Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

Università degli studi di Trieste

LAUREA MAGISTRALE IN GEOSCIENZE

Classe Scienze e Tecnologie Geologiche

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Analisi di Bacino e Stratigrafia Sequenziale (426SM)

Docente: **Michele Rebesco**

Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

Modulo 3.4 – Mass-transport deposits

Docente: **Jonathan Ford**

Outline:

Part 1: **Subaqueous mass-movements and their deposits**

Break

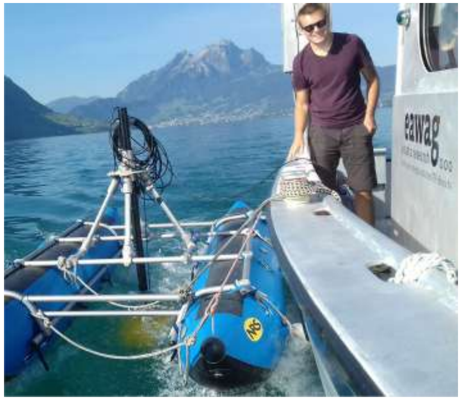
Part 2: **Geophysical imaging of mass-transport deposits**

Objectives:

1. Introduce mass-movements and MTDs and their scientific and societal relevance
2. Understand the architecture of MTDs and how this is reflected in geophysical and outcrop data
3. Explore the challenges and limitations of geophysical imaging of MTDs, and some future directions for geohazard research

Background: Jonathan Ford

- From Manchester, UK
- PhD in Geophysics from University of Trieste
- Currently: post-doc researcher at OGS (Geophysics Section)
  - Seismic characterisation of mass transport deposits
  - Geostatistics
  - Seismic modelling and inversion
- Email: jford@inogs.it

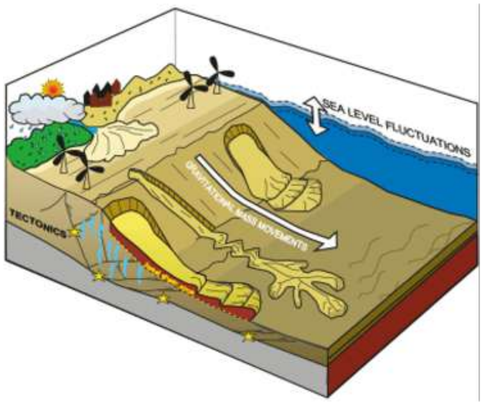


Lake Lucerne, Switzerland

Specchio Unit, Northern Appenines

Subaqueous mass-movements and their deposits

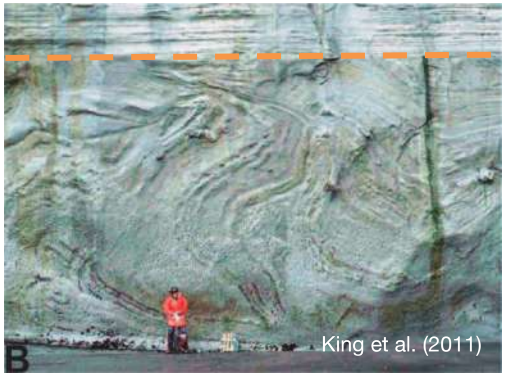
Subaqueous mass-movement



= downslope, gravity-driven transport of previously consolidated sediments

- e.g., submarine landslides, creep, slumps, debris/turbidity flows*
- underwater, slope environment: seas, lakes, rivers, fjords

Mass-transport deposit (MTD)

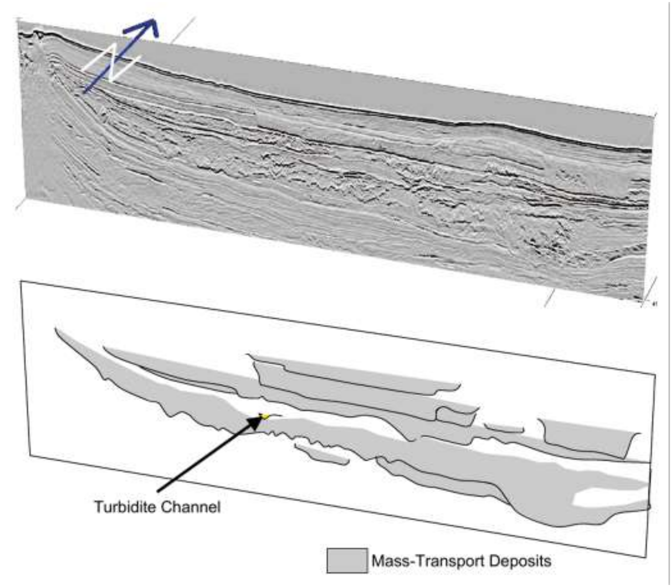


= single mass-movement preserved in the sedimentary record

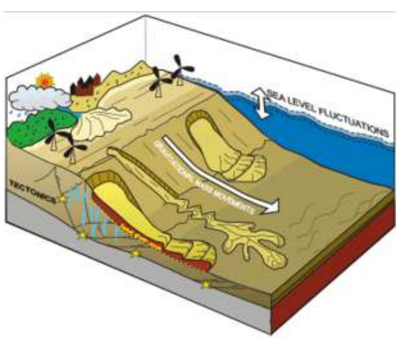
- Re-deposition: often significantly deformed, reworked, lithological changes
- Across many scales, up to megaslides >1000 km^3 volume

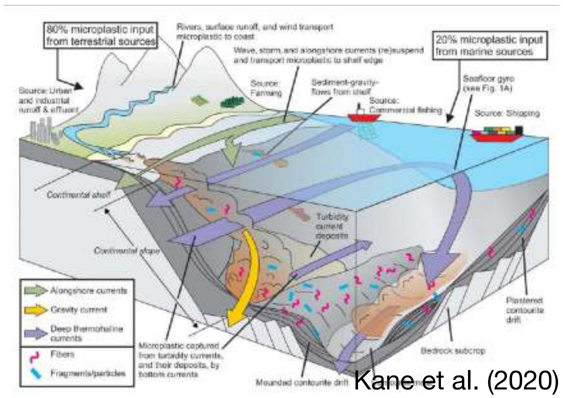
Why study subaqueous mass-movements?

1. MTDs = large-scale, ~instantaneous events in the sedimentary-stratigraphic record:
    - Paleo-seismology (earthquakes)
    - Paleo-climatology (sea level rise/fall)
    - Basin reconstruction
2. Significant sediment pathway from continental shelf to deep ocean:
    - Large % of deep-water basin sediment fill
    - Organic carbon, microplastics
    - Hydrocarbons: MTDs can form source, seal and reservoir material
3. **<u>Submarine geohazards</u>**



Gulf of Mexico, ~3000 m water depth (Posamentier and Martinsen, 2011)



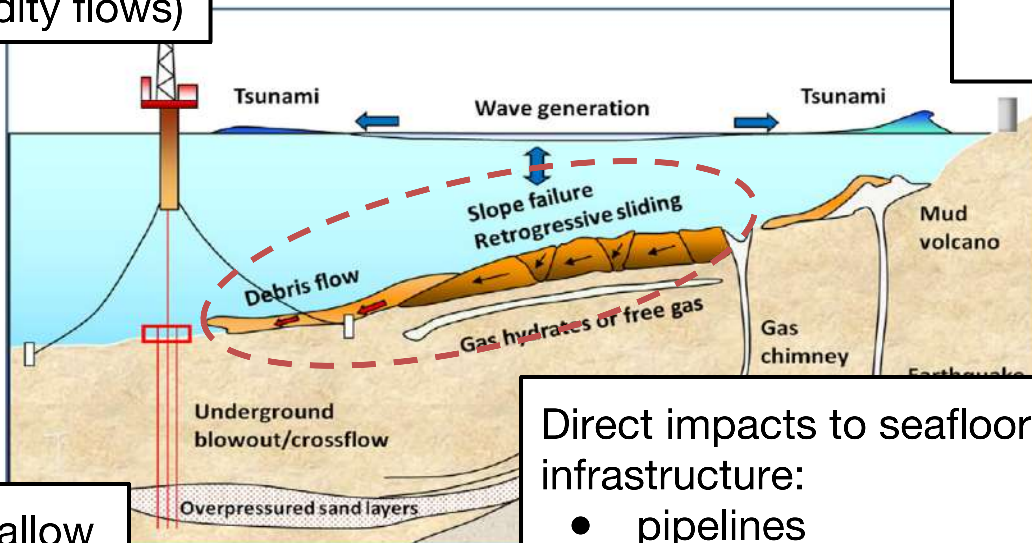


Kane et al. (2020)

Mass-movements as submarine geohazards

Trigger secondary mass-flows (debris flows, turbidity flows)

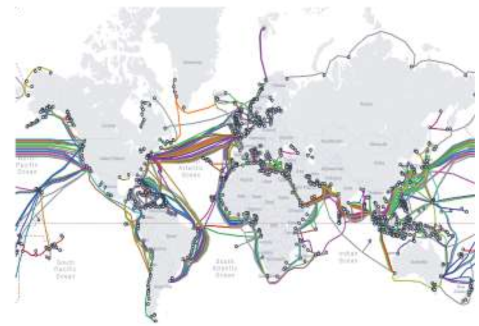
Tsunami: can be on a scale comparable to the largest earthquake generated tsunami



