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Mass transport-dominated sedimentation in a foreland basin, the Hidaka Trough, northern Japan

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ABSTRACT

Mass transport is an important process of sediment redistribution from shallow to deep sea basins. It is vital to understand this process for disaster prevention and protection of economic interests in offshore areas. We describe mass transport-dominated sedimentation in an active foreland basin, the Hidaka Trough, which developed from collision between the northeastern Japan arc and the Kuril arc. The basin is deformed by east-west compression associated with large, frequent earthquakes. The trough is filled with thick (>4.5 km) sediments, ranging from coal-bearing Cretaceous terrestrial strata to modern diatomaceous hemipelagic mud and volcanic ash. Bottom-simulating reflectors and the distribution of mud volcanoes, pockmarks, and acoustic wipe-out zones on the seismic records suggest the presence of subsurface gases in the sediments. The basin features stacked mass transport deposits (MTDs), but no channel-levee systems have developed. The MTDs are relatively thin (<30 m) and are derived from three sides of the basin margin. Initiation of submarine slope failure in this area may be controlled by multiple factors that increase driving forces and decrease resistance of the slopes. The driving forces include oversteepening of the margin slope as a result of thrusting and folding, and additional downslope gravitational acceleration caused by cyclic shaking during earthquakes. Decreased resistance in the slopes may be caused by the accumulation of excess pore- water pressure driven by a high-sedimentation rate, gas hydrate dissociation accompanying changes in sea level or seawater temperature, and liquefaction in coarse-grained beds during earthquakes.

Study area

- The Hidaka Trough was a forearc basin caused by subduction of the Pacific Plate along the Japan Trench until the Miocene.
- Thick coal beds were depositis in the Cretaceous and Paleogene (A3-Coal Marker in Figure 1).
- From the Miocene, the Kuril arc began to collide to the Northeastern Japan arc, leading to uplift the Hidaka Mountains and to subside the Hidaka Trough as a foreland basin.

