Topography
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We'll spend a large fraction of the second half of the course discussing Earth's surface. Today we'll do two things: First, we'll discuss the ways topography is commonly represented in maps, and how it interacts with geologic structures at depth. This will help prepare you for the geologic mapping lab you will begin next week. Second, we'll discuss first-order controls on the shape of Earth's surface, starting at the largest scales.

I. Topographic maps

This is mostly common sense and geometry, but it can be tricky to visualize.

1. Map projections: ways of representing a spherical surface in 2D
- Geographic/"Plate Carrée" (= "square plane")/Simple Cylindrical: convenient (x = lon, y = lat), but geometrically unfortunate [PPT]
- Most topo maps of small regions will be in Universal Transverse Mercator (UTM), or some variation thereon.
    - o Mercator: projection onto cylinder parallel to rotation axis, with a transformation between latitude and vertical height on the cylinder.
    - o UTM: projection onto cylinder perpendicular to rotation axis, rotated around Earth in 60 increments to make 60 slices ("zones") [PPT]

2. Contour Maps
- Contour lines on maps
    - o Need to plot 3D data on 2D surface. Contours are lines indicating constant value of "z" coordinate – can be elevation, or anything else
    - o Contours show:
        - Slope: contour spacing reflects gradient of z
        - Valleys: contours make Vs pointing upslope (up valley)
        - Ridges: contours make Vs pointing downslope (down ridge)
        - Peaks: concentric closed contours, with contour values increasing inward
        - Sinks (local minima): concentric closed contours, with contour values decreasing inward. Usually marked with hatches. (Why the special notation, i.e., why are sinks uncommon?)

- Drainage
  - In general, water flows downslope, so flow paths usually are normal to contours
  - Rivers generally follow valleys (indeed, usually the valley was created by the river). River paths can be identified by following the chain of Vs that point upslope
  - Watersheds
    - Regions that all drain to a common point.
    - Every point on the map falls within a watershed
    - Drainage divides are the boundaries between watersheds. They follow ridgelines, where the flow diverges. So drainage divides can be identified by following the chain of Vs that point downslope, starting at the outlet of a watershed and moving upslope until the divide reaches a peak (local maximum).
- Cross-sections
  - Can be constructed by drawing a transect across a contour map and measuring horizontal position where transect intersects each contour.
  - Then we can draw a plot of z (elevation) vs. x (horizontal distance)
  - Vertical exaggeration
    - The ratio of the length of a given unit on the z scale to the length of the same unit on the x scale.
    - Topography is subtle, so vertical exaggeration > 1 is often used, especially over long distances.
    - Usually reported as, e.g., 2:1

3. Geologic cross-sections
   - How can we infer the orientations of planes from the geometry at which they intersect the surface?
   - Rule of Vs
     - Horizontal beds follow contour lines [PPT: Grand Canyon]
     - If dipping bed intersects valley, its surface outcrop will make a V in map view that points in the direction of dip. [PPT: Block models]
     - The sharper the V, the shallower the dip (vertical beds make no V)
     - Only exception: if a bed is very shallowly dipping down-valley at an angle less steep than the valley slope, it will make a V upstream, like a horizontal bed would
   - Apparent thickness of beds [PPT: Block models]
     - The more nearly parallel the bed is to the surface, the thicker the bed appears
     - The more perpendicular, the thinner the bed appears

4. How do we measure topography?
   - Leveling surveys

- Stereo photos
- RADAR
  - Altimetry
  - Interferometric
- Laser altimetry [PPT]

II. Large-scale topography

0. To zeroth order, Earth is spherical. Why?
  - Earth is held together by its own gravity
  - Over long timescales, Earth behaves as a fluid. Fluids seek their own level; that is, they tend to evolve toward hydrostatic equilibrium unless acted on by other forces.
  - Consider perturbations in the shape of a spherical, non-rotating body. These perturbations will induce pressure gradients, which will drive flow that restores the spherical shape.
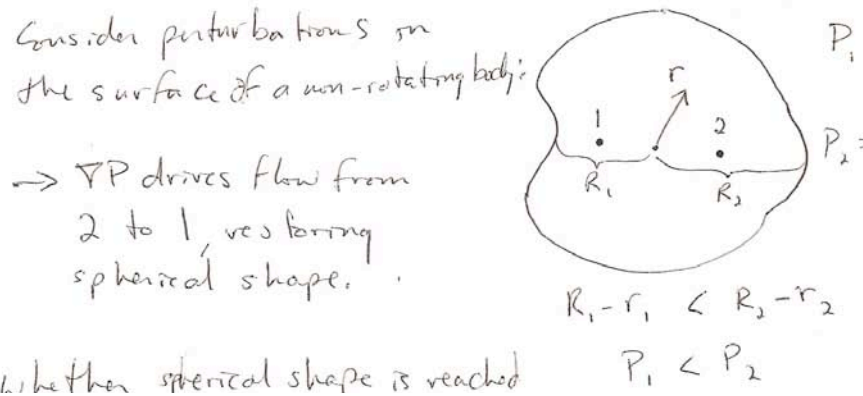
  - Whether spherical shape is achieved depends on pressure gradient, viscosity, and time. [PPT: Earth vs. Hyperion]

