Sediment Transport & Fluid Flow

- Downslope transport
- Fluid Flow
  - Viscosity
  - Types of fluid flow
  - Laminar vs. Turbulent
  - Eddy Viscosity
  - Reynolds number
  - Boundary Layer
- Grain Settling
- Particle Transport

Loss of intergrain cohesion caused by saturation of pores…
Different kinds of mass movements, variable velocity (and other factors)

From weathering to deposition: sorting and modification of clastic particles
Effects of transport on rounding, sorting

How are particles transported by fluids?

What are the key parameters?
Fluid Flow

- Fundamental Physical Properties of Fluids
  - Density ($\rho$)
  - Viscosity ($\mu$)
  
  Control the ability of a fluid to erode & transport particles

- Viscosity - resistance to flow, or deform under shear stress.
  - Air - low
  - Water - low
  - Ice - high

$\Delta \mu$ with $\Delta T$, or by mixing other materials
Shear Deformation

Shear stress ($\tau$) is the shearing force per unit area
- generated at the boundary between two moving fluids
- function of the extent to which the slower moving fluid retards motion of the faster moving fluid (i.e., viscosity)

Fluid Viscosity and Flow

- **Dynamic viscosity** ($\mu$) - the resistance of a substance (water) to Δ shape during flow (shear stress)
  \[
  \mu = \frac{\tau}{du/dy}
  \]
  where,
  - $\tau$ = shear stress (dynes/cm$^2$)
  - $du/dy$ = velocity gradient (rate of deformation)

- **Kinematic viscosity** ($v$) = $\mu/\rho$
Behaviour of Fluids

Viscous

Increased fluidity

Types of Fluids

**Water** - flow properties function of sediment concentrations

- **Newtonian Fluids** - no strength, no $\Delta$ in viscosity as shear rate $\Delta$'s (e.g., *ordinary water*)
- **Non-newtonian Fluids** - no strength, but variable viscosity($\mu$) as shear rate $\Delta$'s (e.g., *water w/ sand (>30%) or cohesive clay*)
  - Muds flow sluggishly at low flow velocities, but display less viscous flow at high velocities
- **Bingham Plastics** - initial strength, must be overcome before yield occurs (e.g., debris-flows)
  - No $\Delta$ in viscosity after yield strength is exceeded
  - If $\mu$ varies, as with water laden sediment, or ice, this is referred to as a **pseudoplastic**
Flow regimes in a stream

Laminar to Turbulent flow

- What controls this change in flow?
  - Depth ($L$) & Velocity ($U$)
Laminar vs. Turbulent Flow

Two modes of flow dependent upon:

1. **Velocity**
2. **Fluid viscosity**
3. **Bed roughness**

- **Laminar Flow**: streamlined, uniform current. Requires:
  - Low fluid velocity or
  - High viscosity or
  - Smooth beds

- **Turbulent Flow**: discontinuous, distorted, flow w/ considerable motion perpendicular to primary flow direction.
  - Eddies - highly turbulent flow (water and air)

- **Eddy Viscosity**: internal friction at a larger scale
  - Turbulent flow resists distortion to a much greater degree than Laminar flow
  - Fluid under turbulent flow appears to have **high viscosity**

Eddy Viscosity

- Shear stress for Fluid undergoing turbulence require an extra term to account for e.v.
  - For laminar flow:
    \[ \tau = \mu \frac{du}{dy} \]
  - For turbulent flow:
    \[ \tau = (\mu + \eta) \frac{du}{dy} \]
  - Where \( \eta \) is eddy viscosity
What controls the transition from turbulent to laminar flow?

Reynolds Number ($R_e$)

- Laminar vs Turbulent differences arise from ratio of inertial / viscous forces
  - Inertial forces ($U\rho$) - enhance turbulence
  - Viscous forces ($\mu/L$) - suppress turbulence
- Relationship of inertial to viscous forces is described by:

$$R_e = \frac{UL\rho}{\mu}$$

$U$ = mean velocity, $L$ = water depth, $\rho$=density

When $\mu$ dominates, $R_e$ is small (<500), flow is laminar
  - e.g., low velocity, shallow, or ice flows
At high $U$ and/or $L$, flow becomes turbulent (>2000)
Viscosity effects on $Re$: laminar vs. turbulent

- High viscosity - low $Re$
- Low viscosity - high $Re$

**Boundary Layers**

- Area of reduced flow: Fluid flow over a stationary surface (the bed of a river)
  - fluid touching the surface is brought to rest by the shear stress (boundary) at the wall.
  - $U$ increases to a maximum in the main stream of the flow.
  - Laminar flow transitions to an area of turbulent flow
Boundary Layer (BL) Transition: laminar vs. turbulent

- **Turbulent flow** - thins BL
- **Rough bed** - thins BL
Surface Waves & Froude Number

Fluid Flow variables:
- Viscosity (ignore for water)
- Inertial forces
- Gravity & depth (surface wave velocity)

Froude # ($F_r$) - ratio of inertial forces to gravity,

$$ F_r = \frac{U}{\sqrt{gL}} $$

Froude #
- $< 1$, max wave velocity exceeds current, tranquil (sub-critical)
- $> 1$, current velocity exceeds max wave velocity (supercritical)