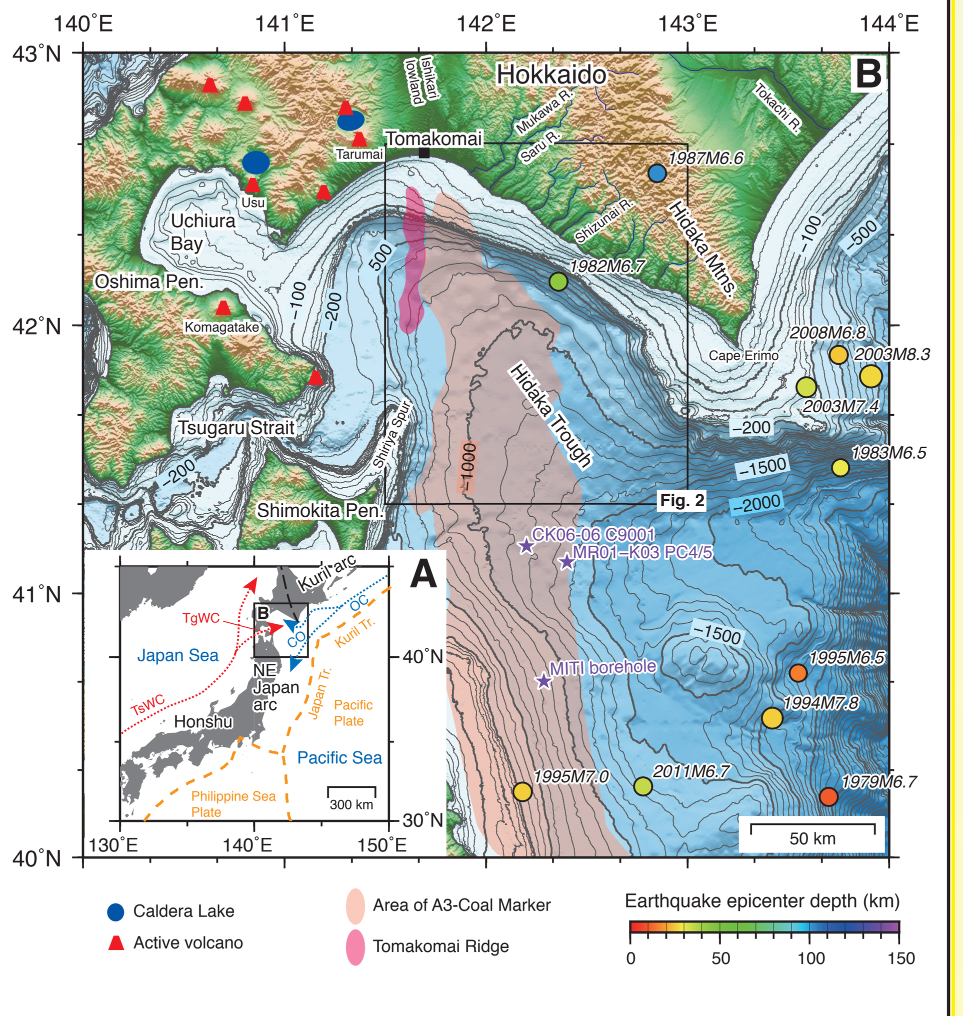

Figure 1: (A) Index map of the study area. (B) Topography and bathymetry around the study area, showing the epicenters of major earthquakes post-1973. Abbreviations: OC, Oyashio Current; CO, Coastal Oyashio; TsWC, Tsushima Warm Current; TgWC, Tsugaru Warm Current.

Introduction

Background

- Mass transport caused by submarine slope failures is a significant process in marine sedimentary basins.
- They induce hazards including tsunami, and the destruction of coastal communities and offshore infrastructure, such as submarine cables.
- Few studies have focused on mass-transport-dominated sedimentary basins at active margins.
- Studying their process is important in understanding mass wasting systems, as well as for disaster prevention and protecting economic interests in coastal and marine environments.

Purpose

- Focus on mass transport deposits (MTDs) in a tectonically active foreland basin, the Hidaka Trough, northern Japan.
- Describe the characteristics of MTDs with regard to local geological structures, sedimentation, and subsurface environments.
- Discuss factors controlling the initiation of submarine slope failures.
- Propose a depositional model for mass-transport-dominated foreland basins.

Methods

- A narrow multibeam echosounder (HydroSweep) for bathymetry.
- A sub-bottom profiler (SBP; Parasound, Atlas) for shallow subsurface structures.
- Air gun (355 inch^3) and multichannel (6 or 16-ch) streamer cables for subsurface structures.
- Grab and gravity corers for sediment samples.

