Plate Tectonics and the role of water on planets

0- What is known within our solar system

1- Summeren et al., Mantle convection, plate tectonics and volcanism on hot exo-earths, 2011.

2- Albarede, 2009: how water came on Earth

3- Karato, 2011: water distribution in planet's mantle

4- O'Neill et al., 2007: the role of water in plate tectonics and convection for different planets

5- VanHeek & Tackley 2011: plate tectonics on super Earths
3. Heat production decreased and slowed mantle convection
- larger convection cells
- larger plates travel farther and cool more
- Subduction and modern plate tectonics

1. Period of accretion ~10-30 Ma; and then heavy bombardment

Early plates became bigger and thicker
- Recycling of oceanic crust formed large amounts of buoyant continental crust.
- Separation of Si from Mg and Fe
- Conversion of mafic to felsic material

2. Archaen-Proterozoic transition
To modern plate tectonics:
Period of rapid crustal growth
Les supercontinents regroupent la quasi-totalité des terres émergées à leur époque:
- PANGEE (300 à 180 millions d’années).
- RODINIA (1,1 milliard à 750 millions d’années).
- COLUMBIA (1,8 à 1,5 milliard d’années).
- UR (3 milliards d’années, plus petit que l’Australie, mais unique à son époque).
- VAALBARA (~3,6 ou 3,3 milliards d’années) comprenant le craton du Kaapvaal et de Pilbara.

Le terme de supercontinent désigne une masse continentale regroupant tous les continents actuels. Le plus ancien supercontinent connu, la Rodinia, se serait fragmenté il y a 750 millions d’années. Ces fragments se rassemblèrent au paléozoïque pour former la Pangée, qui se divisa ensuite en deux autres supercontinents, la Laurasia au Nord et le Gondwana au Sud.

Il semblerait que les supercontinents se forment par cycles, tous les 400 à 500 millions d’années : c'est le cycle de Wilson.
The uprising mantle crosses the geotherm it begins to melt, and as the **solidus** temperature of mantle falls with decreasing pressure, the temperature of the melt increases relative to this solidus, thus giving **melting** with decompression, as shown. The amount of melt generated will be limited by the latent heat of fusion (which is high for silicates), and as the melting range of mantle **peridotite** lies between ca. 1100- 1700°C. The magma may enter a chamber in the ocean crust and begin **crystallising**.
What does Plate Tectonics have to do with Climate?

• Changes the topography
• Changes the ocean circulation
• Affects the re-cycling of volatiles
  re-cycling of water vapor is particularly important on planets besides Earth, such as Mars, Venus & Io
• In turn, climate affects the creation of continental crust & the long-term evolution of a planet

In earliest days, Earth resembled Io. The slow buildup of continental crust over Earth’s history shaped the course of its evolution.
Silicate rocks are about 90% of the Earth’s surface. They form in the magma chamber of a volcano and their chemistry depends upon the pressure and temperature inside the chamber.

Hydrated minerals, such as kyanite, a byproduct of the breakdown of granite, help make the crust of the Earth “slippery”, and so facilitate the subduction of the plates.

Subduction in turn scraps the crust and helps creating light-weight components (silicate-rich) that do not sink.

Subducted plates are re-melted and return to the surface as volcanoes, where volatiles are re-released.
Granite vs. Gabbro

• The continental crust of the Earth is formed of light weight rocks such as **granite** (silica-rich).
• The crust of the Moon is made of more silicate-poor rocks such as **gabbro**.
• The crust of Mars is made of basalt of as-yet unknown silica%.
Plate Tectonics on Venus?

Venus has a thick atmosphere (94 bars), which reduces the efficiency in recycling of volatiles.

There are features on the surface of Venus called “coronae” which strongly resemble terrestrial island arcs - a manifestation of plate tectonics.
Mountains on Venus

- **On Earth**, because of plate tectonics, the “island” created by hotspot volcanism moves away, and a new island forms.