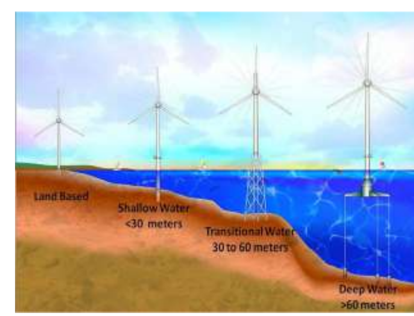
MTDs = shallow drilling hazards

Direct impacts to seafloor infrastructure:

- pipelines
- telecommunications cables
- offshore wind farms



https://www.submarinecablemap.com/



https://commons.wikimedia.org/wiki/File:Foundations_NREL.jpg

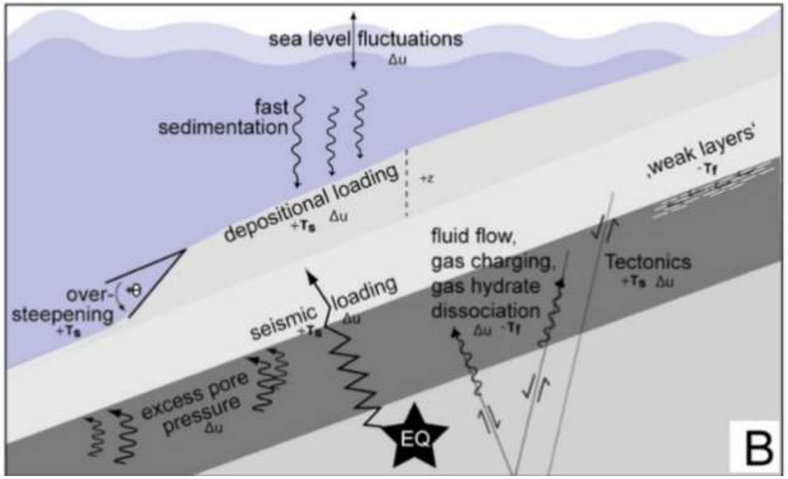
Key differences observed compared to terrestrial mass-movements:

- failures on much lower slope angles (<1°)
- much longer runout lengths (>100 km)
- much larger area/volume of sediment

What controls the stability of submarine slopes?

- Slope failure occurs when downslope shear stresses overcome the shear strength of the sediments
- Either increase the stress (eg rapid sedimentation, slope steepening) or reduce the strength (eg cyclic loading from earthquakes)

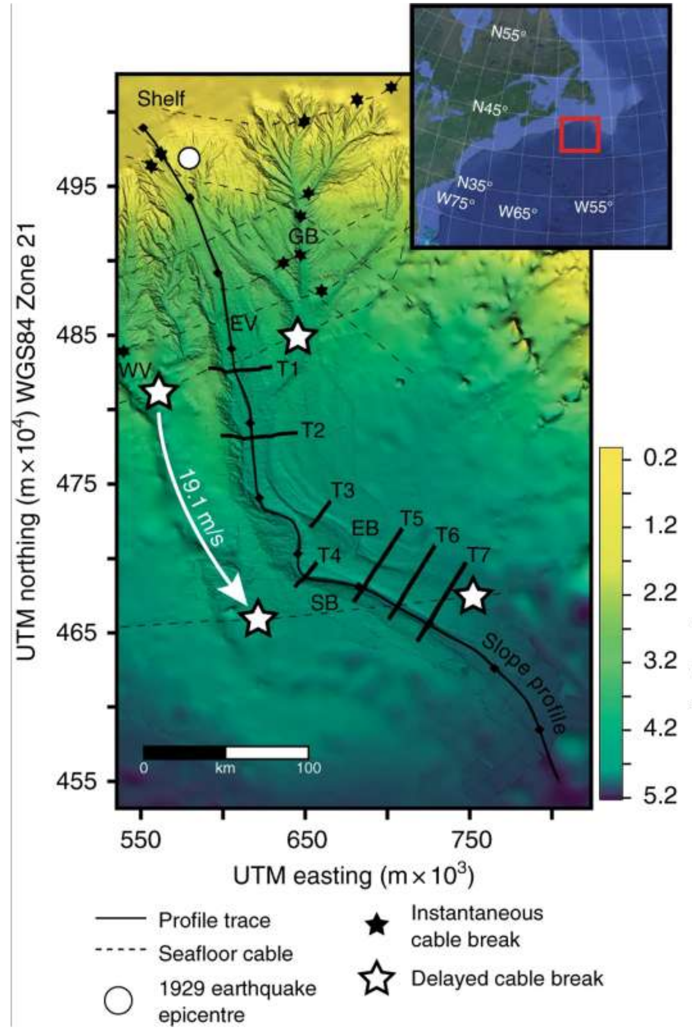
- Often very difficult to isolate specific triggers and pre-conditioning factors for individual events: this is one of the primary goals of geohazard characterisation



Triggers for slope failure	Pre-conditioning factors
Earthquakes	High sedimentation rate
Wave loading/tides	Erosion
Gas hydrate dissociation	Slope steepening (tectonics, diapirism)
	Excess pore-pressure/fluid flow
	Weak layers

Case study: Grand Banks (1929)

- M_w 7.2 earthquake offshore Newfoundland, Canada
- Landslide + secondary debris flows/turbidity currents
  - Associated tsunami -> 28 deaths
  - Total volume of failed sediment estimated at ~100 km^3
- Caused progressive cable breaks downslope for >1000 km from continental slope to abyssal plain
- First evidence of existence of destructive underwater "sediment avalanches" (now called turbidity currents)



Stevenson et al. (2018)

<u>Aside:</u> sub-sea telecommunication cables now carry >95% of global internet traffic - mass-movements are an important consideration when locating new cables in slope environments

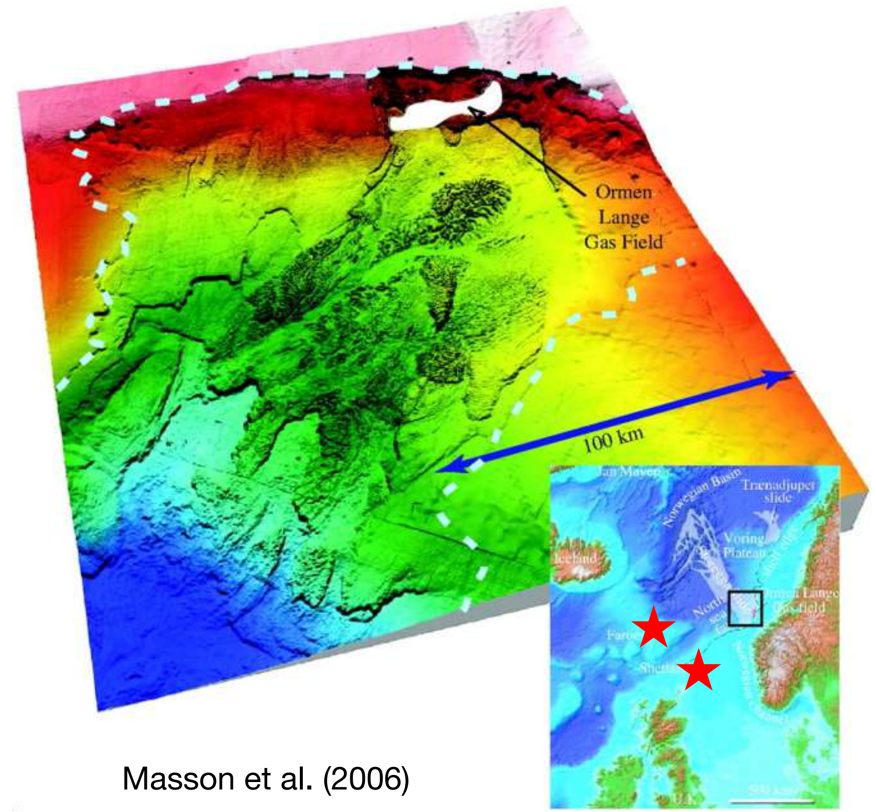
Case study: Storegga megaslide

Evidence in geological record of megaslides and associated basin-scale tsunami:

- Storegga event(s) ~8200 ka
- Displaced >3000 km^3 sediment on Norwegian continental slope
- Runup heights 3-5 m recorded in the Faroe and Shetland Islands

“Modern” examples of tsunami induced by submarine landslides:

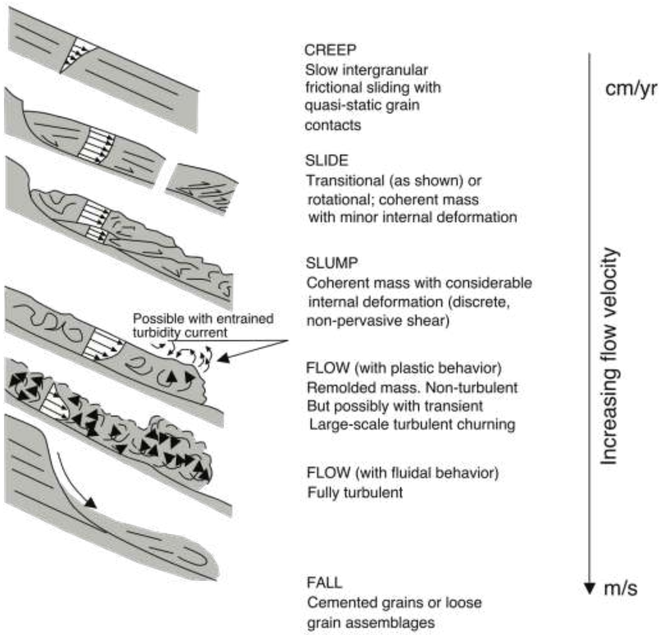
- 1964 Alaska earthquake (M_w 9.2) + landslides
- 1998 Papua New Guinea
- 2011 Tohoku
- 2018 Palu, Indonesia

