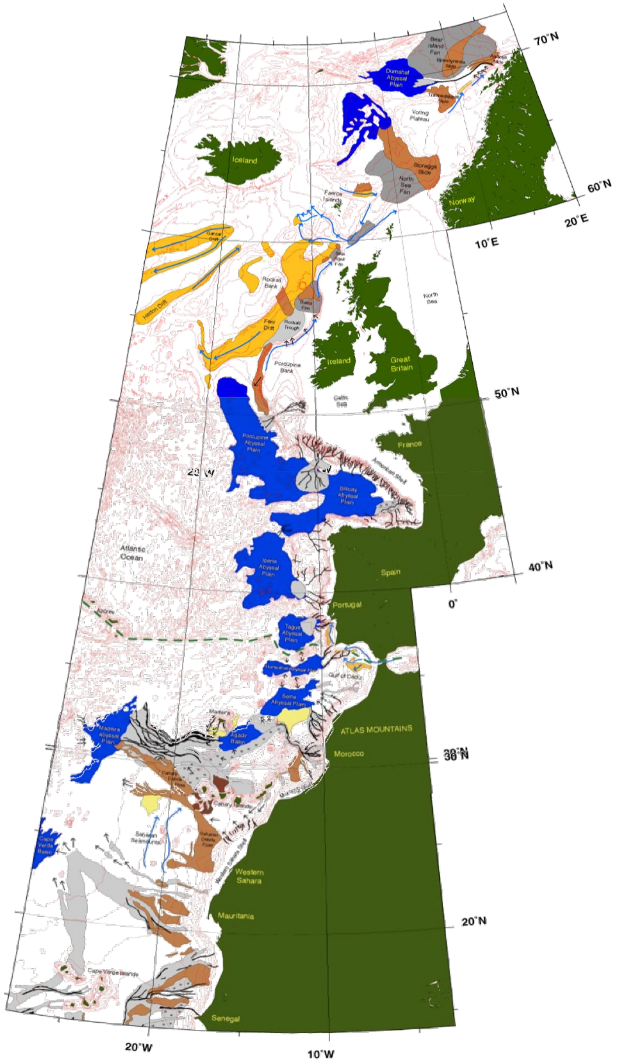
Autosub6000, a new AUV, NOCS



NOOA Grey Reef Expedition

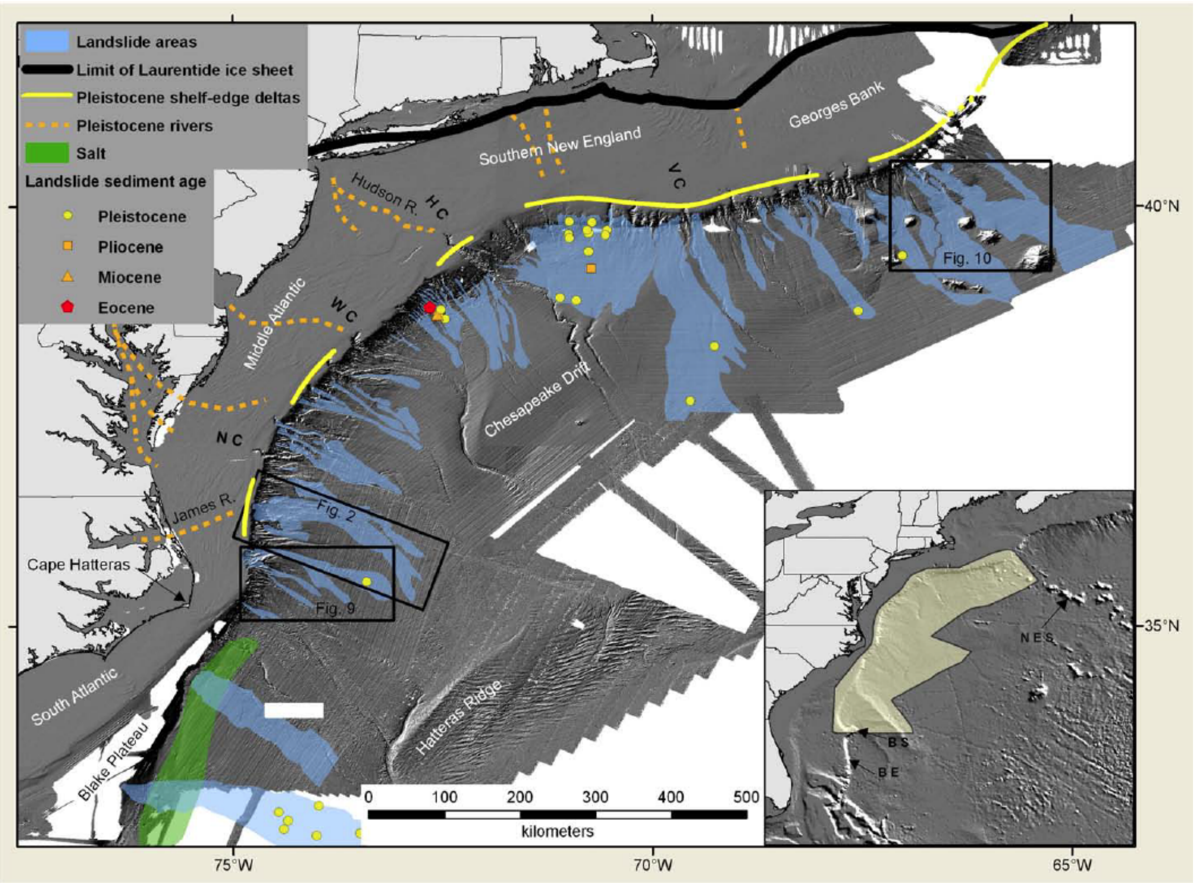
Seismic surveys

West European and African Margin



Weaver et al., 2000. Sedimentology

USA Atlantic Coast



Twichell et al., 2009. Marine Geology

The paradigma of earthquakes as triggers of modern submarine landslides

The paradox of the distribution of submarine landslides on present-day continental margins

↓

Geological control on the distribution of submarine landslides

The paradigma of earthquakes as triggers of submarine landslides

Masson, D.G., Harbitz C.B., Wynn R.B., Pedersen, G. and Løvholt, F. 2006. **Submarine landslides: processes, triggers and hazard prediction**. *Phil. Trans. R. Soc.* A 364, 2009–2039. doi:10.1098/rsta.2006.1810
"Elevated pore pressures can result from normal depositional processes or from transient processes such as **earthquake shaking**"

"Historical evidence suggests that the majority of large submarine landslides are **triggered by earthquakes**"

Canals, M., Lastras, G., Urgeles, R., Casamor, J.L., Mienert, J., Cattaneo, A., De Batist, M., Haflidason, H., Imbo, Y., Laberg, J.S., Locat, J., Long, D., Longva, O., Masson, D.G., Sultan, N., Trincardi, F. and Bryn, P., 2004. **Slope failure dynamics and impacts from seafloor and shallow sub-seafloor geophysical data: An overview**, *Mar. Geol.*, 213, 9–72.
"In addition to pre-conditioning factors related to geological setting and sedimentation conditions, a final trigger is required for submarine landslides to take place, which is most often assumed to be an **earthquake**"

Locat, J. and Lee, H.J., 2002. **Submarine landslides: advances and challenges**. Can. Geotech. J., 39, 193-212.
Seismic loading and oversteepening are considered as main triggers of submarine landslides

Sultan, N., Cochonat, P., Canals, M., Cattaneo, A., Dennielou, B., Haflidason, H., Laberg, J.S., Long, D., Mienert, J., Trincardi, F., Urgeles, R., Vorren, T.O., Wilson, C., 2004. **Triggering mechanisms of slope instability processes and sediment failures on continental margins: a geotechnical approach**. *Mar. Geol.*, 213, 291– 321.

"No specific statements"

Very common statement found in the literature:

……… The trigger is most likely an earthquake.

TRIGGERS vs FACTORS

TRIGGERS

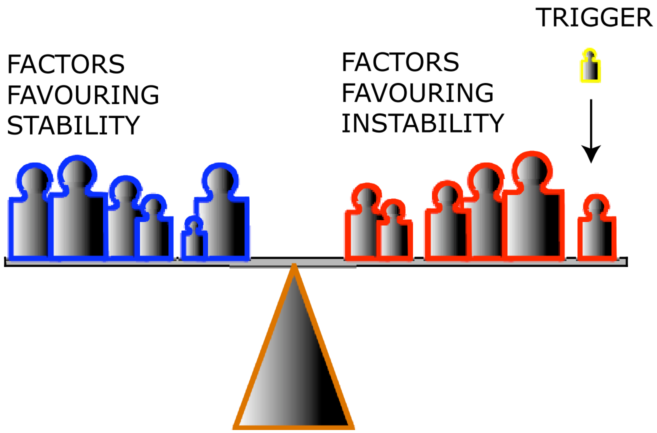
A **triggering mechanism** is an **external stimulus** that initiates the slope instability process (Sultan et al., 2004).

Examples of triggering (or "external") mechanisms (Locat and Lee, 2002)
Also called **short-term triggers**

- oversteepening
- seismic loading (earthquakes)
- storm-wave loading
- rapid sediment accumulation and under-consolidation
- gas charging
- gas hydrate dissociation
- low tides
- seepage
- glacial loading
- volcanic island processes

importance of

short-term TRIGGERS against **pre-conditioning FACTORS**:

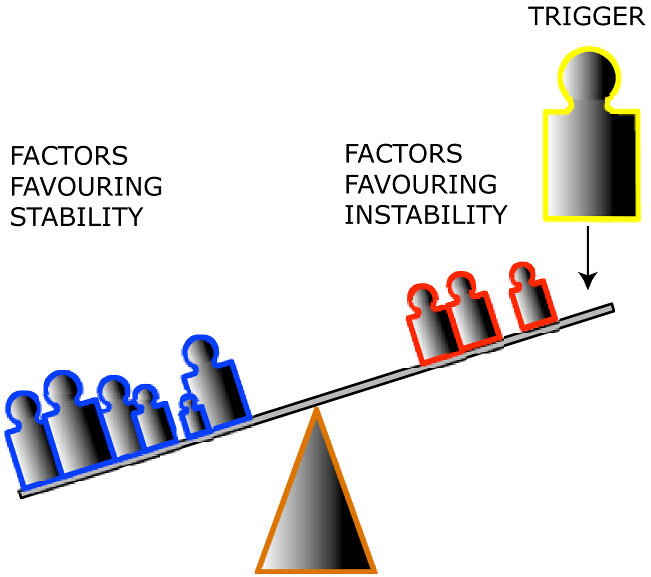


FACTORS FAVOURING STABILITY

FACTORS FAVOURING INSTABILITY

TRIGGER

F ≈ 1



FACTORS FAVOURING STABILITY

FACTORS FAVOURING INSTABILITY

TRIGGER

F >> 1

Marine sediment behaviour in response to a cyclic loading (earthquake)

During earthquakes, soil layers are subjected to **multi-directional cyclic stresses** with different amplitudes and frequencies that lead to **cyclic deformations** and to **changes in stress-strain and strength properties of soil layers**. Thus, the response of soil layers and the earthquake characteristics on the ground surface are affected from the **properties of soil layers**.

