Workshop on the origin and evolution of plate tectonics

Congressi Stefano Franscini, Monte Verità,
Locarno, Switzerland

17-22 July 2016

Motivation

The question "Why does Earth have plate tectonics?" stands among the top ten research questions shaping 21st-century Earth Science (National Academy of Sciences). Coming on the 10 year anniversary of the Penrose workshop "Why did plate tectonics begin", this conference will bring together international experts in Earth's geological history, geophysics and geodynamics and introduce students and young researchers to this interdisciplinary research topic in an informal setting conducive to establishing ties with new colleagues and advancing this potentially transformative topic.

The discussions will be organized around four themes:

1- When did plate tectonics start?

2- How did plate tectonics start?

3- What was before plate tectonics?

4- Broader Impacts: Why do we care?\l

and there will be a one day field trip to the Alps

Sponsors: Congressi Stefano Franscini/ETH Zurich, SNSF, Deep Carbon Observatory

Main organizers: Bob Stern (U. Texas, Dallas), Paul Tackley and Taras Gerya (ETH Zurich)

Workshop Program

Sunday July 17th:

Arrival and registration (check in time 15:00), welcome receiption at 18:30 and dinner at 19:00.

Monday July 18th: Why is it important to know the evolution of plate tectonics?

8:00 – 9:00	Breakfast
9:00 – 9:15	Welcome address (organisers and Monte Verità Foundation)
9:15 – 10:10	**Maruyama, Shigenori** (Tokyo Inst. Technology, Japan) Earth history
10:10 – 11:05	**Coltice, Nicolas** (U. Lyon) Importance of plate tectonics for the geochemical evolution of Earth's mantle
11:05 – 11:35	Coffee break
11:35 – 12:30	**Breuer, Doris** (DLR, Germany) Is there plate tectonics on extrasolar planets (exoplanets)?
12:30 – 14:30	Lunch (including meeting of students with invited speakers)
14:30 – 15:30	Short (3 Minutes) presentation of posters
15:30 – 17:30	Posters + refreshments
17:30 – 19:00	Plenary discussion
19:00 –	Dinner

Tuesday July 19th: When did plate tectonics start?

8:00 – 9:00	Breakfast
9:00 – 10:00	**Brown, Michael** (U. Maryland, USA) Evidence from the metamorphic rock record for the onset of plate tectonics
10:00 – 11:00	**Harrison, T. Mark** (UCLA) Geochemical evidence for early plate tectonics
11:00 – 11:30	Coffee break
11:30 – 12:30	**Condie, Kent** (New Mexico Tech) The onset of plate tectonics on Earth: A planet in transition between 2 and 3 Ga
12:30 – 14:30	Lunch (including meeting of students with invited speakers)
14:30 – 15:30	**van Hunen, Jeroen** (Durham U., UK) Modelling the dynamics and observables of subduction in early Earth
15:30 – 16:30	Short (3 Minutes) presentation of posters

16:30 – 17:30	Posters + refreshments
17:30 – 19:00	Plenary discussion
19:00 –	Dinner

Wednesday July 20th: Field trip to the Alps (Jean-Pierre Burg, leader)

8:30 – 11:30	Departure, introduction and various points of stop 1 in Arcegno
11:30 – 12:15	Travel to Lavertezzo
12:15 – 13:00	Lunch on Lavertezzo river
13:00 – 14:30	Stop 2
14:30 – 14:45	Travel to “James Bond” dam
14:45 – 15:30	Stop 3
15:30 – 16:15	Travel to Bellinzona
16:15 – 17:00	Stop 4
17:00 – ...	Apero at Bellinzona Castle and return to Monte Verita (arrival ~18:30-19:00)

Thursday July 21st: "How did plate tectonics start?"

8:00 – 9:00	Breakfast
9:00 – 10:00	**Solomatov, Slava** (WUSTL) Scaling of plate tectonics
10:00 – 11:00	**Ricard, Yanick** (U. Lyon) Onset of plate tectonics by accumulated lithospheric damage
11:00 – 11:30	Coffee break
11:30 – 12:30	**Sobolev, S.** (GFZ) Plate tectonics initiation as running hurdles.
12:30 – 14:30	Lunch (including meeting of students with invited speakers)
14:30 – 15:30	Short (3 Minutes) presentation of posters
15:30 – 17:30	Posters + refreshments
17:30 – 19:00	Plenary discussion
19:00 –	Dinner

Friday July 22nd: What was before plate tectonics?