- **On Venus**, because of no plate motion, volcanic islands keep growing, called **Volcanic Rises**.
  - Mountains of **Venus** are of the biggest in the Solar system (Mount Maxwell is 11 km high).
  - The crust may be very thick in order to support the weight.
  - Other data suggest the opposite, that the crust may be thin.
  - The uncertainties imply that the surface of Venus may **turn over** in a manner which is completely unlike that of the Earth.
Cratering History  
& theories of catastrophic turn-over of the surface

No present-day plate tectonics
- continents, volcanic rises, coronae
- thick lithosphere (maybe)
- lithosphere = frozen (maybe)
- plate tectonics is not understood
  there is some evidence of rifting & faulting

- The surface of **Venus** has just as few craters as does the Earth. This means that the surface is just as young as Earth’s surface!
- Suggests a cataclysmic **turn-over** process may be at work.
- The inside heats up until, POW! The whole surface melts.
Martian bi-hemispheric situation

Mars has severe topographic differences between north and south.

The presence of a volcanic rise suggests a thick, and immobile lithosphere.
Mars

A thin atmosphere,
no present-day plate tectonics
  – continents, volcanic rises, magnetic stripes
  – thick lithosphere (maybe)
  – lithosphere = frozen in place

Plate tectonics must have taken place in the past
there is some evidence of rifting & faulting
Magnetic Stripes: Earth and Mars

- **On Earth**, the biggest proof of the mechanism of plate tectonics, sea-floor spreading, is in the striped ocean floor.

- **Mars** has been found to have similar stripes, indicating plate tectonics in the past.

- Martian geological epochs:
  - Hesperian: *When the super continent at the southern hemisphere formed*
  - Something: *90% of the rest of martian history, when the cratering eased off*
Evolution of modern plate tectonics

• Presence of moderate temperatures – Venus is too hot so lithosphere never cool enough to subduct

• Heat removal from mantle through subduction of cool oceanic lithosphere and upwelling of new crust
  – Drives convection cells
  – Allows basalt eclogite transition to be shallow
  – Subduction leads to fractional melting of oceanic crust and segregation to form continental crust

• Presence of water
  – Needed for granite formation
  – Catalyzes fractional melting in subducting sediments
MANTLE CONVECTION, PLATE TECTONICS, AND VOLCANISM ON HOT EXO-EARTHS

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ABSTRACT

Recently discovered exoplanets on close-in orbits should have surface temperatures of hundreds to thousands of Kelvin. They are likely tidally locked and synchronously rotating around their parent stars and, if an atmosphere is absent, have surface temperature contrasts of many hundreds to thousands of Kelvin between permanent day and night sides. We investigated the effect of elevated surface temperature and strong surface temperature contrasts for Earth-mass planets on the (1) pattern of mantle convection, (2) tectonic regime, and (3) rate and distribution of partial melting, using numerical simulations of mantle convection with a composite viscous/pseudo-plastic rheology. Our simulations indicate that if a close-in rocky exoplanet lacks an atmosphere to redistribute heat, a >400 K surface temperature contrast can maintain an asymmetric degree 1 pattern of mantle convection in which the surface of the planet moves preferentially toward subduction zones on the cold night side. The planetary surface features a hemispheric dichotomy, with plate-like tectonics on the night side and a continuously evolving mobile lid on the day side with diffuse surface deformation and vigorous volcanism. If volcanic outgassing establishes an atmosphere and redistributes heat, plate tectonics is globally replaced by diffuse surface deformation and volcanism accelerates and becomes distributed more uniformly across the planetary surface.
Purple dotted curves show atmospheric escape estimates for EUV heating for a 6 ME planet and stellar wind erosion for an Earth-sized planet.

Tidal locking is likely at distances < tidal lock orbit (black dots line). Colored dots show effective temperatures, for Kepler candidate exoplanets with R < 2 RE.

Different dot size reflects variability in planet size. For planets with a substantial atmosphere, uniform surface temperatures are expected.