Decreasing sediment strength

and

Increasing sediment strength

Marine sediment behaviour in response to a cyclic loading (earthquake)

Decreasing sediment strength

- **Degradation** (weakening) of **soft** (normally consolidated) **clays** (cohesive) (e.g. Pestana et al., Soil Dynamics and Earthquake Engineering 19 (2000) 501-519):
    - degradation of the sediment stiffness (elasticity)
    - degradation of the shear strength (accumulation of plastic strain)
    - increase in shear-induced pore pressure (non-drained)

- Effective stress reduction and liquefaction of **loose**, **saturated granular sediment** (coarse silts and sands):
  Ground shaking produces compaction. Because the duration of the cyclic loading is too short to ensure the drainage of water, an increase in pore water pressure produces an equal magnitude decrease in the effective confining stress. If the vertical effective stress drops to zero then liquefaction occurs.

- Significant loss of strength in **clays** (cohesive):
  sensitive clays (high ratio between undisturbed and remoulded shear strength) may loos nearly entirely their shear strength after cycling loading and behave as liquefied soil (typically in terrestrial **quick clays**).

Increasing sediment strength
“seismic strengthening”

Repeated, **non-failure**, seismic events can actually strengthen the sediment column through development of excess pore-water pressures during earthquakes and subsequent drainage, resulting in a densification during intervening periods. (Locat and Lee (2000) Can. Geotech. J., 39, 193-212).

Back to the paradigma:

Even in the most studied submarine landslide, the relation to the earthquake activity is not so evident. Only a very strong, 10^{-4} yearly probability shock could have caused the failure of the slope of Storegga Slide.

Surely, not enough experience has been gained on the subject.

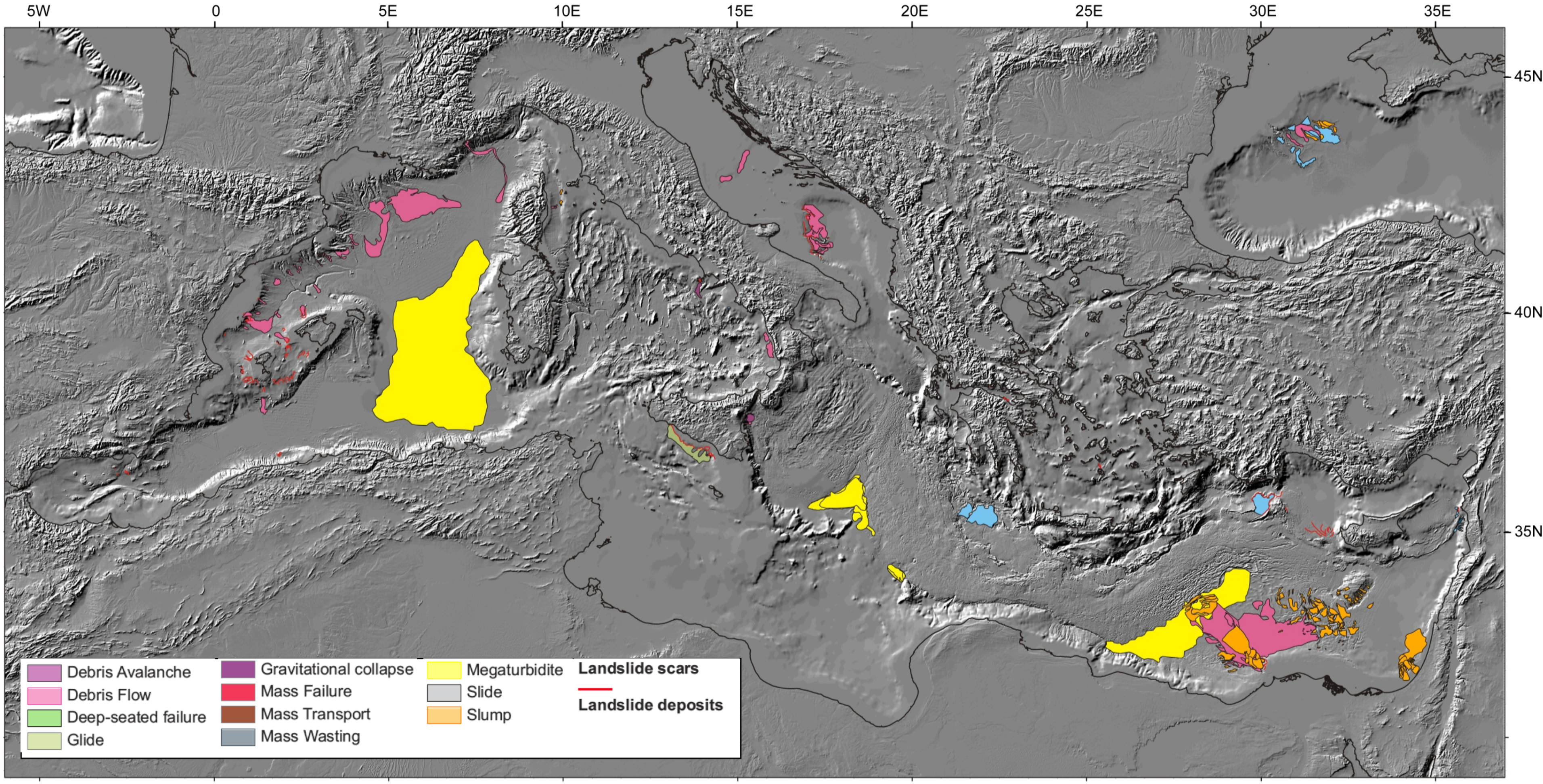
Now the Paradox:

The distribution of submarine landslides on present-day continental margins


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

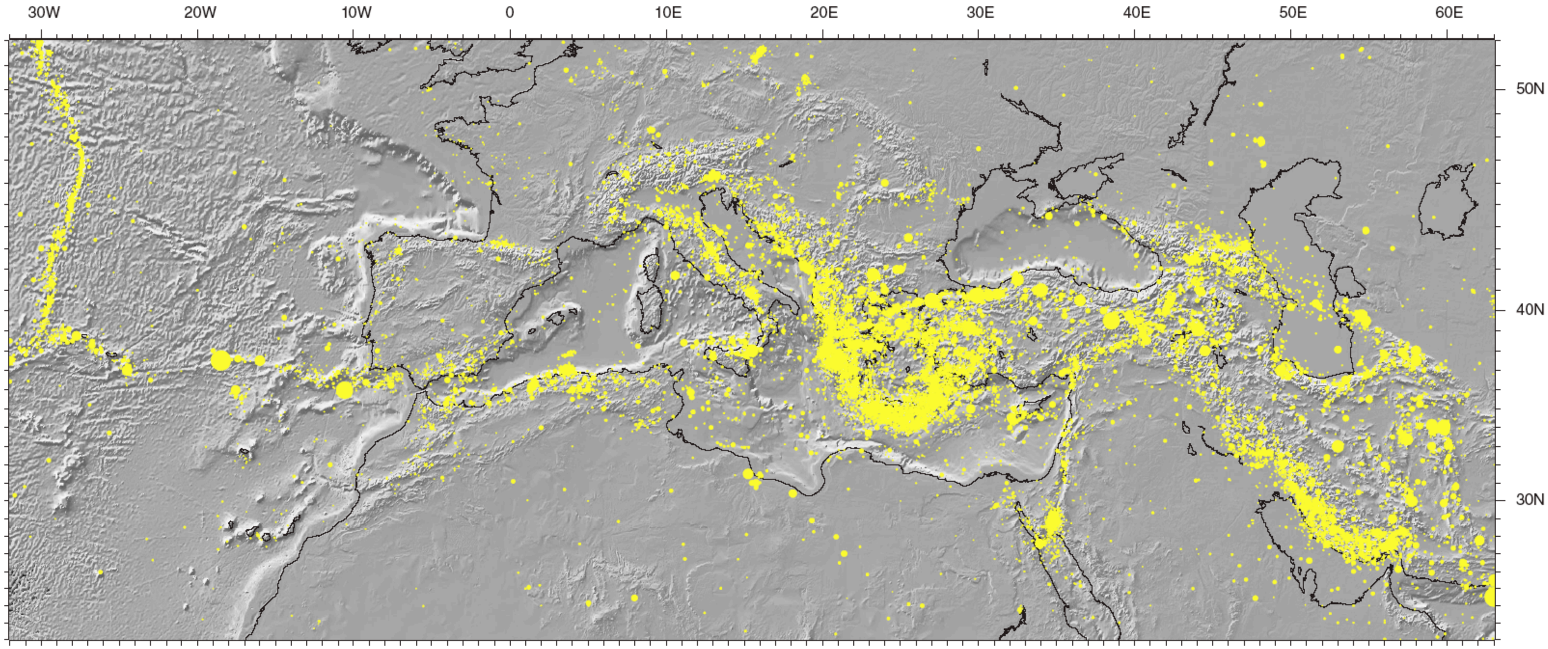
Case study: the Mediterranean Basin

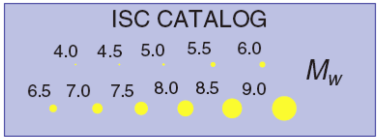
A database on submarine landslides of the Mediterranean Sea



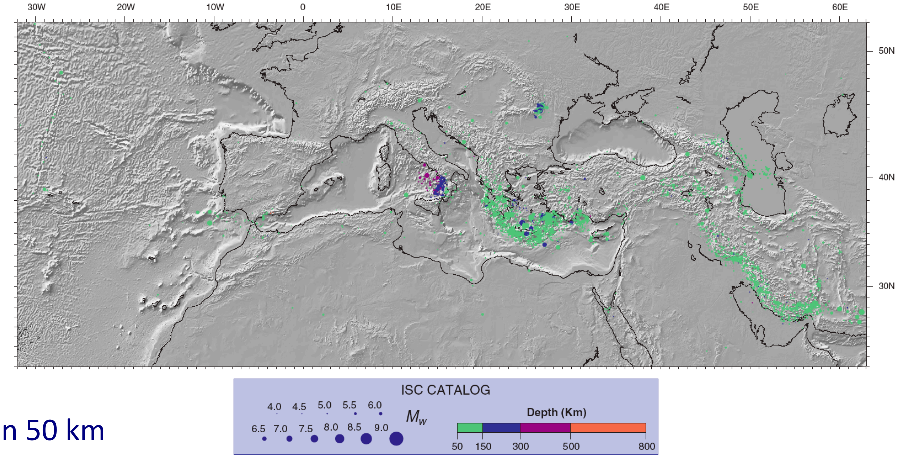
Camerlenghi, Urgeles, and Fantoni, 2009

Relation to geological setting and seismicicty.
Active and inactive margins.