8:00 – 9:00	Breakfast
9:00 – 9:55	**Sizova, Elena** (U. Vienna) Plume tectonics and formation of TTG in the Archean
9:55 – 10:50	**Harris, Lyal** (INRS-ETE, Canada) Comparisons Early Earth with Venus
10:50 – 11:20	Coffee break
11:20 – 12:20	Final Plenary Discussion: What have we learned and where do we go from here?
12:20 – 12:30	Presentation of “Best Young Scientist Presentation” award and closing remarks.
12:30 – 14:00	Lunch (including meeting of students with invited speakers)
14:00 –	Departure

Abstracts

Compositional layering within the large low shear-wave velocity provinces in the lower mantle

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Seismic tomography reveals two antipodal Large Low Shear-Wave Velocity Provinces (LLSVPs) in the Earth's mantle, each extending from the core-mantle boundary (CMB) up to ~1000 km depth. The LLSVPs are thought to host primordial mantle materials that bear witness of early-Earth processes, and/or subducted basalt that has accumulated in the mantle over billions of years. A compositional distinction between the LLSVPs and the ambient mantle is supported by anti-correlation of bulk-sound and shear-wave velocity (Vs) anomalies as well as abrupt lateral gradients in Vs along LLSVP margins. Both of these observations, however, are mainly restricted to LLSVP bottom domains (2300~2900 km depth), or "deep distinct domains" (DDD). Seismic sensitivity calculations suggest that DDDs are more likely to be composed of primordial mantle material than of basaltic material. On the other hand, the seismic signature of LLSVP shallow domains (1000~2300 km depth) is consistent with a basaltic composition, but a purely thermal origin cannot be ruled out.

Here, we explore the implications of the hypothesis that LLSVPs are compositionally layered with a primordial bottom domain (or DDD) and a basaltic shallow domain. We test this hypothesis using 2D geodynamic models. Depending on the density difference between primordial and basaltic materials, materials either mix or remain separate as they form thermochemical piles in the deep mantle. Separation of both materials provides an explanation for LLSVP seismic properties, including substantial internal vertical gradients in Vs observed at 400-700 km height above the CMB, as well as out-of-plane reflections on LLSVP sides. Predicted pile geometries are compared to LLSVP and DDD shapes. Geodynamic models predict short-lived "secondary" plumelets to rise from LLSVP roofs and to entrain basaltic material that has evolved in the lower mantle. Long-lived "primary" plumes rise from LLSVP margins and entrain a mix of materials, including small fractions of primordial material. These predictions address the geochemical and geochronological record of Pacific hotspot volcanism. In general, the parameter range spanned by models that are able to reconcile observations provides a constraint for the intrinsic density anomaly (or composition) of DDDs. We use this constraint to evaluate the origin of DDDs from magma-ocean cumulates. The study of LLSVP compositional layering indeed has important implications for our understanding of the evolution and composition of the Earth's mantle.

Origin of plate tectonics: from grain to global scale

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The emergence of plate tectonics was Earth's defining moment. How and when plate tectonics started is shrouded in mystery because of the paucity of observations in the Archean as well as the challenge of understanding how plates are generated. The damage theory of lithospheric weakening by grain-reduction provides a physical framework for plate generation [1]. This model builds on grain-scale physics to describe planetary-scale processes, and is consistent with lab and field observations of polycrystalline rocks and lithospheric mylonites. Grain-damage accounts for the evolution of damage and healing by grain growth, hence predicts plate boundary formation and longevity, and how they depend on surface conditions. The establishment of global plate tectonics likely started between >4Ga and 2.7Ga, and may have taken over a billion years to develop. Under Earth-like conditions, grain-damage combined with intermittent Archean protosubduction produces persistent weak zones that accumulate into well-developed plates by 3Ga. However, Venus' hotter surface promotes healing, suppresses damage and inhibits weak zone accumulation, which suggests why plate tectonics failed to spread on our sister planet [2].

New work posits that interface damage is possibly suppressed at moderate grain-size; this induces a hysteresis loop wherein three equilibrium deformation branches coexist [3]. These branches include (a) a stable large-grain, weakly-deforming state in dislocation creep analogous to the classical paleopiezometer, (b) a stable small-grain rapidly-deforming state in diffusion creep analogous to mylonite and ultramylonite behaviour, and (c) an unstable intermediate-grain state possibly related to protomylonites. However, the transition to the mylonite state likely depends on the efficiency of inter-grain mixing, which is also tied to the competition between damage and grain-boundary migration at the inter-phase boundary. But, at the right conditions, the lithosphere can conceivably acquire two stable deformation states characteristic of plate tectonics; i.e., both slowly deforming plate interiors and rapidly deforming plate boundaries can co-exist. Earth currently sits inside the hysteresis loop and can have coexisting deformation states, while Venus sits at the end of the loop where only the weakly deforming branch dominates. The hot post-Hadean Earth might have had peak deformation only on the weakly-deforming branch. However, with surface cooling, diffuse deformation zones could be de-stabilized toward the mylonitic, rapidly-deforming branch and thus transform into localized plate-boundaries. Thus the Earth's initial surface cooling may itself have facilitated a bifurcation to a plate-tectonic state.

