GLGY 377: Geophysics

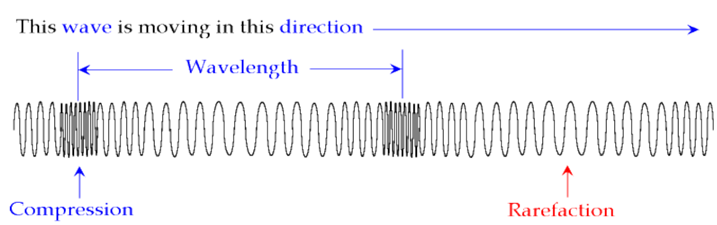
- **Seismology:** study of propagation of seismic waves through the earth.
- **Seismograph:** instrument which records seismic waves
- **Seismogram:** record of the motion of seismic waves over time.
- **Event:** an appearance of seismic data (ie. diffraction, reflection, reflection)

- Uses:
    - Make inferences about earth interior
    - Find hydrocarbons (oil and gas)
    - Find minerals
    - Analogues: x-rays, CT scans, MRI scans, magnetic resonance, ultrasounds

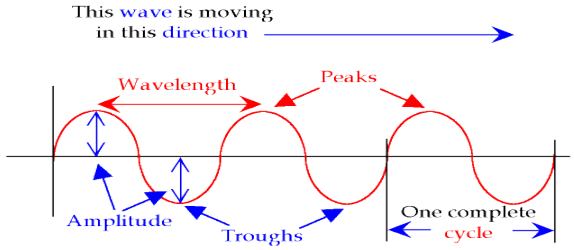
Modes of seismic waves:

Body waves:

- P-waves
    - Primary, Longitudinal (push or pull) waves
    - Particles compress and dilate
    - Fastest velocity of the four seismic modes
    - Most frequently used mode

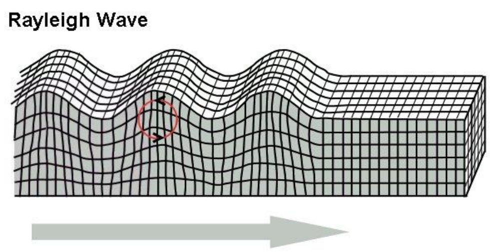


- S-waves
    - Secondary, Transverse (shear) waves
    - Particles displaced perpendicular to direction of propagation
        - Sine or Cosine wave
        - Wave on a string (guitar string)
    - 1/2 to 2/3 of P-wave velocity
    - **S-WAVES DO NOT PROPOGATE THROUGH LIQUIDS**

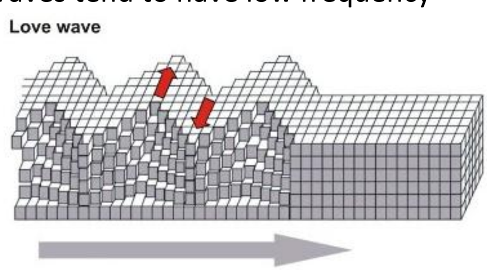


Surface Waves

- Rayleigh Waves
    - Propagated along the surface
    - Particles travel in elliptical path
        - Parallel to propagation direction
    - Highly energetic near the surface
    - Velocity is slower than S and P waves
    - Waves tend to have low frequency



- Love Waves
    - Propagated along Earth's surface
    - Perpendicular to propagation direction
    - Highly energetic near the surface
    - Velocity is slower than S and P waves
    - Waves tend to have low frequency

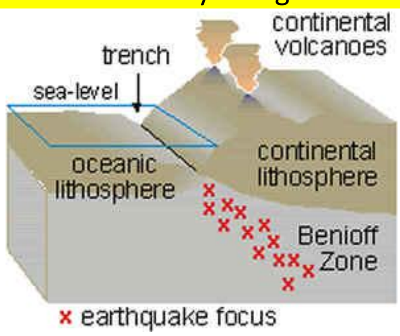


Tectonics

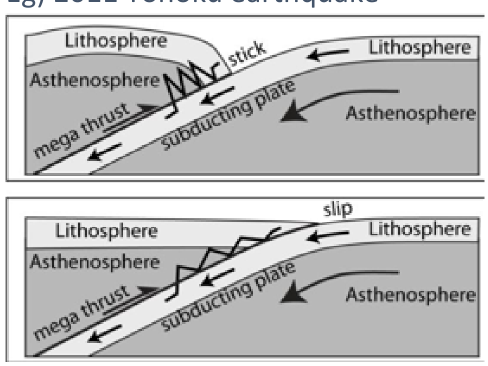
- **Plate Tectonics:** interaction of rigid lithospheric plates as they move slowly over the underlying mantle.
- **Earthquake:** sudden and violent shaking of the ground
    - Great Tohoku-oki earthquake

- Occurred in 2011 caused nuclear accidents
- Pacific plate sub-ducting (pushing underneath) Japan (Okhotsk Plate)
  - Earthquakes to occur at different depths

- Wadait-Benoif Zone
  - Zone of seismic activity along a subduction zone.



- Stick-slip
  - Occurs when two sides of the fault become unstuck
  - Fast movement (thrust) occurs
    - Causes earthquakes
    - Eg) 2011 Tohoku earthquake



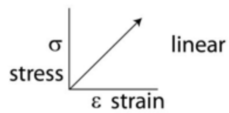
- Notes on Tectonics
  - Convection in mantle induces plates to move
  - Causes shifting of continents
    - Pangaea ⟶ Present day continent
  - Volcanoes related to tectonic plates
    - Eg) Ring of Fire
    - Active volcanoes on North American west coast
  - Analogy of Earth: Crust is like the skin of an apple, not an orange
  - Becoming a continent mentioned a lot during class

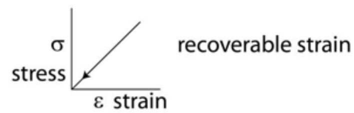
Fundamentals of Seismic Wave Propagation

- Elastic properties of rock:

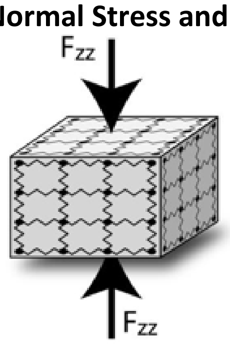
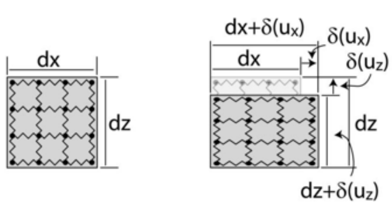
Stress and Strain

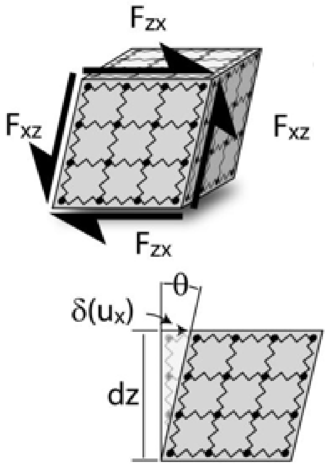
- **Stress** is force per area relative to *internal forces*
- **Strain** is force tending to pull or stretch
  - Solid experiences change in shape
  - **Normal strain** is perpendicular stress 
  - **Shear strain is** parallel stress 
    - Unequal forces = shear strain
- Elastic properties (ratio of stress to strain)
  - Strain is directly proportional to stress





  - Strain is recovered when applied stress is removed

Normal Stress and Strain   	Normal Stress $$Stress\ (\sigma) = \frac{Force}{Area}$$ $$\sigma_{zz} = \frac{F_{zz}}{dxdy}$$ $\sigma_{xx} = \sigma_{yy} = 0$ *(normal stress)* Normal Strain $$\varepsilon = \frac{-\delta(u_z)}{dz}$$	$\sigma_{zz} = Stress\ in\ z\ direction$ $\sigma_{xx} = Stress\ in\ x\ direction$ $\sigma_{yy} = Stress\ in\ y\ direction$ $F_{zz} = Force\ in\ z\ direction$ $dxdy = Stressed\ Area$ $\delta(u_z) = change\ in\ length\ due\ to\ strech$ $dz = original\ length$ Notes: Stress units: Pascal (Pa) Strain units: Dimensionless (+) Compression (-) Tension
Shear Stress and Strain	Shear Stress $$\sigma_{zx} = \frac{F_{zx}}{dxdy}$$ $$\sigma_{zx} = -\sigma_{xz}$$	$\sigma_{zx} = Stress\ in\ zx\ plane$ $\sigma_{xy} = Stress\ in\ xy\ plane$ $\sigma_{zy} = Stress\ in\ zy\ plane$ $F_{zx} = Force\ in\ zx\ plane$ $dxdy = Stressed\ Area$

	$\sigma_{yx} = \sigma_{xy} = 0$ $\sigma_{yz} = \sigma_{zy} = 0$ (no forces acting at these planes) <u>Shear Strain</u> $\varepsilon_{zx} = \frac{\delta(u_x)}{dz}$ $\varepsilon_{zx} = \tan(\theta)$	$\delta(u_x) = change\ in\ length\ due\ to\ strech\ in\ x$ $dz = original\ length$ $\theta = angle\ of\ shift$ <u>Notes:</u> Shear stress units: Pascal (Pa) (+) Clockwise shear stress Unequal subscripts=shear strain Why?⟶ unbalanced forces

Young's Modulus

- Measures the stiffness of a material
- How much a material will stretch (strain) as a result of a given amount of stress

$Young's\ Modulus\ (E) = \frac{\sigma}{\varepsilon}$	$\sigma = normal\ stress$ $\varepsilon = normal\ strain$

Poisson's Ratio

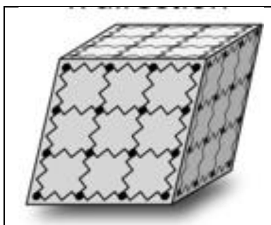
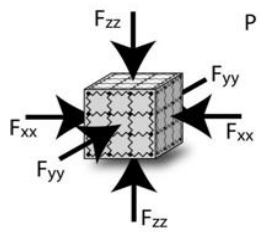
- Measure the compressibility of a material
- Ratio of proportional decrease in lateral measurement to proportional increase in length of material when stretched.

$Poisson's\ Ratio\ (v) = \frac{-\varepsilon_{xx}}{\varepsilon_{zz}} = \frac{-\varepsilon_{yy}}{\varepsilon_{zz}}$ $\varepsilon_{xx} = \frac{-\delta(u_x)}{dx}$ $\varepsilon_{yy} = \frac{-\delta(u_y)}{dy}$ $\varepsilon_{zz} = \frac{-\delta(u_z)}{dz}$	$\varepsilon_{zz} = normal\ strain\ in\ z\ direction$ $\varepsilon_{yy} = normal\ strain\ in\ y\ direction$ $\varepsilon_{xx} = normal\ strain\ in\ x\ direction$ $\delta(u_z) = change\ in\ length\ due\ to\ strech$ $dz = original\ length$

- <u>Notes</u>
  - The ratio is always positive
  - Unit-less

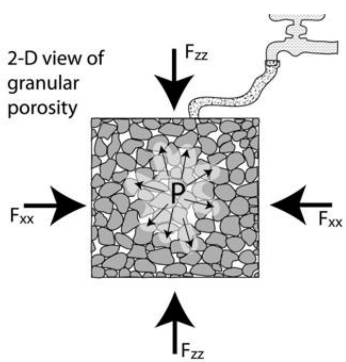
Bulk and Shear Modulus

- **Shear Modulus:** material's response to shear stress
    - Ratio of shear stress to shear strain
    - Eg) Cutting with dull scissors
- **Bulk Modulus**
    - Ratio of stress intensity to volume strain
    - Isotropic stress (hydrostatic pressure)

	$Shear\ Modulus\ (\mu) = \frac{\sigma_{zx}}{\varepsilon_{zx}}$	$\sigma_{zx} = shear\ stress\ in\ zx\ plane$ $\varepsilon_{zx} = shear\ strain\ in\ zx\ plane$
	$Bulk\ Modulus\ (K) = \frac{P}{\delta V/V}$ $P = \sigma_{xx} = \sigma_{yy} = \sigma_{zz} = \frac{F_{zz}}{dxdy}$	$P = Stress\ (Pa)$ $\delta V = change\ in\ volume$ $V = original\ volume = dxdydz$ $F_{zz} = Force\ in\ z\ direction$ $dxdy = Stressed\ Area$

- Elastic Properties
    - Completely described by the pair:
        - Young's Modulus (E) and Poisson's ratio (ν)

          OR
        - Bulk Modulus (K) and Shear modulus (μ)
    - Stress and strain curves
        - When strain and stress become too great ⟶ rocks crack
        - Rocks are naturally fractured (cracked)
            - Fractures allow flow of fluids
            - Increasing confining stress will close cracks
            - Increasing pore pressure will open cracks
        - Recall
            - **Confining stress** ⟶ stress imposed by weight of overlying material
            - **Pore Pressure** ⟶ pressure of fluids in between pores.
    - Summary
        - Bulk Modulus ⟶ volume stress and strain
        - Shear Modulus ⟶ rigidness
            - Young's Modulus ⟶ stiffness
            - Poisson Ratio ⟶ compressibility
    - Effective Stress (σ-P)