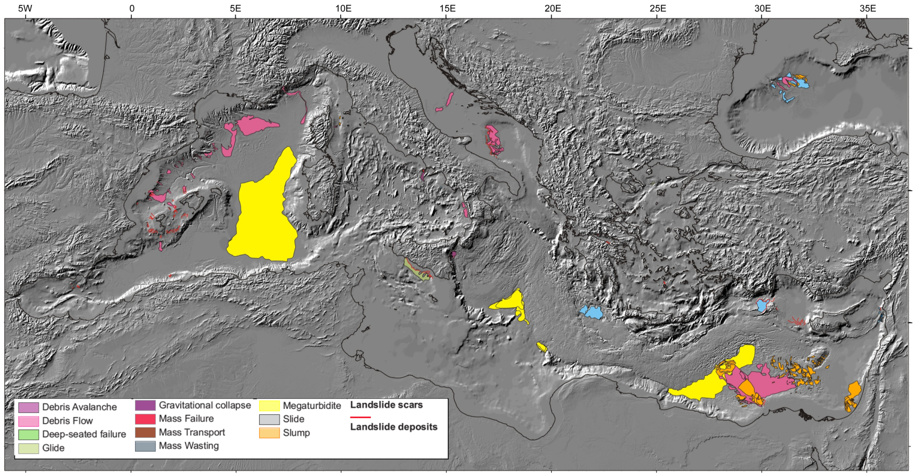
Shallower than 50 km



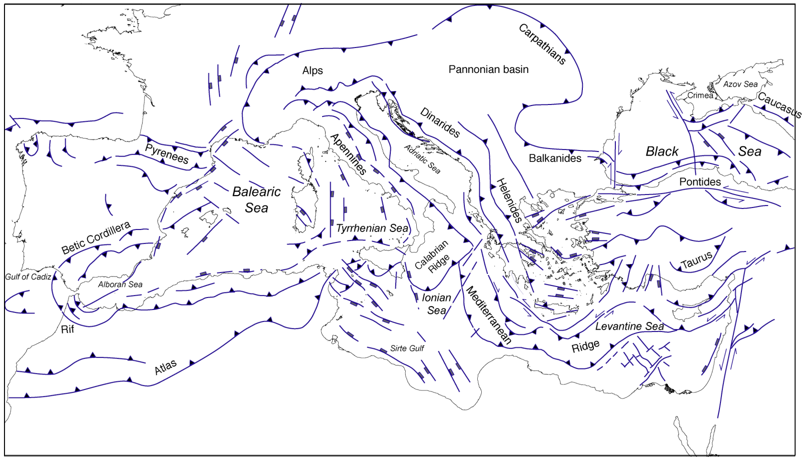
Deeper than 50 km

Vannucci, G. et al., 2004. An atlas of Mediterranean seismicity. Ann. Geophys. Suppl. V. 47(1),247- 306.

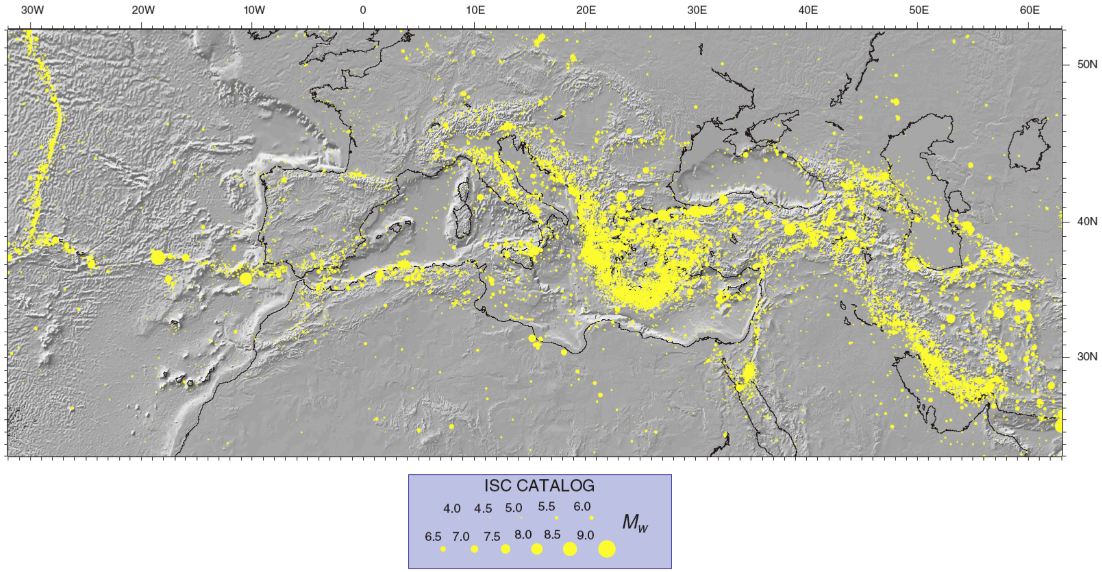
Relation to geological setting and seismicicty



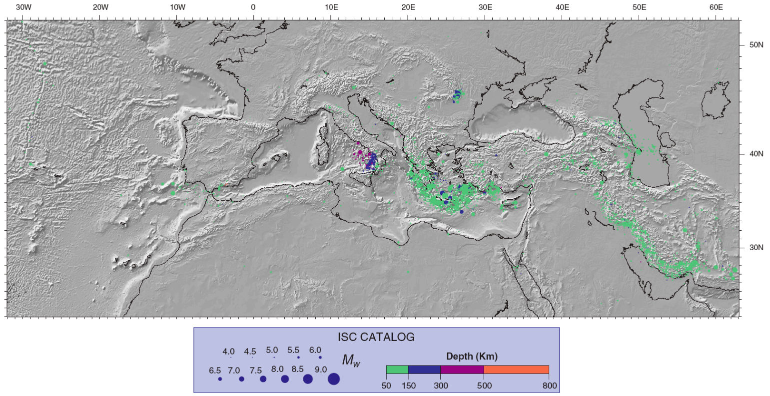
Camerlenghi, Urgeles, and Fantoni, 2009



Camerlenghi and Pini, 2009



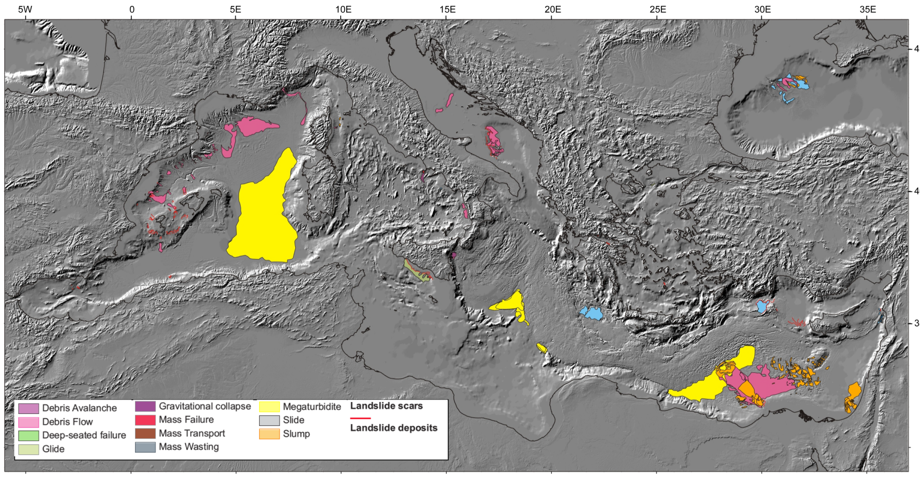
Shallower than 50 km



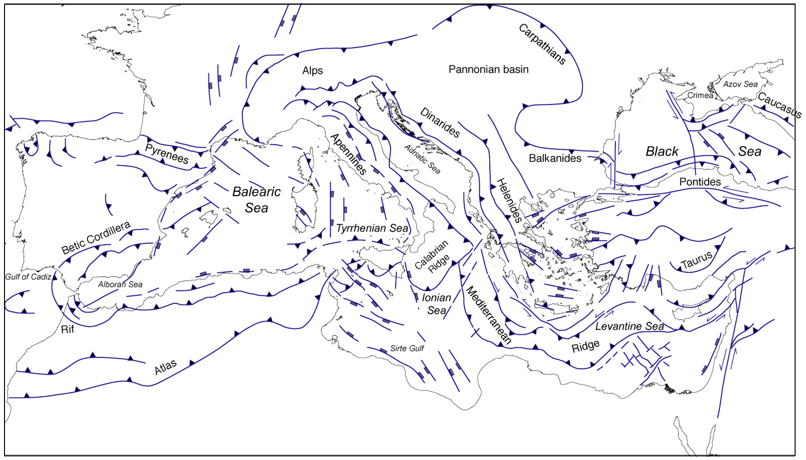
Deeper than 50 km

Vannucci, G. et al., 2004. An atlas of Mediterranean seismicity. Ann. Geophys. Suppl. V. 47(1),247- 306.