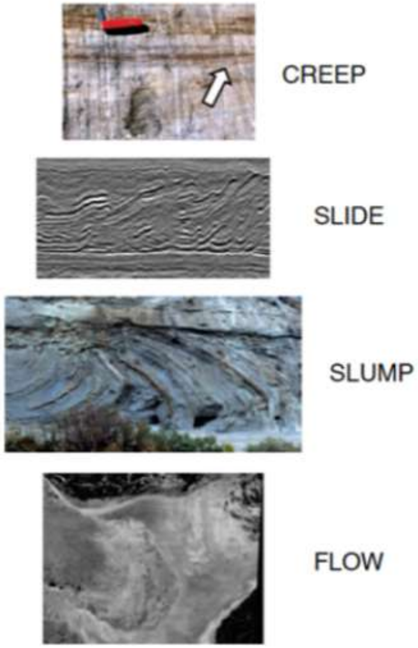


Masson et al. (2006)

★ Tsunami deposits

Classification of subaqueous mass-movements





Steventon (PhD thesis, 2020)

- Mass-movement processes are diverse, complex, strongly linked to flow velocity (ie geohazard potential)
- MTDs *can* preserve evidence of flow type/velocity (kinematic indicators), but not always possible to identify from deposits alone
- Individual events can show characteristics of <u>multiple</u> flow types

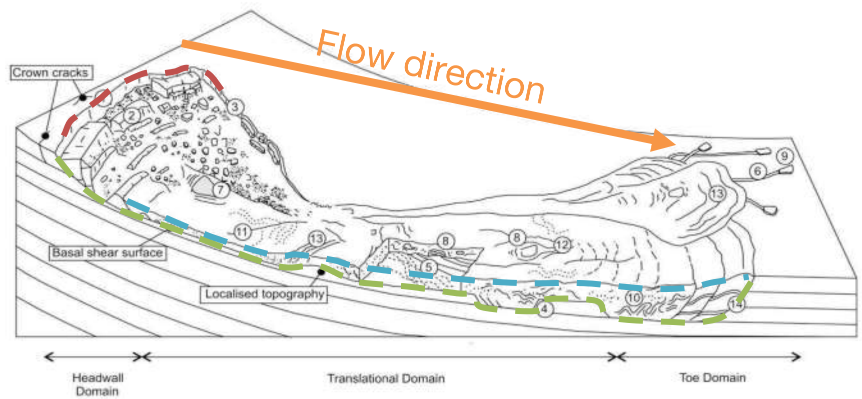
MTDs are complex, heterogeneous, often difficult to classify

Anatomy of a mass-transport deposit

Common structural elements:

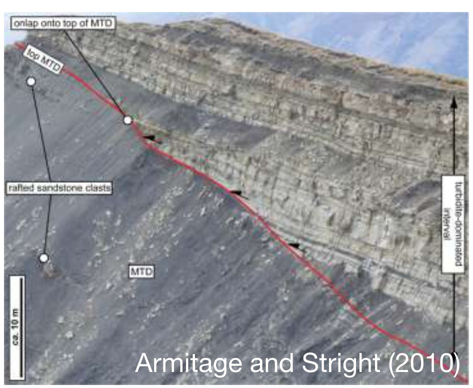
- Headscarp (and evacuated zone)
- Top surface: rough topography, pressure ridges
- Basal shear surface:
  - Often erosive
  - Can form along pre-existing interfaces or weak layers (eg ash layers)
  - “Ramp-and-flat” topography common
- Steep lateral margins (shear zones)
- Headwall, translational and toe domains
- Internal structure: complex and heterogeneous!

Stylised submarine landslide deposit (Bull et al., 2009)



Extension → **Compression**

Important: MTDs can look very different depending on eg sediment properties, flow type, post-failure dynamics, preservation



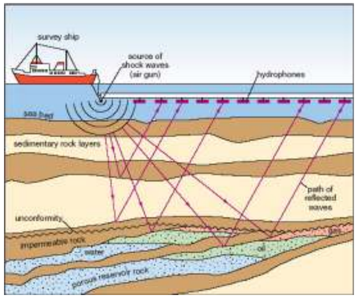
Armitage and Stright (2010)


https://twitter.com/zanejobe

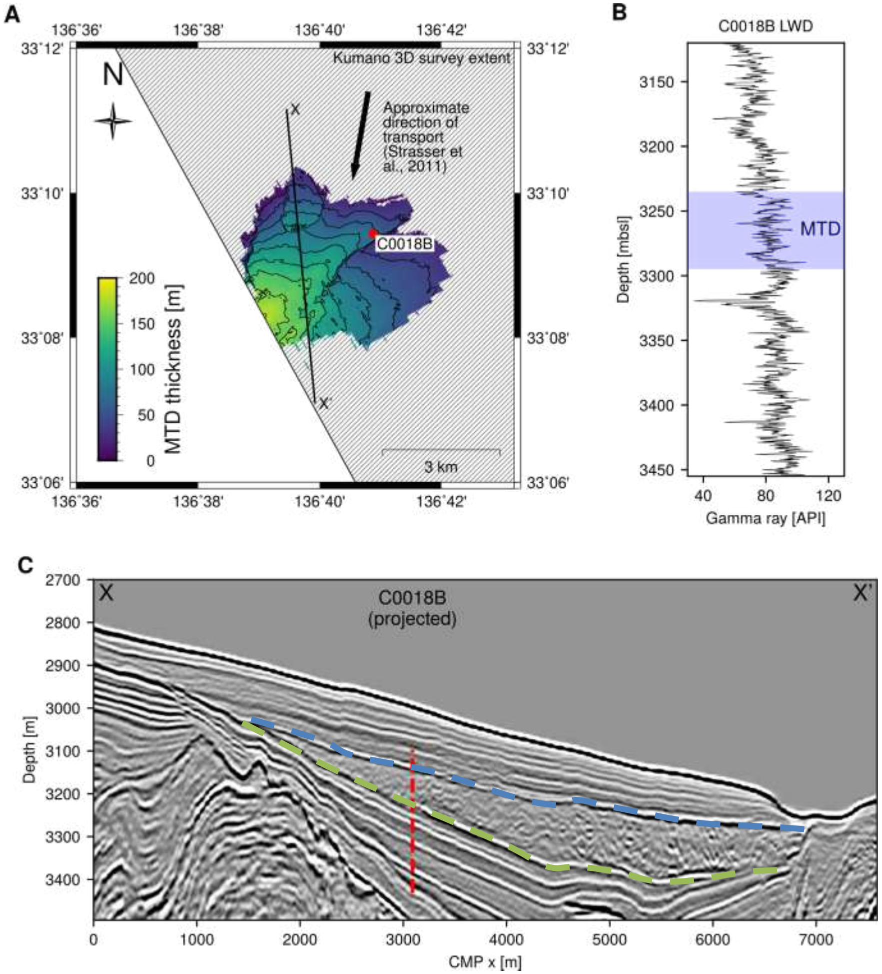
Yamamoto et al (2007)

Mass-transport deposits in reflection seismic data

- <u>Reminder: seismic images approximate the subsurface reflectivity (impedance *contrasts*)</u>
- Seismic facies: distinguishable by e.g. amplitude, frequency, continuity, configuration of internal reflectors, external geometry

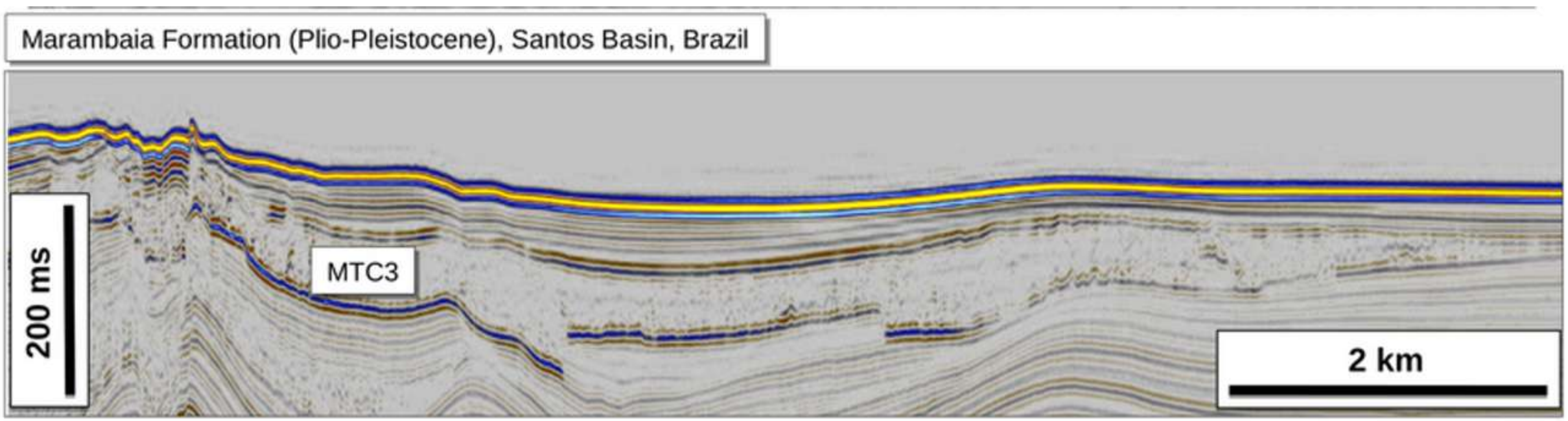


- MTDs can show distinctive external morphology, internal reflection geometry, amplitude
- Classic "MTD seismic facies"
  - Internal character: chaotic-to-transparent (low amplitude) internal character
  - External geometry: high-amplitude, rough top and basal reflectors