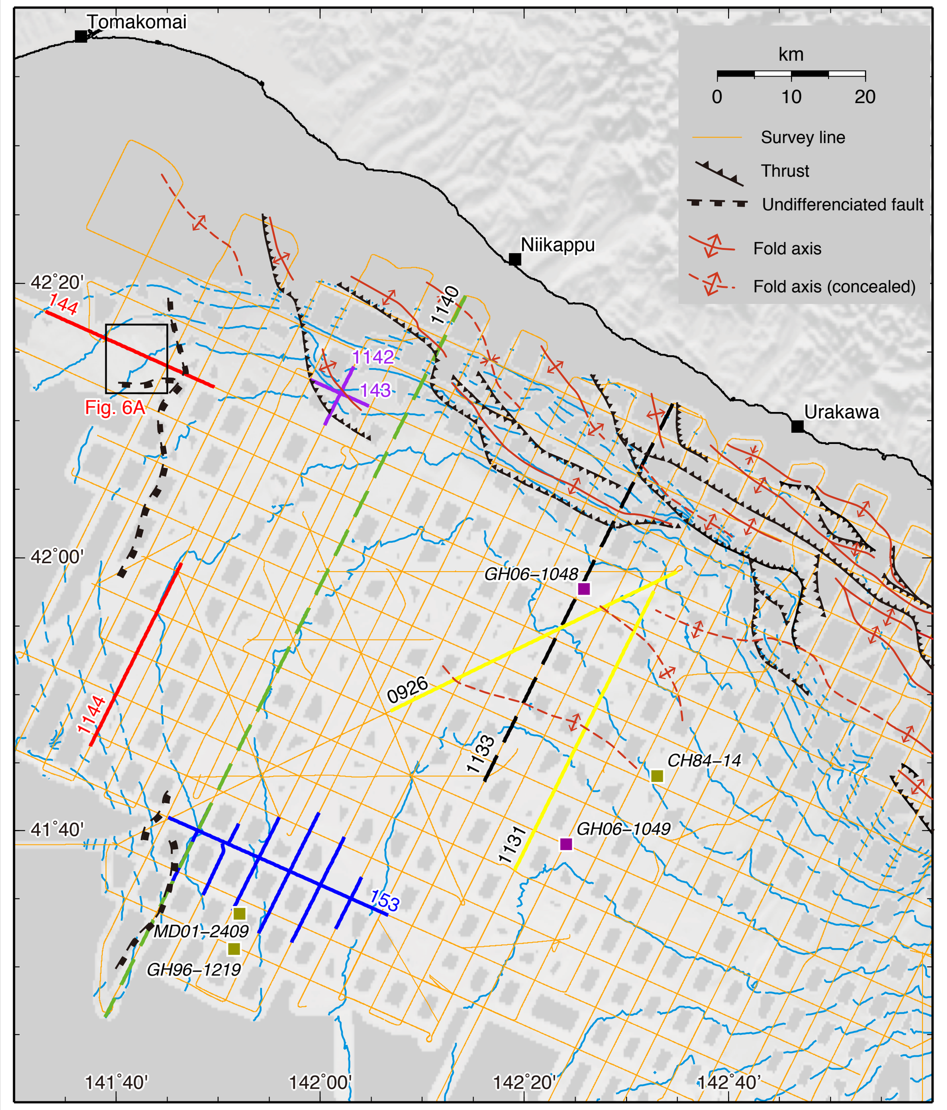

Figure 2: Locations of seismic survey lines and coring sites, showing geological folds and faults.

Results

Mass transport deposits

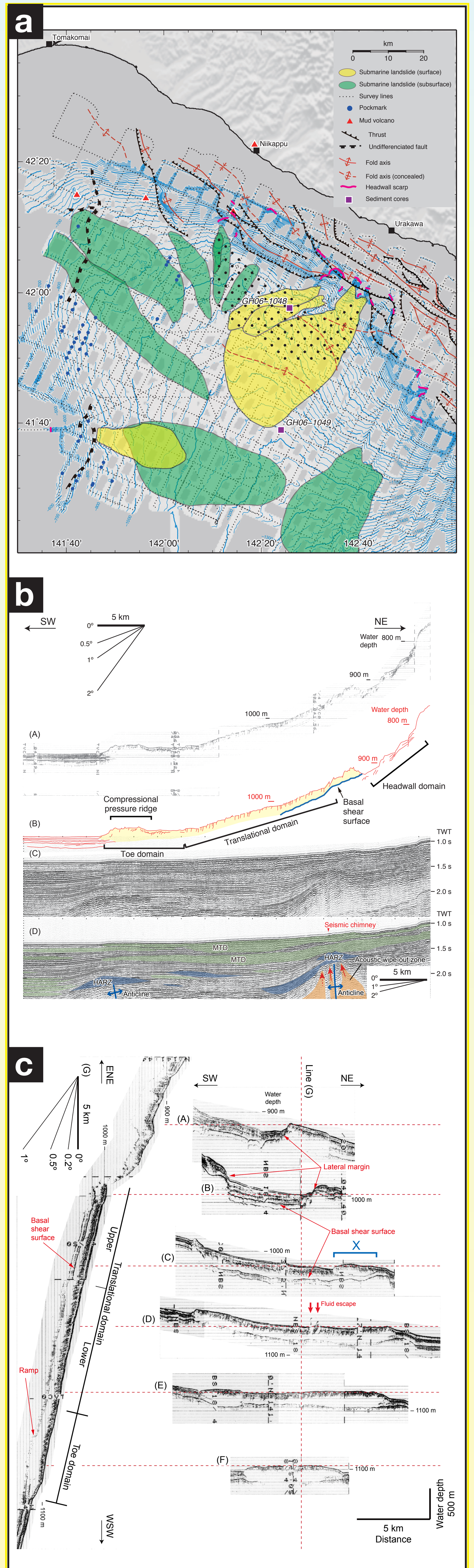

Figure 3: (a) Bathymetry and spatial distribution of MTDs on the surface (yellow) and in the subsurface (green) of the Hidaka Trough. (b) MTD off Urakawa. (c) Transverse (A–F) and longitudinal (G) cross sections of sub-bottom profiles for the MTD.