The theoretical habitable zone lies between the 273 and 373 K isotherms where liquid water can be maintained.

Possible occupation of planets in orbital distance-stellar-mass domain space.
The frost line, also known as the snow line or ice line, refers to a particular distance in the solar nebula from the central protosun where it is cool enough for hydrogen compounds such as water, ammonia, and methane to condense into solid ice grains.

Depending on density, that temperature is estimated to be about 150 K. The frost line of the Solar System is around 5 AU.
WHERE DOES THE WATER COME FROM?

Comet: ~50%
Carbonaceous chondrite: ~10%
Ordinary chondrite: ~1%
Enstatite chondrite: <0.1%
(continuous range of compositions, Gounelle, 2011)

Isotopic observations (not only D/H but also C, N isotopes)
- The main source of water on Earth is not comets but some materials similar to common meteorites.
- Did most of water-rich materials come from regions beyond the ice-line in the later stage of planetary accretion?

Albarède (2009)

Earth and chondrites are “depleted” (95% or more)
- volatiles comes from material away from the “ice-line”
- late stage volatile acquisition

Figure 5 | A tentative chronology of the Earth’s accretion. Chronometers shown in brown. Accretion of planetary material was interrupted by energetic electromagnetic radiation (T Tauri phase) sweeping across the disk within a few Myr of the isolation of the solar nebula. Runaway growth of planetesimals produces Mars-sized planetary embryos, which, collision after collision, form the planets with their modern masses. The last of these ‘giant’ collisions left material orbiting the Earth that later reassembled to form the Moon. The $^{182}\text{Hf}-^{182}\text{W}$ chronometer dates metal–silicate separation. The identical abundance of radiogenic $^{182}\text{W}$ between the Earth and the Moon indicates that either the Moon formed after all the short-lived $^{182}\text{Hf}$ had disappeared (>60 Myr) or, rather, the Moon-forming impact and terrestrial core segregation took place simultaneously 30 Myr after isolation of the solar nebula. Addition of a late veneer of chondritic material coming from beyond 2.5 AU provides a strong explanation for the modern abundances of siderophile and volatile elements in the terrestrial mantle. This material also contained water and other volatile elements, which account for the origin of the terrestrial ocean. Such a model indicates that most of the terrestrial Pb and Xe was delivered by the asteroids that constituted the late veneer, and
Asteroids impacting the Earth partly volatilize, partly melt. While metal rapidly segregates out of the melt and sinks into the core, the vaporized material orbits the Earth and eventually rains back onto its surface.

The siderophile and chondritic content of the mantle hence is accounted for, not by the impactors themselves, but by the vapor. The impactor’s hydrogen, is added to the mantle and hydrosphere.

The addition of late veneer may have lasted for 130 Ma after isolation of the Solar System. Constraints from the stable isotopes of oxygen and other elements suggest that ∼4% of CI chondrites accreted to the Earth. The amount of water added in this way and now dissolved(oxidized Fe in the mantle an core), may correspond to 10–25 times the mass of the present-day ocean.

The Moon is globally 100 times more depleted than the Earth in volatile elements.
Water-bound hydrogen in the Solar System behaves coherently with respect to other volatile elements.

For example, once normalized to refractory calcium, Zn and water in chondrites are remarkably well correlated. Nitrogen (N2 and NH3), and carbon (CO2 and CH4), show similar trends.

The choice of a refractory element reflects mixing between distinctive planetary components, one nearly volatile-free and the other remarkably rich in H, C, N, and Zn.

The volatile-free component is itself a binary mixture.
Oxygen isotope compositions of the Earth and different groups of chondrites. CI-normalized concentrations of terrestrial volatile elements compared with predictions by the conventional late veneer assumption (brown) and by the addition of 4% CI chondrites.