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[2] Bercovici D and Ricard Y (2014) Nature 508: 513-516
[3] Bercovici D and Ricard Y (2016) Phys. Earth Planet. Int., in press

Crystallisation and Cooling of a Deep Silicate Magma Ocean

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Impact and accretion simulations of terrestrial planet formation suggest that giant impacts are both common and expected to produce extensive melting. The moon-forming impact, for example, likely melted the majority of Earth's mantle to produce a global magma ocean that subsequently cooled and crystallised. Understanding the cooling process is critical to determining magma ocean lifetimes and recognising possible remnant signatures of the magma ocean in present-day mantle heterogeneities. Modelling this evolution is challenging, however, due to the vastly different timescales and lengthscales associated with turbulent convection (magma ocean) and viscous creep (present-day mantle), in addition to uncertainties in material properties and chemical partitioning.

We consider a simplified spherically-symmetric (1-D) magma ocean to investigate both its evolving structure and cooling timescale. Extending the work of Abe (1993), mixing-length theory is employed to determine convective heat transport, producing a high resolution model that parameterises the ultra-thin boundary layer (few cms) at the surface of the magma ocean. The thermodynamics of mantle melting are represented using a pseudo-one-component model, which retains the simplicity of a standard one-component model while introducing a finite temperature interval for melting. This model is used to determine the cooling timescale for a variety of plausible thermodynamic models, with special emphasis on comparing the center-outwards vs bottom-up cooling scenarios that arise from the assumed EOS.

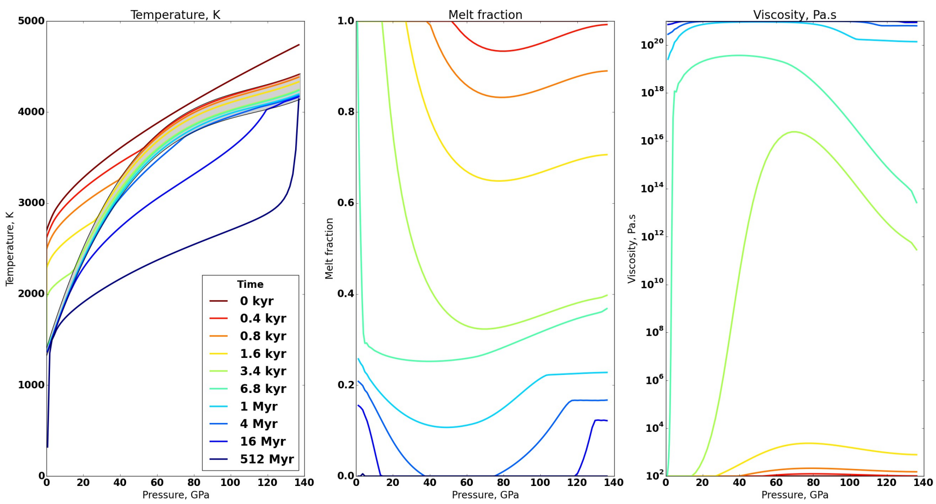

Figure 1. Evolution from turbulent magma ocean to present-day solid-state convection for a center-outwards cooling scenerio.

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The influence of water to mantle convection and plate tectonics

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Water has a significant influence to mantle rheology and therefore also to the convection of the mantle and the plate tectonics. The viscosity of the mantle can be decreased by up to two orders of magnitude when water is present in the mantle. Another effect of the water is the change in the solidus of the mantle and therefore the melting regime. This two effects of water in the mantle have a significant influence to mantle convection and plate tectonics. The influx of water to the mantle is driven by plate tectonics as wet oceanic lithosphere is subducted into the mantle and then brought back to the litho- sphere and the surface by MOR-, arc- and hotspot volcanism. Studies show that the amount of water in the mantle is about three times bigger than the water in the oceans. To model this water cycle multiple additions to StagYY are necessary. A water diffu- sion to complement the water transport due to advection and water dependent viscosity law are implemented. This additions to StagYY will be followed by implementations of a pressure-temperature law for water content, additional transport mechanisms for water, water dependent solidus functions and the implementation of recent values for plate velocities and water capacities in subducting slabs. This will allow to research the influence of water to the mantle convection and rheology of the past 200Ma.

Is There Plate Tectonics on Extrasolar Planets (Exo-planets)?