- MTDs are widely distributed in the trough (Figure 3a).
- The SBP profiles commonly show a typical tripartite anatomy: discontinuous and irregular reflections in the **headwall domain**, transparent or chaotic internal reflections in the **translational domain**, and mound-like configurations in the **toe domain** (Figure 3b).
  - Headwall domain is characterized by topographically depressed and discontinuous reflections.
  - The translational domain has transparent internal and irregular surface reflections. It contains vertically elongate features with upward-warping surface reflections suggesting fluid escapes from the deposits.
  - The toe domain is represented by a compressional pressure ridge that forms mound-like depositional lobes
- The MTDs were sourced from three sides of the marginal slope, but predominantly from the northeastern margin where headwall scarps are located closest to thrusts.
- The thicknesses range from 10 to 200 m, but most are less than 30 m. The deposits are located in water depths of 700–1500 m, and the average gradient of the slopes is 0.2–0.8°.
- The transverse and longitudinal slices of the MTD (Figure 3c) show internal structural variations.
  - The upper translational domain is restricted by a relatively narrow (5 km) channel, and retains the stratification of its internal reflections (A–C).
  - The lower translational domain, which shows mound-like features at the margins, located higher than the central area (C–E).
  - The toe domain is mound-like, with its highest point in the center (F). Internal reflections in this domain are completely transparent. From the SBP records, it appears that this MTD has not evolved into debris flow or turbidity currents downslope.

Sediment cores

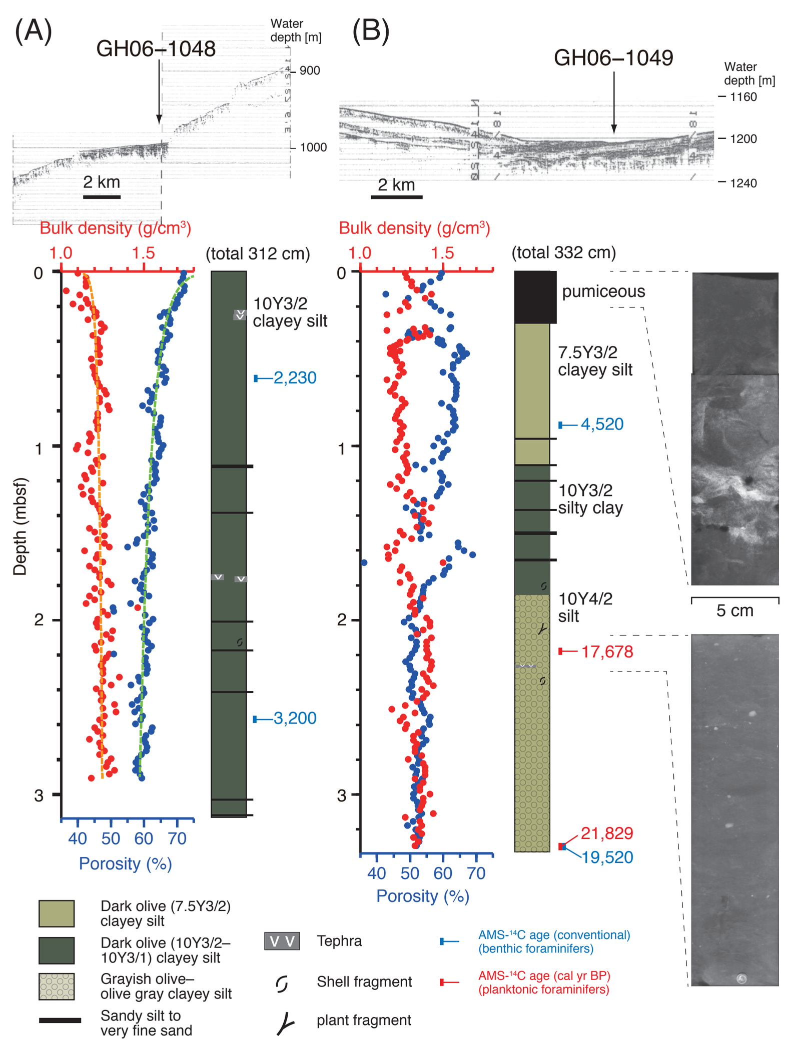

Figure 4: Description, porosity, bulk density, and soft X-radiographs of sediment cores GH06-1048 and 1049. The sampling locations are shown on the SBP records and Figure 2.

