PLATE TECTONICS: A GEOLOGICAL PERSPECTIVE

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Drivers and Forces

Convection model for 100 Myrs courtesy of B. Hansen, Münster

Nstep = 1220  Time = 0.118323

Oceanic lithosphere
Ridge push
Slab-pull at trench
Upper mantle
Lower mantle
Core

Layering at 660 kilometers
Lithosphere strength: A gourmet’s perspective

Source: Bürgmann & Dresen, 2008
... and why plates may move over the mantle
But why do they move past each other?
How weak are fault zone rocks?

Coefficient of friction

San Andreas Fault; California
What this means ....

effective coefficient of friction on plate interface and active faults $< 0.1$

friction of banana peel $\approx 0.07$

Awarded with 2014 Ig Nobel Prize

PHYSICS PRIZE:
for measuring the amount of friction between a shoe and a banana skin, and between a banana skin and the floor, when a person steps on a banana skin that's on the floor.
200 Mill. Years of plate motion – and present GPS

Gibbons et al., 2015

Source: GFZ
Exploring the Andes at depth

Source: Y-W. Chen et al., 2019
Deep subduction initiates deformation of South America and rise of the Andes

Source: Faccenna, Oncken, Holt, Becker, 2017
Nazca-Platte is anchored in viscous lower mantle
Climate and tectonics

Patagonian ice shield

Trench fill
Continuous Neogene – recent upper plate contraction

Upper plate contraction fades at 6 Ma

Onset of glaciation

Characteristic thickness threshold

Shortening velocity (mm/yr)

Trench fill sediment thickness (km)

Modified from Vietor & Echtler, 2006

Chile trench fill evolution

- S-Chile
- N-Chile

Present range
Climate controls mass flux and crustal growth
Storing and removing CO$_2$ by tectonics – example Alps

Marine carbonate sediments deformed and uplifted (Central Alps)

Weathering of mafic silicate rocks (Central Alps)
The silicate weathering thermostat is tuned by plate tectonics.

This cycle operates on 0.5 - 1 million year timescale.
Earth evolution and plate tectonics – when did it start?

Courtesy G. Wörner
Crustal evolution suggests plate tectonics started around 3 Billion Years ago?

Source: Dhuime et al., 2015
Or did modern plate tectonics only exist in the past 750 Ma??

Rapid evolution of multicellular life
Fuelling the plate tectonic machine

c. 80% from radioactive decay

rest from
- residual energy from early Earth accretion
- crystallization of Earth’s core
- friction

based on Arevalo Jr et al., 2009
Evolving Earth – evolving plate tectonics

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<thead>
<tr>
<th>plt tect</th>
<th>single lid</th>
<th>vigorous single lid</th>
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<tr>
<td>stage 5</td>
<td>stage 4</td>
<td>3C 3B</td>
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- ‘boring billion’
- least active
- active
- very active

- true subduction
- mantle temperature

Source: Stern, 2018
Plate tectonics is not an inevitable fate of radiogenic silicate planets.
Plate tectonics, mountain building, atmosphere evolution and life appear to form a system coupled via multiple feedbacks.
Earthquake triggering – natural and anthropogenic

von Hagke et al., 2013
Gondwana fragmentation follows simple geometric principles on a sphere – a consequence of self organization.

Source: Anderson, 2002; Sears et al., 2005
Emerging picture of 'Earth-style' plate tectonics shows these attributes ...

- ...a silicate planet with characteristic chemical and mechanical properties
- ...a limited temperature regime with stable (radiogenic) heat source
- ... positive and negative feedbacks stabilizing thermal boundary conditions (internal and at surface) and mass flux
- ... self-organization of system components maintains one of potentially several stable tectonic regimes

..., but many open questions remain
Generalized diagram of the Earth system
Multiple coupled processes
- Cross-scale and non-linear
- Limited predictability
- Incomplete observability
The geological cycle of CO₂

CO₂ in the air combines with water

To a weak acid, which brings elements from silicate rocks in solution

Among these: Ca-ions ...

„cycle rate“ : 60 Ma

... enter via rivers into the oceans

where they form carbonates ...

some carbonates are recycled to the atmosphere through volcanoes and metamorphic reactions in orogens
Plate tectonics and Earth dynamics

A. A metastable static Earth
(an unsustainable hypothetical construct, presented just to get started)

Material that is cooling as heat is lost to atmosphere; cooling makes this outer rind more dense.

Colors represent zones of different temperatures and thus of differing rigidity; differences of material are ignored here.

Material that is heating because of radioactive decay of dense atoms, like those of uranium. Heating makes this material less dense.

B. Metastability fails

Brittle rind begins to crack as rind to right moves to right.

Material made more dense by cooling sinks.

Material that has been made less dense by heating, and ductile with that heat, rises.

Differential heating in the atmosphere produces rising thermals and falling rain in a matter of hours. Much the same concept is illustrated here, but with a time scale of tens of millions of years.

C. Earth becomes dynamic

Brittle rind cracks further as rind moves to both left and right; underlying material moves up.

Material made more dense by cooling sinks, cooling Earth’s interior.

Material that has been made less dense and more ductile by heating continues to rise.

Those who see the sinking cold rind as the main driver are advocates of “slab pull” or perhaps better “plate slide”; those who see the rising hot mass as the main driver are advocates of “ridge push” or perhaps better “ridge rise”; those who see a circular flow of variably heated material as the main driver are advocates of “mantle convection.”

One might ask “why is there plate tectonics?”

This page provides the answer: because heating of Earth’s interior by radioactivity, and cooling of Earth’s surface, create inversions of density. Those density inversions lead to vertical movements that result in horizontal movements of Earth’s cold brittle outer rind. We call those horizontal movements of Earth’s cold brittle outer rind “plate tectonics.”
Final Estimate of Heat Flow (mW m^-2) (Area-weighted Median)

Source: Davies, 2013
Kinematic locking prior to the Mw=8.8 Maule earthquake of 27.2.2010
Andean architecture
magnet ic pole variation

Climate tuning of mass flux

Earth tides

ocean tides

topographic coupling

Earth rotation

magnetic field

ice

electro-magnetic coupling

mountain building-silicate weathering thermostat

- temperature
Measuring active deformation with GPS
World strain rate

Kreemer et al. (2003)
GSRM v.1.2

Second Invariant Strain Rate, $1 \times 10^{-9} \text{yr}^{-1}$
Earth’s crust is in failure equilibrium globally!

Byerlee’s Law

Rock strength in experiments

... and stress state in deep wells.