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The detection of rocky exoplanets up to 10 Earth masses by space missions such as Kepler and CoRoT has fostered the discussion whether or not these planets would have plate tectonics similar to the Earth (Here, the aspect of the recycling of crust with the mantle is more impostant than the rheological feature of stiff plates.) Posing that question has been motivated by the search for life beyond our solar system and by the general presumption that the habitabilty of Earth - in particular for developed life - is related to its tectonic regime. Plate tectonics provides a continuous supply of “nutrients” through the renewal of surface rock, promotes the generation of a magnetic field that protects the biosphere from radiation and the atmosphere from erosion, and stabilizes the climate through the long-term carbonate-silicate cycle.

It is undeniable that we cannot answer the question about the existence of plate tectonics on exoplanets satisfactorily as long as we lack sufficient understanding of how plate tectonics works on Earth. Of course, it would help if we detected an exoplanet operating in the plate tectonic regime. However, understanding Earth plate tectonics is still to be achieved (viz. the present workshop) and there are no known markers indicating plate tectonics on exoplanets that could be observed with the present observation capabilities.

Thus, as a first step, we need to rely on numerical (or other) modeling. Most modeling studies of plate tectonics on exoplanets have focused on the impact of an increasing planetary mass while keeping the core to planet mass ratio constant and while assuming an Earth-like composition. Increasing the mass then goes along with increases in planetary radius, pressure gradient, mantle thickness and mantle density with values derived from mass-radius scaling relationships (e.g., Valencia et al. 2006; Wagner et al. 2011). For a ten Earth mass exoplanet, the pressure at the core-mantle boundary (CMB) is about ten times the pressure at Earth's CMB, the radius is about 1.9 times the Earth radius and the mantle thickness is about 1.6 the Earth mantle thickness. The operation of plate tectonics in these numerical models is then usually assumed to require convective stresses exceeding the lithospheric yield stress -- similar to what is assumed in global convection models for Earth. In 2D or 3D mantle convection models, either a pseudoplastic rheology (e.g., van Heck and Tackley 2011) or grain-damage (e.g., Foley et al. 2012) has been incorporated. The latter model further assumes a weak-zone memory in addition to lithosphere weakening and shear localization. In parameterized convection models, average convection velocities and yield stresses are calculated using boundary layer theory (e.g., Valencia and O’Connell 2009; Stamenkovic and Breuer 2014). It should be noted that all these studies typically neglect chemical buoyancy variations in the crust with respect to the mantle which depend on the melting processes and thus the temperature evolution.

During the last decade, various studies have been published that examined not only the influence of planetary mass on the likelihood of plate tectonics but also of different heating rates, water abundance and surface temperature (e.g., Valencia et al. 2007, O'Neill and Lenardic 2007, O'Neill et al. 2007, Van Heck and Tackley 2011; Foley et al. 2012, Stein et al. 2013; Noack and Breuer 2013; Stamenkovic and Breuer 2014). In addition, it has been shown that the pressure effect on thermal conductivity, thermal expansivity and viscosity plays an important role for mantle dynamics and plate tectonics (Tackley et al. 2013; Wagner et al. 2011; Stamenkovic et al. 2012; Miyagoshi et al. 2015) – parameters that are currently not well known for the high pressure range expected in massive rocky exoplanets. In this presentation, I will provide an overview of the various models in the literature, how they differ and what we have learned so far.

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Evidence from the metamorphic rock record for the onset of plate tectonics

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Earth's present (mobile-lid) plate tectonics regime is characterized by asymmetric (one-sided) subduction of ocean lithosphere at convergent plate boundaries. In this regime, the downgoing slab depresses isotherms creating an environment with low d*T*/d*P*, whereas dehydration-generated fluids and melts promote magma generation in the mantle wedge above the slab leading to high d*T*/d*P* in the overriding plate. Horizontal plate motions lead to collisions between arcs, ribbon terranes and continents, sometimes also involving ocean plateaus, preserving evidence of low d*T*/d*P* metamorphism in the suture, and creating thickened lithosphere to generate intermediate d*T*/d*P* metamorphism in the mountain belt and high d*T*/d*P* metamorphism in the hinterland. At issue is whether a hotter mantle and higher heat production in the past precluded globally linked subduction and plate tectonics. If so, to identify the onset of plate tectonics we must recognize the first imprint of one-sided subduction in the metamorphic rock record. Using a new dataset of ~450 robust determinations of peak metamorphic *P*–*T* conditions and accurate ages retrieved from the rock record back to the Eoarchean, we investigate secular change in apparent thermal gradients of metamorphism and, by implication, tectonic settings. Issues to consider in reading the rock record include the role of preservation, effect of sampling bias and reliability of data gaps. In addition, we must weigh global (commonly younger) vs local (commonly older) datasets and distinguish initiation from episodic or continuous (local or global) subduction.