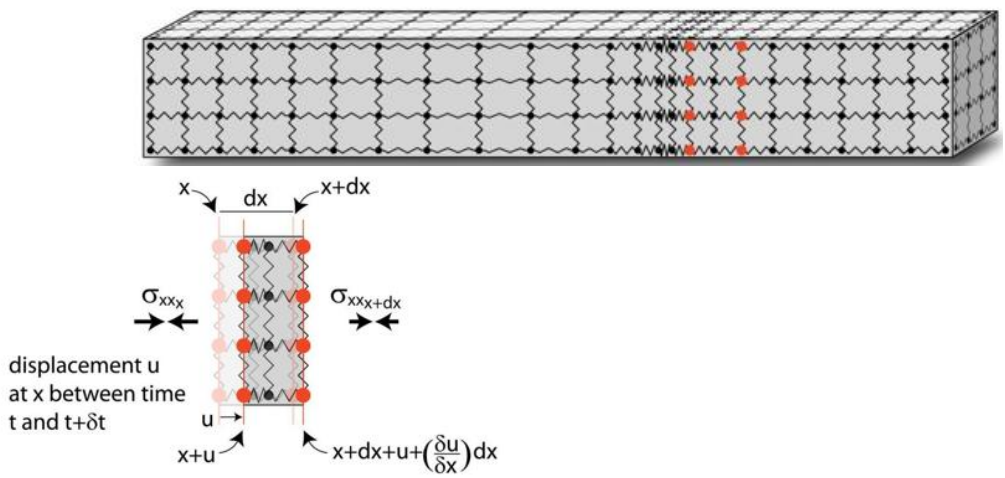
- Total Stress (σ) consists of two parts
  - P acts in the fluid and in the solid in every direction
    - Equal intensity
  - The balance of forces (σ-P) seated exclusively in the sold part

$$Effective\ Stress = Total\ Stress - Pore\ Pressure$$

$$Effective\ Stress = \sigma - P$$

Wave Propagation of P and S Waves

- Given a propagated P-wave moving with respect to time.
- Allows us to derive formulas for Newton's 2nd Law and Hooke's Law



Newton's Second law

- Force is mass times acceleration (F=ma)
  - Force is $\frac{\delta \sigma_{xx}}{\delta x}$*dx*dy*dz
  - m is mass = ρ*dx*dy*dz
    - ρ is density
  - Solving for a and subbing the force and mass into the 2nd formula gives:

$$\rho a = \frac{\delta \sigma_{xx}}{\delta x} = \rho \frac{\delta^2 u}{\delta t^2}$$

Hooke's Law

- **IMPORTANT:** **K**' is not Bulk Modulus in this context, it is HOOKES LAW
- **Hooke's Law** → Strain is proportional to applied stress
  - $\sigma_{xx} = \mathrm{K}' * \varepsilon_{xx}$
  - K' is hooke's law
- Subbing in our previous formula for strain (ε) gives

$$\sigma_{xx} = K' * \frac{\delta u}{\delta x}$$

Propagating P-wave and S-wave

- Combining Hooke's Law and Newton's Second Law gives:

$$\frac{\delta^2 u}{\delta x^2} = \frac{\rho}{K'}\frac{\delta^2 u}{\delta t^2}$$

  - This simplifies to:

$$\frac{\delta^2 x^2}{\delta^2 t^2} = V^2 = \frac{K}{\rho}$$

- Note that for:
  - P waves: $K' = \boldsymbol{K} + \frac{4}{3}\mu$
    - **IMPORTANT NOTE: K** is bulk modulus
  - S waves: $K' = \mu$
- So solving gives:

$$V_p = \sqrt{\frac{K + 4/3\mu}{\rho}}$$

K = Bulk Modulus
μ = Shear Modulus
ρ = Density
V_p = P-Wave velocity

$$V_s = \sqrt{\frac{\mu}{\rho}}$$

K = Bulk Modulus
μ = Shear Modulus
ρ = Density
V_s = S-Wave velocity

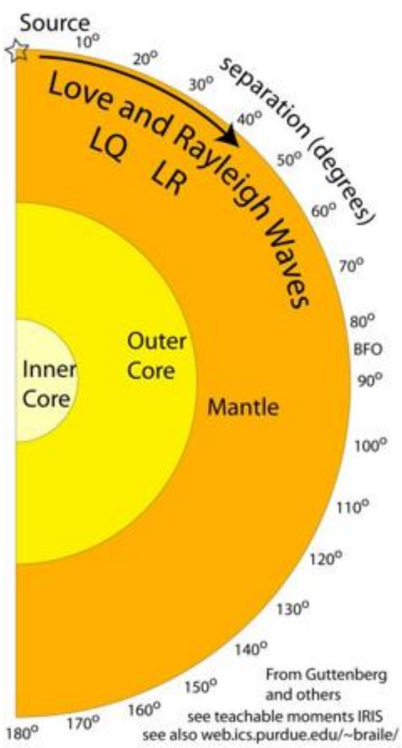
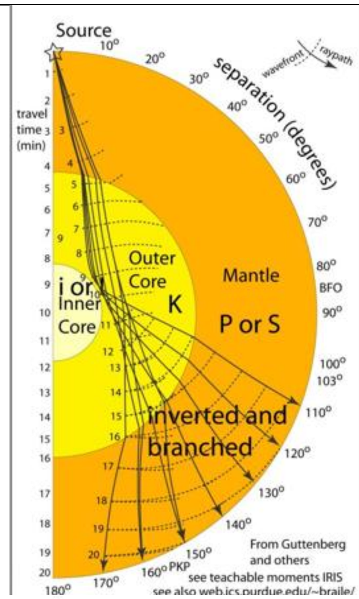
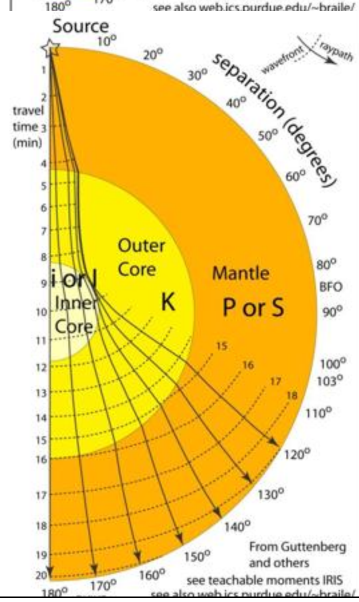
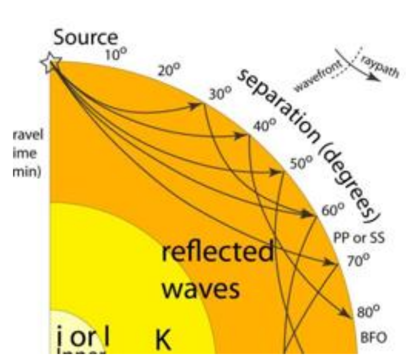
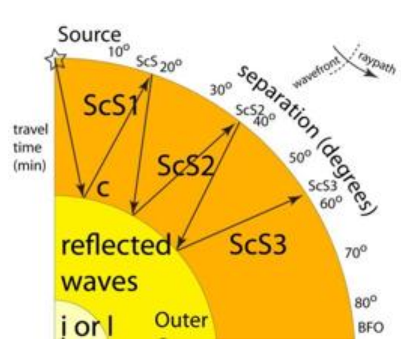
  - Notes:
    - $V_p > V_s$
    - $1.5 < V_p / V_s < 2.0$
    - Elastic stiffness

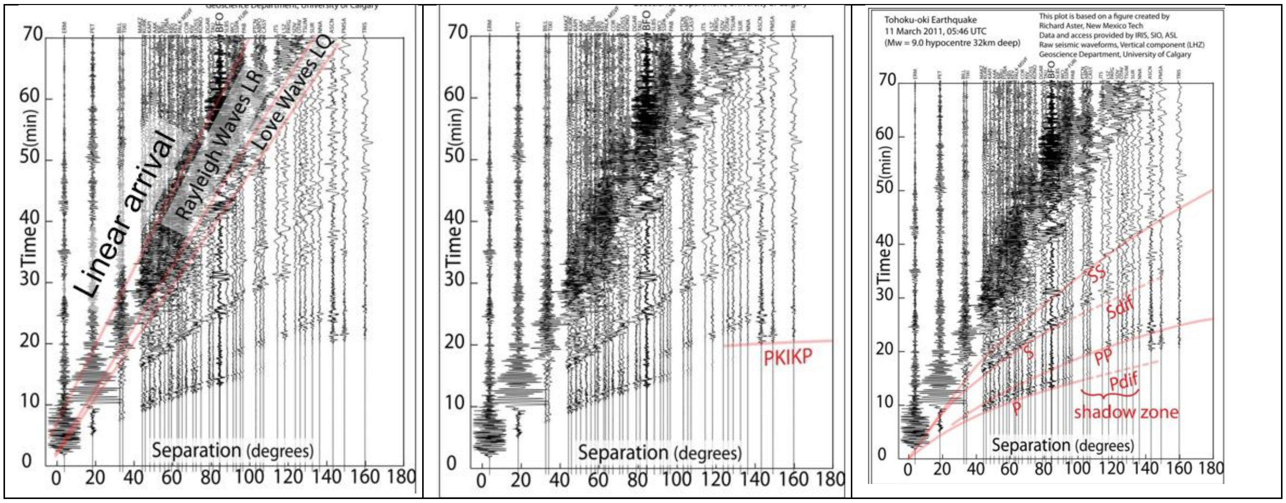
Wave Properties

- Repeat at standard intervals with the same amplitude and period
  - Angular wavenumber $k = \frac{2\pi}{\lambda}$
  - Angular frequency is $\omega = \frac{2\pi}{\tau}$
    - Where τ is period and λ is wavelength
  - Frequency is $f = \frac{1}{\tau}$
  - Phase velocity is $V = f\lambda \; or \; \lambda = V\tau$

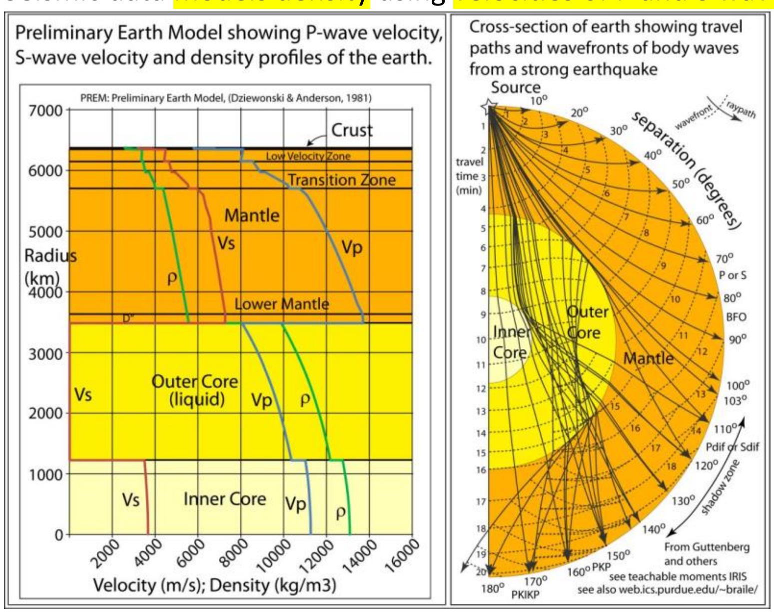
Producing Seismic Data

- Measure arrival of waves around the earth
  - Measure wave arrival time
  - Arrival times depend on angular separation not distance
    - First arrival is p wave
    - Second arrival is s wave
      - Why? P waves are faster than s waves
  - Waves can be reflected and refracted
    - Reflected waves are weaker than refracted waves

Surface waves	Refracted waves	Reflected waves
		



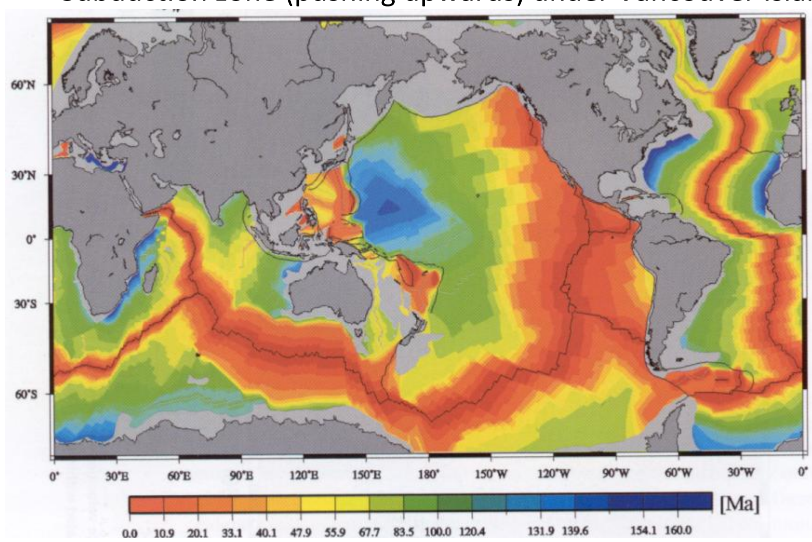
- Modelling
    - Seismic data models density using velocities of P and S waves.



