Fundamentals of Fluid Flow (GEOL 334)

Before we can interpret sedimentary structures, we first need to learn a few key aspects of fluids, including material properties, how they move, and the difference between fluids and plastics.

Fluid = "a substance that changes shape continuously *as soon as an external force (or stress)* is applied" … because it has zero cohesive strength. Fluids include: water, oil, air, other gases.

(1) Key Properties of Fuids: (1) density (ρ); and (2) viscosity (μ)

Density (ρ) = mass/volume. E.G. kg/m^3, g/cm^3. Density is important because it controls:

- Magnitude of forces exerted on a bed
- Buoyancy of particles in transport
- Settling velocity of particles in a fluid

Density of water: $\rho_w = 1\ g/cm^3$ ($= 1000\ kg/m^3$)

Density of air: $\rho_a = 0.00125 – 0.0014\ g/cm^3$ ($= 1.25 – 1.4\ kg/m^3$)

Difference: **ρ_w ~ 700-800 times ρ_a.** Represents a very strong force. Combined with zero strength of water, this difference causes water to flow downhill even on very low slopes.

Viscosity (μ) = a measure of internal resistance to flow. Viscosity is important because it:

- *Resists* internal deformation and flow
- Controls rate of lava flowing downhill (e.g. basaltic eruptions on Hawaii)
- Determines velocity of debris flows in mountain valleys

Qualitative:

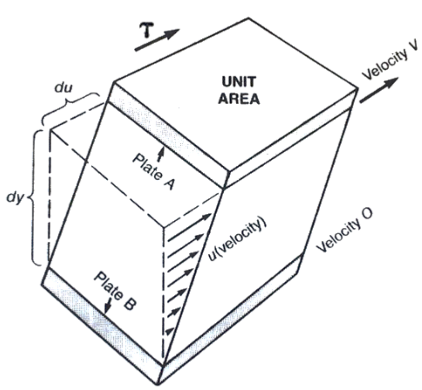
Low-viscosity fluids: are "thin and runny", flow rate is relatively fast
High viscosity fluids: are "thick and sticky", flow rate is relatively slow

Quantitative:

Units of μ: 1 poise = 1 [dyn sec. / cm^2] (= 0.1 Pa sec.)
1 Pa sec. = 1 [N sec. / m^2] (= 10 poise)

Viscosity of water (μ_w) ~ 0.01 poise (~ 0.001 Pa sec.)

Important: ***When a fluid is subjected to a shear stress (τ), the rate of internal deformation (du/dy) is directly proportional to the fluid's viscosity.*** We can quantify this:



Text Figure 2.1.1 (Boggs, 2012)

Imagine a Laboratory Experiment

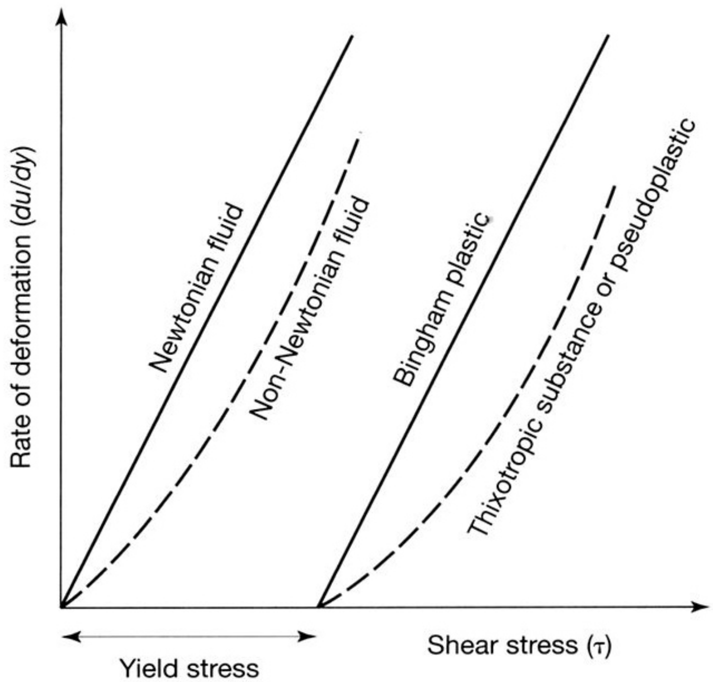
- Fluid confined between two rigid plates
- Lower plate is stationary, upper plate moves at velocity V
- Apply a known shear stress (τ) to upper plate, and measure the resulting velocity of the upper plate (du = V)
- *Velocity Gradient* = du/dy (dy = distance between plates)

Viscosity Defined: $$\mu = \frac{\tau}{du/dy}$$

(2) Behavior of Fluids and Plastics

First, a key difference between fluids and plastics (as commonly defined in earth sciences):

- **Fluid** has no shear strength: deformation (flow) starts *as soon as stress applied.*
- **Plastic** ***has*** shear strength (yield strength): when shear stress (τ) is first applied there is no deformation, no flow. When τ is increased to the yield stress, then motion is initiated.



$$\mu = \frac{\tau}{du/dy}$$

Note that slope of the line in above plot *is* viscosity *(in above plot, steeper slope = lower μ)*

Linear vs. nonlinear relationship between shear stress and deformation gradient (du/dy) … tells us whether viscosity (μ) is constant, or changes, as a function of changing du/dy.