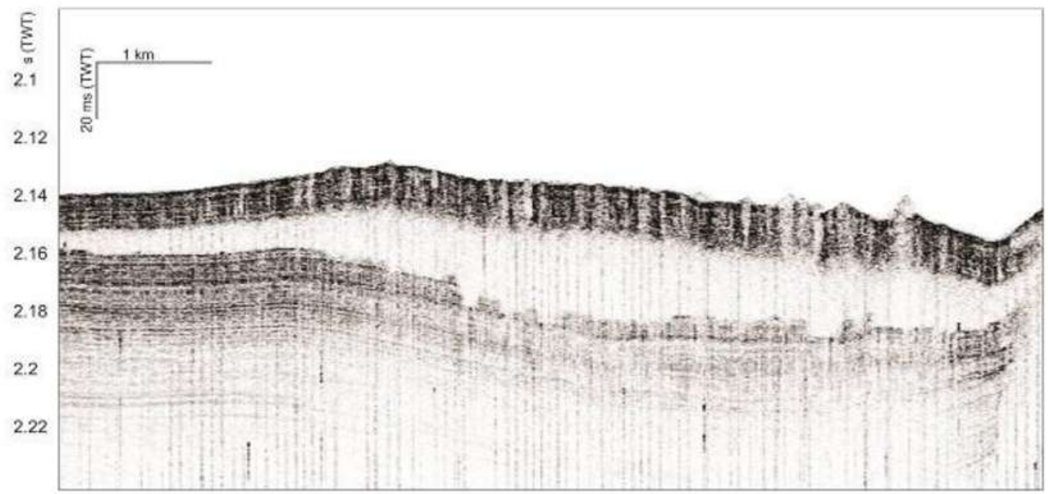


Ford and Camerlenghi (2019)

Mass-transport deposits in reflection seismic data



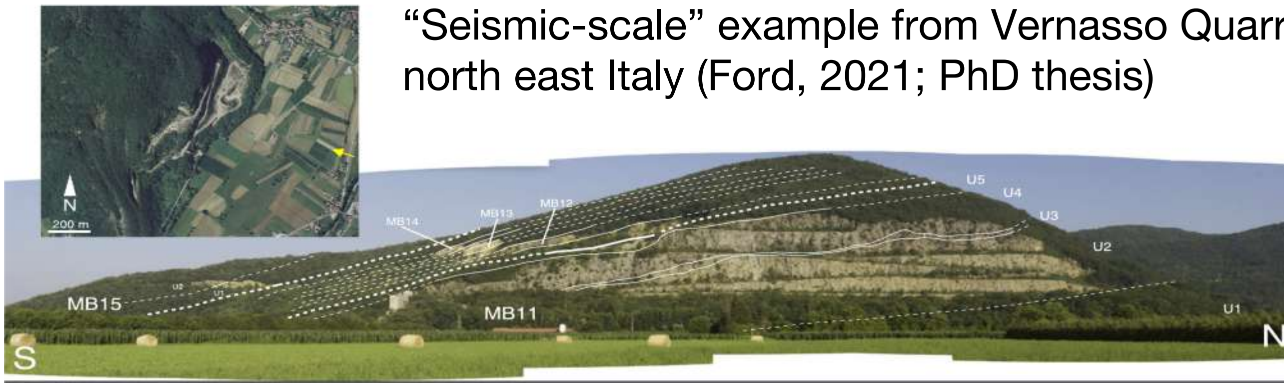
Jackson (2019); https://doi.org/10.6084/m9.figshare.9833558.v2



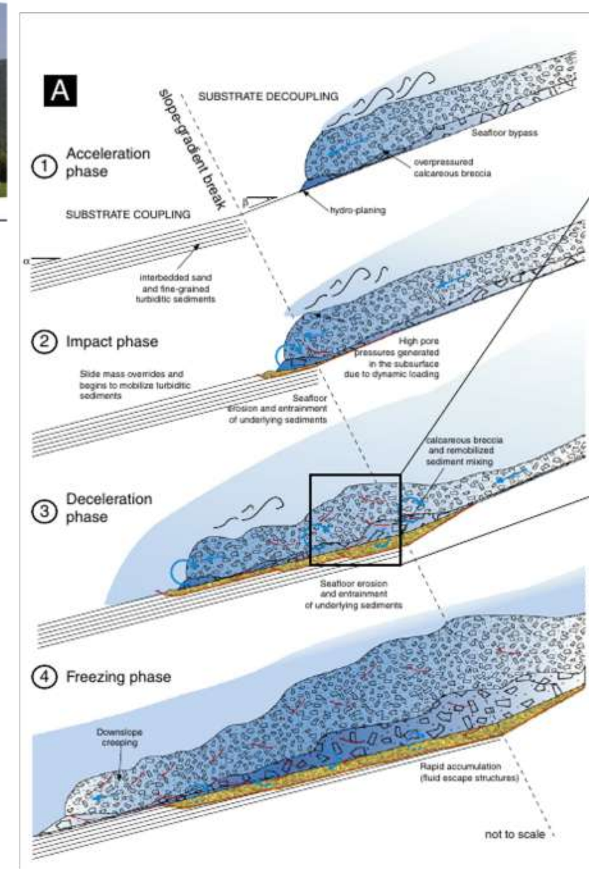
Single-channel sub-bottom profiler data from Crotone-Spartivento Basin, south Italy (Candoni; PhD thesis, 2018)

Mass-transport deposits in outcrop

“Seismic-scale” example from Vernasso Quarry, north east Italy (Ford, 2021; PhD thesis)



Intact blocks of sub-stratum



Ogata et al. (2014)

Summary

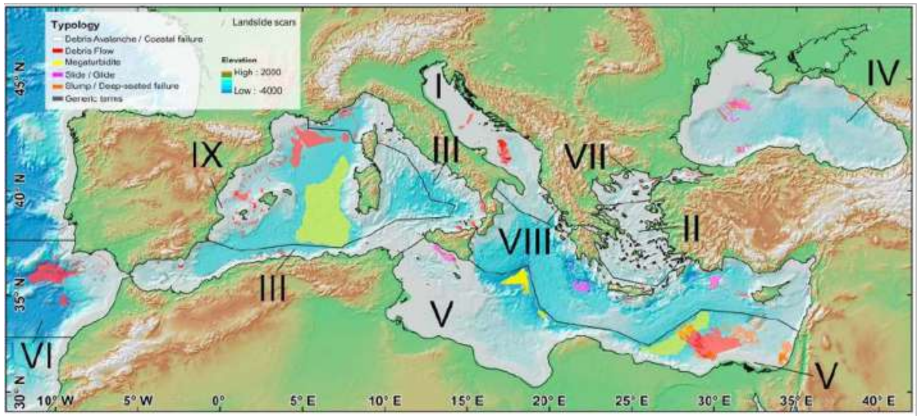
- Subaqueous mass-movements are a significant marine geohazard
  - to seafloor infrastructure
  - to coastal populations by induced tsunami
- MTDs are significant stratigraphic events, have economic significance and comprise large % of deep-water basin fill
- Often have a distinctive seismic character (non-conformal bounding surfaces, “chaotic” internal structure)
- Few outcrop examples of seismic-scale (10s metres thick) MTDs - much of our understanding comes from geophysical data

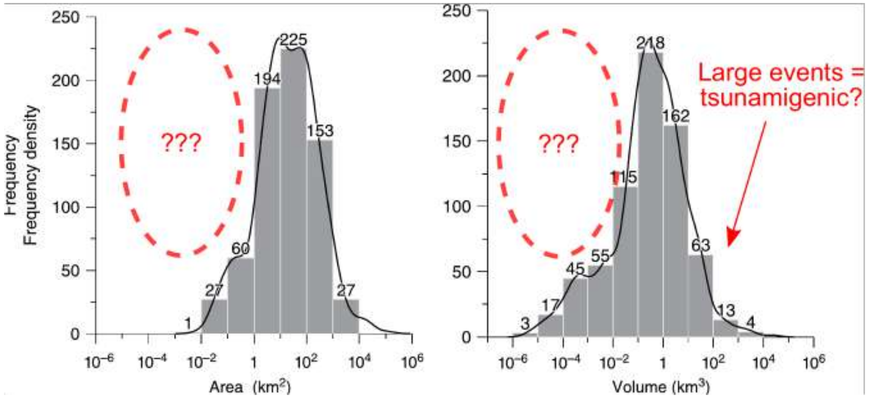
Questions?