- Methods to model the earth from seismic data:
    - Eg. PREM (Preliminary Earth Model)
    - **Travel time inversion (TTI)**
        - Used to estimate velocity field
    - **Ray-tracing**
        - **Ray paths:** line of propagation of wave motion
        - Generating and running ray-paths through a velocity model.
    - **Steps to generate a *velocity field*:**
        1. Generate and run ray-paths through a velocity model

2. Compare ray-path and observed travel times
    a. Record any errors
3. Apply travel time inversion method
    a. Adjusts velocity model iteratively
    b. Each iteration reduces error between observed and modelled times

- Geophysicists use velocities to produce 3-D models
    - Can model age of rock
        - Figure below [Color Code] Red is new, green is 100 billion, and blue is 160 billion years
    - Subduction zone (pushing upwards) under Vancouver Island



Processing Seismic Data

- **Seismic Imaging**: creation of picture of subsurface geology.
    - Used to infer rock properties
- Treating seismic data to reduce obscuring images

Zoeppritz Equations:

- Acoustic Impedance
    - Measure of opposition of acoustic flow

$$I = V_p * \rho$$

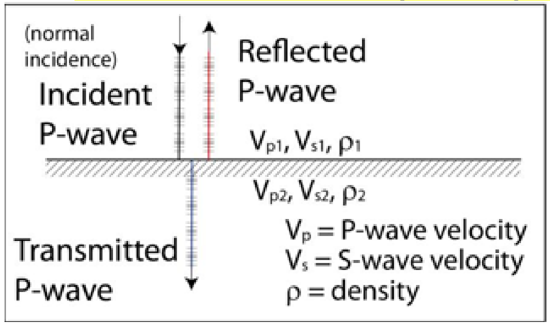
- Reflection Coefficient
    - Proportion of radiation reflected off a surface

$$R = \frac{I_2 - I_1}{I_2 + I_1} = \frac{V_{p2}\rho_2 - V_{p1}\rho_1}{V_{p2}\rho_2 + V_{p1}\rho_1}$$

- Transmission Coefficient

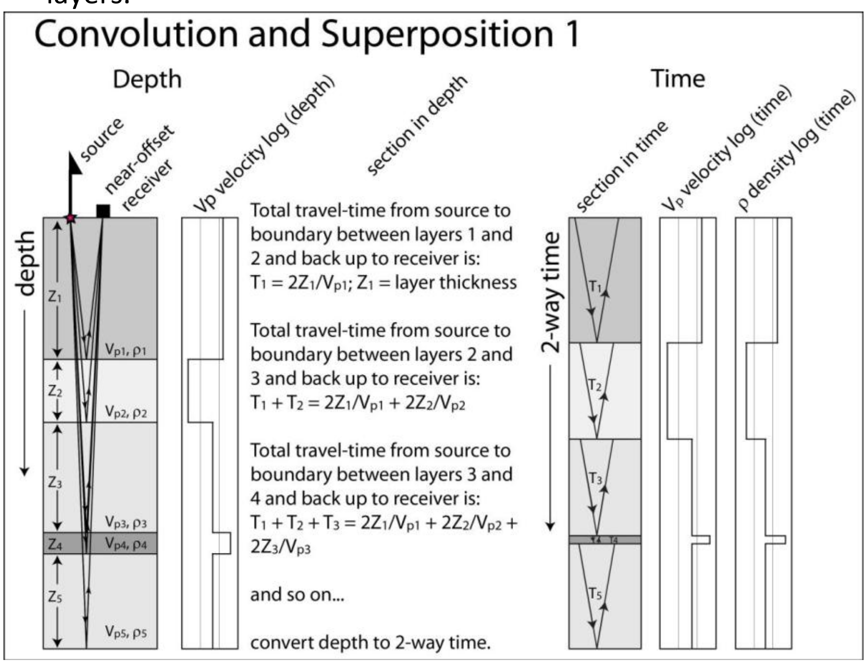
- Ratio of transmitted field strength to incident field strength

$$T = 1 - R = \frac{2I_1}{I_2 + I_1} = \frac{2V_{p1}\rho_1}{V_{p2}\rho_2 + V_{p1}\rho_1}$$

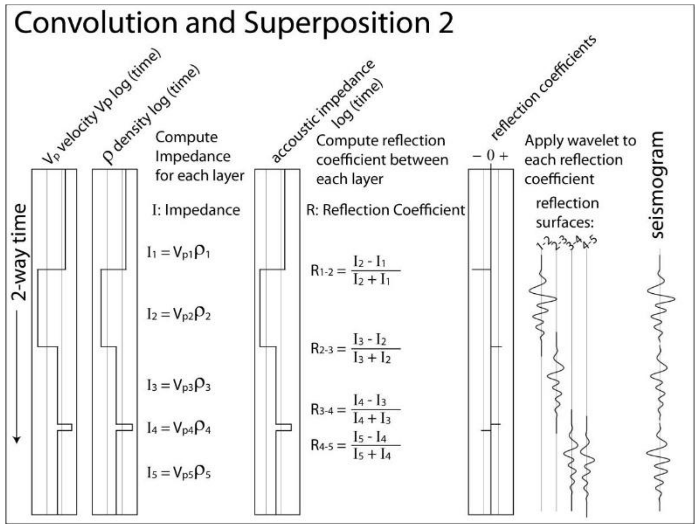


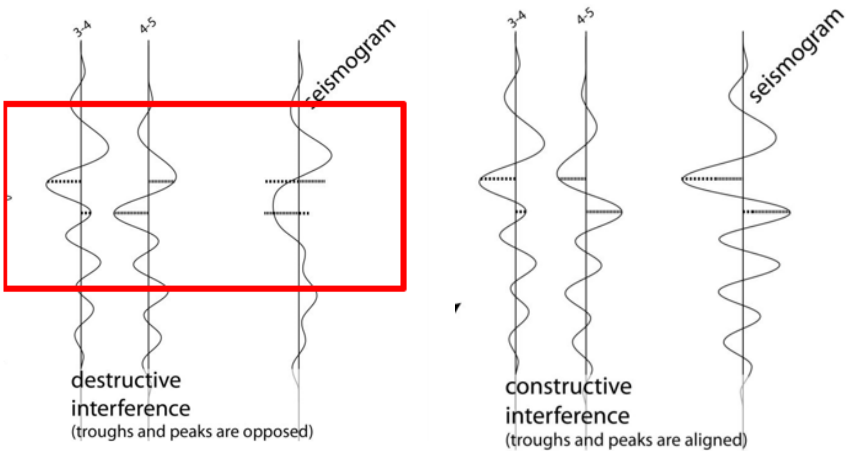
Convolution and Superposition

- **Convolution:** A function derived from two given functions that expresses how the shape of one is modified by the other.
- In seismic data, super-impeding wave lengths give readings
  - Example: Notice that the travel times (T1, T2, T3…) are added between layers.



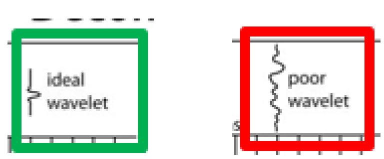
- Steps to convolute data into a *seismogram*:
  1. Compute impedance of each layer
  2. Compute reflection coefficient of each layer
  3. Apply wavelet to each reflection coefficient
  4. Sum amplitudes of waves (gives seismogram readings)
     a. Constructive interference adds
     b. Destructive interference subtracts



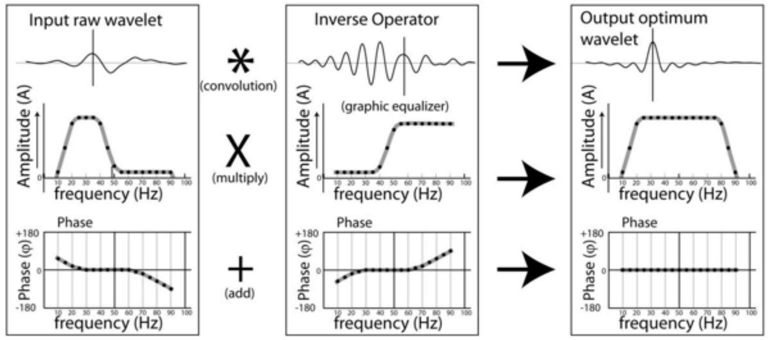


Deconvolution

- Resolution of a convolution function
  - Eg) Making a blurry picture focus
- Corrects for loss of frequency bandwidth and fidelity
- Optimal wavelet
  - Optimal wavelength is short, symmetric, and consistent on the seismogram



- Can get optimal wavelet by using deconvolution which:
  - Broadens the amplitude
  - Makes phases consistent



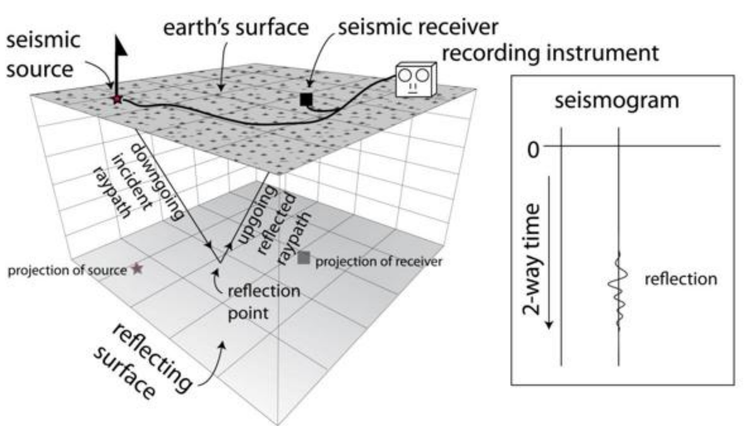
- Higher frequencies yield better resolution

- Fourier Transform
  - Allows us to focus on features of an image
  - Gives better seismic data for geophysics

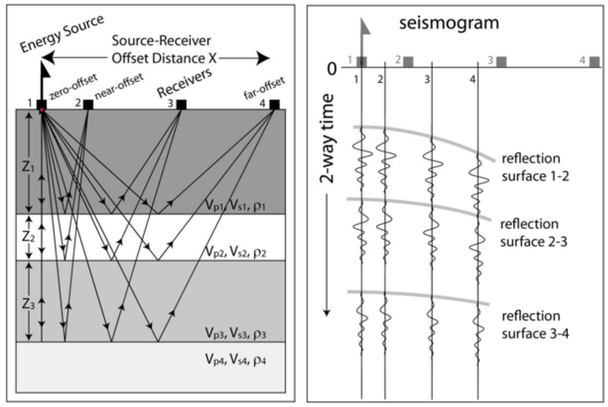
Reflection Seismology

- Used to image subsurface geology
- Processing seismic data
  - Refraction surveys
  - Reflection surveys
- Fundamentals
  - Elastic properties of rocks
  - Seismic wave propagation
  - Seismic reflection, convolution, superposition

- Seismic survey
  1. Seismic source generates seismic energy
  2. Seismic energy propagates down and is reflected back up
  3. Receiver senses reflected seismic energy
  4. Recording instrument stores data from receiver
  5. Seismogram shows motion detected by receiver



- 2-D seismic survey
  - Receivers laid out in straight line from seismic source
  - Seismograms generate a profile of reflecting surface
  - Eg) Marine seismic, seismic line along rural road



  - Complications of 2-D seismic survey
    - Elevation of energy source
    - Elevation of receiver
    - Thickness and velocities of shallow layers
    - Source-receiver offset distance
    - Depth of reflecting surface
    - Dip of reflecting surface

NMO (Normal Moveout)

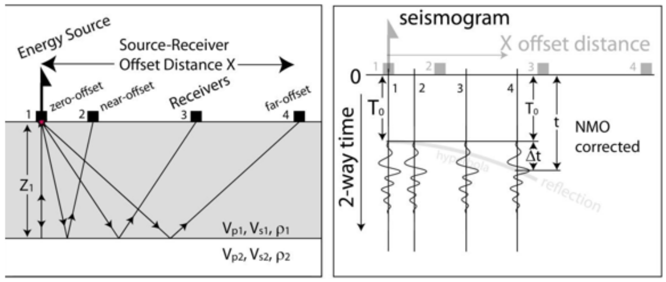
- Source-receiver geometry (NMO normal moveout)
  - Seismic data follows a *hyperbolic curve*
- Describes the effect distance between source and receiver has on reflection arrival time.
  - To correct for this effect, use the Moveout Equation:

$$T^2 = T_0^2 + \frac{4h^2}{V_p}$$

    - Where:

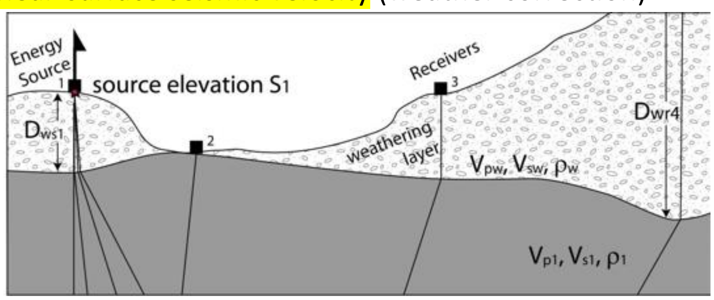
      T = Offset time　　　　h = Offset

      T_0 = Zero offset time　　　　V_p = Velocity (p-wave)
    - This is a hyperbolic equation with asymptote slope: $1/V_p$
    - Can be used to estimate V_p



Statics (Static Correction)

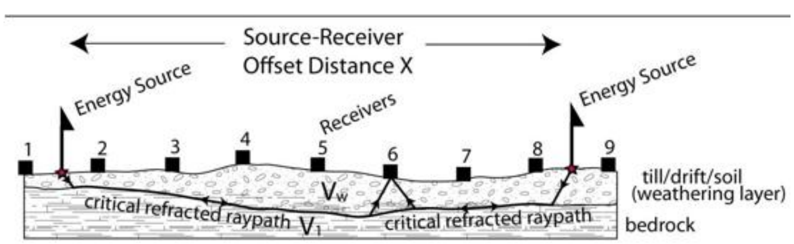
- Bulk shift of seismic data in time
- Corrects for:
  - Variations in surface elevation
  - Variations in near-surface seismic velocity (weather correction)