Blueschist and ultrahigh-pressure metamorphism, characterized by d*T*/d*P* <375 °C/GPa (mean of ~253 ± 55 (1sd)), extends back to the Cryogenian globally, with two (local) outliers, one in the Mesoproterozoic and another in the Paleoproterozoic. Since this low d*T*/d*P* type of metamorphism is linked to subduction, Stern (2005) argued that "the modern style of subduction tectonics began in Neoproterozoic time." However, two contrasting types of metamorphism—one with apparent thermal gradients of 375–775 °C/GPa (mean of ~573 ± 117 (1sd)), producing eclogite, high pressure granulite and garnet amphibolite, and another with apparent thermal gradients >775 °C/GPa (mean of ~1109 ± 254 (1sd)), producing granulites and ultrahigh temperature metamorphic rocks—are registered widely in the rock record back to *c.* 2.8 Ga. The emergence of 'paired' metamorphism at the end of the Mesoarchean was interpreted by Brown (2006, 2007, 2014) to manifest the onset of globally linked one-sided subduction at newly created convergent plate boundaries, where the lower apparent thermal gradients were inferred to be associated with the subduction-to-collision suture and the higher thermal gradients with the hinterland in the overriding plate. Ages of metamorphism between the late Mesoarchean and the early Mesoproterozoic define two clusters, similar to zircon age peaks for the crust, that correlate with supercraton assembly (2.8–

2.4 Ga) and formation of the first supercontinent (Columbia/Nuna; 2.0–1.6 Ga), demonstrating the beginning of the supercontinent cycle that many relate to plate tectonics. The appearance of blueschists in the record in the Cryogenian was interpreted by Brown (2006) to reveal a change to lower d*T*/d*P* during subduction, probably generated by deeper slab breakoff that also enabled subduction of continental lithosphere to mantle depths (Sizova et al., 2014). By contrast, the suggestion that the emergence of blueschists on Earth was linked to secular changes in oceanic crust composition (Palin & White, 2016) is unlikely as there is no evidence of significant secular variation in the MgO content of greenstone basalts since the Mesoarchean (Condie et al., 2016). Importantly, the compositions of common greenstone basalts are appropriate to source the widespread Archean TTG crust (Johnson et al., 2014).

Prior to 2.8 Ga the crust registers moderate apparent thermal gradients in both ‘high-grade’ gneiss terranes and ‘low-grade’ greenstone belts, with only sporadic occurrences of higher d*T*/d*P* metamorphism and rare examples of lower d*T*/d*P* metamorphism, although reliable quantitative data are limited. This pattern may reflect a stagnant–deformable lid tectono-magmatic regime in which occurrences of lower d*T*/d*P* metamorphism record episodes of local subduction/collision (Sizova et al., 2015). The change to a (mobile-lid) plate tectonics regime is related to secular cooling since the Mesoarchean (Sizova et al., 2010), which facilitated a transition to global subduction registered by the appearance of ‘paired’ metamorphism in the rock record at *c*. 2.8 Ga. Thus, the onset of plate tectonics probably occurred in the late Mesoarchean.

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Viscosity, Dissipation and Layers: A Parametrised Model

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Parametrised models are a simple tool used to examine the thermal and rheological evolution of a cooling planet. They have previously been used to investigate the effects of water-dependent rheology layered convection (Crowley and O'Connell, 2012, McNamara and van Keken, 2000) and viscous dissipation (Rose and Korenaga, 2011, Crowley and O'Connell, 2012) on Earth's thermal evolution. We present a model that combines all three effects, which are thought to play a large part in the evolution of planet Earth.

We solve for the conservation of mass and the conservation of energy across 3 reservoirs - a surface ocean, upper and lower mantle - using a variable order finite difference solver to determine the temperature and water concentration of the reservoirs. The initial inclusion of viscous dissipation applies an adaptation of Conrad and Hager (1999) scaling of the Nusselt-Rayleigh relation, $Nu = (Ra/Ra_c)^{\beta}$, with exponent β ranging from β<0.01 representing a weak coupling between the mantle and a tectonic plate and the canonical β=1/3 for steady convection predicted by boundary layer theory (Turcotte and Oxburgh, 1967).

By separating upper and lower mantle we are able to include large scale differences arising from an expected increase in viscosity in the lower mantle and differing water concentrations with important consequences for rheology (Bolfan-Casanova et al., 2000, Bolfan-Casanova et al., 2003, Inoue et al., 2010) and the overall dynamics of the system.

As in Crowley et al. (2011) we investigate the water dependence of the viscosity by using an experimentally determined water fugacity relation (Li et al., 2008) and the viscosity of the form presented in Mei and Kohlstedt (2000a,b). The initial water concentration is chosen such that the surface reservoir contains one ocean mass and the surface heat flow is 36TW (Lay, 2008) at the present day.