Geophysical imaging of mass-transport deposits

Imaging MTDs for geohazard characterisation: why?

- Mapping: screen for MTDs from background sedimentation, assess area/volume
- Mass-movement catalogues:
  - Where and when do large slides occur?
  - Frequency/magnitude relationships (how often, and how big?)
- Inputs for modelling:
  - Tsunami modelling
  - Slope stability
  - Runout modelling
- Characterise individual events: volume, runout, internal structure (kinematic indicators)





MTD catalogue from the Mediterranean Sea
(Urgeles and Camerlenghi, 2013)

Classifying individual MTDs

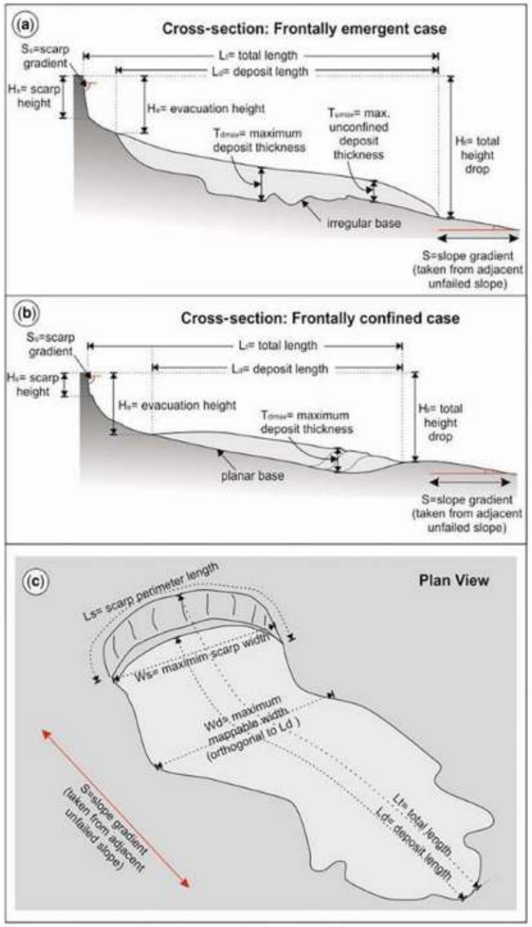
Parameters:

- scarp length/height
- maximum/average thickness
- height drop
- slope gradient
- length/width/area

...of deposit AND evacuated zone.

Why? Informs geohazard potential

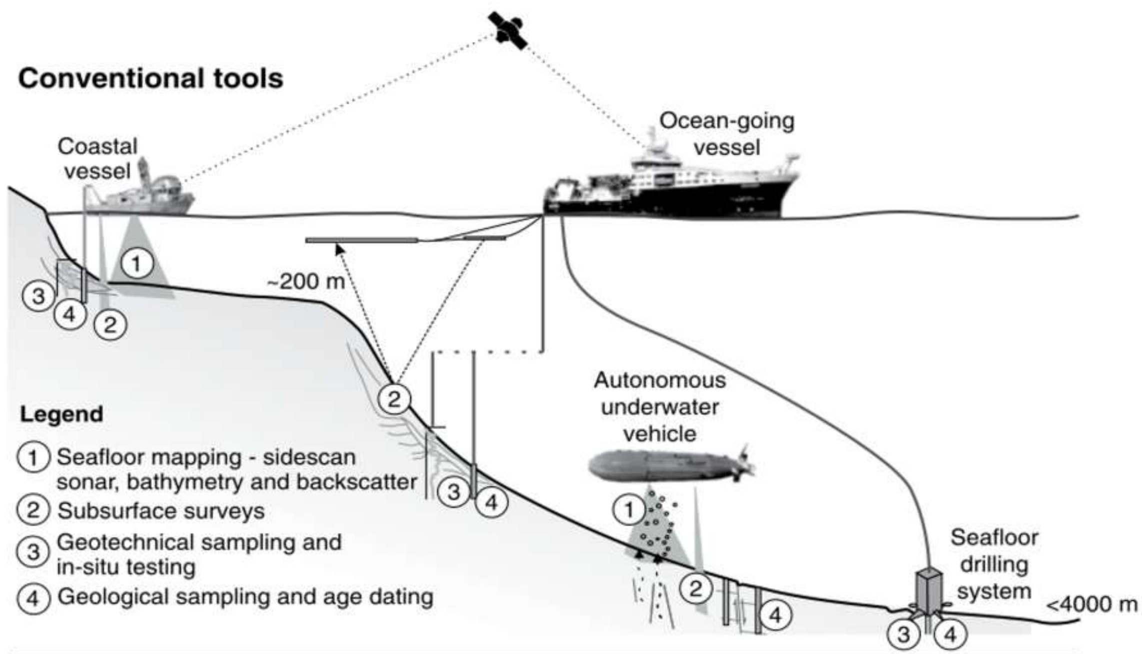
To assess these parameters for MTDs *in situ* we need geophysical data



Clare et al (2019)

Methods to investigate mass-transport deposits

- Seismic methods:
  - Multi-channel seismic data (2-D and 3-D)
  - Single-channel sub-bottom profiler data
- Core samples
- Borehole logs and cone-penetration tests
- (Outcrop analogues)



Clare et al (2017)

Resolution of investigation methods

Seismic reflection resolution is roughly proportional to the dominant wavelength of the seismic source (ie coupled to the source bandwidth)

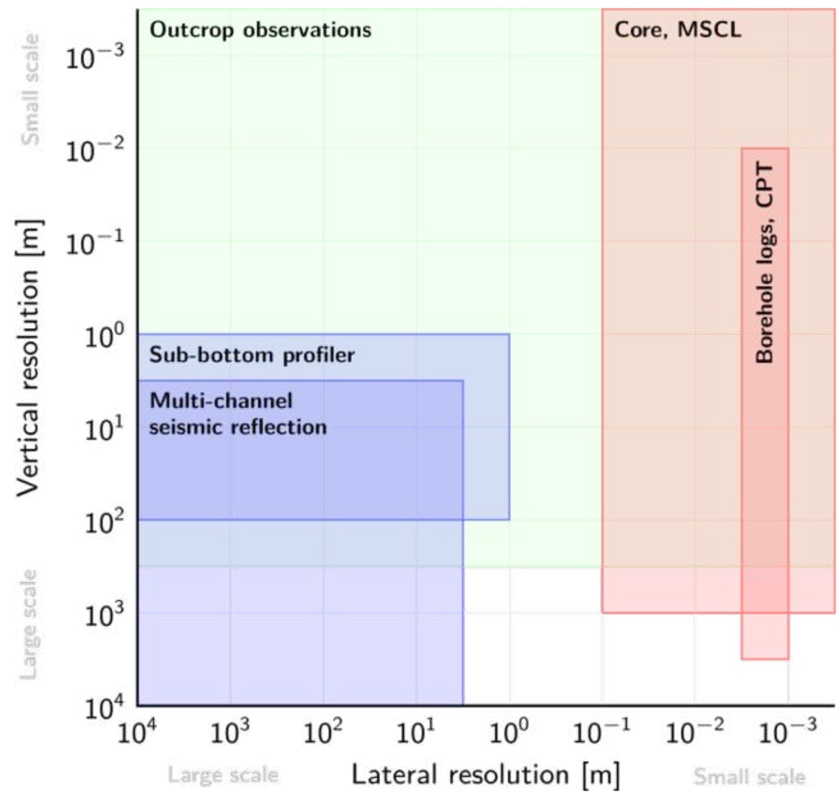
Vertical resolution $\approx \frac{\lambda}{4}$

Horizontal resolution more complicated, a function of

- Fresnel radius (in unmigrated data)
- Rayleigh criterion (migrated data) $\approx \frac{\lambda}{2}$

Typical airgun bandwidth might have dominant frequency ≈ 50 Hz. In seawater:

$$\lambda = \frac{v}{f} = \frac{1500\, ms^{-1}}{50\, Hz} = 30\, m$$



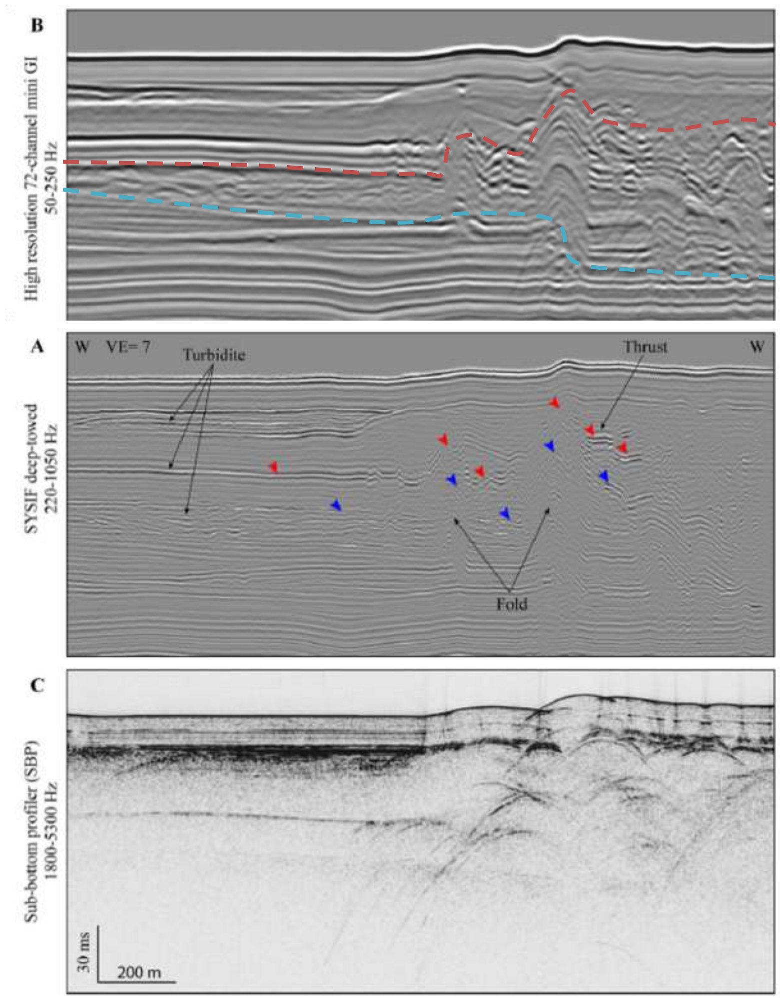
Why not just increase the resolution?