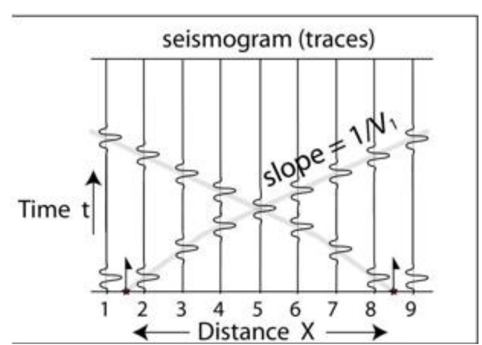


  - Each trace on the seismogram is time shifted
    - Corrects for source and receiver

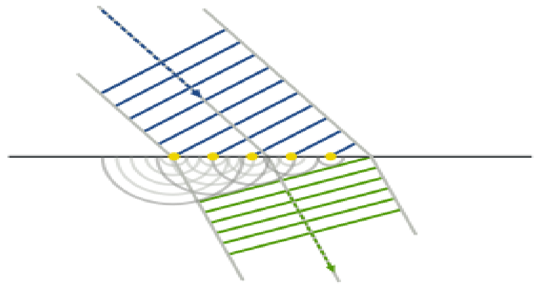
Lab: Refraction Analysis (layer thickness)

  - Measure inverse slope from arrivals, which gives seismic velocity
    - Using data from both directions reduces error (Lab 8)
      - Notice in the picture there are two seismic sources





- Huygen's-Fresel Principle → critically refracted waves generate new waves (below)



- In the lab we found thickness of layers using:

$$T_{i1} = \frac{2Z_1 \cos(\theta_{12})}{V_{p1}}$$

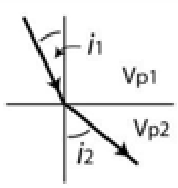
T_{i1} = Zero Offset Time (y − intercept)
θ_{12} = refraction angle between layer 1 and 2
V_{p1} = velocity of p − wave through layer 1
Z_1 = thickness of layer 1

$$T_{i2} = \frac{2Z_1 \cos(\theta_{12})}{V_{p1}} + \frac{2Z_2 \cos(\theta_{23})}{V_{p2}}$$

$$\cos\theta = \sqrt{1 - \sin^2\theta}$$

T_{i2} = Zero Offset Time layer 2
θ_{23} = refraction angle between layer 2 and 3
V_{p2} = velocity of p − wave through layer 2
Z_2 = thickness of layer 2

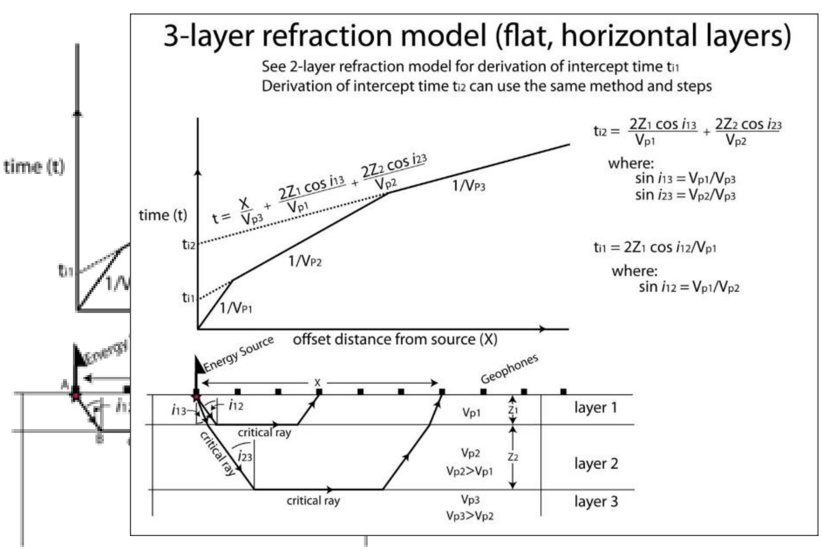
- Recall **Snell's Law**



$$\frac{\sin i_1}{V_{p1}} = \frac{\sin i_2}{V_{p2}}$$

For the critically refracted ray
$i_1 = i_{12}$; $i_2 = 90^\circ$ and $\sin i_2 = 1.0$
therefore: $\sin i_{12} = \frac{V_{p1}}{V_{p2}}$

- Illustrations of the data:

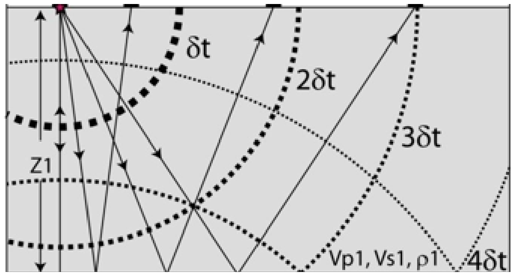


Loss of Amplitude

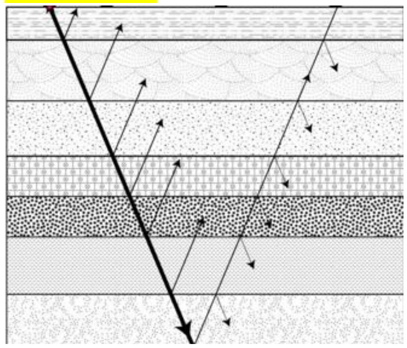
- Spherical Divergence (geometric spreading)
  - Loss of energy as wave spreads

during travel

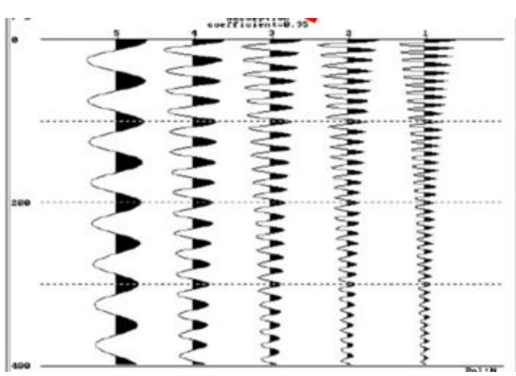
- Decreases by $1/R^2$



- Transmission-Reflection Loss
    - Energy lost due to reflections
        - Energy is reflected upwards as wave passes through layers
        - Upward reflected waves lose energy as some waves are re-reflected downwards as wave passes through layers again

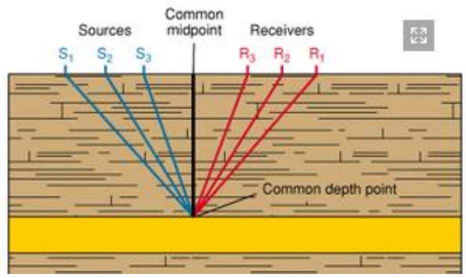


- Dispersive Attenuation
    - Loss of energy as wave passes through media
        - Small amount of energy lost with each cycle
        - Higher frequencies lose more energy
            - Wave becomes increasingly broader with time/depth



Common Mid-Point (CMP)

- Point halfway between receiver and source that is shared by numerous receiver pairs.
  - Exploits the redundancy of multiple fold to enhance data quality by reducing noise.

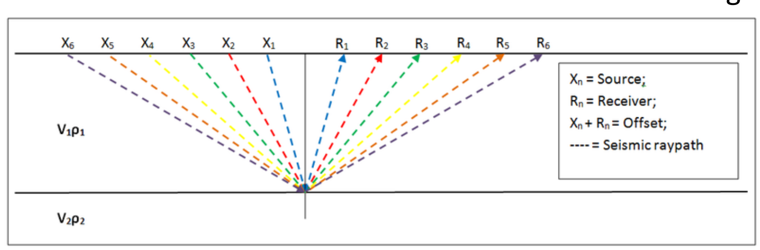


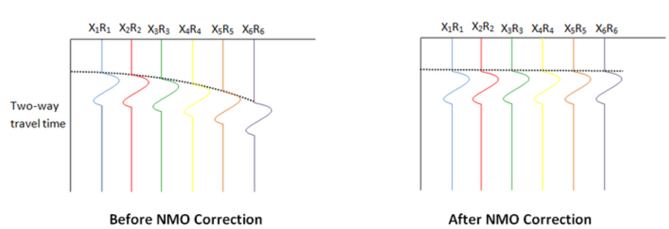
- Source interval is the twice receiver interval
- A fold is the number of traces sharing the same midpoint

$$Fold = \frac{(\#channels)}{2} * \frac{(reciever\ interval)}{(source\ interval)}$$

  - Channel is device carrying data from receiver to recorded (Geophone)

- CMP and Stacking
  - Corrects for weak reflection amplitudes
  - Stack ⟶ traces are added together from different records to reduce noise and improve data quality.
  - Move-out Correction
    - Each NMO corrected trace is aligned and stacked (summed) to produce better reflection signal and reduce noise
    - Recall **NMO** is effect distance between source and receiver has on reflection arrival time
      - In the figure notice:
        - Before NMO correction Travel time is *hyperbolic*
        - After NMO correction Travel time is straight





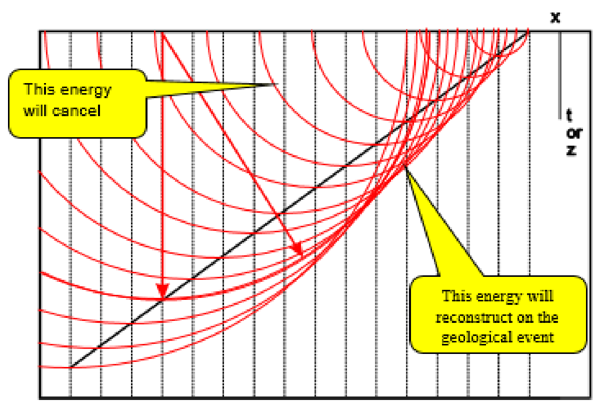
- CMP velocity

analysis: Using NMO (normal moveout) process

- CMP follows the *hyperbolic reflection* NMO
- Analysis of off-set distance vs. time graphs
  - Fast Velocity ⟶ gentle slope ⟶ small NMO correction
  - Slow Velocity ⟶ steep slope ⟶ large NMO correction
- What if we make an **incorrect NMO correction?**
  - Too fast NMO ⟶ under corrects
  - Too slow NMO ⟶ over corrects

Migration

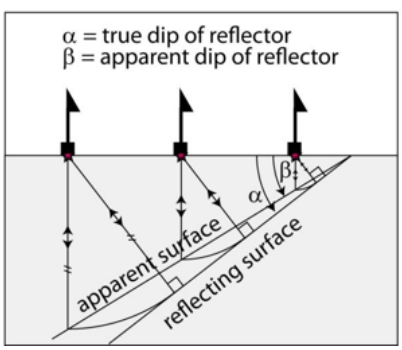
- Technique used to correct for complex geological structures (faults, folding, etc).
  - Seismic data is relocated in either space or time to reading at the subsurface rather than reading at the surface.
  - Creates a more accurate image of subsurface
  - Moves reflection location to reflector location
- Corrects for:
  - Variations in dip of the layered geology
  - Misplaced diffracted energy

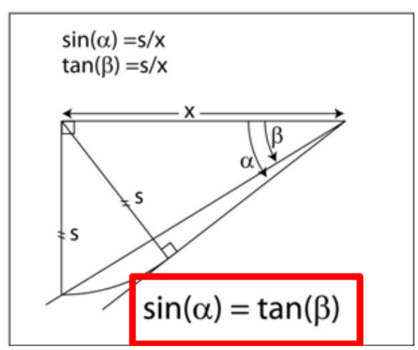


- Migration formula
  - Shifts dipping reflectors to correct position
  - Used to correct for geological dips

$$\tan\alpha = \sin\beta$$

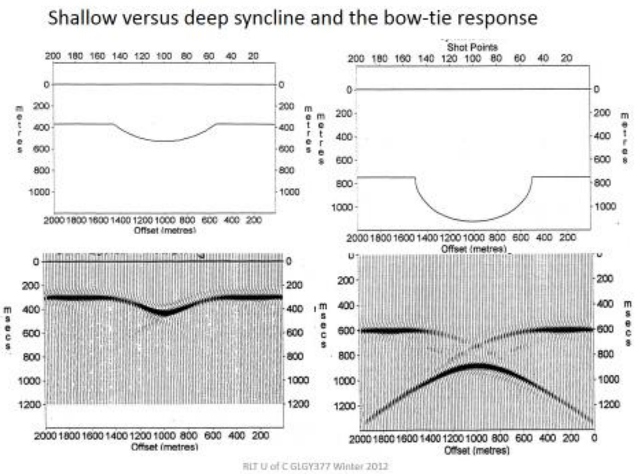
- β = apparent dip of reflector (Geological dip)
- α = true dip of reflector(Seismic dip)

