ECORD Summer School
Submarine Landslides, Earthquakes and Tsunamis

Sediment mass transport processes, deposition and stratigraphic record

Michi Strasser, ETH Zürich
Sediment mass transport processes

Following slope failure, **the failed mass moves downslope** (**Mass Movement**) driven directly by gravity.
Gravitational mass transport

Flow Initiation | Main Long-Distance Transport Process | Late Stage Modifications
--- | --- | ---
Rivers in flood | Fluid turbulence | DEBRIS FLOWS, PEBBLY SSTS., CONGLOMERATES, MASSIVE SANDSTONES, CLASSICAL TURBIDITES
Slump, slide | Remolding, liquefaction | DEBRIS FLOW
Decreasing concentration | High concentration turbidity current | GRAIN INTERACTION
| Low concentration turbidity current | Support mechanisms | TRACTION

Reineck & Singh 1980
Gravitational mass transport

Initiation
- Rockfall
- Slide
- Liquefaction
- Volcanic intrusion near surface
- Pyroclastic flow into water
- Fine underflow
- Storm stirring
- Glacial plumes

Remoulding
- Slump
- Flow slide
- Muddy DF
- Uniform LDT
- Hemipelagic diffusion

Transport process
- Sandy DF
- Surge HDT
- Uniform HDT
- GF-FF-LF at base
- + Coupled TC

Depositional mechanism
- Rockfall
  - Creep
  - Slide/Slump
- Freezing + collapse - megabed
- Momentum loss + freezing
- Plug-freezing
- Plug
- Shearing hot layer
- Suspension - collapse fall-out
- Turbulent flow
- Hindered setting
- Continuous - aggradation
- Turbulent flow
  - Active layer
  - GF, LF, FF
  - Static bed
- Continuous - traction
- Turbulent flow
  - Active layer traction
  - Static bed
- Suspension - slow fall-out
- Turbulent flow
  - Shear sorting through boundary layer
- Very dilute suspension - slow settling

Stow and Mayall 2000
Gravitational mass transport

Transport and deposition of fine-grained sediments in deep waters

(Stow & Mayall 2000)
Gravitational mass-transport

Debris flow-dominated continental margins

Channelized System

Muddy Slump
Muddy Debris Flow
Sandy Debris Flow in Channel

Non-Channelized System

Mud Rich
Muddy Slump
Sandy Slump
Sandy Debris Flow
Turbidity Current
Bottom Current
Plastic Flow

Shelf
Slope
Basin

Muddy Debris Flow
Muddy Slump
Sandy Debris Flow
Sandy Slump
Bottom Current Deposit
Turbidite

(Shanmugam 2000)
The challenge for Earth Scientists studying these dynamic processes is, to infer them from analyzing the “static” deposit, which likely have been affected by forces acting during the de-acceleration phase and/or after the mass has been deposited on the seafloor.
Example:
Differentiation between «submarine landslide» - initiated and hyperpycnal-flow turbidite

**Fig. 4.** Grain size trend for the fining-upward turbidite and hyperpycnal deposit sequences.
Example:
Differentiation between «submarine landslide» - initiated and hyperpycnal-flow turbidite

Mutti et al., 1999
MTD and Turbidites in cores

Debris Flows

Turbidite

Courtesy S. Krastel
Submarine Mass Transport Deposits in IODP cores

IODP Exp-333 Site C0018 (Strasser et al., 2012)

IODP Exp 308 Site U1322 (Strasser et al., 2012)
How to recognize a MTD in the core?

- Turbidite on top (but not always, 1/3)
- Mud pebbles and mixed sediment
- Dipping and folded bedding
- Shear zone(s)
- Physical properties
- Stratigraphic context (hiatus / age reversal)
- core-to-seismic integration
- ....
Turbidite at top of MTD
How to recognize a MTD in the core?

Visual core description missed basal shear zones

CT-scan provides additional evidence

Bright CT lines, formed of pyrite, are potential deformation markers

Henry et al., 2011
Shear zone at base of MTD
Deformation examples within a MTD

Cylindric fold

Mud clasts within fluidized flow

Internal, dipping shear zones

Plastic viscous

Chaotic bedding
Core photos from the top, (c, d) middle, and (e) base of MTD-2 deformation progressively increases form top to base

Sawyer et al., 2009
Core photos document the progression of soft-sediment deformation (b) from the top, (c, d) through the middle, and (e) to the base.