Preliminary results show that the initial viscosity changes the dynamics of the convecting system. The variations of initial viscosity represent varying degrees of water dependence (Figure 1). As the initial viscosity increases, the change from a degassing to a regassing regime is delayed. In cases where the initial viscosity is greater than 10^{20}Pas, the system begins too stiff to convect. The heat is trapped within the layer increasing the internal temperature. As it warms, the viscosity decreases and the Rayleigh number increases above the critical Rayleigh number. This allows degassing of the interior to begin. Tuning the initial water concentration and surface heat flow to present day conditions results in lower peaks in the surface water mass and variation in the rate of internal heating.

We also explore a model for the thermal evolution based on mixing-length theory, which acounts for variation of mantle physical properties as a funciton of pressure, temperature and phase.

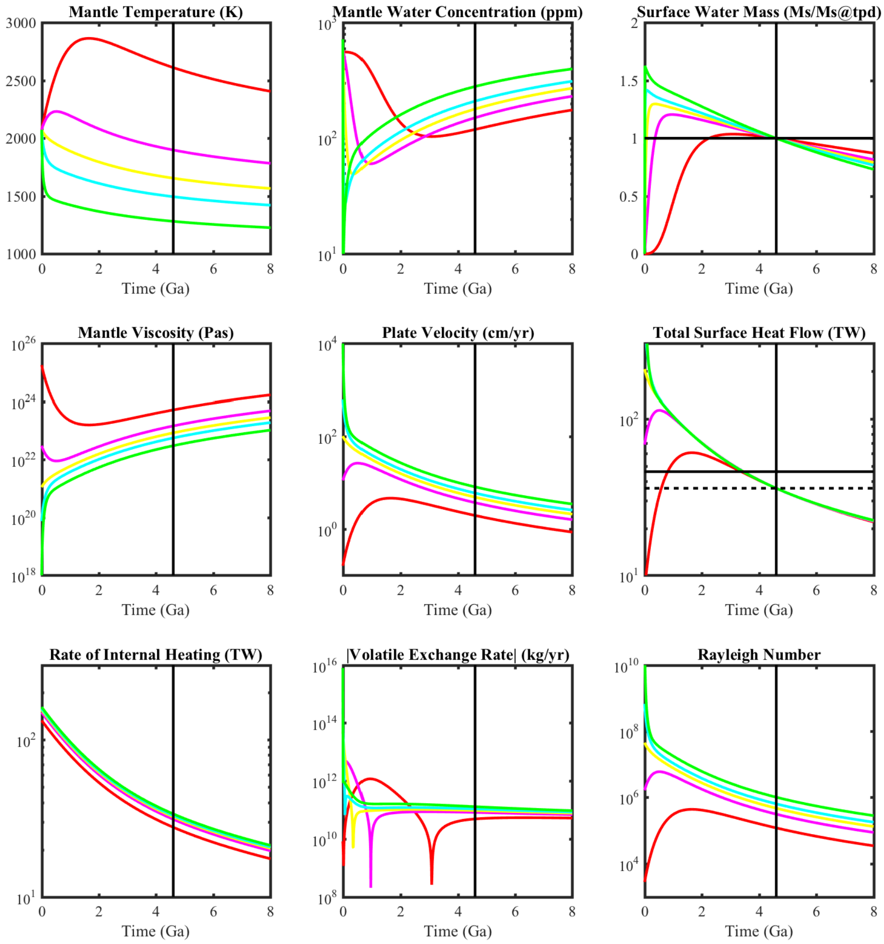

Figure 1. Derivatives are calculated assuming a constant water content which results in different initial viscosities; 0.1ppm ~ 1.81×10^{25}Pas (red), 1ppm ~ 3.06×10^{22}Pas (magenta), 10ppm ~ 1.12×10^{21}Pas (yellow), 100ppm ~ 7.50×10^{19}Pas (cyan) and 1000ppm ~ 7.78×10^{17}Pas (green). 0.1ppm represents a water independent viscosity and 1000ppm represents a viscosity heavily dependent on water.

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Importance of plate tectonics for the geochemical evolution of Earth's mantle

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The mass transfers between the envelopes of a planet shape its long-term chemical evolution. Large fluxes impact small reservoirs over a short time scale, and small fluxes modify large reservoirs over long time scales, potentially as long as the lifetime of the Earth. The dynamics of the lithosphere and mantle are usually thought to represent the longest time scales in Earth evolution, because the motions are the slowest. However, slow motion does not mean small mass fluxes. Time scales of chemical evolution are also conditioned by the dynamic regimes involved, through the degrees of fractionation between elements or isotopes. In this presentation, I will focus on the impact of the regime of plate tectonics.