Subsurface gases

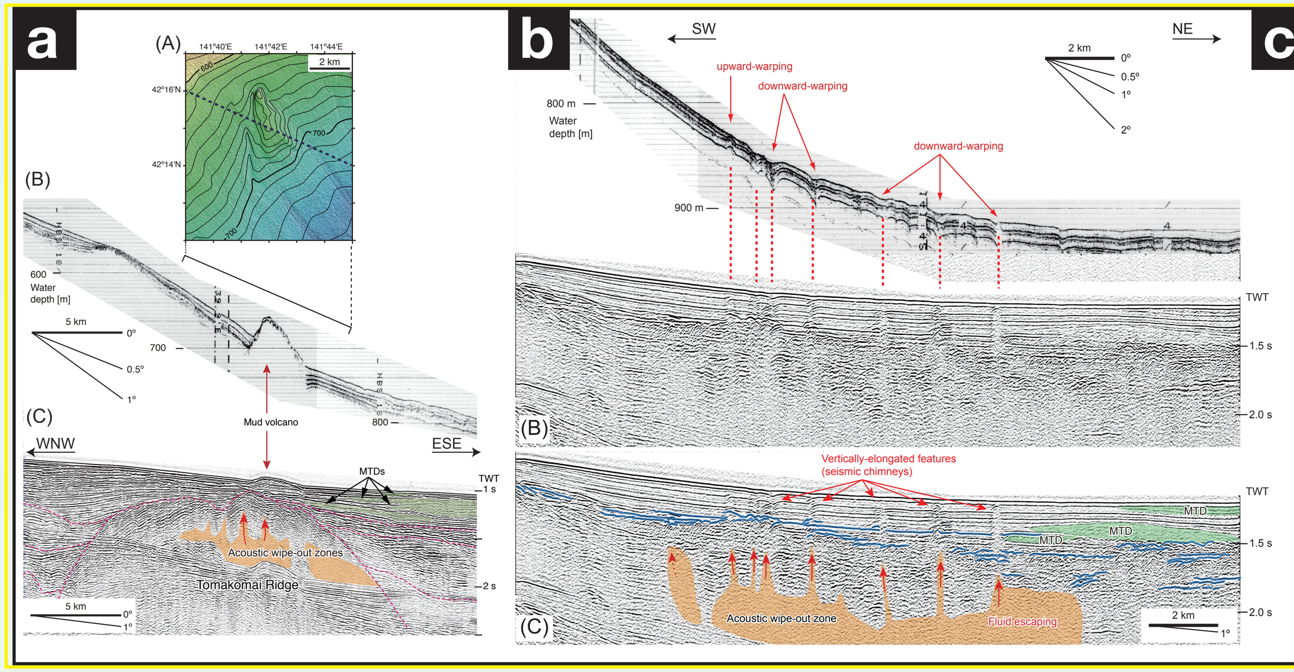

Figure 5: (a) Mud volcano developed on the Tomakomai Ridge. (b) Pockmarks with downward-warping depressions. (c) BSR

- Mud volcanoes occur as dome-like, slightly elongate mounds onto the seafloor (Figure 5a).
- Low-coherency and low-amplitude reflection zones (acoustic wipe-out or blanking zones) occur at depths greater than 1.5–2.0 s TWT (Figure 5b).
- These zones are generally capped by high-amplitude reflection (HAR) anomalies (Figure 5b). The depth of HARs generally increases with water depth, ranging from 0.28 to 0.79 s TWT.
- The HARs are locally connected to the seafloor by vertically elongate features (seismic chimneys). These chimneys cut across horizontally stratified reflections, and are expressed as vertical zones of distorted seismic reflections with low or high amplitude. They usually connected to pockmarks with downwarping structures, suggesting conduits of water escaping upward (Figure 5b).
- BSRs at approximately 0.3–0.4 s TWT (240–320 mbsf), suggesting the presence of gas hydrates in the strata (Figure 5c).