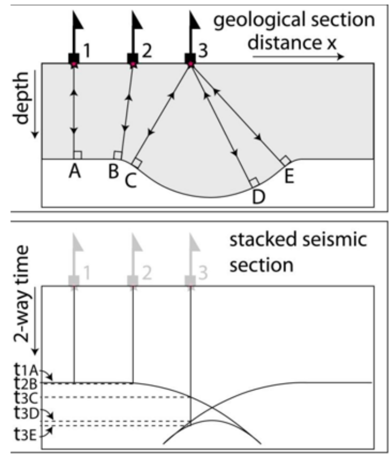




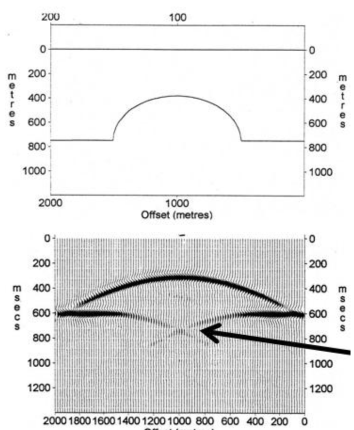
-

- Accounting for Diffractions
  - Migration collapses diffractions back to their sources
  - A **syncline** produces bow-tie shaped seismic data





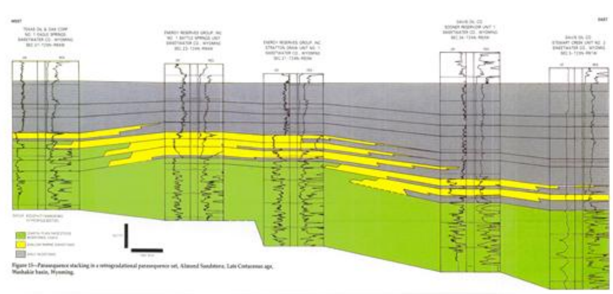
  - An **anticline** creates a hill shape:



Interpreting Seismic Data

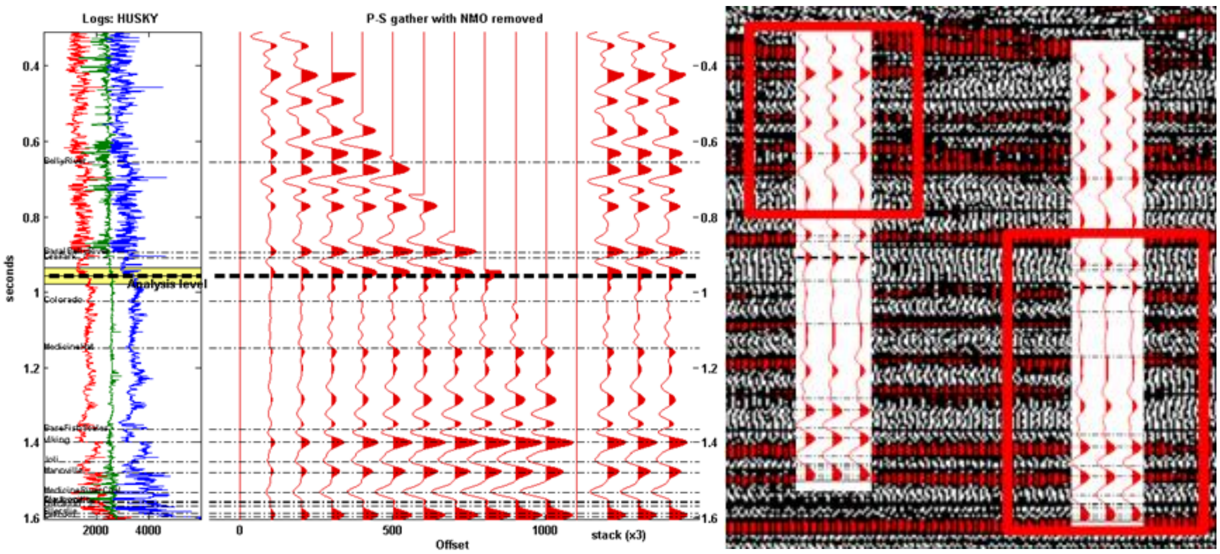
Well Logs

- Can be interpolated based on gamma/sonic readings
  - Seismic data can be used to guide interpolation of well log

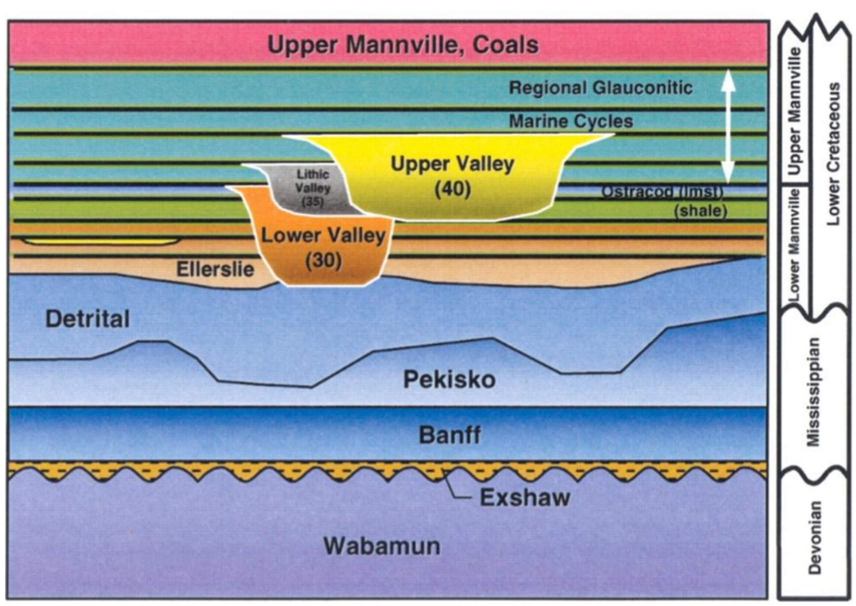


Synthetic Seismogram

- Step of correlation of synthetic seismogram
    1. Core samples to well log
    2. Well log to synthetic seismogram
    3. Correlation – aligning wavelets (figure below)
    4. Identify formation on seismic



- Depositional Period
    - Time in which sediments were layered



Hydrocarbon Traps

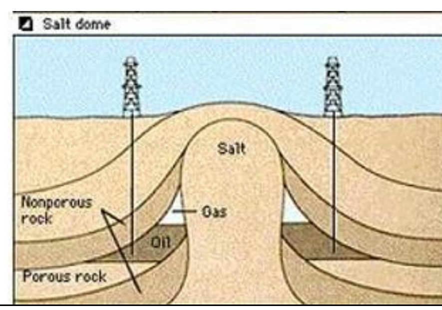
- Require:
  - Sedimentary rocks
  - Porous material (permeable and porous)
  - Seal → Usually Shale (fine grained, mud-like) good seal
  - Shape:
    - Structure
    - Stratigraphic
    - Reef
    - Impact site
    - Tectonic

- Sedimentary Basins
  - Located in Alberta, Atlantic Coast of Canada, Western United States, and Gulf of Mexico.
  - Locations of oil and gas fields

- Geological Structure Traps

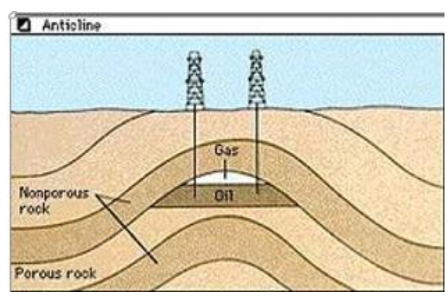
Salt Dome Trap

- Traps oil and gas in domes
- Low density causes salt to rise up.
  - Creates salt dome shape



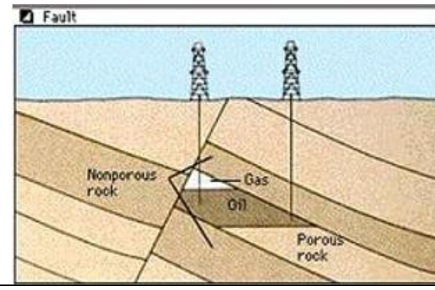
Anticline Trap

- Traps oil and gas under folds



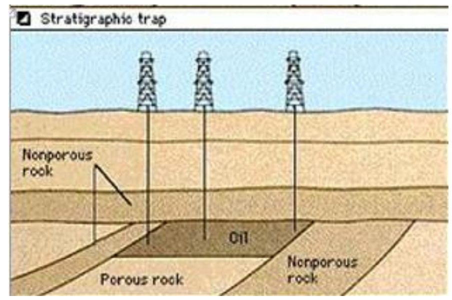
Fault Trap

- Traps oil and gas between faults



Stratigraphic Trap

- Traps oil and gas under layers of rock

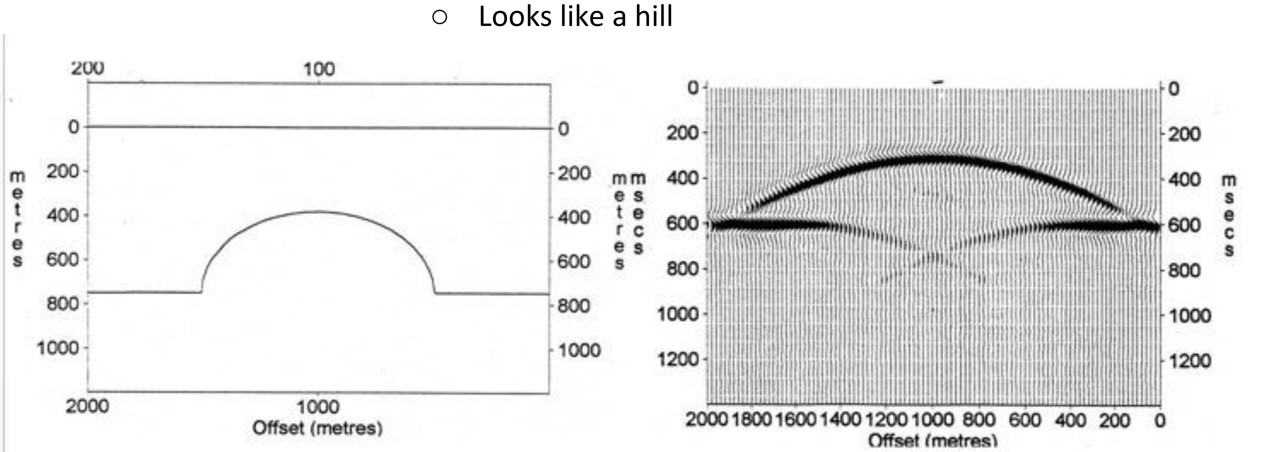


Structures

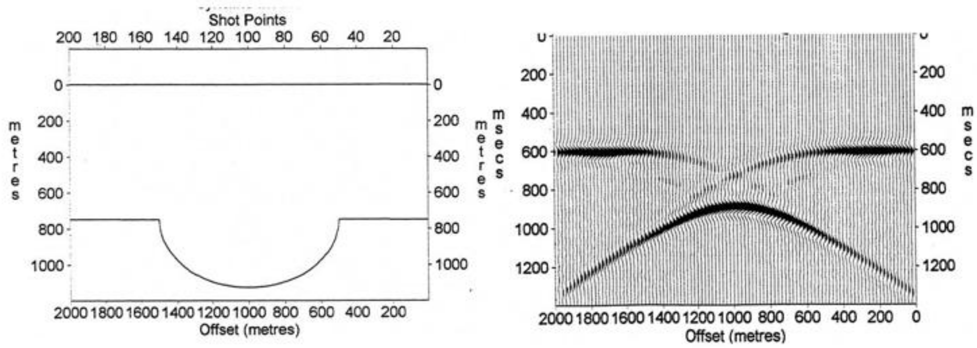
- Sunken volcanoes create coral islands
  - Coral forms a ring shaped island

- Meteor Impacts
  - Can study the exposed rocks of meteor sites
  - Potentially find oil if lucky

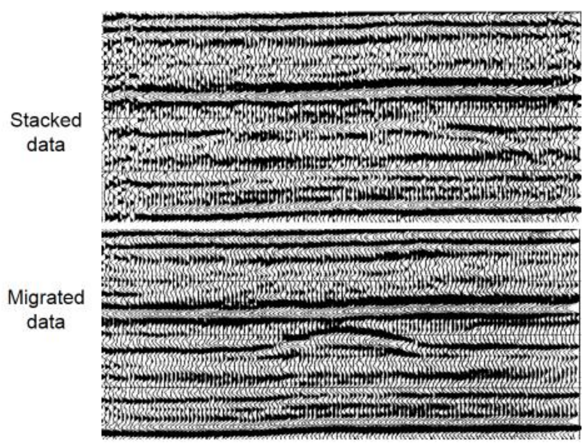
- Anticlines
  - Buried reefs
    - Reef → Mound, ridge, or build-up of sedimentary rocks
      - Looks like a hill



    - Synclines
        - Buried channels
            - Channel → concave depression
                - Looks like a frown

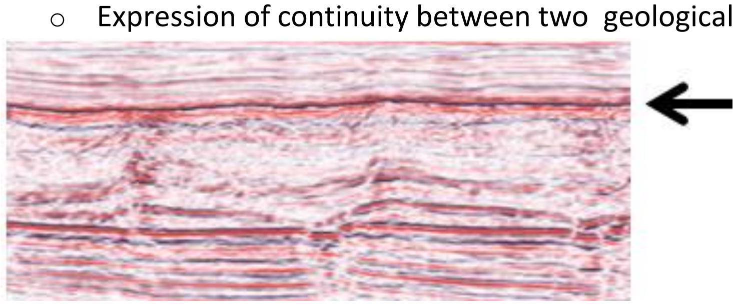


    - Use migrated of stacked data to enhance image quality
        - Migration reconstructs wave length to better interpret data