Relation to geological setting and seismicicty.
Present day deformation

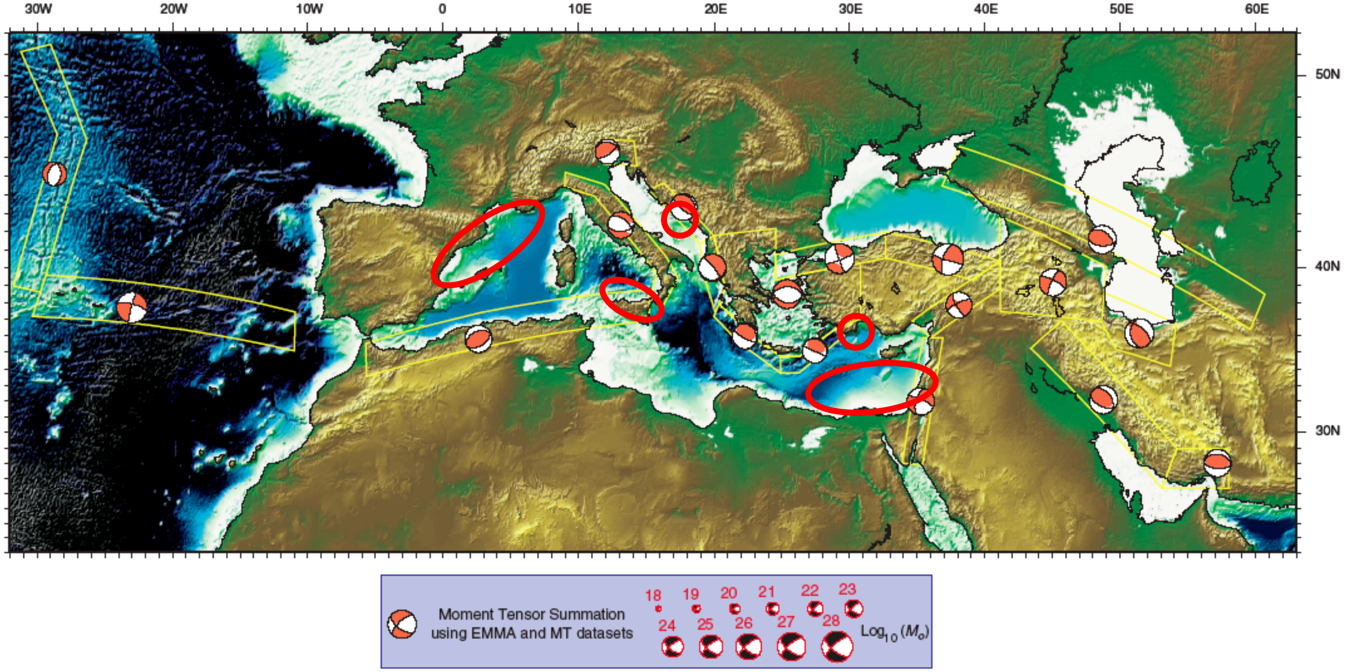


Camerlenghi, Urgeles, and Fantoni, 2009



Camerlenghi and Pini, 2009

Yellow boxes: main deformation areas.



The focal mechanism within each box represents the sum of moment tensors of earthquakes with depth < 50 km contained in the box.

Vannucci, G. et al., 2004. An atlas of Mediterranean seismicity. Ann. Geophys. Suppl. V. 47(1),247- 306.

Seismicity of passive margins

A significant **intraplate seismicity exist on passive margins**, that correspond to the transition between continental and ocean lithospheres.

Various processes have been proposed to explain long terms deformation affecting the structures:

- isostatic response due a loading/unloading (ice, sediment accumulation or removal),
- regional thermal adjustments,
- regional compression,
- ridge-push.

Type and magnitude of eartquakes are **variable**
Relatively **shallow**
Recurrence time is **long**

Deschamps et al., 2006, Seismicity of passive margins EUG amstract

US atlantic margin

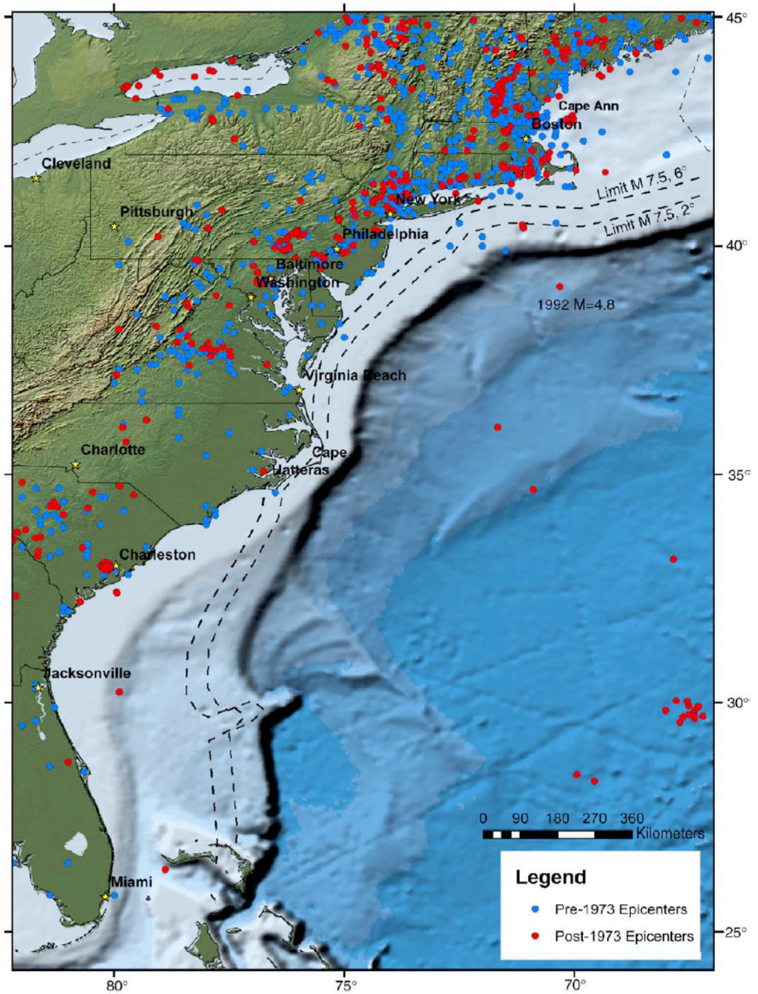
Relationships between the **sizes of submarine landslides** and **earthquakes recurrence intervals** to estimate the maximum sizes of submarine landslides and their recurrence.

Upper slope (≤6°) will be affected by earthquakes with magnitudes of 5.5, 6.5, and 7.5, only if the earthquakes occur at distances less than 14, 42, and 102 km from the upper slope, respectively.

Lower slope (≤2°), the distances are much smaller (i.e., 7, 28, and 62 km, respectively).

This analysis suggests that, with the exception of Cape Hatteras, only offshore earthquakes may be able to trigger submarine landslide-generated tsunamis.

Maximum predicted distances based on slope stability analysis, for an M7.5 earthquake, to cause a catastrophic failure of the continental slope with slope angles of 2° and 6°, respectively. Smaller magnitude earthquakes will have to be located closer to the continental slope to cause catastrophic slope failures.



ten Brink, U.S., et al., Assessment of tsunami hazard to the U.S. East Coast using relationships between submarine landslides and earthquakes, Mar. Geol. (2008), doi:10.1016/j.margeo.2008.05.011

Seismicity of active margins

Subduction zones produce roughly 60% of Earth's shallow earthquakes large enough to be detectible from distant seismic stations and more than 90% of the seismic moment release for such earthquakes

Seismic moment release in most subduction zones is typically heterogeneous depending on:

- existence and rate of backarc spreading
- thickness of incoming sediment layer
- convergence rate
- dip of subducting plate
- width of the seismogenic zone
- nature of interplate stresses,
- physical, chemical and hydrogeological properties.
- pore fluid pressures and permeabilities

Type and magnitude of eartquakes are **variable**
Also very **deep**
Recurrence time is **short**

Morgan et al., Workshop Report: Addressing Geohazards Through Ocean Drilling, (submitted, 2008), Scientific Drilling

Case study: the Oregon/Washington US margin

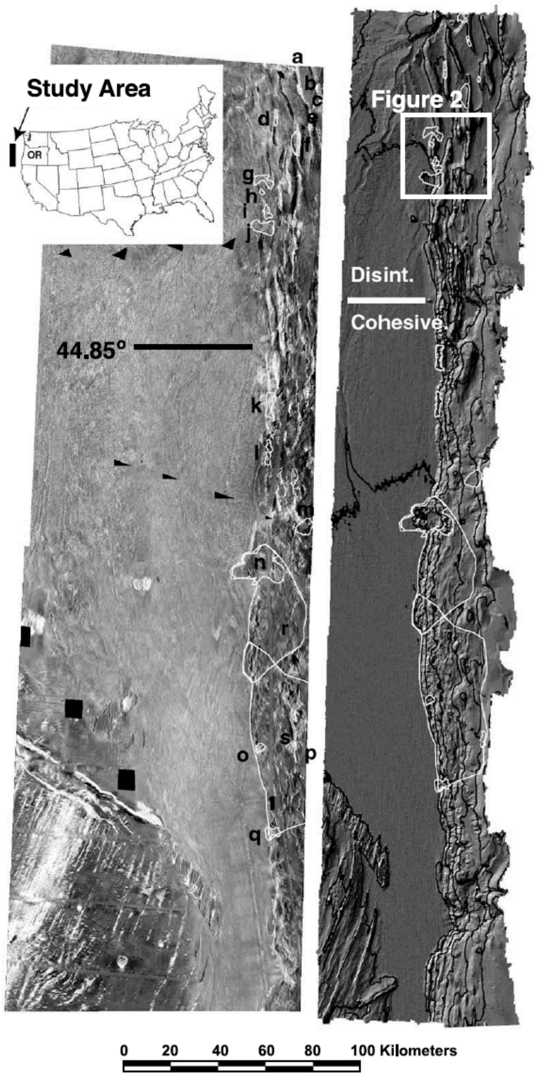
- Despite **large magnitude earthquakes**, the slopes of the northern Oregon margin in many places **have not failed** (*there is very little strong shaking a the base of the northern Oregon continental slope*.)