Discussion

Earthquake

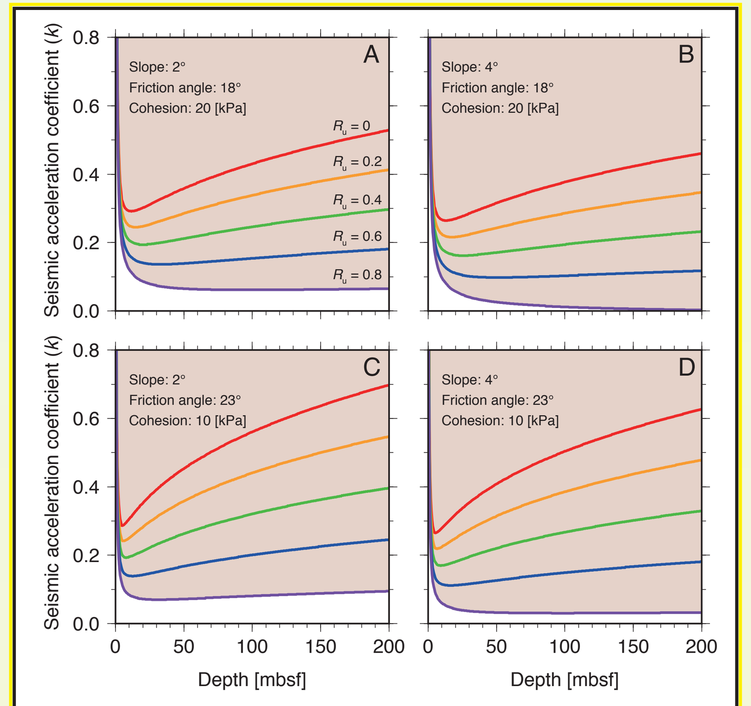

Figure 6: Relationship between sediment depth [mbsf] and the seismic acceleration coefficient (k) required for slope failure (F < 1) at various excess pore pressure ratios (R_u). Regions of potential slope failure are marked by the colored area.

Gas hydrate

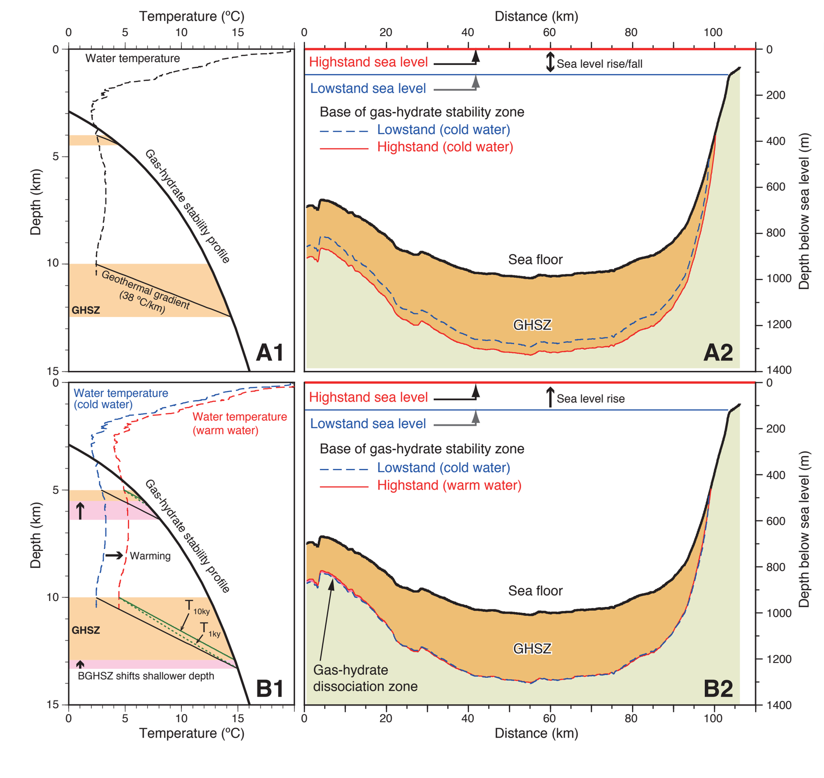

Figure 7: (A1) Gas hydrate stability in the pressure–temperature domain under the present conditions. (A2) Changes in the base of gas-hydrate stability zone (BGHSZ) with changes in sea level. (B1) Gas hydrate stability in the pressure–temperature domain under conditions of seawater warming. Green lines of T_{1ky} and T_{10ky} represent subsurface sediment temperatures after 1 kyr and 10 kyrs of seawater warming, which were obtained by solving a one-dimensional heat conduction equation with the thermal diffusivity of 5×10^{-7} m^2 s^{-1}. (B2) Changes in the BGHSZ when warming seawater temperature (2°C) is accompanied by sea level rise (120 m) after 10 kyrs of the seawater warming. The topographic cross section was derived from survey line 1140 in Figure 2.