1. Earth is *almost* spherical.
  - Oblate spheroid with flattening (a-c)/a = 1/298.26
    [SKETCH: XS of ellipsoid, showing equatorial radius *a* > polar radius *c*]
  - If a ~ 6370 km, then a-c ~ 21 km
  - Largest topo features on Earth:
    - Mt. Everest = 8.8 km
    - Mariana Trench = -11 km
  - So Earth's flattening is its largest topographic feature
  - Why is Earth oblate?
    - The answer once again is hydrostatic equilibrium, and the contribution of rotation to interior pressures
    - At any point in the interior, $P_{net} = P_{gravitation} - P_{centrifugal}$
    - Because $P_{centrifugal}$ is smaller at higher latitudes, a rotating sphere develops a pressure gradient that drives flow toward the equator, and planets develop a rotational bulge.

o The first-order model of Earth's shape is therefore an ellipsoid.

## 2. Earth is a *lumpy* ellipsoid [PPT]

- Another way to think about this ellipsoidal surface is that it is a surface of *approximately* equal gravitational potential. Gravitational potential, P, is a field whose gradient is the gravitational acceleration vector, g ($\mathbf{g} = -\nabla P = -GM/r^2\ \mathbf{r}$). (P has units of work/mass, or J/kg in SI units.)
- This ellipsoid of *approximately* equal gravitational potential is the "reference geoid".
- If we measure actual gravitational potential over the Earth's surface, there are deviations from the reference geoid ("anomalies") of as much as 100 m. [PPT: Geoid anomaly map]. Some of these anomalies have a known explanation:
    o Subducting slabs create positive anomalies over Andes, Indonesia
    o Remnant depressions from ice sheets creates negative anomaly over Hudson Bay
    o Some anomalies (negative over Southern India) unexplained

3. Global distribution of elevations

- Earth's surface elevations are bimodal [PPT: Shaded relief, then PDF and CDF of elevations]. These distributions are known as the "hypsometry".
- Mean elevations:
    o Continents: +0.8 km (often called "freeboard")
    o Ocean basins: -3.8 km
    o What controls these elevations? To first order, bimodal elevations reflect bimodal crustal composition and thickness

4. Isostasy and topography

- What effect will erosion of continental crust have on elevations?
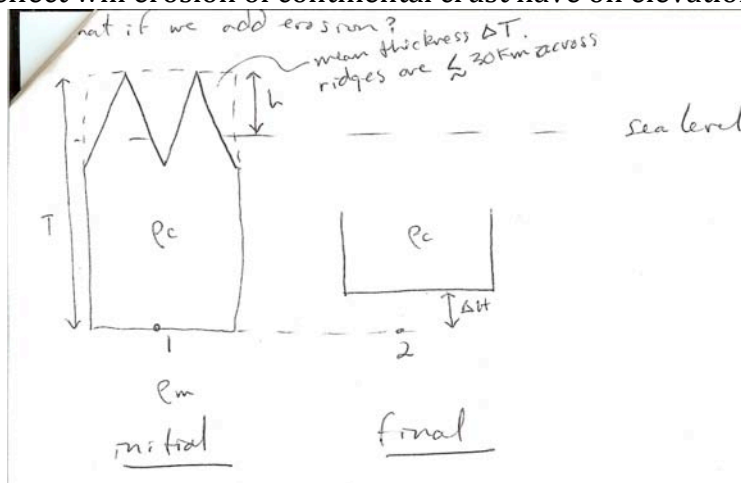
- Lesson: non-uniform erosion can cause uplift
- This may be one of the reasons why margins of Tibetan Plateau are higher than interior [PPT: Satellite image of plateau]

- We can use a space-for-time substitution to track elevation and mountain root thickness over ~ 2 Gyr [PPT: Terry Blackburn paper]. Because continents are amalgamations of old mountain ranges, this gives us a first-order picture of the controls on continental topography.

5. Topographic effects of mantle processes
  - Isostatic rebound: time-dependent isostatic reponse. Mantle is viscoelastic.
    o Uplift in response to removal of ice loads [PPT: Hudson Bay shorelines]
    o Ongoing subsidence in response to sediment deposition in large river deltas, despite recent changes in load (e.g. Mississippi)
  - Flexure: Lithosphere responds to loads as an elastic shell
    o Trough and forebulge around ocean islands
    o Differential "warping" of glacial lake shorelines following removal of ice sheet loads
  - Dynamic topography: deflection of Earth's surface due to flow in upper mantle (= topography – isostasy). Amplitude can be as much as 1 km – as large as mean continental elevation!
    o Mitrovica: Hudson Bay uplift is less than expected for postglacial rebound, presumably b/c of downwelling beneath Canada
    o Upwelling beneath east coast of North America may explain why Appalachians are still high, despite lack of orogenic events for hundreds of Myr.

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