- Most of submarine landslides are **cohesive failures** (blocky landslides+slumps) in the seaward vergent section of the southern margin, only one is a large disintegrative failure.
The blocky landslides suggest failure of **overconsolidated** material.

- Cohesive landslides tend to have higher headscarps than the slides that lose cohesion, suggesting that they occur in **stronger sediment**, and have the potential to produce larger tsunamis.

- Offshore Oregon, most of the landslides occur on **slopes over 15º;** the failures on the steeper slopes tend to produce larger tsunamis, while on passive margins of the US landslides tend to occur on slopes less than 4º.

- There are **surprisingly few large failures** along the seismically active northern margin.



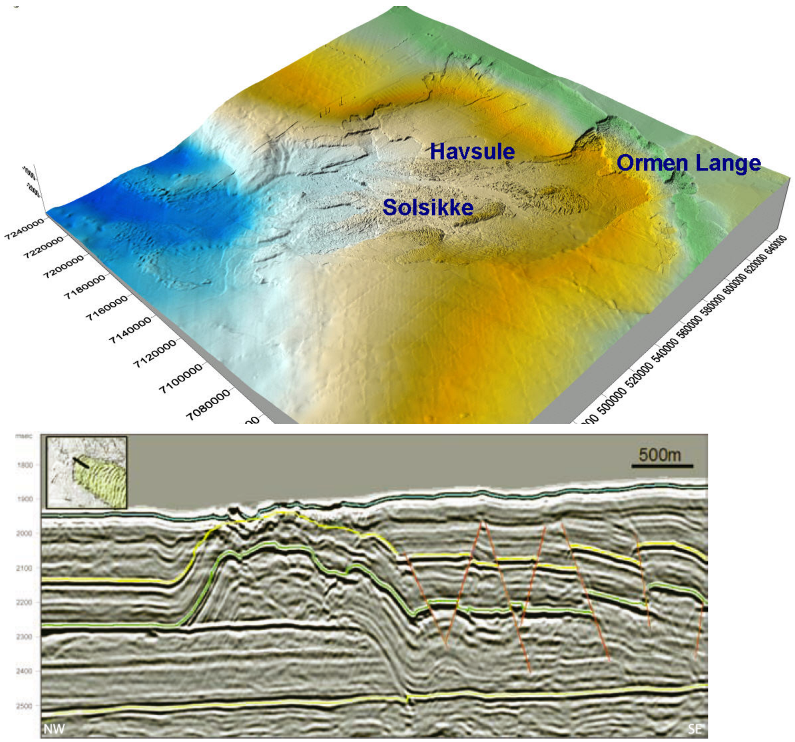
McAdoo and Watts, Tsunami hazard from submarine landslides on the Oregon continental slope (2004), Marine Geology, 203 235-245

Summary of the paradox

Throughout the geological history of a sedimentary basin, **earthquakes** are occur both inactive and passive continental margins, with depth of the depocenter and recurrence time being the main difference (not magnitude)

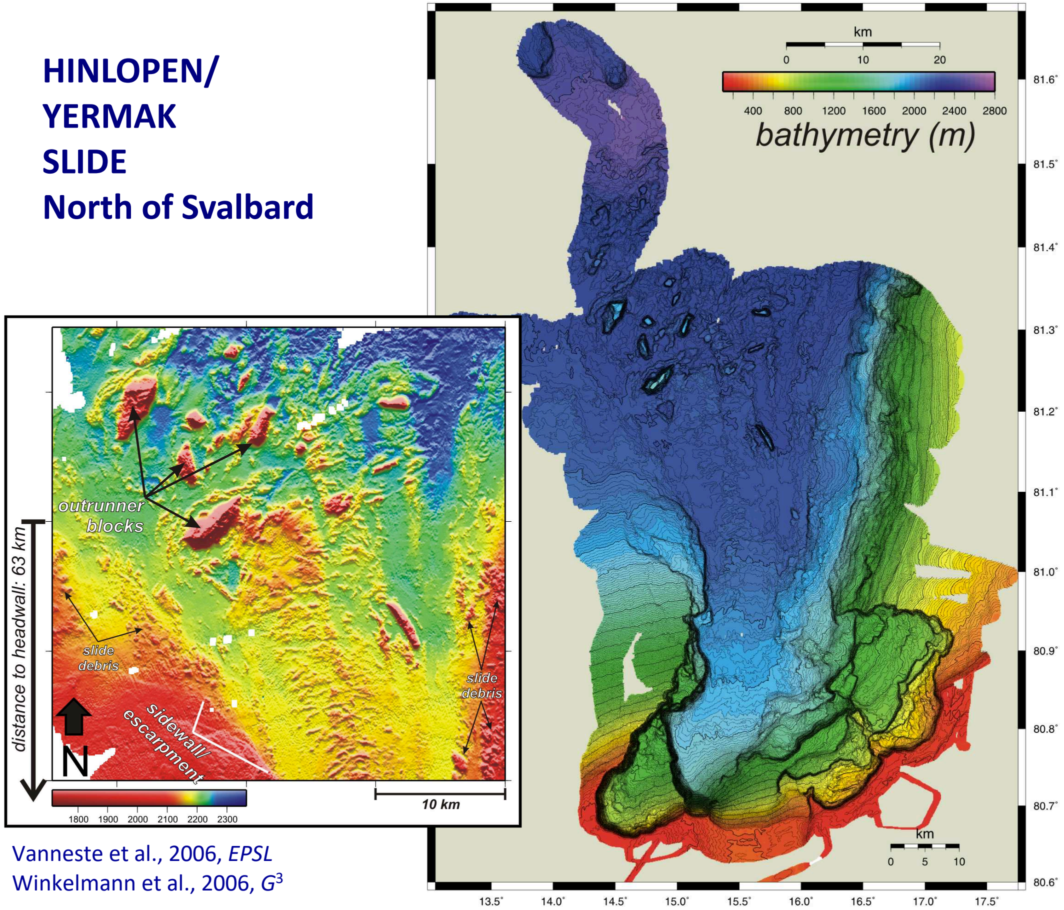
Case study analysis points out that recent **submarine landslides** are more numerous and are larger on passive continental margins.

STOREGGA SLIDE
Norwegian margin



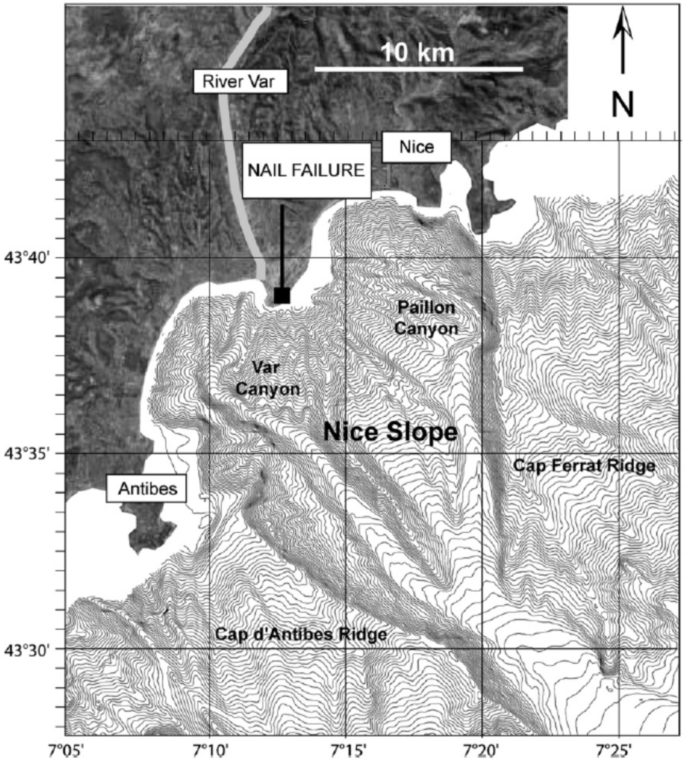
Færseth & Bjørn Helge Sætersmoen, 2008, *Norwegian J. of Geology*

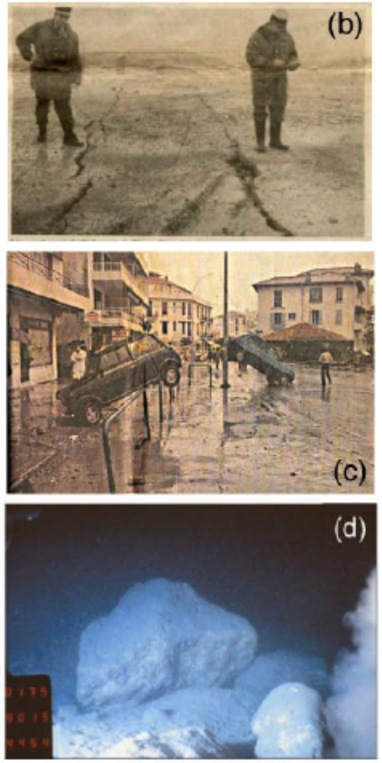
HINLOPEN/
YERMAK
SLIDE
North of Svalbard