I will start with an overview of the geochemical datasets we have for the Earth: elemental composition of rocks in the ocean and continents, elemental ratios and isotopic ratios of a diversity of elements, oxidation sates. While making this catalogue, I will highlight the physical processes at play that have a connection with the dynamics of the mantle and lithosphere. I will show that a variety of tectonic regimes can produce similar geochemical signals, our limitations being our poor knowledge of the dynamics for the early Earth.

I will follow with a description of several dynamic regimes, hypothesised or computed, for planetary evolutions: magma ocean, stagnant lid, intermittent subduction, plate tectonics, ridge-only, heat pipe. Based on models in the literature, I will discuss the geochemical imprint of these regimes, using our knowledge about the chemistry of other planets.

I will finish with a discussion on how the geochemical identities of the Earth and planetary rocks tell us since when and how plate tectonics have operated.

The Onset of Plate Tectonics on Earth: tracking subduction indicators through time and a comparison of mantle sources on Earth, Mars and the Moon

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Refinement of isotopic ages and an increasing database of geologic and trace element geochemical features from greenstone volcanics and associated TTG plutonic complexes helps constrain the timing and onset of plate tectonics on Earth. Comparison of incompatible element ratios in terrestrial oceanic basalts to those from well-dated basalts from the Moon and Mars also contribute to our understanding of when Earth evolved from a stagnant lid to a plate tectonic regime. Robust plate tectonic indicators such as paired metamorphic belts, collisional orogens, and paleomagnetic evidence for lateral plate motions of thousands of kilometers first appear in the geologic record between 3 and 2 Ga. The oldest occurrence of paired metamorphic belts is at about 2.8 Ga (Brown, 2014), and the oldest collisional orogens are the Majorqaq and MacQuoid orogens in Laurentia at 2.7 Ga (Dyck et al., 2015; Pehrsson et al., 2013). The oldest precisely dated paleomagnetic evidence for large lateral plate motions is from the Superior, Rae-Hearne, and Slave cratons between 2.0 and 1.75 Ga (Mitchell et al., 2014). Also decreasing rapidly between 3 and 2 Ga is the ratio of oceanic non-arc to arc type basalts, the ratio of TTG to granite in orogenic provinces, and the Na/K and Sr/Ba ratios in TTG complexes (Condie, 2016). Based on calculated magma generation temperatures from oceanic basalts through time, a great thermal divergence between enriched and depleted mantle begins at 2.5-2.0 Ga, possibly controlled by the widespread propagation of plate tectonics (Condie et al., 2016). Increasing data in the last few years does not support the existence of a crustal age gap at 2.4-2.2 Ga as previously suggested based on incomplete global sampling.

Enriched (EM), depleted (DM) and hydrated (HM) mantle domains can be tracked to about 2.5 Ga with geologic and geochemical characteristics (Condie, 2015). Prior to this time DM and EM basalts are difficult to distinguish in terms of incompatible element ratios Zr/Nb, Nb/Th, Th/Yb, Nb/Yb and La/Sm, and the three mantle domains seem to collapse into one domain centered near Earth's primitive mantle (PM) composition (Fig. 1). A single grouping is also evident for lunar Apollo 11, 12 and 15 basalts in which samples cluster tightly around PM for these element ratios. Martian enriched and intermediate shergottites also scatter around the PM composition. The fact that prior to 2.5 Ga, Earth's oceanic basalts have similar incompatible element signatures suggests they came from a relatively unfractionated mantle source (PM). Such a source may be characteristic of a stagnant lid planet or satellite, like Mars or the Moon

(Condie and Shearer, 2016), and if so, this suggests that Earth also may have been in a stagnant lid or episodic tectonic regime prior to 2.5 Ga. The widespread propagation of plate tectonics on Earth by 2 Ga may have led to the production of DM and EM mantle sources, which may be characteristic of a plate tectonic planet.

Collectively, these features are consistent with the appearance of plate tectonics on Earth at about 3 Ga and the widespread propagation around the planet by 2 Ga.