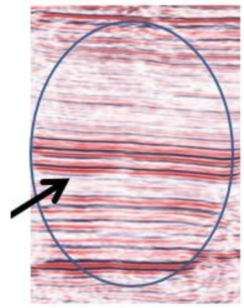


Interpolation Basics

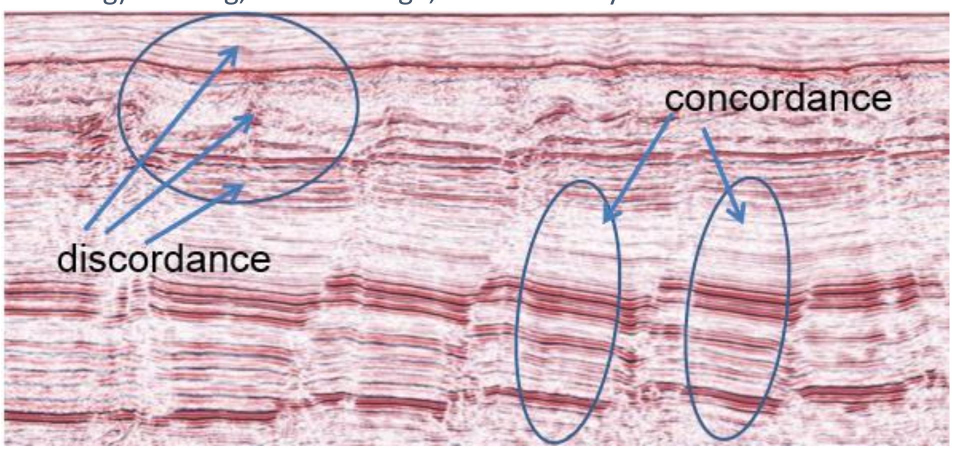
- Continuity
    - Recognized by successive traces
        - Creates an alignment extending a long distance
    - Continuity → Does an event go nicely across a section or does it break up?
    - Expression of continuity between two geological units



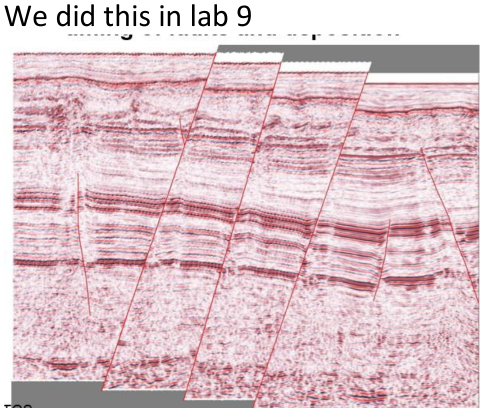
- Correlation
  - Sequence of reflections that creating a recognizable pattern
    - Can be correlated across image
  - Amplitudes and arrival times similar from trace to trace.



- Concordance
  - Sequence of reflections creating an alignment in a sub-parallel arrangement
- Disconcordance
  - Two or more concordant sequences that are geometrically distinct
    - Eg) Faulting, facies change, unconformity



  - Structural restoration
    - Aligning faults and deposition (layers of sediments)
    - We did this in lab 9

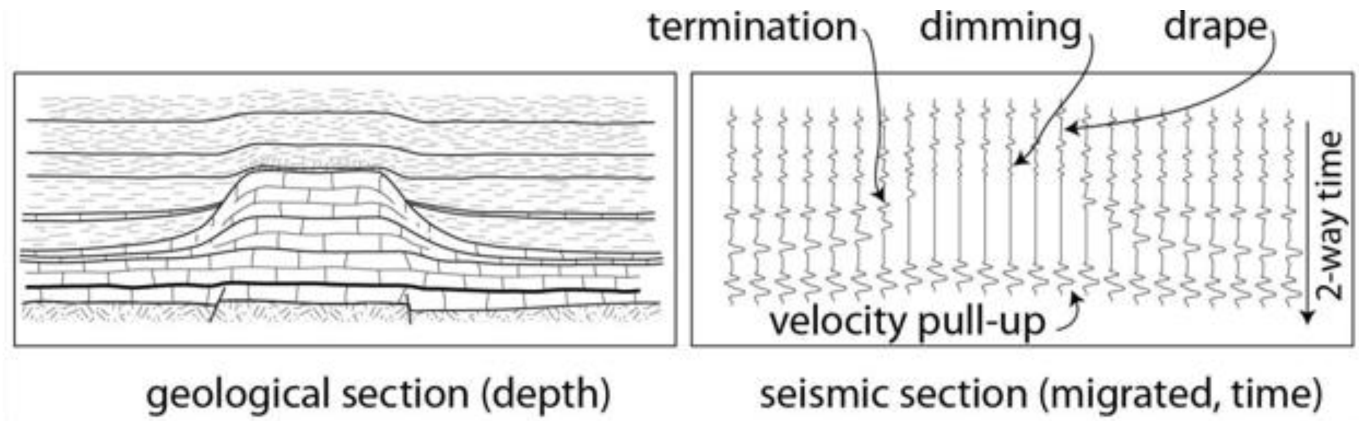


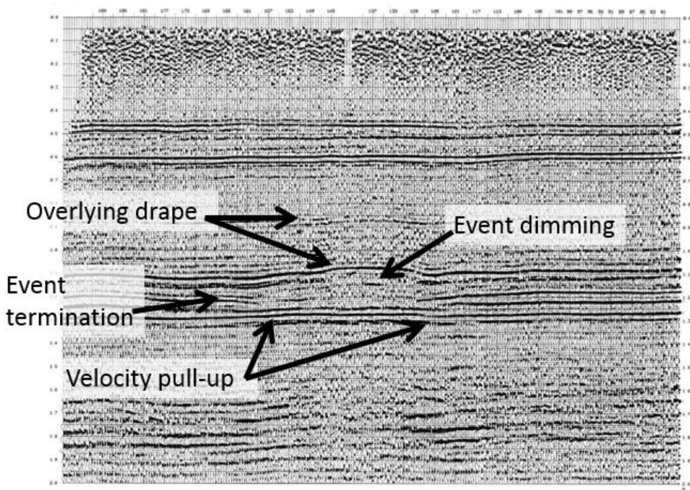
Uncertainty in Seismic Data (Caution)

- The following causes uncertainty in seismic data:
  - Time vs. Depth
    - Seismic section measured in *time*
    - Geology measured in *depth*
  - Noise
    - Seismic contains elements without relationship with reflecting horizons
  - Correlation with Geology
    - Seismic data is of limited use
    - Must be correlated with geological processes (well log)
  - Limited resolution
    - Vertical and horizontal resolution of seismic data is coarse.
  - Limited Aperture
    - Source and receiver do not always image subsurface properly
  - Non-reflection
    - Some wave reflections are weaker than noise level
    - These waves are lost in the data

Understanding Geological Processes

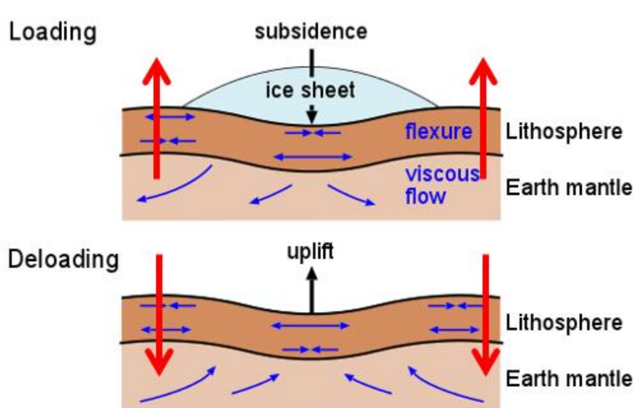
- Reefs
  - Carbonate reefs in western Canada have petroleum reserves
  - Imaged using reflection seismic
    - **Drape:** sediments drape over reef due to compaction of shale and carbonate
      - Compaction occurs over time and causes reef to sink down (drape)
      - Creates a trap for sediments below
    - **Termination of events:** events (waves) terminate against reef
    - **Velocity pull-up**: contrast between fast carbonates (reef) and slow shale (basinal shales)
      - Produces a pull up of events
    - **Dimming of events:** velocity field over top of reef produces weak reflection





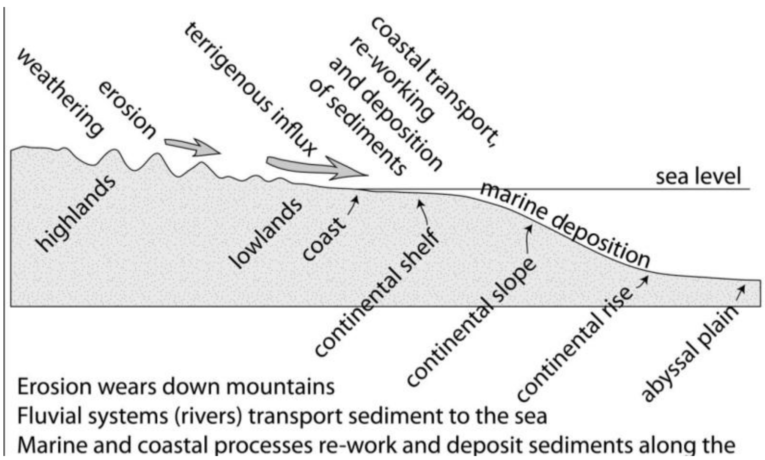
Ocean Levels

- Ocean levels changed based on:
  - Snow accumulation on polar cap
  - Melting of polar cap
  - Mantle convection
  - Isotactic Rebound
    - Rise of land masses that were depressed by ice sheets



Stratigraphy

- Study of rock layers and layering
  - Looks at origin, composition, distribution, succession of strata
  - Describes rock successions and their interpretations over time
  - Can indicate biological activity
- Background
  - Erosion
    - Process of denudation (removing layers) of rocks
  - Transportation
    - Movement of material by water, wind, ice, or gravity
  - Deposition
    - Process in which sediments, soil, and rocks are added to a land mass



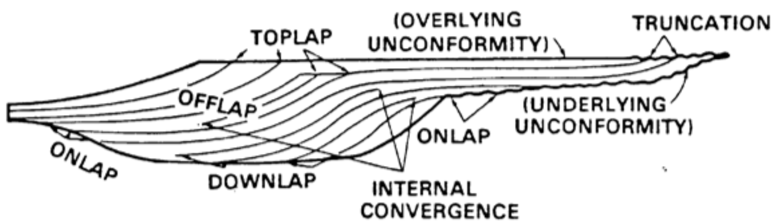
Sea Level Based on Seismic Stratigraphy

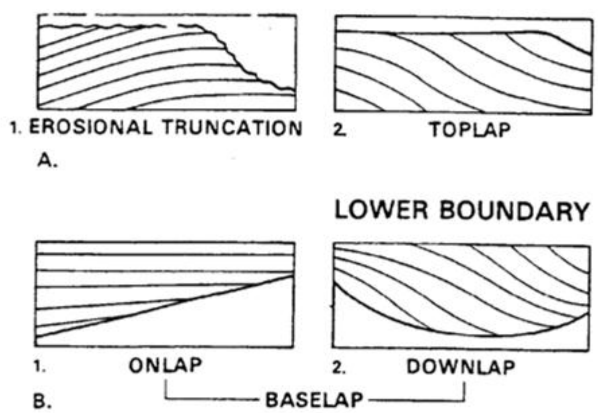
- *Stand* is measured relative to sea level
  - **High stand:** time at which sea levels are at their highest
    - *Sea level rises → High Stand*
  - **Low stand:** time at which sea levels are at their lowest
    - *Sea level drops → Low Stand*
  - **Still stand:** time at which sea levels are stationary
    - *Sea level is constant → Still Stand*

- **Terrigenous Influx:** sediments derived from erosion of rocks on land
  - Sediments are carried to the sea by rivers

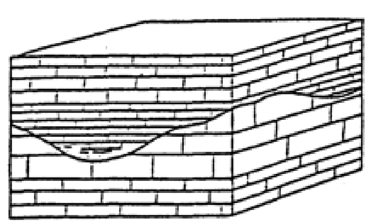
Seismic Stratigraphy

- Strata Boundaries
    - **Erosional Truncation:** termination of strata or seismic data along an unconformity surface
    - **Top lap:** termination of strata or seismic data against an overlying surface
    - **Downlap:** termination of strata or seismic data against an underlying surface
    - **Onlap:** termination of shallowly dipping, younger strata against more steeply dipping, older strata



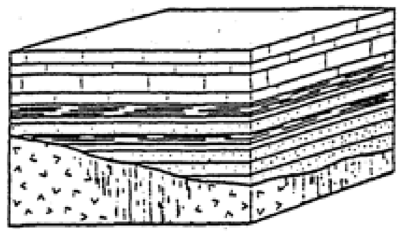


- Unconformity
    - Erosional or non-depositional surface separating two strata of different ages
    - Types of Unconformities:
        - **Disconformity**
            - Exists between layers of sedimentary rocks
            - Marked by features of sub-aerial (exposed to surface) erosion



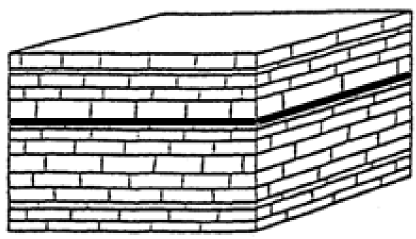
Disconformity

- **Non-conformity**
  - Exists between sedimentary and metamorphic or igneous rock
  - Occurs when sediment lies above eroded metamorphic or igneous rocks