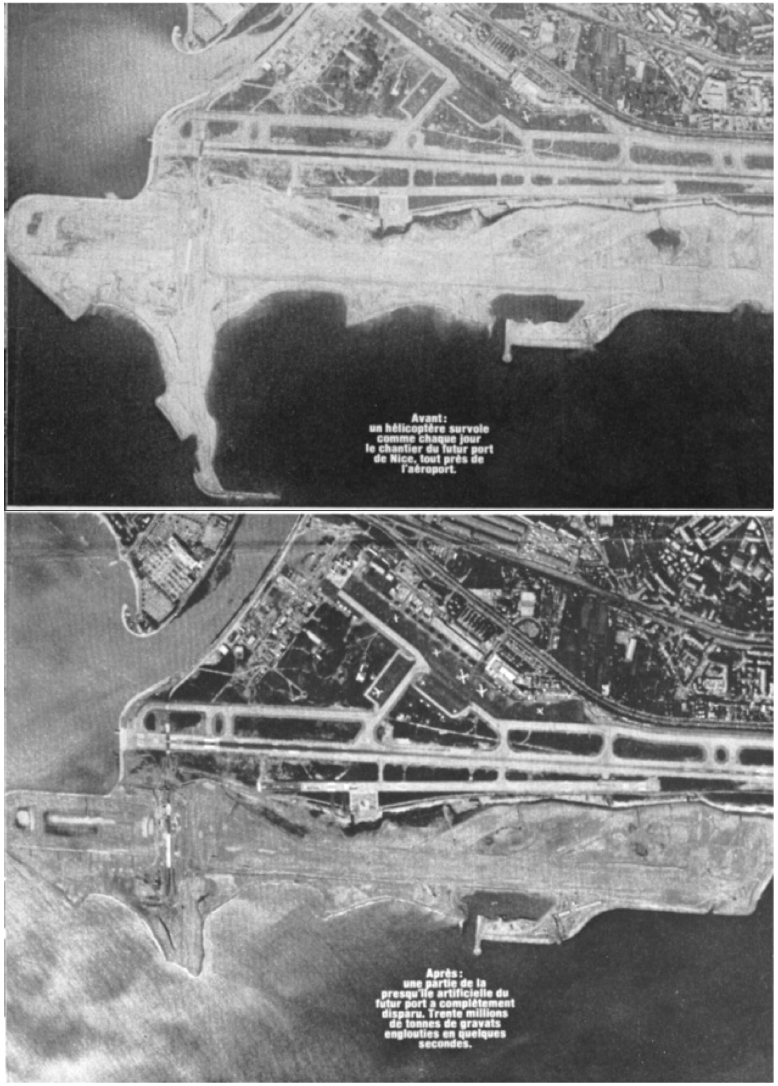


Vanneste et al., 2006, *EPSL*
Winkelmann et al., 2006, *G*^{3}

1979 October 16
Nice international airport submarine landslide



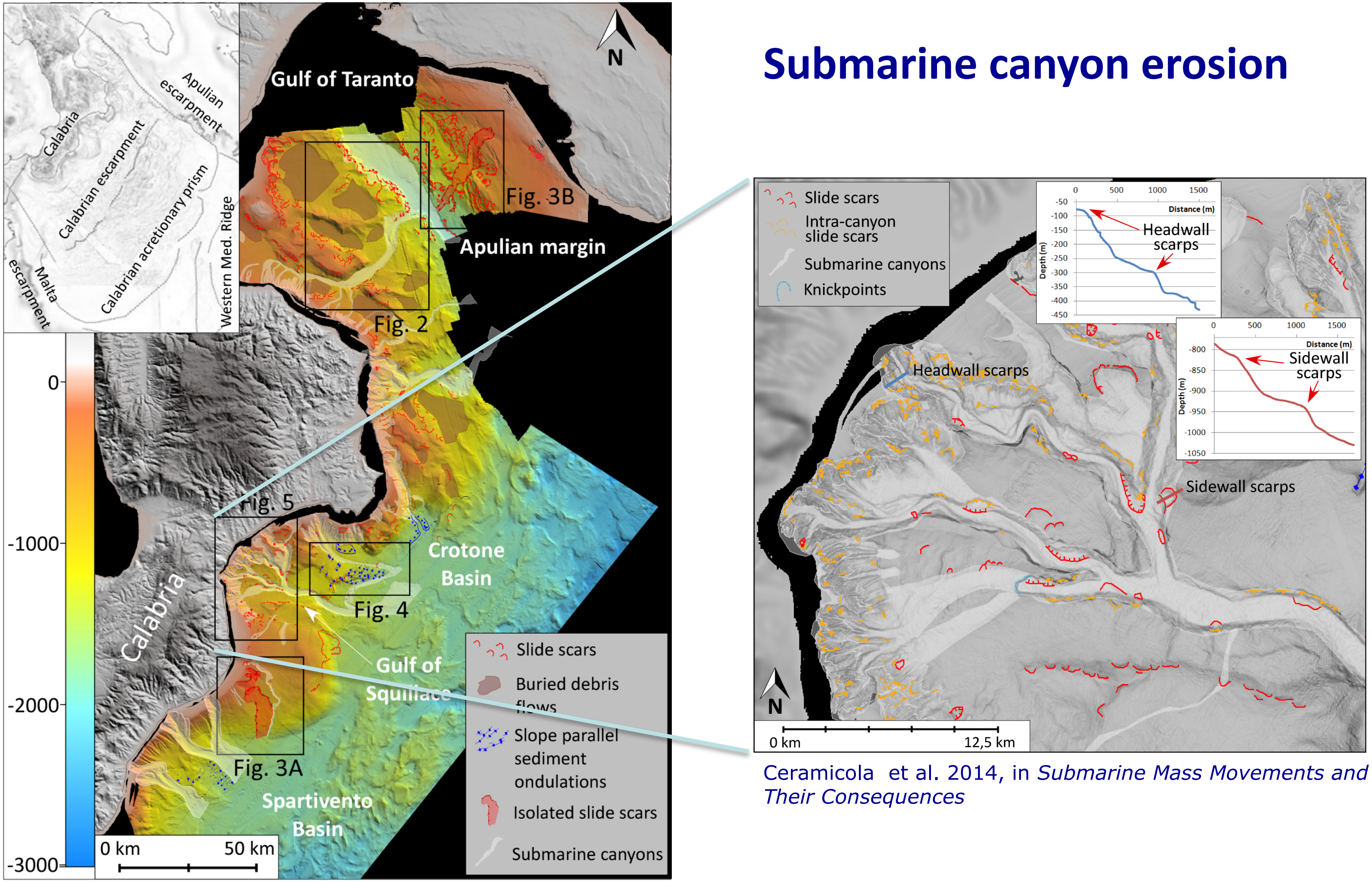



Avant :
un hélicoptère survole
comme chaque jour
le chantier du futur port
de Nice, tout près de
l'aéroport.

Après :
une partie de la
presqu'île artificielle du
futur port a complètement
disparu. Trente millions
de tonnes de gravats
englouties en quelques
secondes.