Summary

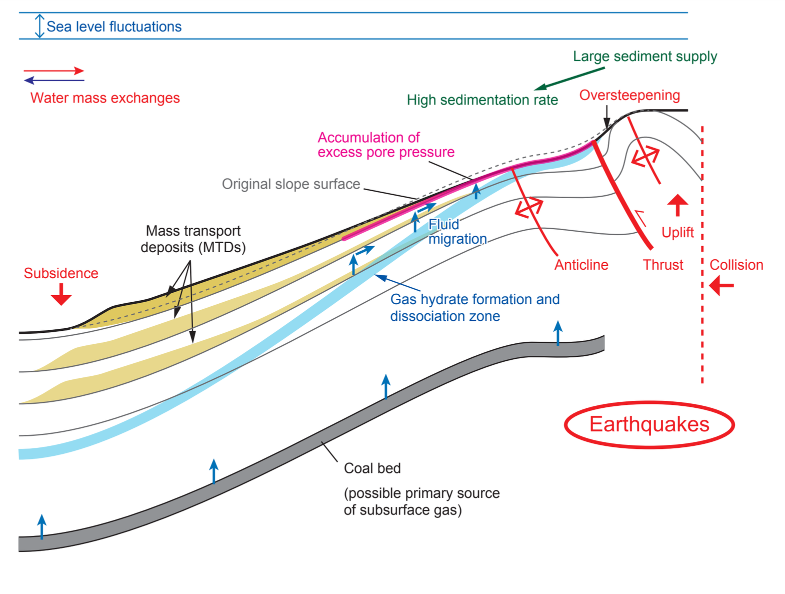

Figure 8: Conceptual model of mass-transport-dominated sedimentation in a foreland basin. Upper slope instability in the study area is controlled by multiple factors, including collisional tectonics, depositional conditions, and subsurface gases. These factors individually or collectively decrease resistance in the sediments or increase driving forces, leading to slope failure. Repeated failure in the upper slope may prevent the development of channel–levee systems on the slope; therefore, sedimentation in such environments may be dominated by mass transport rather than consistent transport through persistent conduits.

Geophysical and geological surveys in the active foreland basin of the Hidaka Trough have revealed the following conclusions:

- The Hidaka Trough is extensively covered by **mass transport deposits** (MTDs).
- **Active compressional tectonics**, including folding and thrusting, generally control the morphology of the basin margins.
- Seismic records show BSRs, pockmarks, mud volcanoes, seismic chimneys, and acoustic wipe-out zones, which provide evidences for the **existence of free gases and escape of water** from the seafloor.
- Submarine slope failures are caused by increases in gravitational forces and reductions in resisting forces.
  - Increases in gravitational forces may be induced by:
    - **oversteepening of the marginal slopes** as a result of compressional tectonics
    - additional **downslope gravitational acceleration during earthquakes**
  - Reduction of resisting forces depends mainly on accumulation of excess pore water pressure, which may be induced by:
    - **high sedimentation rates** at basin margins
    - **liquefaction caused by frequent earthquakes** in the volcanic ash beds
    - **free gases** originating from older coal beds or generated during decomposition of terrestrial and marine organic materials
    - **gas hydrate dissociation** due to pressure reductions resulting from sea level fall or sea temperature rise by the inflow of warm water
- The MTDs in this area are generally thin (10–100 m thick) and stacked. The most recent MTDs deposited during the last transgression (17–6 ka) might have originated from rapid sedimentation during transgression and the occurrence of earthquakes. Gas-hydrate dissociation by seawater warming is unlikely to be the primary trigger of submarine landslides, at least for the most recent events, although it may have contributed to the generation of excess pore pressure during the regression stages.

References

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