The addition of small proportions of CI chondrites (15–20% water and 310 ppm Zn) to anhydrous chondrites is the only efficient way for a terrestrial planet to acquire significant amounts of water. Such a mixture should be detectable with oxygen isotopes.

In order to explain the heterogeneities of oxygen isotope abundances across the Solar System, it has been suggested that water ice scattered beyond the frost line was endowed with dynamics of its own (Lyons and Young, 2005), hence making its distribution with heliocentric distance a critical parameter of planetary water contents.
Mantle Convection and Plate Tectonics: Toward an Integrated Physical and Chemical Theory

Paul J. Tackley

Plate tectonics and convection of the solid, rocky mantle are responsible for transporting heat out of Earth. However, the physics of plate tectonics is poorly understood; other planets do not exhibit it. Recent seismic evidence for convection and mixing throughout the mantle seems at odds with the chemical composition of erupted magmas requiring the presence of several chemically distinct reservoirs within the mantle. There has been rapid progress on these two problems, with the emergence of the first self-consistent models of plate tectonics and mantle convection, along with new geochemical models that may be consistent with seismic and dynamical constraints on mantle structure.

Fig. 2. Some possible locations of mantle reservoirs and relationship to mantle dynamics. Convection features: blue, oceanic plates/slabs; red, hot plumes. Geochemical reservoirs: dark green, DMM; purple, high 3He/4He ("primitive"); light green, enriched recycled crust (ERC). (A) Typical geochemical model layered at 660 km depth (7). (B) Typical geodynamical model: homogeneous except for some mixture of ERC and primitive material at the base. (C) Primitive blob model (71) with added ERC layer. (D) Complete recycling model (83, 84). (E) Primitive piles model (developed from (85)). (F) Deep primitive layer (86).
Influence of water content (CW) on electrical conductivity (σ) at 1500 K in olivin, garnet and wadsleyite (15 GPa) and fO2 (oxygen fugacity).

**MORB** : formed by melting eclogite-poor rock,
**OIB** : formed by melting of eclogite-rich rock.

*If eclogites are connected or if they are distributed as fine lamellae*

=> **MTZ will have higher conductivity than the upper mantle** : consistent with the electrical conductivity observations.
Models of water distribution based on the geochemical observations of water in basalts assuming that water-rich regions are in the lower mantle.

In model b) the source regions of OIB occur as patchy regions occupying ~7% of the mantle. If water-rich regions occur homogeneously or only in the lower mantle, then such a model is not supported by the observation of electrical conductivity.

In model c), the volume fraction of water-rich (eclogite material) is assumed higher in the MTZ than in the upper mantle.
Valencia-O’Connell (2007):

Planetary mass is most important
→ large mass → high Rayleigh number
→ large driving force + thin plate

Korenaga (2010): friction coefficient (strength of lithosphere) is most important, the planetary mass is NOT important
Foley-Bercovici (2012):
Plate strength is controlled by **grain-size reduction**. Driving force increases with planet size. Grain-size reduction depends on (near surface) temperature through grain-growth. Both planet size and surface temperature are important.
How to weaken the lithosphere?
Brittle ↔ Ductile

Weakening in the ductile regime depends on T and water content.
Viscosity changes also with crystal structure/chemical bonding.

In most of super-Earth’s mantle, MgO is the softest phase. MgO changes its structure from B1 to B2 at ~0.5 TPa. B2 structure is softer than B1 structure.

(modified from Karato (1989))
Conclusions

(According to Karato)

• In order to assess if Plate Tectonics occurs on other planets (e.g., super-Earths), we need to know what controls the magnitude of driving force and the resistance for plate deformation.

• Major remaining issues:
  - Physical mechanisms of localized deformation
  - Dependence of viscosity on pressure (phase transformations)

• Volatile acquisition during planetary formation
  • early or late acquisition? (⇔ H in the core?)
    • geochemical observations
  • liquid phases control volatile acquisition
    • volatility ⇔ affinity to liquids (to Fe etc.)