Froude Number

- If flow $U >$ wave $U$ ($F_r > 1$) flow is supercritical. lower $U$ ($F_r < 1$), flow subcritical (i.e., waves can travel upstream)
- A spatial transition from subcritical to supercritical flow (or vice versa) is characterized by a ‘hydraulic jump’
FLOW REGIMES

Deeper Subcritical (Fr<1)

Shallow Supercritical (Fr>1)

Figure 4.3

(A) Sequence of bedforms produced through increasing flow strength conditions. (From Blatt et al., 1980, Origin of Sedimentary Rocks, 2nd ed., p. 137; by permission of Prentice-Hall, Inc., Englewood Cliffs, N.J.) (B) Changes in bedforms resulting from different flow velocities (vertical axis) and grain sizes (horizontal axis). (Flow from 1980.)
Sediment Transport

Two critical steps
1. Erosion and entrainment
   - Lifting
   - Critical velocity threshold
2. Down current/wind transport
   - Rolling/bouncing/suspension
   - Critical velocity

Particle Entrainment:

Forces acting on a grain

Drag \( (F_D) \)  Lift \( (F_L) \)

\[ F_D \sim \tau (\text{shear stress}) / \# \text{ of grains} \]

\[ F_L - \text{Bernoulli Effect} - \text{Pressure diff. top & bottom of a grain} \]
Modes of sediment transport in water

Bedload Transport

Courtesy Dietrich, UCB
Particle Transport

3 Modes
1. Traction (rolling, sliding)
2. Saltation (bouncing)
3. Suspension (floating)

Traction + Saltation = Bedload

Particle Settling

Stokes’ Law (settling velocity in a static fluid)

\[ V = \frac{gD^2(\rho_g - \rho_f)}{18\mu} \]

\( V = \) settling velocity; \( D = \) grain diameter; 
\( \rho_g = \) grain density; \( \rho_f = \) fluid density; \( \mu = \) dynamic viscosity

\[ V = CD^2 \]

\[ C = \frac{g(\rho_g - \rho_f)}{18\mu} \]

- Stokes’ Law only applies to fine (<200 \( \mu \text{m} \)), quartz-density grains in water

Sediment transport varies with flow velocity...

- Velocity to pluck (lift) grain > velocity needed to maintain suspension

...and leads to characteristic bedforms (the geologic record)
Deposition by Fluid Flows (water/wind)

- **Deposition** - Decrease in velocity
  - Decrease in slope
  - Increase in bed roughness
  - Low of water volume
- **Deposition** - permanent or temporary
  - River channels, point bars, beaches, reentrained & transported
- **Sediment deposits characteristics:**
  - Layers, Lack of size grading
  - Variable sorting

**Different kinds of mass movements, variable velocity (and other factors)**
Deposition by Mass Transport

• Transport by gravity
  – Fluid is a lubricant (reduces), supports particles
  – Flow stops when sediments are deposited
  – Subaqueous or subaerial

• Categories:
  1. Rock Fall
  2. Slide
  3. Sediment Gravity flows
     – Debris flows
     – Grain flows
     – Fluidized flows

Deposition by Sediment Gravity Flows (water/wind)

• Mass Flows (grain supported, cohesionless flow)
  1. Debris/Mud - slurrylike flows of highly concentrated, poorly sorted mix of sediment/water (>10°) - Bingham plastics
  2. Grain - avalanching of cohesionless sediment (sand) on steep slope (>30°)

• Fluid Flows (fluid and grain supported flow)
  1. Liquefied
  2. Fluidized
  3. Turbidity
Gravity flows

- **Debris flows**
  - Sediment/water >50%
  - both subaerial and subaqueous
  - Low Reynolds numbers

- **Turbidity currents**
  - Sediment/water <50%,
  - always subaqueous,
  - move due to density contrasts
  - Higher Reynolds numbers
Modes of sediment transport in water

Turbidity Currents
Bouma Sequence

<table>
<thead>
<tr>
<th>Grain Size</th>
<th>Bouma divisions</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mud</td>
<td>pelite</td>
<td>pelagic sedimentation or fine grained, low density turbidity current deposition</td>
</tr>
<tr>
<td>Silt</td>
<td>upper parallel laminae</td>
<td>lower part of lower flow regime</td>
</tr>
<tr>
<td>Sand</td>
<td>ripples, wavy or convoluted laminae</td>
<td>plane parallel laminae</td>
</tr>
<tr>
<td>Sand and silt</td>
<td>Massive, graded</td>
<td>upper flow regime, rapid deposition and quick bed</td>
</tr>
</tbody>
</table>

Bouma sequence, the idealized sequence of sediments and structures deposited in a turbidite by a turbidity current

MIGRATION OF CROSS-BEDS
**REACTIVATION SURFACES**

A. Constructional event

B. Destructional event

C. Constructional event

D. Destructional event

*Sedimentary rock textures, sorting, size*
Sediment transport: forming graded bedding

Depth/Velocity & Sediment Size

- Sediment transport, forming graded bedding
- Depth/Velocity & Sediment Size
- Diagrams showing the relationship between depth, velocity, and sediment size.
shear-stress can be used to predict the velocity 1 m above the bed ($U_{100}$) caused by waves of various heights and lengths (expressed as period, $T$)

Fluid Viscosity and Flow

**Kinematic Viscosity ($\nu$)** - ratio of the dynamic viscosity to density

Determines the extent to which fluid flows exhibit turbulence

$$\nu = \frac{\mu}{\rho}$$
Rocks lose sharp edges…