With increasing depth:

- seismic velocities generally increase (wavelength increases for same frequency)
- higher frequencies are preferentially attenuated ⇒ lose resolution with depth ⇒ <u>trade-off between source bandwidth and signal penetration</u>

Consequences:

- Miss small, deep events
- Lose resolution of fine-scale MTD internal structure



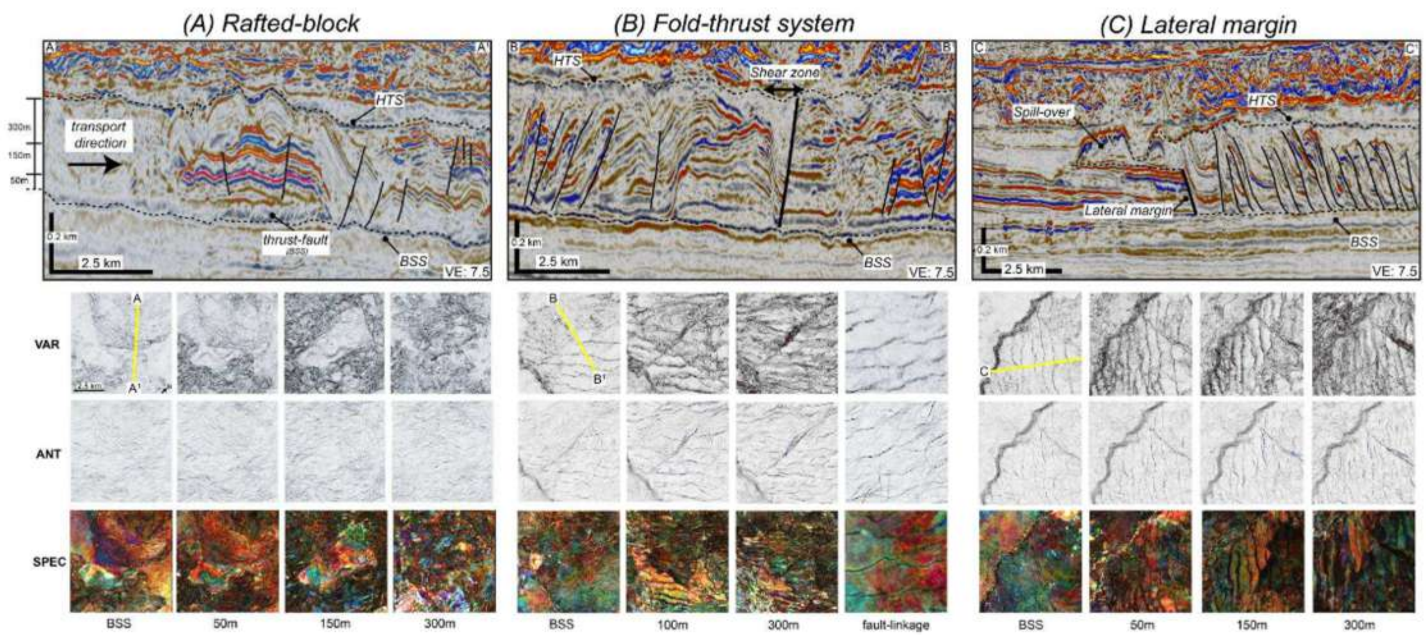
Miramontes (PhD thesis, 2018)

MTDs imaged with modern geophysical datasets

Traditional view of “MTD seismic facies”

- Internal character: chaotic-to-transparent (low amplitude) internal character
- External geometry: high-amplitude, rough top and basal reflectors

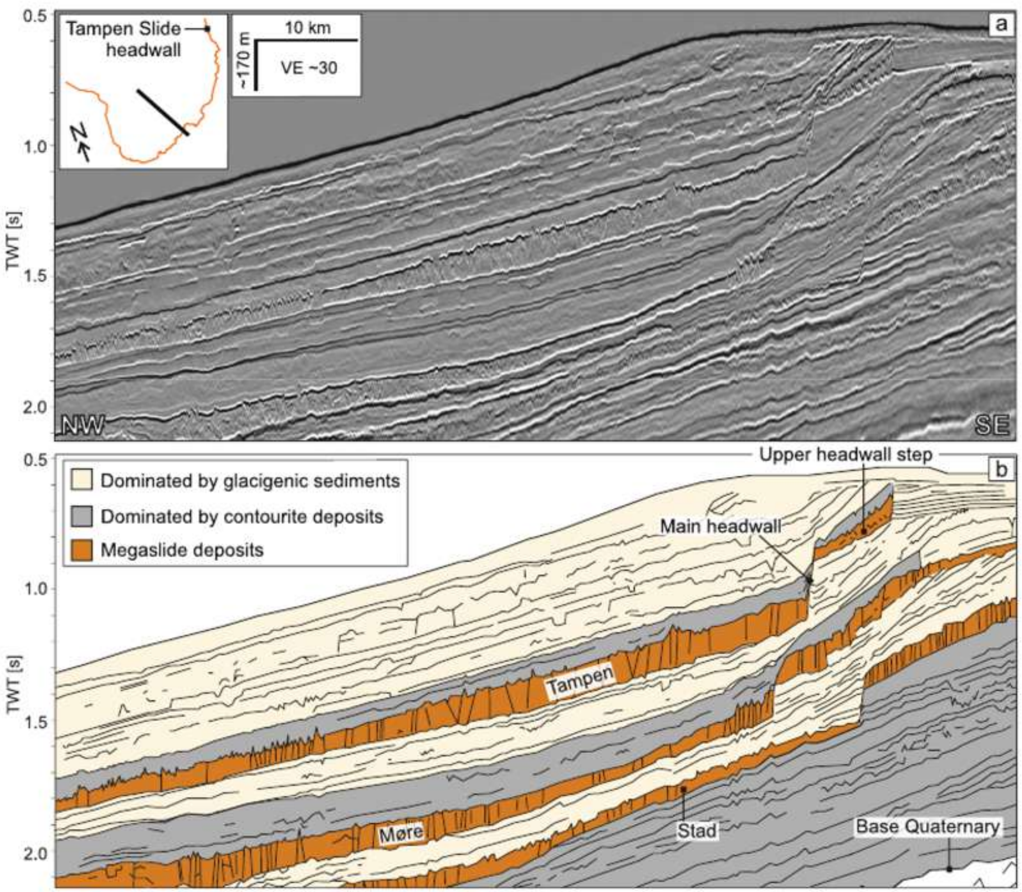
However… modern geophysical datasets (3-D seismic, AUV sub-bottom profiler data, seismic re-processing...) are beginning to tell a different story:

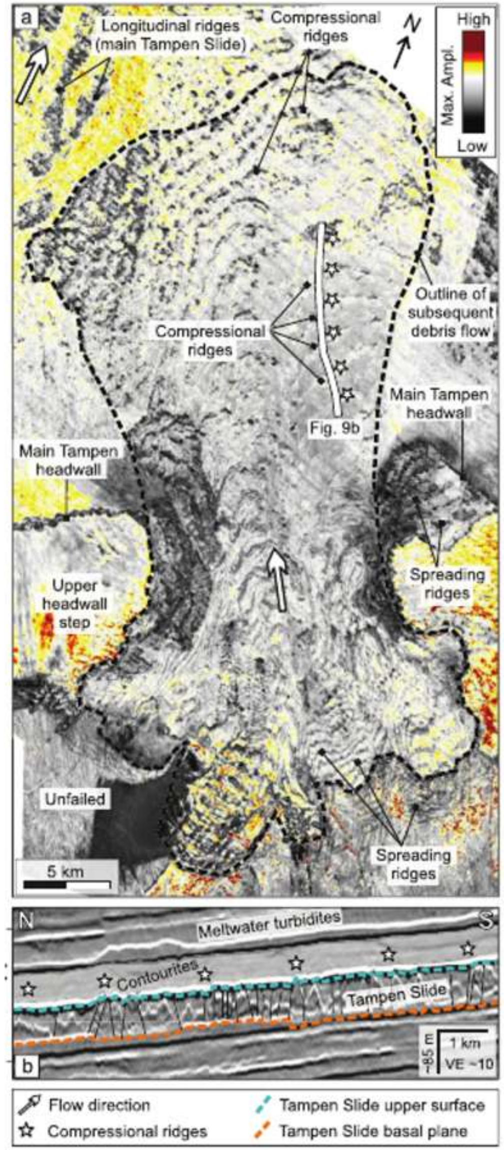


Conventional structural geology studies (strain analysis) inside an MTD, offshore Uruguay (Steventon et al., 2019)