• Volatile circulation in a planet
  (longevity of the surface ocean)
  • The role of deep (mid-) mantle melting
  • Plate tectonics on other planets?
    • “rheological properties”
      • shear localization, deep mantle viscosity
Conditions for the onset of plate tectonics on terrestrial planets and moons

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For plate tectonics driven by convecting mantle to exist on any planet like on Earth, stresses associated with mantle convection must exceed the \textit{strength of the lithosphere}. This condition is sufficiently restrictive that mantle convection in most terrestrial bodies remain in a \textit{stagnant lid regime}.

Convective stresses on the lithosphere depend on the viscosity and velocity of underlying cold downwellings. The lithospheric yield stress is controlled by its friction coefficient and elastic thickness (the depth to the brittle–ductile transition or BDT). Both convective stresses and the plate's yield strength depend critically on the size, thermal state and cooling history of a planet.

Numerical simulations and scaling theory help to identify conditions in which mantle convection leads to lithospheric failure for a range of conditions relevant to the terrestrial planets.

- Whereas \textbf{Earth} is expected to be in a plate-tectonic regime over its full thermal evolution, the \textbf{Moon} and \textbf{Mercury} are expected to have always remained in a stagnant lid regime.

- \textbf{Venus}, \textbf{Io} and \textbf{Europa} fall on the transition between the two regimes, which is consistent with an episodic style of mantle convection for Venus, a tectonic component to deformation on Io, and the resurfacing history and lithospheric evolution of Europa. While stagnant now, it is plausible that \textbf{Mars} may have also been in an active-lid regime, depending on the presence of liquid water on the surface.
The lid behaves elastically at low stress and temperature (T), i.e. above the BDT, and viscously below the BDT. The lid fails and behaves in a brittle manner once lithospheric stresses exceed the yield stress.

A strong lid of thickness d over a mantle at constant Tm, with a viscosity ηm, the mantle is stirred by two conveyor belts (shown by horizontal arrows) turning at a velocity Vm, which are set to vary. The convective stress imparted on the lid is a function of the velocity of the active downwelling (centre, Vm).

Sub-lithospheric velocities due to cold-downwellings, either in the form of a sinking drip (left) or steady flow into a conduit (right).
Mantle viscosities are temperature dependent.

Viscosity depends on internal heating $H$. 

Lithospheric Rayleigh number:

Convective stress depends on 

Linear plot of $F_{\text{drive}}/\mu$ vs $BDT/d$ (for $n=1$). The transition between failed and intact lithosphere follows the relationship: $F_{\text{drive}} \sim 33.7 + 1.4 \times 10^4 (BDT/d)^2$.

Log–log plot of $Ra$ vs. $(BDT/d)\mu$ (for $n=1$). The transition between failed and intact lithosphere behaves as $Ra \sim 4.4 \times 10^{13} (\mu BDT/d)^3$.
Log-linear plot of the variation in tectonic style with increasing driving motive and depth to the brittle–ductile transition (BDT).

Planets and satellites for which reliable estimates of mantle depth, elastic lithospheric thickness and mantle velocity exist are also non-dimensionalized and plotted.

Driving forces at 4.5 Ga are determined assuming higher internal heat production and Rayleigh numbers.
The primary difference between Earth and Venus, is free water at the surface.

This lowers the friction coefficient \( \mu \) (0.6 to 0.15), reduces resistive strength of the lithosphere.

Free surface water results in the alteration of fault zones (chemical), and influences the pore pressure \( (pf) \), which reduces rock strength by an order of magnitude. The estimated maximum supportable stress is 50–200 MPa for Earth.

If Venus had surface water at any time in its past, it could have been in an active-lid mode of convection. Even without water, it could have been in an active-lid regime, because higher temperatures increased convective velocities and lowered \( T_e \).