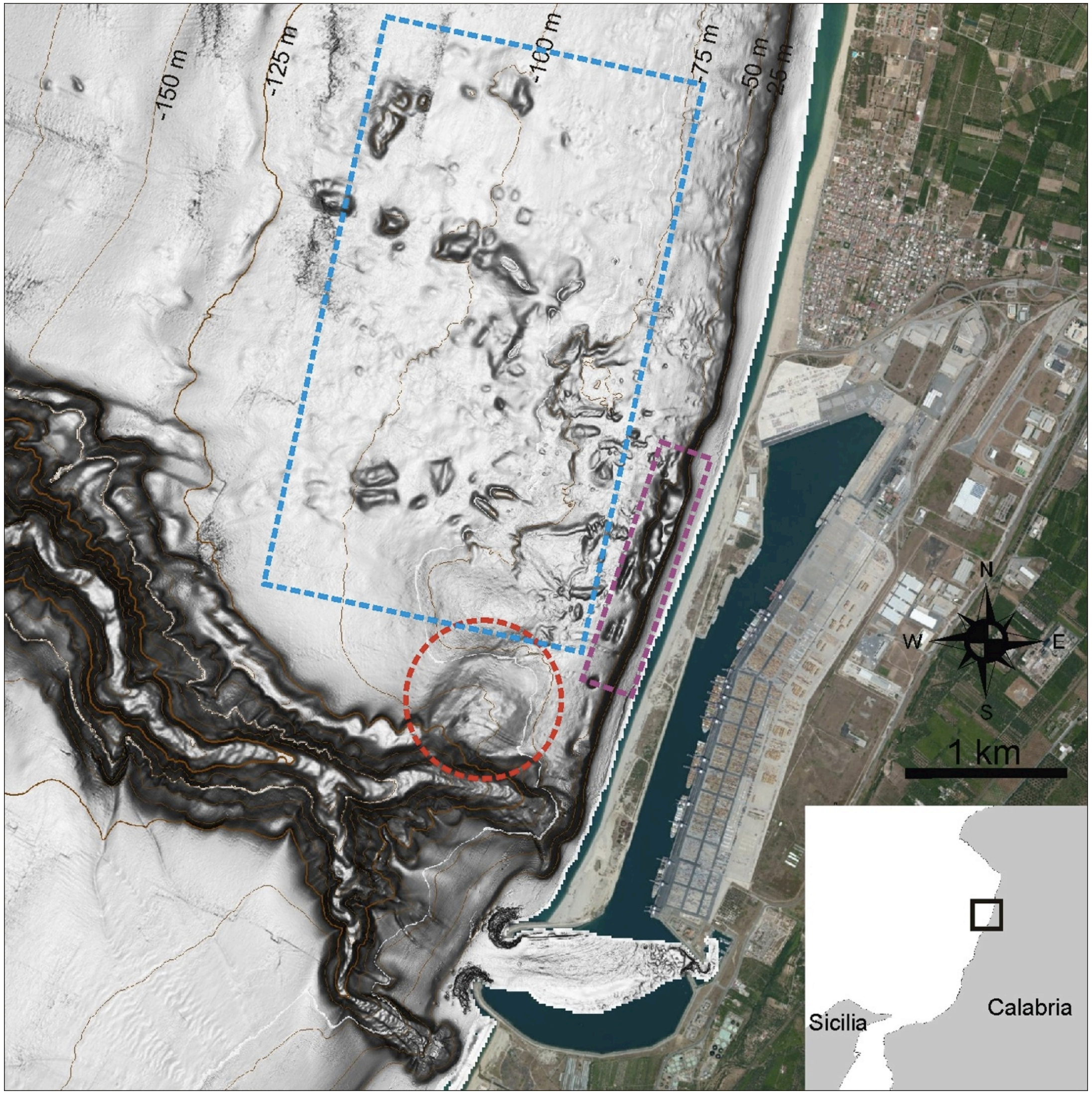
Seed et al., 1988

Submarine canyon erosion



Ceramicola et al. 2014, in *Submarine Mass Movements and Their Consequences*

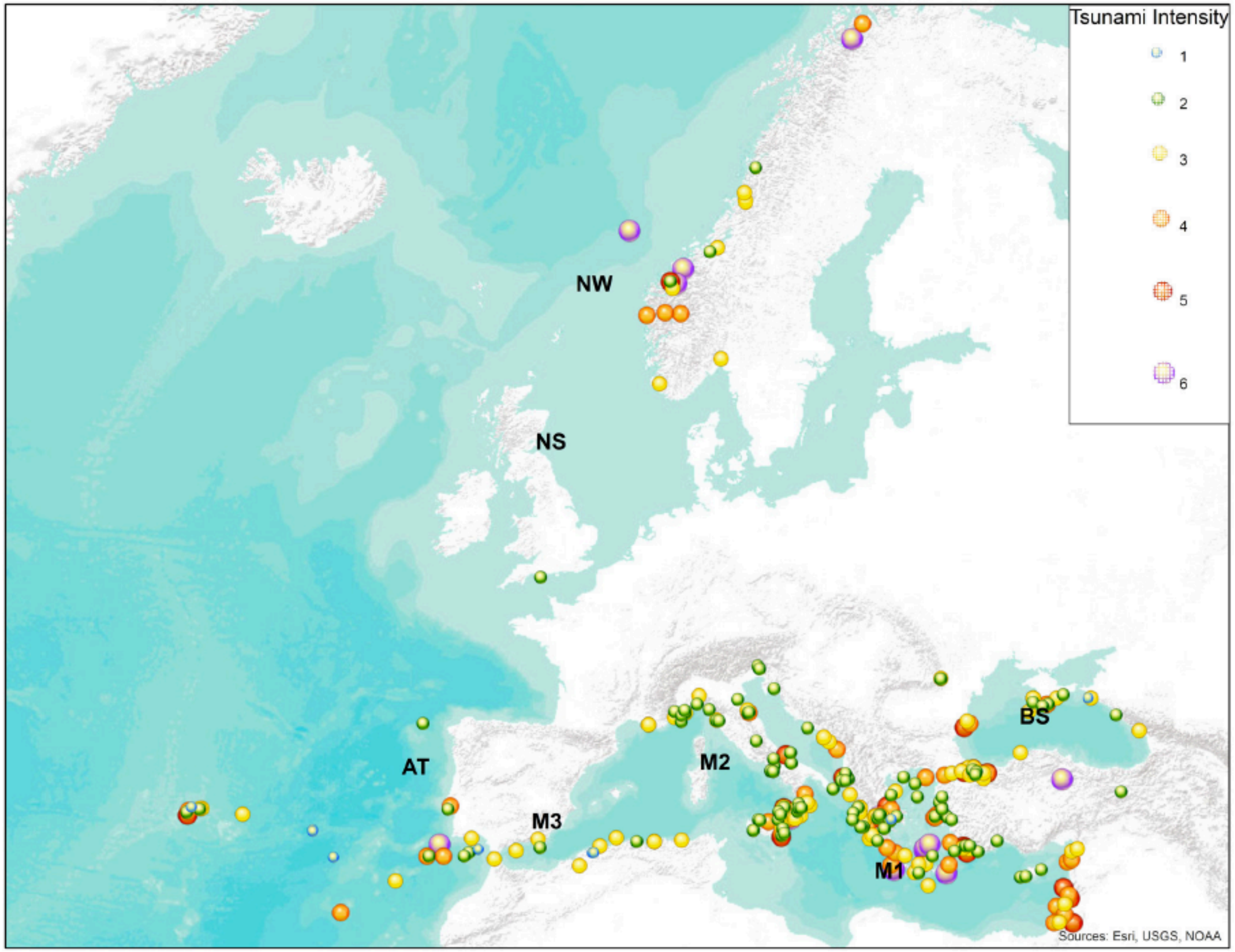
Turbidity-current erosion: Gioia Tauro seaport, Calabria



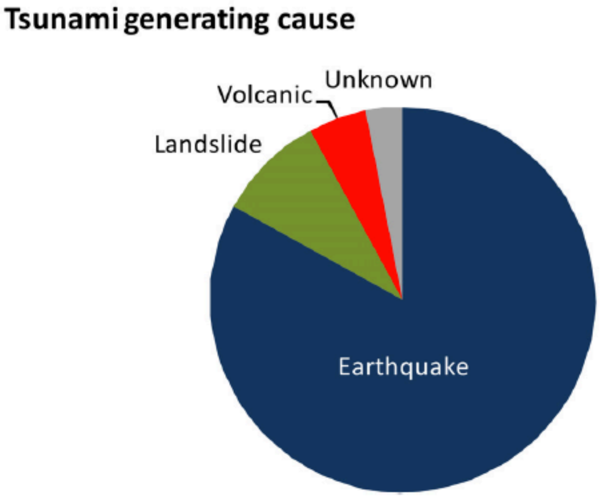
Casalbore et al., 2011, Hydto International.

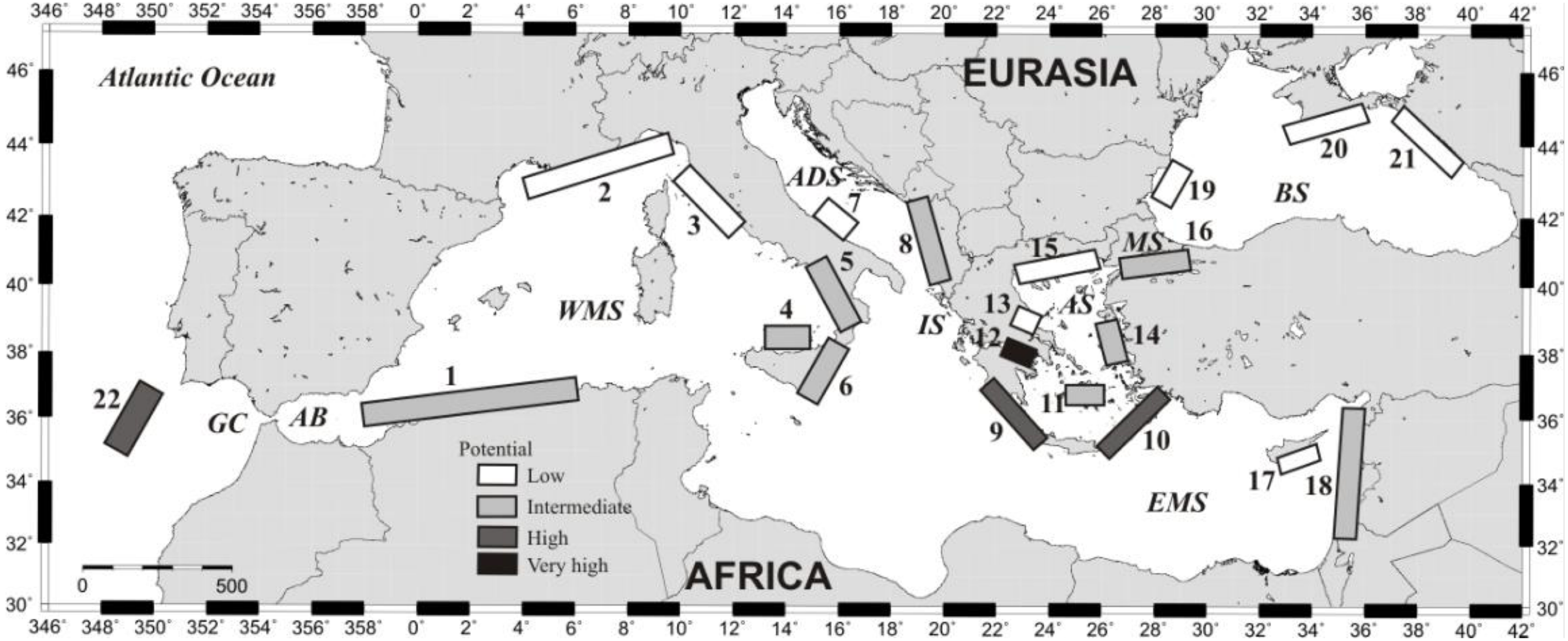
The Euro-Mediterranean Tsunami Catalogue
Alessandra Maramai, Beatriz Brizuela, Laura Graziani
ANNALS OF GEOPHYSICS, 57, 4, 2014, S0435; doi:10.4401/ag-6437S0435

290 tsunamis generated in the European and Mediterranean seas since 6150 B.C. to current days