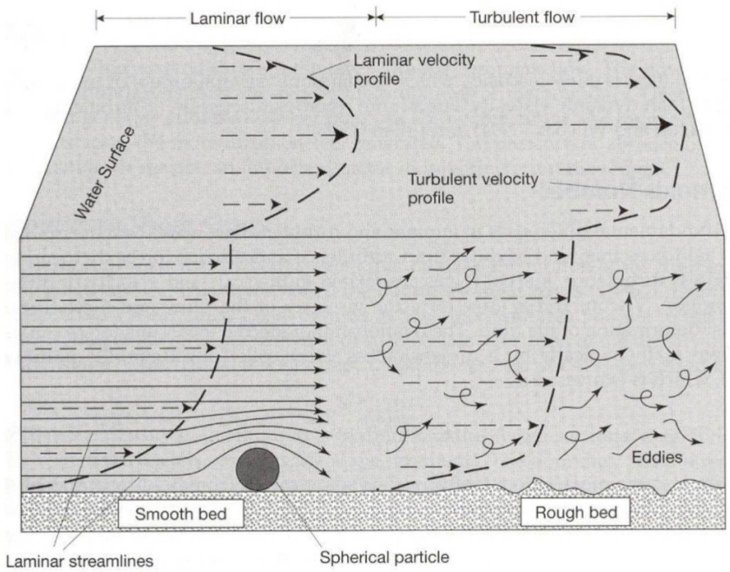
So, we can define and describe different types of dynamic behavior as follows:

- Newtonian Fluid: Has no internal strength, viscosity is constant across a range of different flow rates (i.e. independent of du/dy). Examples include clear water, air.
- Non-Newtonian Fluid: No internal strength, viscosity varies as a function of flow rate. Examples: soda pop, muddy slurries, sand-in-water dispersions (turbidity currents)
- Bingham Plastic: *Has* yield strength (= cohesive strength, often due to clays), viscosity is constant across different flow rates. Example: silly puddy, potter's clay.
- Pseudoplastic: Does have yield strength, but viscosity varies as a function of flow rate. Examples: lava, blood, ketchup, paint, nail polish, some (cohesive) debris flows …
- Thixotropic Substance: Has internal strength at rest, viscosity decreases when sheared. Examples: corn starch, gels and colloids, certain muds and clays. Important for understanding slope failures and liquefaction during landslides, earthquakes, etc.

(3) Laminar vs. Turbulent Flow

Two major types of flow:

- **Laminar**: stream lines (path of fluid particles) are mostly planar and parallel.
- **Turbulent**: fluid particles exhibit random motion, highly irregular, disorganized. Includes significant component of flow *across* average flow path, perpendic. to bed (more erosive).



Text Figure 2.1
Schematic representation of laminar and turbulent fluid flow. Compare streamline flow under laminar flow conditions to the chaotic pattern of flow under turbulent conditions. Also, compare the shape of the laminar velocity profile to that of the turbulent velocity profile (heavy dashed lines).

We can predict if a flow will be laminar or turbulent, using the Reynolds number (Re):

$$\text{Re} = \frac{\mathbf{U\,D\,\rho}}{\boldsymbol{\mu}} = \frac{\textbf{inertial (driving) forces}}{\textbf{viscous (resisting) forces}}$$

U = average velocity; D = flow depth; ρ = density; μ = viscosity

In general: Laminar flow if Re < ~ 500 – 2000
Turbulent flow if Re > ~ 500 – 2000

(the range of values reflects "other factors" such as bed roughness that control this threshold)

Turbulent Flow is important because:

- It increases ability of a moving fluid to erode bed and entrain particles
- Vertical velocity profile is different than for laminar flow: rapid flow lines are compressed toward base, which increases the erosive properties of the flow
- The upward component of turbulent flow decreases particle settling velocities

Calculate Re: water ($\mu = 0.001$ Pa sec; ρ = 1000 kg/m^3), 1 m deep, flowing at 1 cm/s (= 0.01 m/s)

Answer: Re = 10,000! (much higher than transition from laminar to turbulent flow)

Result: Most natural flows (rivers, etc.) are turbulent!

What is the Reynolds number for a 1-meter deep flow of water ($\rho = 1000\ kg/m^3$, $\mu = 0.001$ Pa-s) that is moving at a velocity of 1 cm/s (0.01 m/s)? Is the flow laminar or turbulent?

$$Re = \frac{\overset{(m/s)}{U}\ \overset{(m)}{L}\ \overset{(kg/m^3)}{\rho}}{\underset{(Pa\cdot s) = \left(\frac{kg}{s\cdot m}\right)}{\mu}} = \frac{\overset{U}{0.01} \times \overset{L}{1} \times \overset{\rho}{1000}}{.001\ (\mu)} = \boxed{10{,}000}$$

Flow is Turbulent

Must Deal with UNITS:

$$Pa = N/m^2 \qquad N = \frac{kg\,m}{s^2} \quad \Rightarrow \quad Pa = \frac{kg\,m}{s^2 m^2} = \frac{kg}{m s^2}$$

$$Pa \cdot s = \frac{kg}{ms^2} \times s = \frac{kg}{sm}$$

$$\text{So, Units} = \frac{m/s \cdot m \cdot kg/m^3}{kg/s\cdot m}$$

all cancel out!

Note: Pa = Stress (N/m^2)

Pa·s = Viscosity