Its position on the transition of the stagnant-lid regime today is consistent with the recent (~750 Ma) cessation of surface activity, and also permits the possibility of an episodic style of convection.
While **Mars** is probably in a stagnant regime now, at 4Ga their would have been higher convective velocities, thinner thermal boundary layers, and surface water. Therefore it would have been active-lid regime. Crustal magnetization in the Southern Highlands requires the existence of a dynamo on early Mars, suggesting plate-tectonics.

On the **Moon** and **Mercury**, there is no evidence of surface water, and both are predicted to have been stagnant for their entire history.

**Io** is the most volcanically active body in the solar system as a result of severe tidal heating from Jupiter. In fact, its predominant mode of heat loss is by volcanic resurfacing, and so it is clearly not in the “classic” stagnant lid mode of most other terrestrial planets. The resurfacing rate of Io constraints interior velocities, and estimates plot Io on the transition between active and stagnant lid regimes. Identification of rugged mountain ranges over ~2% of Io's surface show evidence of uplift and thrusting not directly related to Io's voluminous volcanism but rather evidencing tilted blocks, in response to far-field volcanic loading and subsidence.

Similarly, assuming large strain-rate estimates for **Europa**, the surface tectonic activity observed may have an intrinsic endogenic component, separate to tidally-induced cracking. Recent evidence for convergent features on Europa strongly suggests interior convective motions. Based on the lack on cross-cut impact craters, the bulk of Europa's surface is estimated to be very young (30–80 Myr), and that since then the regime has switched to a far more subdued cryovolcanic-dominated one. This is also consistent with the inferred thickening of the elastic lithosphere. Based on our results, and its lithospheric history, we suggest that Europa may in fact be in an episodic regime similar to Venus.

In contrast, despite having a relatively small elastic lithosphere, the extremely small estimated strain rates estimated for icy shell of **Ganymede** preclude any surface deformation other than tidally-induced tectonic features.
Extra-solar super-Earths are likely to be undergoing active plate tectonics like on Earth, or be stagnant lids like on Mars and Venus. The origin of plate tectonics is poorly understood for Earth, likely involving a complex interplay of rheological, compositional, melting and thermal effects, which makes it challenging to make reliable predictions for other planets. One numerical study on super-Earths finds that plate tectonics is less likely on a larger planet (O'Neill and Lenardic, 2007), in contradiction of an analytical scaling study (Valencia et al., 2007). We here present new calculations of yielding-induced plate tectonics as a function of planet size, focusing on idealized end members of internal heating or basal heating, and strength.

We model super-Earths as simple scaled up versions of Earth, i.e., assuming constant physical properties, keeping the ratio of core/mantle radii constant and applying the same temperature difference between top/bottom boundaries and the same internal heating rate. Effects that originate outside of the planet, such as tidal forces, meteor impacts and intense surface heating from a nearby star are not considered. We find that for internally-heated convection plate tectonics is equally likely for terrestrial planets of any size, whereas for basally-heated convection plate tectonics becomes more likely with increasing planet size. This is indicated both by analytical scalings and the presented numerical results. When scalings are adjusted to account for increasing mean density with increasing planet size, plate tectonics becomes more likely with increasing planet size. The influence of the pressure variation of viscosity, thermal expansivity and conductivity may, however, act in the opposite sense. At least in the simplest case, factors other than planet size, such as the presence of surface water, are most important for determining the occurrence of plate tectonics.
For each scenario four snapshots are shown: mobile lid convection for size 1, 1.5 and 2, plus stagnant lid convection (with a higher yield stress or yield stress gradient) for size 2. For the images showing a stagnant lid regime a different color scale is used as indicated since (non-dimensional) internal temperatures exceed 1.
CONCLUSION

* In addition to temperature, Volatile content, and presence of atmosphere need be detected in future planets...

... to enable the mechanical weakening of planetary material, and allow development of plate tectonics...

which differ from « localised volcanism » mainly by the existence of structured plate recycling (subduction) ...

... therefore witnessing the presence of water...and life...

In details, strength and mechanical weakening are still poorly understood...