Sawyer et al., 2009
Where would you «guess» is an MTD?
Where would you «guess» is an MTD?

Boso-Peninsula, Japan, Yamamoto et al., 2007
What would you «guess» is an MTD?

Boso-Peninsula, Japan, Yamamoto et al., 2007
Gravitational mass transport

- SLUMP, SLIDE
- REMOLDING, LIQUEFACTION
- DEBRIS FLOW
- DEBRIS FLOWS
- PEBBLY SSTS., CONGLOMERATES
- MASSIVE SANDSTONES
- CLASSICAL TURBIDITES

- TIME AND/OR SPACE
- DECREASING CONCENTRATION

- FLUID TURBULENCE
- HIGH CONCENTRATION TURBIDITY CURRENT
- LOW CONCENTRATION TURBIDITY CURRENT

- RIVERS IN FLOOD

- FLOW INITIATION
- MAIN LONG-DISTANCE TRANSPORT PROCESS
- LATE STAGE MODIFICATIONS

Reineck & Singh 1980
Newtonian fluids: turbidity currents
Debris flows exhibit strength,
turbidity currents are turbulent

Bingham plastics: debris flows
whereas turbidity current do not
and debris flows are laminar in state
# Fluid Dynamic Perspective

<table>
<thead>
<tr>
<th>Rheology</th>
<th>Newtonian</th>
<th>Plastic</th>
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<tbody>
<tr>
<td>Sediment Support</td>
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<tr>
<td>Dispersive Pressure</td>
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<td>Cohesive Strength, Frictional Strength &amp; Buoyancy</td>
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<td>Turbulence</td>
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<td>Mass Transport</td>
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<td>Suspended Load</td>
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<td>Transport Mode</td>
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<td>Grain Flows</td>
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<tr>
<td>Sandy Debris Flows</td>
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<tr>
<td>Muddy Debris Flows</td>
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<tr>
<td>Hyperconcentrated Flows</td>
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<tr>
<td>“High Density Turbidity Currents”</td>
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<tr>
<td>Low Density Turbidity Currents</td>
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<tr>
<td>Flow Type</td>
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</tbody>
</table>

Sediment Concentration (% by volume)

(Shanmugam 2000)
# Fluid Dynamic Perspectives

<table>
<thead>
<tr>
<th>Transportation</th>
<th>Deposition</th>
<th>Deposit</th>
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<tbody>
<tr>
<td><strong>Turbulent Flow</strong></td>
<td></td>
<td>Normal Grading</td>
</tr>
<tr>
<td>Turbidity Current</td>
<td>Rheology: Newtonian&lt;br&gt;Support: Turbulence</td>
<td>Deposition: Settling</td>
</tr>
<tr>
<td>Sandy Debris Flow</td>
<td>Rheology: Non-Newtonian&lt;br&gt;Support: Dispersive Pressure, Hindered Settling, Matrix Strength, Buoyant Lift</td>
<td>Deposition: Freezing Settling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inverse to Normal Grading</td>
</tr>
</tbody>
</table>

Shanmuganm 2000
How can we study subaqueous sediment mass transport

- Analog model in flume tanks
- Numerical models

Ilstad et al., 2004
Analog model in flume tanks

Fig. 3. Fronts of laboratory debris flows. (A) Low sand/clay ratio. Hydroplaning front, lifted off the bed. (B) High sand/clay ratio. Turbulent front.
«Outrunner blocks» and «Hydroplaning»

Fig. 3. Fronts of laboratory debris flows. (A) Low sand/clay ratio. Hydroplaning front, lifted off the bed. (B) High sand/clay ratio. Turbulent front.