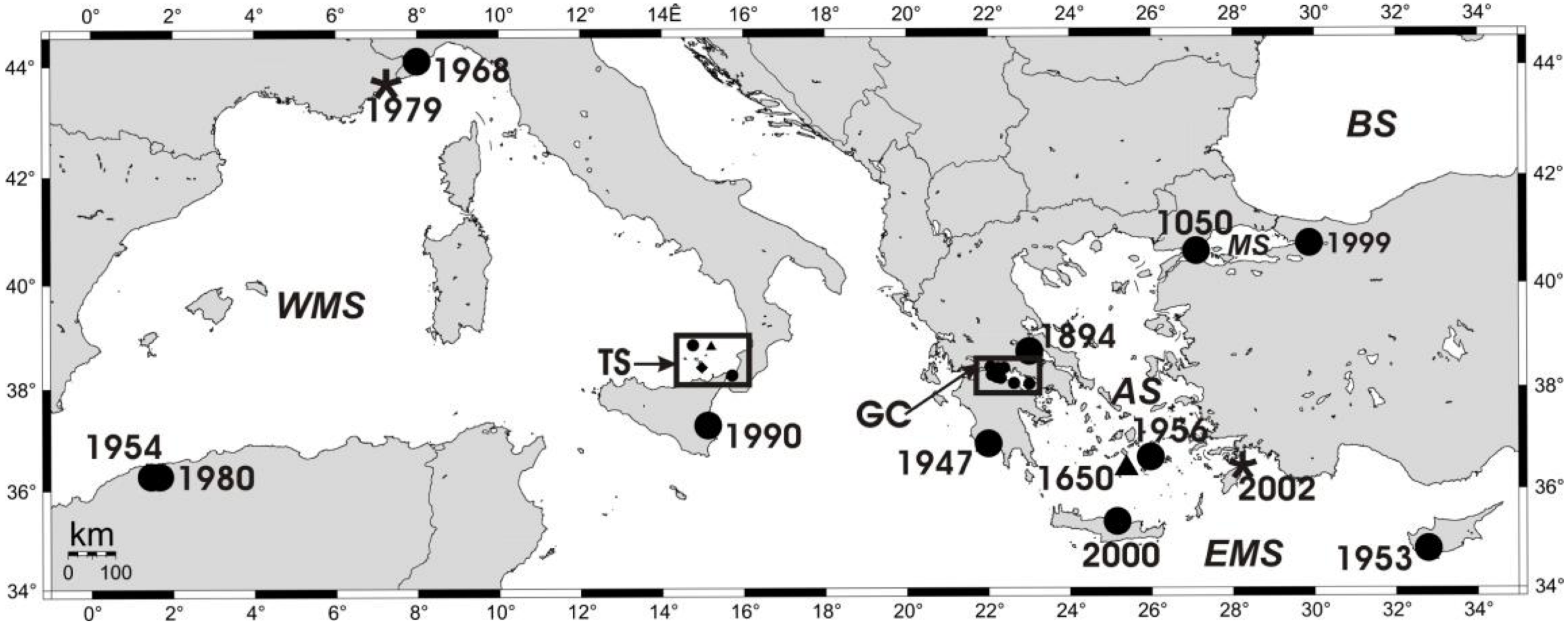


Sources: Esri, USGS, NOAA





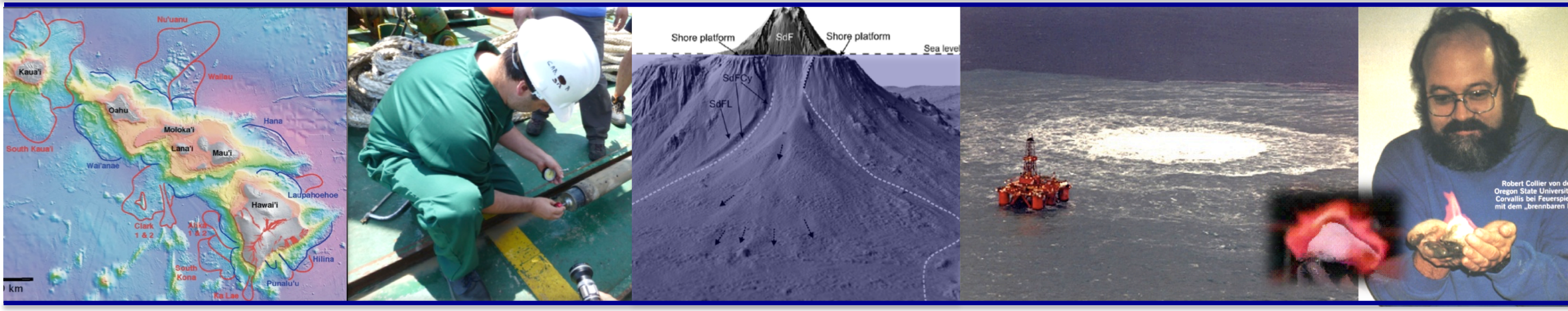
22 tsunamigenic zones and their relative potential for tsunami generation
Papadopulos et al., 2014. Marine Geology



Geographic distribution of landslide tsunami sources historically documented in the Mediterranean region.

Papadopulos et al., 2014. Marine Geology

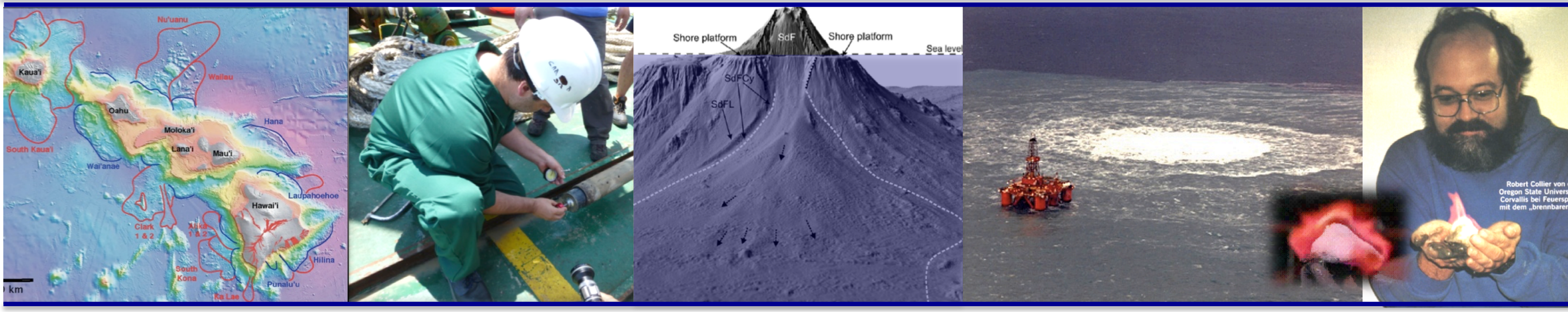
SUBMARINE GEOHAZARDS



CONCLUDING REMARKS (1/3)

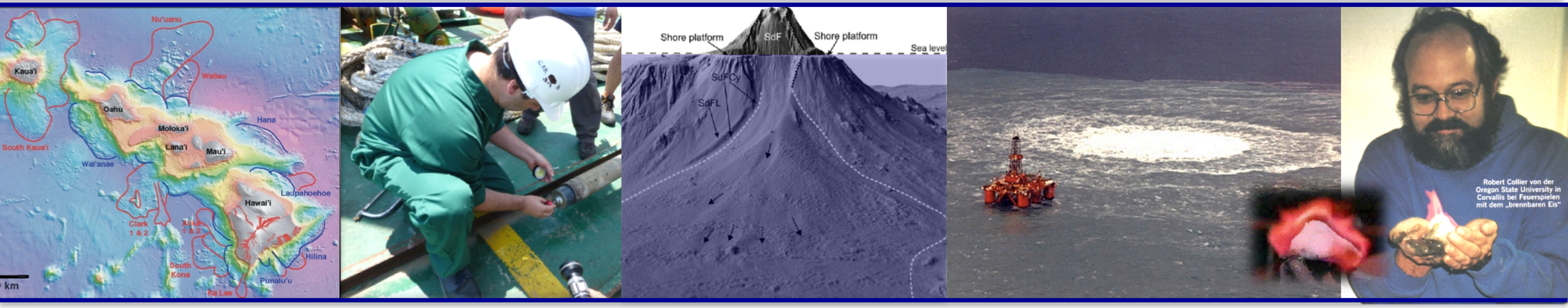
- THERE ARE THINGS MOVING DOWN THERE
- TECHNOLOGY HAS PERMITTED TO IDENTIFY GEOLOGICAL PROCESS ON THE SEAFLOOR THAT CAN BE DEFINED AS HAZARDS
- VULNERABILITY IS INCREASED DUE TO INCREASED USE OF THE SEAFLOOR

SUBMARINE



CONCLUDING REMARKS (2/3)

- CLIMATE CHANGE CAN INCREASE THE FREQUENCY AND MAGNITUDE OF CERAIN SUBMARINE GEOHAZARDS (GAS EMISSIONS AND SUBMARINE LANDSLIDES)
- UNDERSTANDING OF MECHANISMS IS STILL POOR
- THERE ARE UNCERTAINTIES ON RECURRENCE TIMES
- MAGNITUDE OF EVENTS IS EXTREMELY VARIABLE

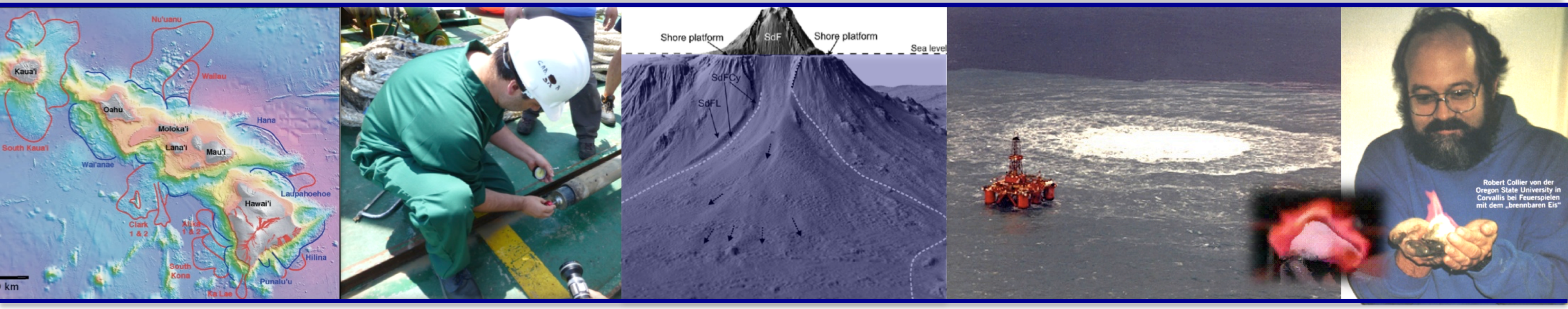


CONCLUDING REMARKS (3/3)

THERE IS A NEED FOR IMPROVED KNOWLEDGE!

Which means bright students in oceanography earth science, geophysics, engineering, biology, chemistry

SUBMARINE



Camerlenghi, A. and Pini, G.A., 2009. **Mud volcanoes, olistostromes and Argille scagliose in the Mediterranean region**. *Sedimentology*, 56, 319–365 doi: 10.1111/j.1365-3091.2008.01016.x

Morgan, J., Silver, E., Camerlenghi, A.**,** Dugan, B., Kirby, S., Shipp, C., and Suyehiro, K., 2009. **Addressing Geohazards Through Ocean Drilling**. *Scientific Drilling*, 7, 25-30. doi:10.2204/iodp.sd.7.01.2009

Urgeles, R., and Camerlenghi, A., 2013. **Submarine landslides of the Mediterranean Sea: Triggermechanisms, dynamics, and frequency-magnitude distribution**. *Journal of Geophysical Research*, 118, 1–19, doi:10.1002/2013JF002720.

Papadopoulos, G.A., Gràcia, E., Urgeles, R., Sallares, V., De Martini, P.M., Pantosti, D., González, M., Yalciner, A.C., Mascle, J., Sakellariou, D., Salamon, A., Tinti, S., Karastathis, V., Fokaefs, A., Camerlenghi, A., Novikova, T., Papageorgiou, A., 2014**. Historical and pre-historical tsunamis in the Mediterranean and its connected seas: Geological signatures, generation mechanisms and coastal impacts**. Marine Geology, Volume 354, 81-109. doi: 10.1016/j.margeo.2014.04.014