MTDs imaged with modern geophysical datasets

Detailed interpretation of coherent internal structure (Tampen Slide, offshore Norway) (Barrett et al., 2020)

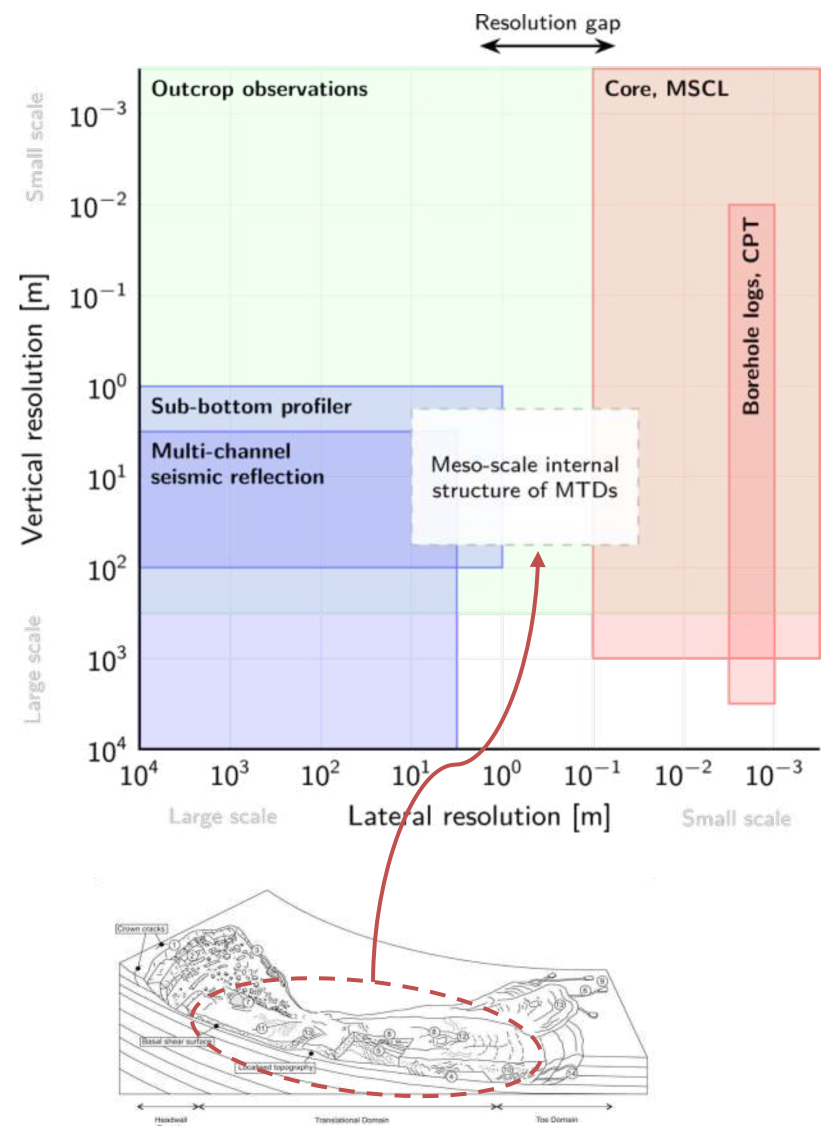




Maybe mass-transport deposits are not so chaotic after all?

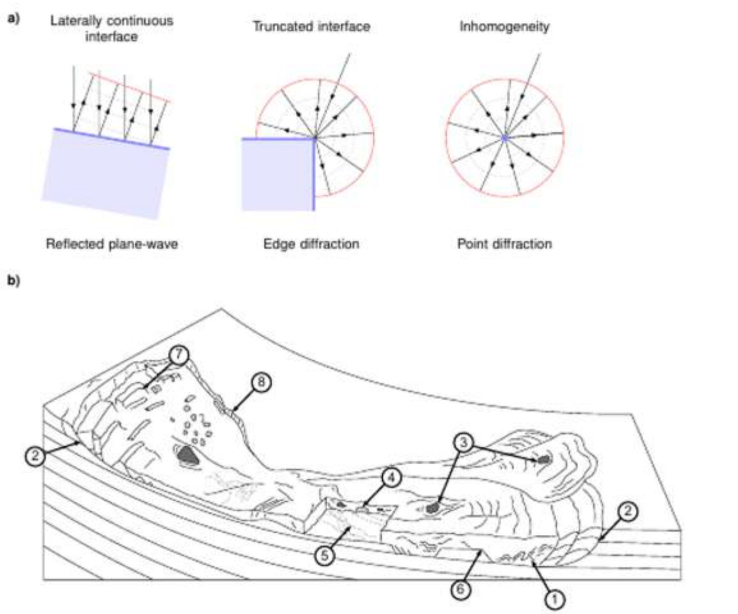
Summary: resolution and seismic imaging of MTDs

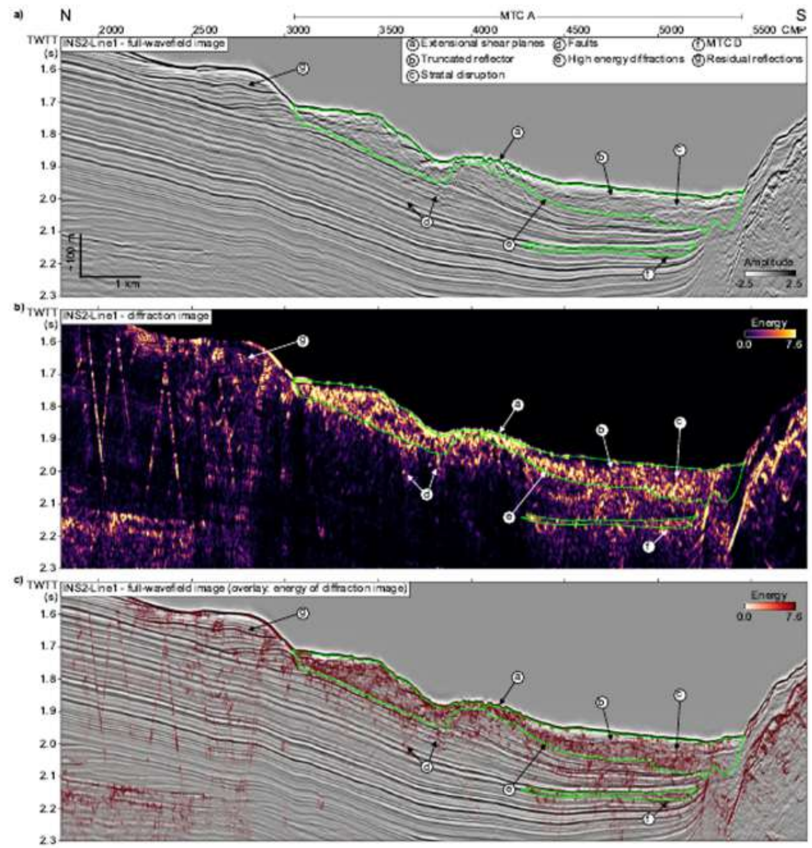
- Increasing evidence that chaotic “MTD seismic facies” are often caused by a lack of resolution, not necessarily “chaotic” geology
- Be careful doing facies analysis! Seismic images are *not* a perfect representation of the surface, especially for heterogeneous geology (need to consider vertical *and* lateral resolution)
- Most metre-scale MTD kinematic indicators observed in outcrop fall into the “lateral resolution gap” between seismic methods and direct sampling methods
- Need outcrop analogues to cross the gap between geophysical and direct sampling methods



Bull et al. (2009)

New direction: diffracted wavefield for "super-resolution" inside MTDs



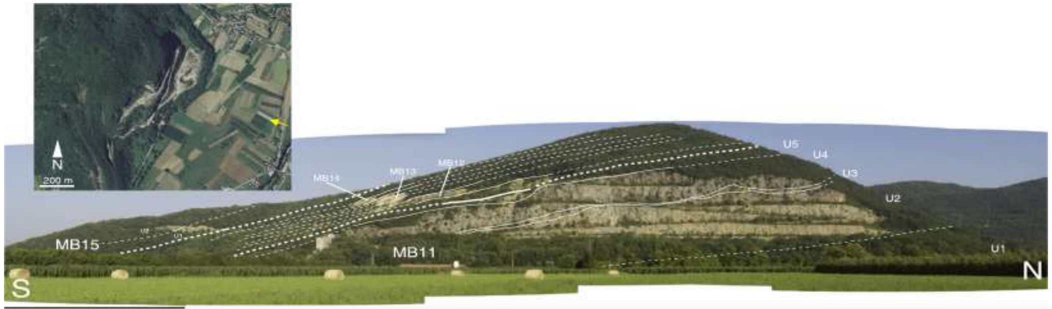


MTC from Gulf of Cadiz (Ford et al., 2021)