(Mohrig et al 1998)
Fig. 1. Finneidfjord slide with slide morphology divided into zones. Zone A: Main lobe, Zone B: Zone with scattered blocks, Zone C: Glide zone, Zone D: Main outrunner block. Average bottom slopes along the slide and glide path are shown in the lower panel.
«Outrunner blocks» and «Hydroplaning»

(Mohrig et al. 1998)
Numerical modelling approaches:

**BING model** (Imran et al., 2001), based on the Bingham rheology

combines Navier-Stokes/continuity equations and equations for advection and hindered settling of grains for a liquefied soil domain, with a consolidation equation for the underlying, progressively solidifying soil domain,

- Navier Stokes Equation // Stokes settling velocity // equation of consolidation

Reproduces the concurrent processes of flow stratification, deceleration, and redeposition,
Gravitational mass transport
Flow transformation

A. TURBIDITY CURRENT FORMS BY MIXING AND DILUTION OF INITIAL DEBRIS FLOW
B. DEBRIS FLOW FORMS BY EROSION OF MUDDY SEA-FLOOR BY INITIAL TURBIDITY CURRENT
C. LOADING OF BASIN MARGIN BY INITIAL TURBIDITY CURRENT TRIGGERS SECONDARY DEBRIS FLOW
D. DECELERATION OF INITIAL TURBIDITY CURRENT
E. DECELERATION OF INITIAL LOOS COHERENCY DEBRIS FLOW

(Talling et al. 2004)
Talling et al. 2007
Turbidity currents
Turbidites = Deposits from turbidity currents

Size - Velocity Diagram

Mean Flow Velocity (cm/sec)

Mean Sediment Size (mm)

No Movement on Flat Bed
Ripples (No Movement on Flat Bed)
Ripples
Flat Bed
“C”
Flat Bed
Sand Waves
“B”
Dunes
“A”
In-Phase Waves

Mud V.F. Sand F. Sand M. Sand C. Sand

Reducing flow intensity
End-members of gravity flows (‘Turbidites’)

1) Turbidity currents:
   - particles are kept aloft in the body of the flow by turbulent suspension
   - suspended particles cause density of flow to be greater than that of ambient fluid
   - both high density and low density turbidity currents exist; the deposit of each type has its own attributes

2) Liquified flows:
   - very concentrated dispersions of grains in fluid
   - usually result from shock of granular sediment (e.g. seismic shock)
   - grains are kept in suspension by fluid pore pressure and from upward movement of fluid that is expelled

3) Grain flows:
   - characterized by grain-grain collisions.
   - no reduction of friction occurs in such flows, so they can only occur on steep slopes where the angle of initial yield has been exceeded.

4) Debris flows:
   - slurry-like flows in which large particles (up to boulders) are set in a fine-grained matrix
   - matrix has ‘yield strength’ which helps support grains during flow
   - matrix serves to lubricate grain irregularities so debris flows may occur on very gentle
Debris Flow / Turbidite
Proximal to distal
Development and Fazies Models

Mutti et al., 2009
Environmental models for submarine fans and slope aprons

Increasing size of source area, depositional system, size of flows, tendency for major slumps, persistence and size of fan-channels, channel-levee systems, tendency to meander, thin sheet-like sands in lower fan and basin plain

Decreasing grain size, slope gradient, frequency of flows, tendency for channels to migrate laterally

Stow & Mayall
2000
Submarine Paleoseismology: The record of «seismo-turbidites»

Goldfinger 2011
Holocene earthquake record offshore Portugal (SW Iberia): testing turbidite paleoseismology in a slow-convergence margin

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Widespread Holocene turbidites vs. earthquakes, tsunamis and tsunamites

<table>
<thead>
<tr>
<th>Event Code</th>
<th>Age Range</th>
<th>Event Description</th>
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<tbody>
<tr>
<td>E1</td>
<td>AD 1971±3</td>
<td>Horseshoe EQ (AD 1969)</td>
</tr>
<tr>
<td>E3</td>
<td>300 - 560 yr BP</td>
<td>Lisbon EQ (AD 1755)</td>
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<tr>
<td>E5</td>
<td>1980 - 2280 yr BP</td>
<td>Gulf of Cadiz EQ &amp; Tsunami (218 BC)</td>
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<tr>
<td>E6</td>
<td>4960 - 5510 yr BP</td>
<td>Tsunamite (5310 yr BP)</td>
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<tr>
<td>E8</td>
<td>6690 - 6985 yr BP</td>
<td>Tsunamite (6000 - 7000 yr BP)</td>
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<tr>
<td>E9</td>
<td>7880 - 8145 yr BP</td>
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</tr>
<tr>
<td>E10</td>
<td>8715 - 9015 yr BP</td>
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</table>
Turbidite Paleoseismology in Chilean Lakes

Mournault et al.
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