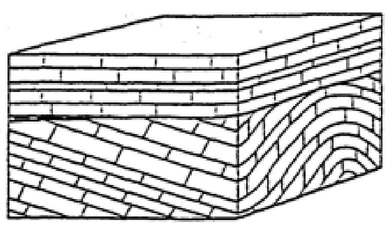
Nonconformity

- **Paraconformity**
  - Strata are parallel and there is little apparent erosion
  - Resembles a bedding plane



Paraconformity

- **Angular unconformity**
  - Horizontally parallel strata (sedimentary rock) deposited on tilted or eroded layers
  - Produces angular discordance



Angular unconformity

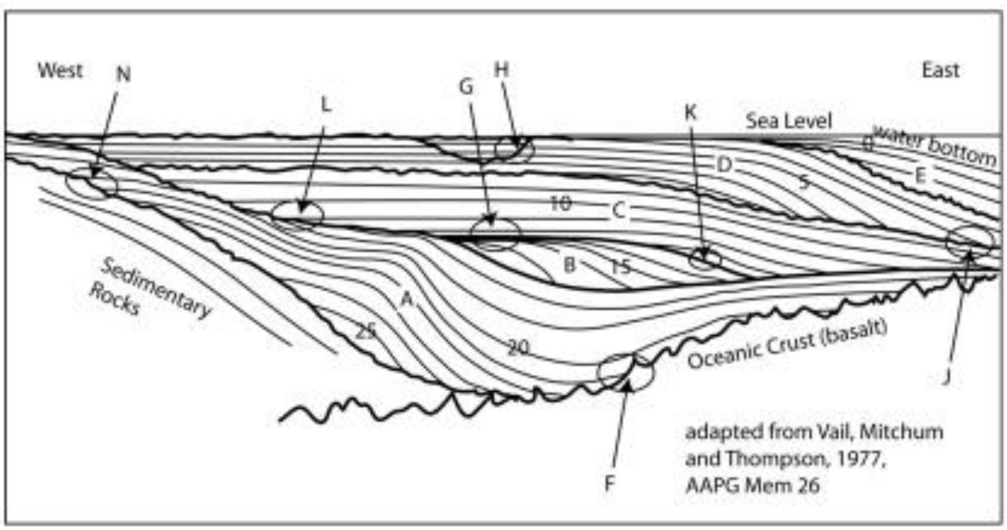
- Chronostratigraphy vs. Lithostratigraphy
  - Chronostratigraphy → measures age of strata relative to time
  - Lithostratigraphy → study of strata and rock layers

- **Primary Seismic Reflections:**
    - Generated by bedding surfaces and unconformities
        - Parallel to time-stratigraphic depositional and structural patterns
    - Reflection is parallel to the depositional surface

- **Sequence Stratigraphy:** deals with genetically related strata bounded by unconformities.
    - **Depositional Sequence**
        - Stratigraphic unit composed of conformable succession of related strata
        - Bounded by either:
            - Top and base of unconformities
            - Non-deposition

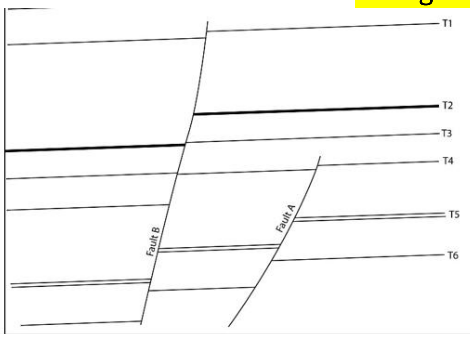
Exercise:

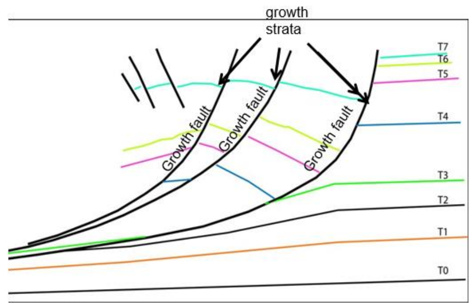
Can you find examples of: Toplap, Downlap, Onlap, Disconformity, Nonconformity, Paraconformity, Angular unconformity
Erosional truncation, high stand, low stand, still-stand, transport direction



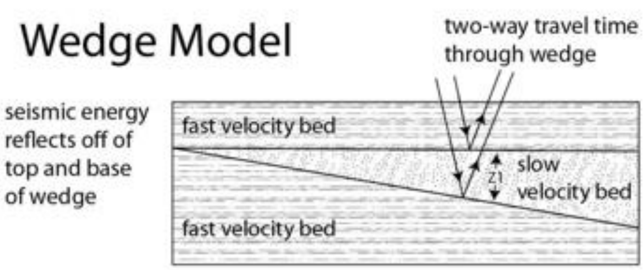
adapted from Vail, Mitchum and Thompson, 1977, AAPG Mem 26

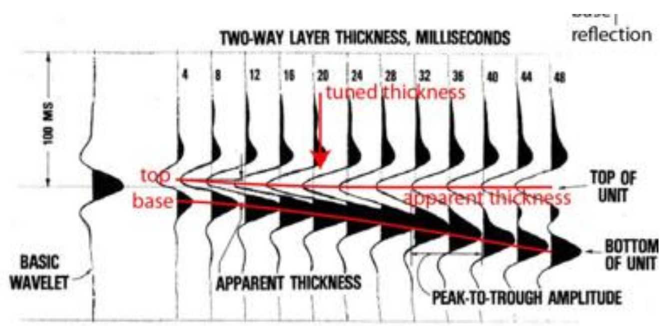
- Structural Restoration
    - Timing of faults and deposition
        - Realigning faults and deposition



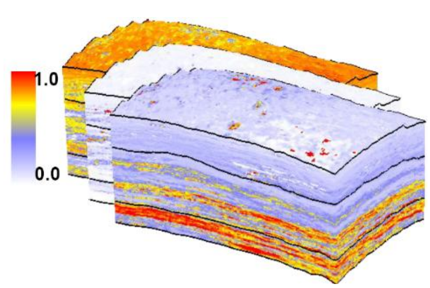


- Wedge Model
    - Used to investigate and analyze the effects of spatially varying rock parameters and thickness on the seismic signature
        - Interpolated mapping of measured or modeled well logs—Vs, Vp, and density
        - Changes in bed thickness are introduced into the model
        - Synthetic seismic model is generated from the wedge model



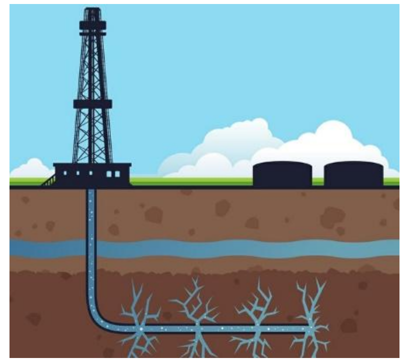


- Well Log to Seismic
    - Steps to convert:
        1. Extract cross plot data at well locations
        2. Compute probability distributions
        3. Probability volume cubes created for presence of any lithology



    - Can find probability of oil, gas, sand, water, shale, etc.

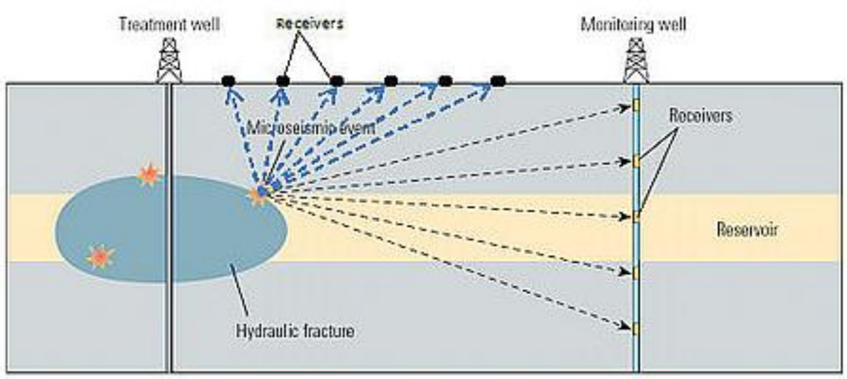
Well Fraccing



- Procedure of creating fractures in rocks by fluid injection
    - Cracks force rock formations to further open
- Proppant (fracturing fluid) can be:
    - Solids, fluids, chemicals
- Uses:
    - Stimulate production
    - Storage
    - Waste disposal

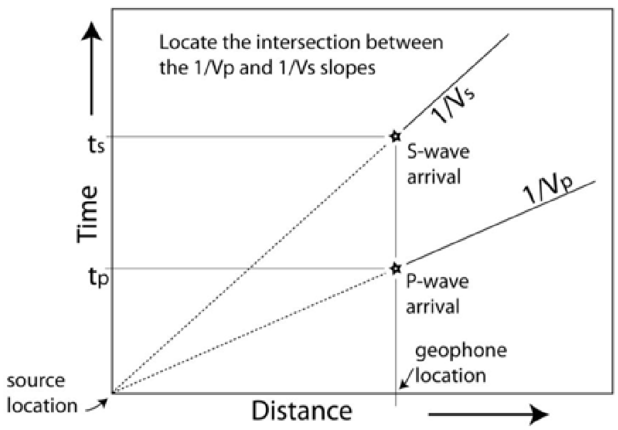
Monitoring the Proppant (Microseismic imaging)

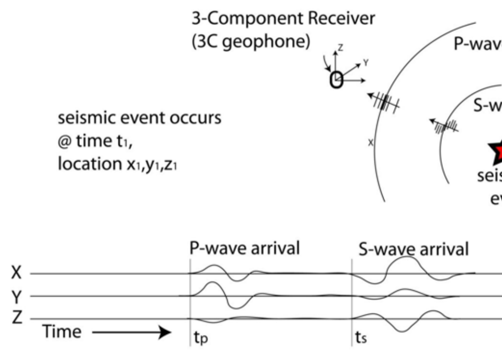
- Microseismic Imaging used in:
    - Monitoring the Proppant (where it is flowing in subsurface)
    - Monitoring steam injection
    - Monitoring mining and disposal operations
    - Passing record (When event occurs)
    - Identify location of an event
- How?
    - Uses *Passive Seismic*
        - Detection of low frequency movements
    - Receivers
        - Located on surface and in wells
    - Identifies:
        - Occurrence of microseismic event (microseism)
            - Location directly or by triangulation



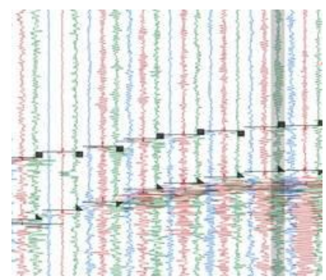
- Location of an Event
    - Location found using 3 component (3C) receiver:
        - Detects seismic events
        - Uses orthogonal components that detect motion along x-y-z axis

- Finding Location Directly
    - Direction: 3 component (3C) receivers (in well)
    - Time: difference between P and S arrival
    - First Arrival Times
        - Knowing velocities of P and S waves:
            - Can solve for distance between 3C receiver and event
            - Find velocities from distance vs. time graph of seismic data

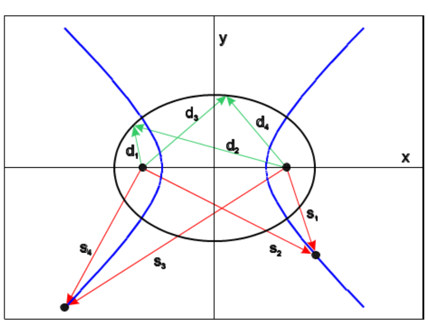




- Event Detection?
    - Anticipating an event
    - Good data
    - Signal much smaller
    - Two window method

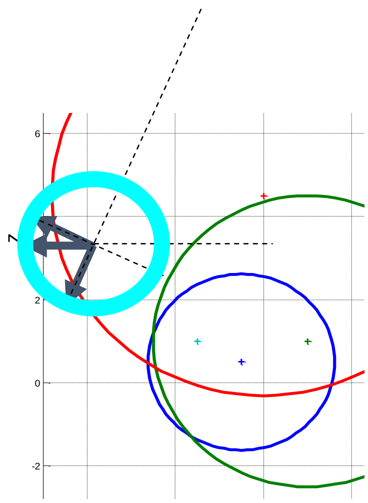


- Finding Location using Triangulation
    - **Triangulation:** process of determining the location of point by measuring angles to it from known points at a fixed baseline.
    - Calculated from:
        - First arrival times
            - Similar process as above



- Hyperbolic intersection
    - Apply Triangulation
    - Time difference between two receivers
        - More receivers = more hyperbolas
    - Intersection point of hyperbolas is location
        - Eg) Loran C (radio

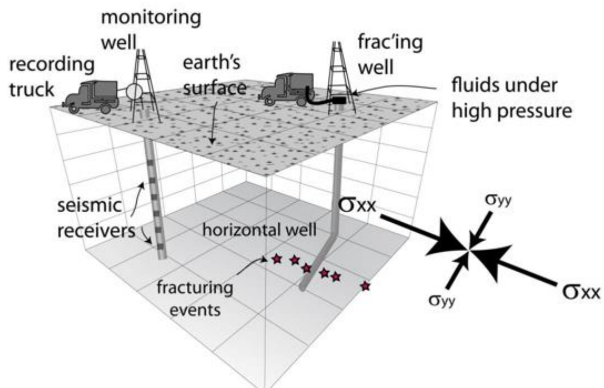
navigation) and GPS (satellite navigation)