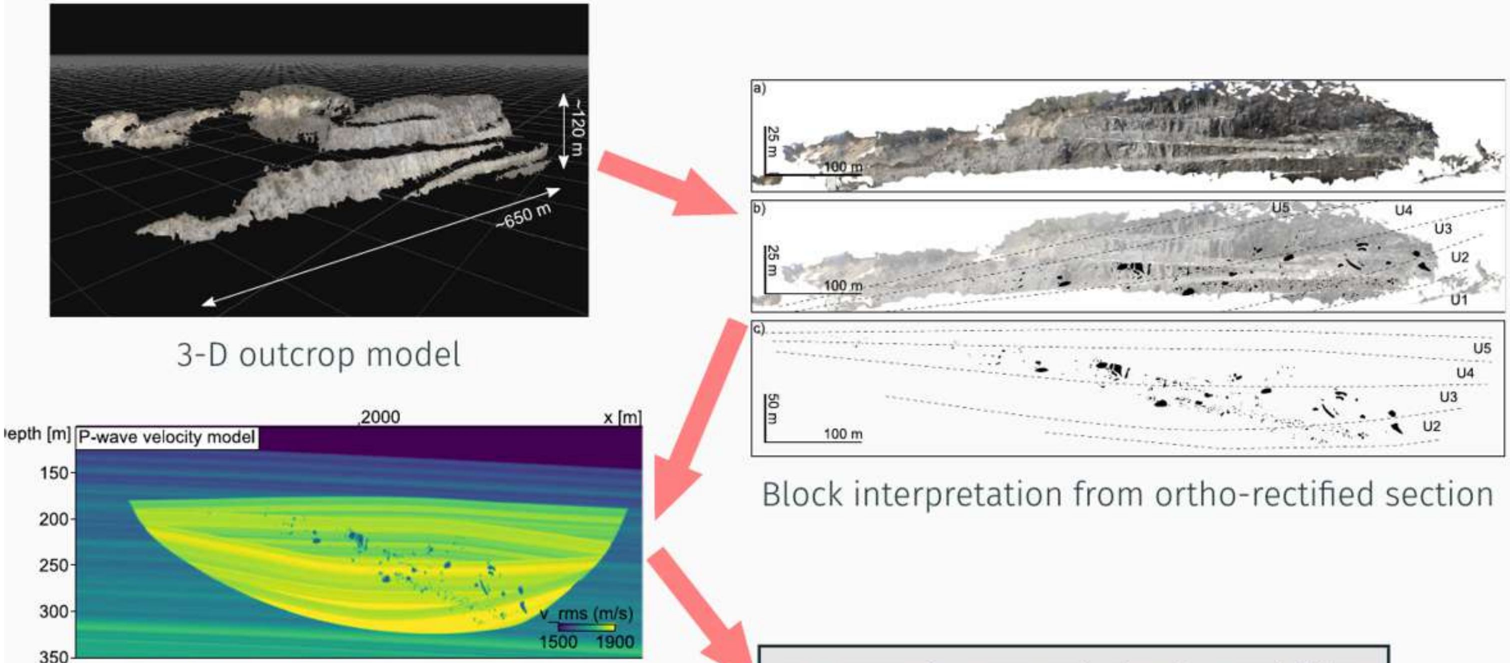
Seismic diffractions:

- generated by lateral discontinuities (faults, fractures, heterogeneities)
- overcome Rayleigh limit on lateral resolution
- usually discarded because they are low amplitude compared to reflections

New direction: closing the loop between outcrop observations and sub-surface geophysics



Vernasso Quarry (north east Italy) example



3-D outcrop model

Block interpretation from ortho-rectified section

Representative elastic model

2-D pseudo-spectral elastic modelling

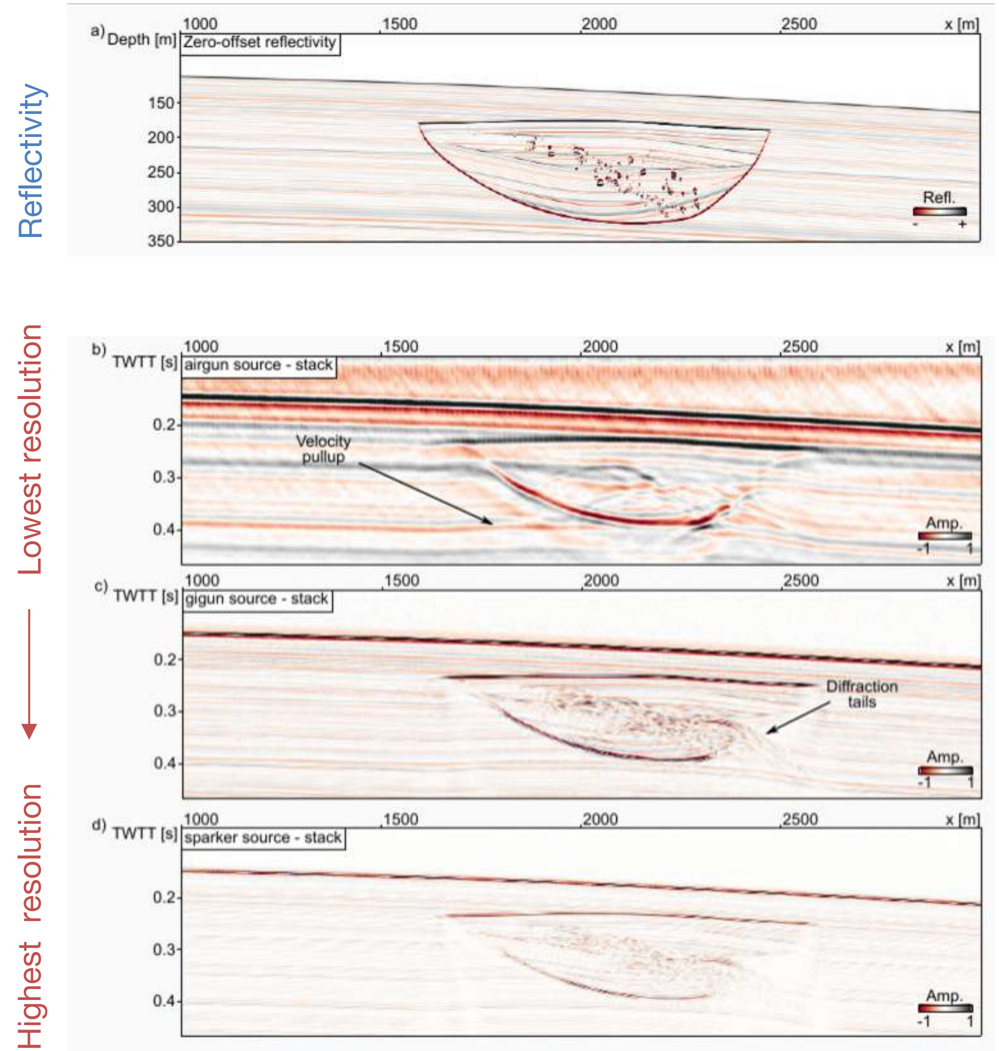
New direction: closing the loop between outcrop observations and sub-surface geophysics

Results:

- Internal seismic response is <u>strongly </u>dependent on the seismic bandwidth
- Diffractions (everywhere)

Future direction:

- Enables direct connection between outcrop observations and seismic facies analysis through full-wavefield modelling



Summary — geophysical imaging of MTDs

- Marine vs terrestrial mass-movements: no direct *in situ* observations of active subaqueous mass-movements*
  - need to study their sedimentary records, MTDs
  - most observational data comes from remote sensing and geophysical methods
- Fundamental problem for MTD geohazard catalogues — sampling bias:
  - largest events (biggest geohazard) are the rarest
  - smaller, recent events may not be well preserved or resolved
- For geophysical methods: trade-off between resolution and investigation depth (sub-seafloor penetration)
  - multi-disciplinary investigation crucial
  - outcrop analogues are important because we can study them at many scales
- Traditional view of MTDs as "chaotic" or "transparent" seismic facies is gradually being eroded by advances in modern geophysical techniques

Further reading

Huhn, K., Arroyo, M., Cattaneo, A., Clare, M.A., Gràcia, E., Harbitz, C.B., Krastel, S., Kopf, A., Løvholt, F., Rovere, M., Strasser, M., Talling, P.J., Urgeles, R., 2019. *Modern Submarine Landslide Complexes: A Short Review*, in: Ogata, K., Festa, A., Pini, G.A. (Eds.), Geophysical Monograph Series. Wiley, pp. 181–200. https://doi.org/10.1002/9781119500513.ch12

Vanneste, M., Sultan, N., Garziglia, S., Forsberg, C.F., L'Heureux, J.-S., 2014. *Seafloor instabilities and sediment deformation processes: The need for integrated, multi-disciplinary investigations.* Marine Geology, 50th Anniversary Special Issue 352, 183–214. https://doi.org/10.1016/j.margeo.2014.01.005

Posamentier, H.W., Martinsen, O.J., 2011. The Character and Genesis of Submarine Mass-Transport Deposits: Insights from Outcrop and 3D Seismic Data, in: Shipp, R.C., Weimer, P., Posamentier, H.W. (Eds.), Mass-Transport Deposits in Deepwater Settings. SEPM (Society for Sedimentary Geology). https://doi.org/10.2110/sepmsp.096

Questions?