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Plate Tectonics Driving Mechanisms: Some Simple Rules that Explain Why the Plates Move the Way They Do

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PLATE TECTONICS: RULES OF THUMB

CRScotese 12/19/93; updated 08/13/12

Rule I. Plates Move Only if They're Pushed or Pulled, not Dragged.

- The mantle plays a mainly passive role.
  - The pattern of flow in the mantle is largely driven by lithospheric motions.
- The motion of the mantle does not drive the plates (by mantle drag).
  - The idea of organized convection cells upon which the plates ride is wrong (though intuitively attractive - unfortunately!).
- Oceanic plates move faster than continental plates.
  - Oceanic plates tend to have ridges (pushing) and attached subducting slabs (pulling).
  - At the base of oceanic plates in the LVZ (low velocity zone), a region of partial melting that provides "lubrication" at the base of the plates.
- Plates with a large area of continent move slowly (e.g., Eurasia) because they have a deep continental keel connected to the mantle.
  - For this reason continental plates are more likely to be affected by mantle flow.
- Plates (oceanic or continental) that are surrounded by ridges tend to move slowly (e.g., Africa, Antarctica).
  - The push from the encircling ridges "cancels out".
- Plates that are not driven by ridge push or slab pull do not move (Caribbean plate, Scotia plate).
- In all cases plate motion can be understood and predicted by "balancing the forces" that drive and resist plate motion (driving: slab pull & ridge push, resisting: mantle drag).
- OK, once and a while a mantle plume can give a plate a little "push" by creating a region of uplift which the plate slides down, but this effect is infrequent and overrated.

Rule II. Subduction Rules.

- Slab Pull is more important than Ridge Push (80% vs 20%?).
- Fast moving plates (>5 cm/yr) are attached to subducting slabs (e.g. Pacific, Nazca, Cocos, Indian)
- The Phanerozoic speed limit is ~20 cm/yr (India, 65 Ma)
- Convenient yardstick: 10 cm/yr = 1° per million year = 111 km/my
- Where there is subduction, there is spreading or rifting. (The converse is not true.)

Rule III. Ridges are Passive Features.

- Ridges are there because the crust breaks when it is pulled.
  - Continental crust breaks first, because at the same depth (as oceanic lithosphere) it's closer to its melting temperature.
- Oceanic crust rarely breaks; when it does it breaks where it has been weakened by a hot spot or subduction realted volcanism.
- Ridges tend to align parallel to trenches.
- One ridge is all you need. You'll never see two ridges side-by-side.
- Fracture zones point to the trench.

Rule IV. Subduction is Forever.

- Collision is the only way to stop subduction.
  - You need big, gob-stopping continent-continent collision, otherwise subduction zone will "jump over" the colliding terrane. (e.g Capricorn trench in Central Indian Ocean).
- Subduction is hard to start.
  - Most likely mechanisms: terrane collision or subduction virus.

- A subduction zone that enters a new ocean can act as a trigger or focus for the start of subduction along an old, cold, heavily loaded passive margin (e.g. Puerto Rican trench and Atlantic passive margin).

Rule V. Pacific versus Tethyan Subduction Systems

- Pacific Subduction Systems (PSS) are characterized by a ring of subduction with a spreading ridge in the middle (e.g. Ring of Fire).
    - PSS are stable and can continue subducting for hundreds of millions of years. (As long as the central ridge doesn't get too close to a trench and is subducted!)
    - PSS generate long-lived Andean-style margins or margin back-arc basins.
- Tethyan Subduction Systems (TSS) are asymmetric or "one-sided".
    - There is only one subducting margin (like Tethys). On the other side of "Tethys" is a passive margin.
    - The ridge in the middle of Tethys must move towards the trench and is eventually subducted.
        - Because there is no longer a ridge in the subducting ocean, a new rift must form.
        - The rift forms in the continental plate that is now being "pulled " towards the Tethyan trench.
            - These new slab pull forces either tear a chunk of continent away from the margin (India), or break the continent apart (breakup of Pangea).
                - A continent is more likely to break apart (Pangea-style), if the continent is weakened by old collision zones or new hot spots.

Rule VI. Plates Subduct Normally (to the Trench).

- Oblique convergence is more work; orthogonal least work.
    - Displaced terranes originate in areas of oblique convergence.
    - The highest mountains along Andean-style margins are in areas of oblique convergence (In NA that's Mt. McKinley).

Rule VII. The Style of a Convergent Margin Depends on the Absolute Motions of the Plates.

- Andean margins - net convergence (~10 cm/yr)
- Western Pacific margins - net divergence (roll back 1-2 cm/yr)

Rule VIII. Island Arcs Don't Ride Their Trenches Across Oceans.

- Back arc basins never evolve into wide (>30,000 km) ocean basins.
    - You'll never find an continental island arc in the middle of an ocean.
    - There is always a continent nearby.
- 90% of all ophiolites originally form in back-arc basins

Rule IX. Slab Rollback Can Create Odd Intracontinental Ocean Basins

- Oceanic lithosphere can become trapped (encircled) by continents (e.g. Mediterranean, Arctic, Tethys north of Alps).
- Small, short-lived subduction zones can consume this ocean floor creating intracontinental extension and small "odd " ocean basins (e.g., Tyrhennian Sea, Pannonian Basin, Makarov Basin).

Rule X. Mantle Plumes (i.e. Hot Spots) are Important (Sort of)

- Hot Spots are derived from the core/mantle boundary (mostly).
- They provide a "good enough" reference frame for absolute plate motions.

- Some Hots are Fixed; Some Aren't.
  - Hot Spots are organized in "proper groups".
    - The Indian-Atlantic Proper Group has been fixed to spin axis since Triassic.
    - The Pacific Hotspots (Hawaii) have moved about 200 km in 100 my.
- Hot Spots "help" break apart continents.
  - They create areas of weakness in the continental lithosphere.
  - Thermal uplift associated with mantle plumes causes uplift which help to give the plate a little "push" (like ridge push).
    - Important: Mantle Plumes and hot spots do not break apart continents. They just make the job easier. The heavy lifting is done by slab pull forces.
  - Hot spots under moving plates speed them up, a bit.
    - They thin the continent's "mantle keel" that usually slows plate motion.
    - They "grease the skids" by melting the base of the lithosphere (decreasing mantle drag forces).
- If mantle plumes and hot spots did not exist, the plates would still move, continents would still break apart, move across the globe, and collide!
  - But the things would be less interesting.

<u>Rule XI. Continental Collisions are Important (Really)</u>

- Continental collision zones (sutures) provide long-lived zones of weakness in the crust that are likely to become future sites of continental rifting.
- A continent with many sutures will be weak and easily deformed (e.g. Asia following collision with India).

<u>Last Rule. Plate Tectonics is a Catastrophic System (not chaotic).</u>

- Plate motions are generally gradual; but every once and a while "WHAM"!
  - "Long periods of boredom interrupted by short moments of terror"
  - Because plate boundaries are metastable, geometries can interact in unpredictable ways to produce global plate tectonic "events".
    - 2 important instabilities: continent-continent collision & ridge subduction.
      - Continental collisions can cause new trenches to form.
      - India's rapid northward flight & the breakup of Pangea were due to ridge subduction.
      - both of these events cause rapid, global falls in sea-level
        - continental collision increases volume of ocean basins because the area of continental lithosphere
        - ridge subduction increases the volume of ocean basins by decreasing the average age of the oceanic lithosphere
- Suprecontinents form and break apart because of the metastable nature of plate evolution.
  - Ridge subduction both breaks supercontinents apart and brings them back together (Wegener or Wilson Cycle).

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