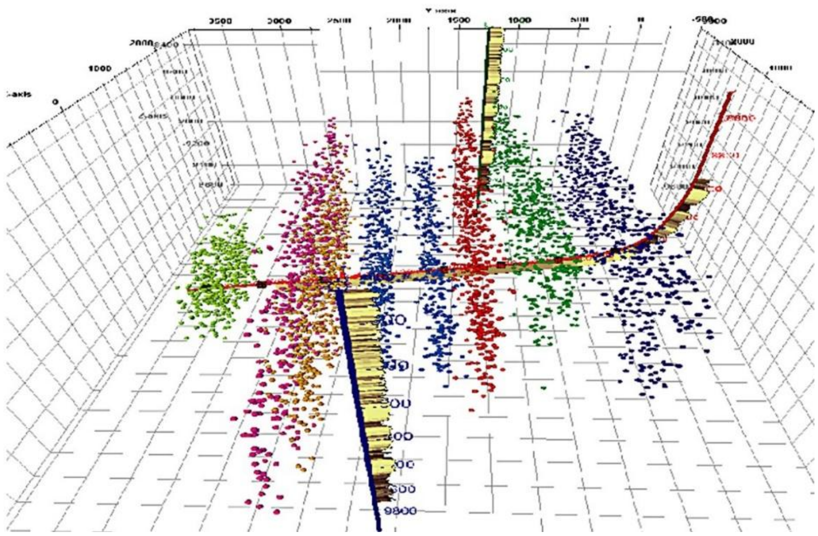
- Circle intersection
  - Apply triangulation
  - Intersection point is of circle radiuses is event location
    - This point is the centre of the cyan circle tangent to all three circles. (figure to the left)
  - This method is easier than hyperbolic
    - Eg) Apollonius Solution
  - Method works for spheres too

Principle Stress Orientations

- Regions of maximum and minimum horizontal stress
  - Fractures planes perpendicular to *minimum horizontal* stress open first when pore pressure is increased
- Position horizontal track of borehole to take advantage of minimum stress orientation



- Multistage Frac (below)

- 

Gravity and Magnetics

- High resolution gravity and magnetics provide:
    - Information to resolve ambiguity (uncertainty)
    - Suggest different interpretations or add confidence to opinions
    - Gross features of sedimentary basics
    - Information on sea floor bathymetry, groundwater usage, and changes in glacier mass
    - Absolute gravity provides sea level variations and subsidence along coastlines.

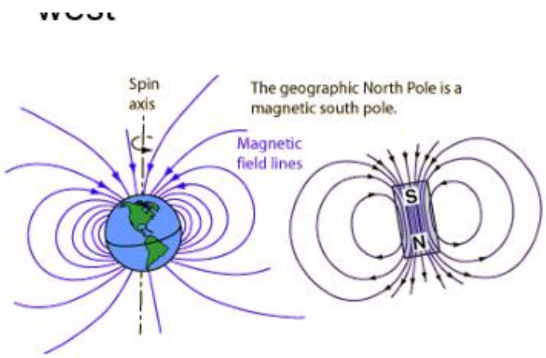
Magnetics

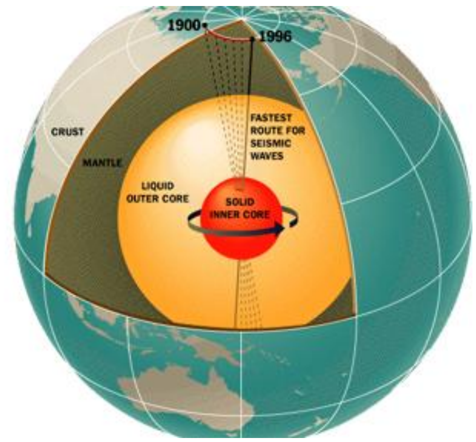
- Compass points to Magnetic North Pole
- Magnetic pole is always moving
    - 80 km loops each day
    - Moving north 40 km/year
    - Reverses every 800-900 million years
        - Each reversal takes 1000 years
- Calgary magnetic pole points 20^o to East
    - Geographic N 340^o on compass (or 20^o to left on compass)

Earth's Magnetic Field

- Ranges from 30,000 nanoTesla (nT) at equator to 60,000 nT near poles
- Earth's magnetic poles and rotational poles do not correspond (different locations)
- Magnetic axis is tiled 11.5^o from rotation axis
- Magnetic field is **NOT STATIC**
    - Caused by Geodynamo
        - Kinetic energy of liquid core converted to magnetic energy
            - Causes field to move

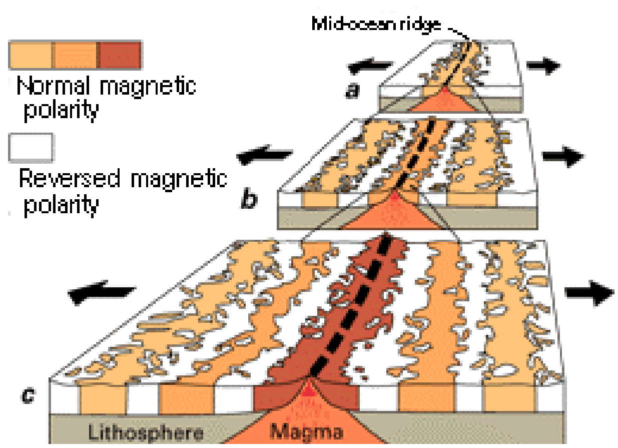
- Magnetic poles periodically flip and tend to drift westward





Magnetism in Rocks

- **Magnetic Susceptibility:** ability of a rock to become temporarily magnetized *while a magnetic field is applied to it*.
  - Independent of rock's mineralogy
- Induced magnetization → temporary magnetization
- Iron content is usually key
- Causes sea floor spreading



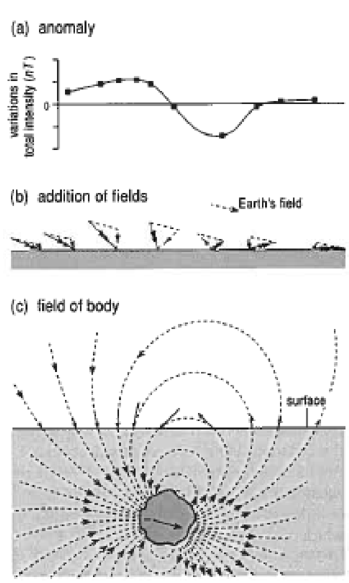


Figure 11.1 Magnetic field of a buried dipole.

the

- Magnetic Field measure as vector addition of Earth's dynamo field plus buried body's (rock) field
- **Magnetic anomaly:** local variation in Earth's magnetic field resulting from variations in chemistry or magnetism of the rocks.
  - Measured anomaly can be used to estimate the depth of body

- Shallow magnetic bodies generate narrow steep-sloping anomaly
- Deep magnetic bodies generate a broad, gently sloping anomaly

Locating Sedimentary Basins (where hydrocarbons are)

- Petroleum exploration beings by locating sedimentary basins
- Done by:
  - Aerial photos
  - Satellite images
  - Magnetic surveys
  - Gravity surveys

- Magnetic Surveys
  - Analyzing **magnetic susceptibility**
  - Usually aerial surveys
  - Sedimentary rocks have lower magnetic signal than basement rocks
  - Thick sedimentary basins (petroleum reserves) show a *quiescent (dormant/inactive)* magnetic field
  - High resolution can detect fabric in sedimentary rocks
    - Eg) Shows Zircon (a gem) located in the Jack Hills of Australia
    - Eg) Shows basement fabric of map of Alberta

- Gravity Surveys
  - Detecting variations in mass density
  - Newton's Universal Law of Gravity

$$F = \frac{Gm_1m_2}{r^2}$$

    - Where: G= Universal Gravitation Constant = $6.672*10^{-11}$ Nm^2/kg^2
      m_1, m_2 = mass of two bodies (kg)
      r = distance between centres of two masses (m)
  - Gravity surveys are sensitive to 1 mGal (1 cm/s^2) [acceleration unit]

- Gravity Anomaly
  - Equipotential surfaces
    - Gravity is stronger over areas of denser equipotential lines
    - Gravity is weaker over areas with spaced equipotential lines

- Gravitational field is stronger over a dense body
- Gravitational field is weaker over a void body
- Gravity surveys measure the *variations* of gravity over an area
  - Gravity over an area depends on density
- Usually measure relative gravity
  - Measure relative to a base station
- Evaluation of anomalies can identify features

- Modifications to Gravity Field
  - Earth's Shape and Rotation of Earth
    - Earth is an oblate spheroid
    - CCW Rotation causes earth to flatten, bulge at equator
      - Radius at poles = 6357 km
      - Radius at equator = 6378 km
      - Difference = 21.3 km
    - Gravity at:
      - Poles = 9.832 m/s^2 or 983,218.6 mGals
      - Equator = 9.780 m/s^2 or 978,032.7 mGals
      - Requires sensitivity of 0.1 mGal

  - Latitude Correction
    - Rotation of earth:
      - Decreases acceleration at equation
      - Does not effect acceleration at the poles
    - Can use geographical latitude to correct gravity
    - Measured gravity increases poleward

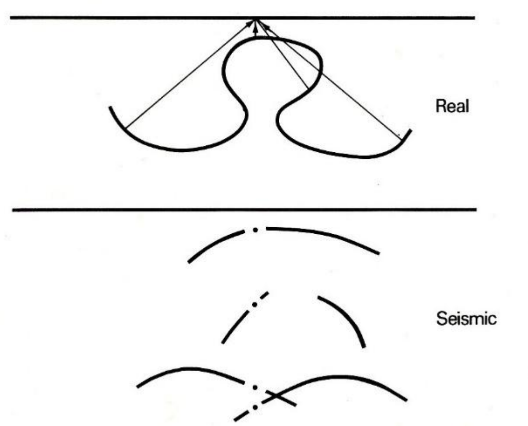
  - Elevation
    - [air correction] Gravitation field decreases with elevation
    - [**Bouguer correction**] Corrects for elevation and **density**

  - Surface topography
    - Rugged terrain impact gravity field (ie) Hills, valleys)
    - Terrain corrections removes the effect of a hill or valley by measuring from a datum

  - Tide (Sun, Moon) and Drift (low frequency error of instrument)
    - Tides impact the shape of the earth and gravity
    - Sensitive gravity instruments calibration drifts
      - Corrected by re-calibrating at base stations

- Note: Gravity profiles are NOT unique
    - Different bodies give identical anomalies

- Seismic Section over a Salt Diapir
    - Salt does not lie along density curve for sedimentary rocks
        - Creates problems and opportunities



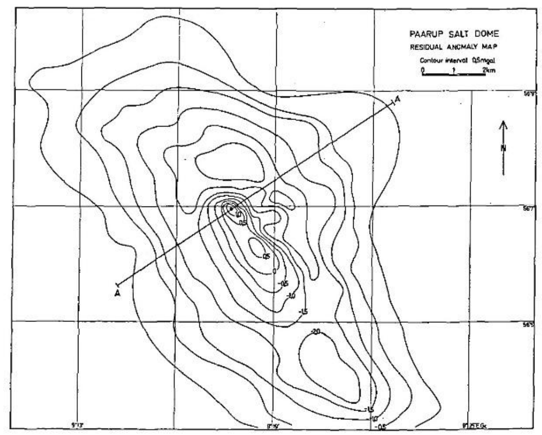
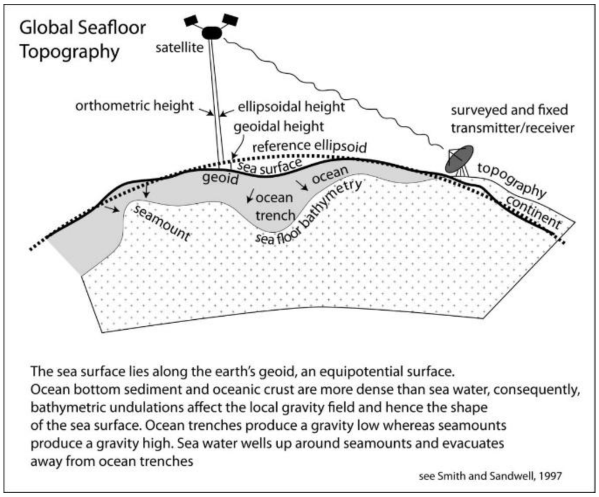


Fig. 5. Residual gravity map, Paarup area.

Satellite Topography

- **Satellite Topography:** study of Earth's surface using satellites
- **Geoid:** The shape that the surface of the oceans would take under the influence of Earth's gravitation and rotation alone
    - Shape of sea surface
    - Surface of constant gravity field
    - Vertical is normal to the **geoid**



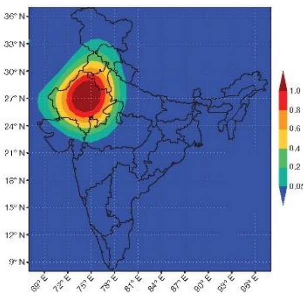


Figure 2 | GRACE averaging function. The unscaled, dimensionless averaging function used to estimate terrestrial water storage changes from GRACE data is mapped.

- Can use Satellite topography to:
    - Identify deep water sedimentary basins
    - Tectonic reconstruction of deep water basins
    - Mapping bathymetry (underwater depth)
    - Identifying underlying structural fabric (geometric configuration)
    - Identify ground water supply using gravity map (figure on left)