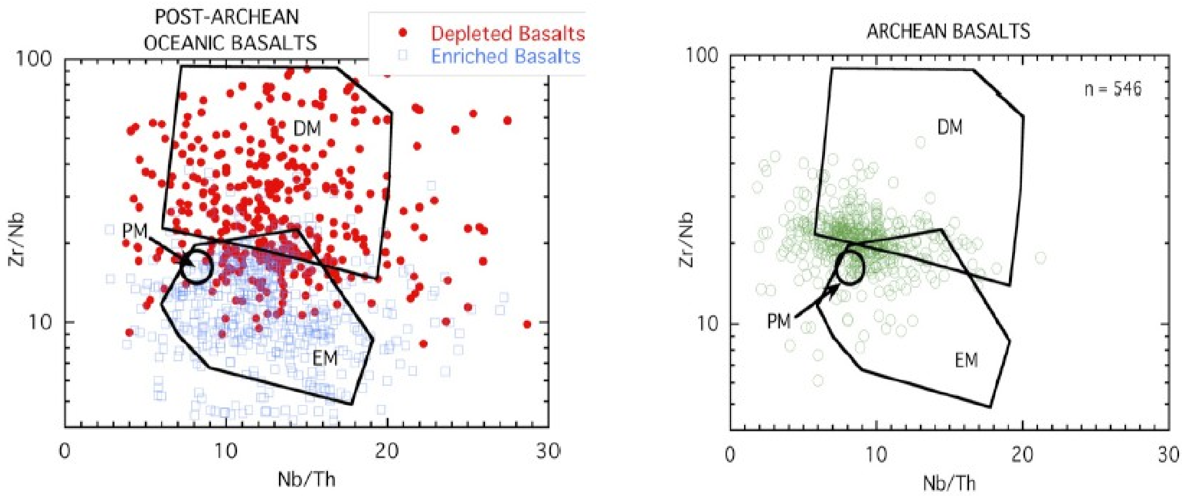

Figure 1. Zr/Nb/-Nb/Th graphs of post-Archean and Archean basalts; PM, primitive mantle; DM, depleted mantle; EM, enriched mantle.

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Subduction Initiation from a Stagnant Lid: New Insights from Numerical Models with a Free Surface and Lithospheric Heterogeneity

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Studying subduction initiation from a stagnant lid is key to better understand how plate tectonics might have started on Earth and why there is this fundamental difference between Earth's tectonic evolution and the tectonic evolution of all other rocky planetary bodies in our solar system. Despite the progress in recent years, the question about how a stiff, mostly stagnant planetary lid can break and become part in the global overturn of the mantle is still unresolved.

Here, we present results on subduction initiation obtained by dynamically self-consistent, time-dependent numerical modelling of mantle convection with a free surface and single-sided subduction (Crameri et al., 2012b) using the finite-difference, multigrid code StagYY (Tackley 2008).

We show that the stress distribution and resulting deformation of the lithosphere is strongly controlled by the top boundary formulation: A free surface enables surface topography and plate bending, increases gravitational sliding of the plates and leads to more realistic, lithosphere-scale shear zones (Crameri and Tackley, submitted). As a consequence, subduction initiation induced by regional mantle flow is significantly favoured by a free surface compared to the commonly-applied, vertically-fixed (i.e. free-slip) surface. We further test the influence of rheologic heterogeneity, like regional weak zones or continental lithosphere, in localising stress and deformation, and in facilitating lithsopheric failure and subsequent subduction initiation.

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On the importance of plumes to initiate subduction, continental growth and plate tectonics : inferences for Venus and the Early Earth.

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Understanding the details of plate failure and the initiation of subduction remains a challenge due to the complexity of mantle rocks. We carried out experiments on convection in aqueous colloidal dispersions heated from below, and dried and cooled from above. The rheology of these fluids depends strongly on solid particle fraction ü $_p$, being Newtonian at low ü $_p$, and presenting memory, yield stress, elasticity, and brittle properties as ü $_p$ increases (Di Giuseppe et al, 2012). Such a behaviour is analogue to the rheology of mantle rocks as temperature decreases (e.g. Davaille, 2016). When drying is sufficiently rapid in the laboratory, a visco-elasto-plastic skin (”lithosphere”) forms on the fluid surface. Depending on its rheology, and on the different scales of convection existing in our laboratory mantle, we observed different modes of one-sided subduction initiation. However, not all of them lead to continuous plate tectonics. If subduction is definitely a necessary condition for plate tectonics, it is not sufficient.

Amongst the different modes of subduction initiation, we observed one of them where one-sided subduction was induced by the impingement of a hot plume under the skin, the trench being localized on the rim of the plume impingement zone under the lithosphere. Due to the plastic/brittle character of the skin, the subduction trench will never describe a complete circle, but several tears and/or transform faults will develop as subduction and roll back proceed. Then depending on the lithospheric rheology, the nascent subduction can either stop as the result of subducted plate necking, or continue to sink smoothly.

Those experiments therefore demonstrate a strong association between plumes and subduction initiation. This could explain on Venus the association of large coronae (created by hot upwelling mantle plumes) with trenches that have topographic signatures similar to Earth’s subduction trenches (Sandwell and Schubert, 1992 ; Smrekar et al, 2016). Moreover, inspection of the geological record on Earth cratons suggests that many continental growth bursts open by a plume event closely followed by generation of granitoids in a subduction environment (e.g. Arndt and Davaille, 2013 ; Condie et al, 2014). This suggests that plume-induced subduction may have been instrumental in the nucleation and growth of cratons and the onset of continuous plate tectonics.

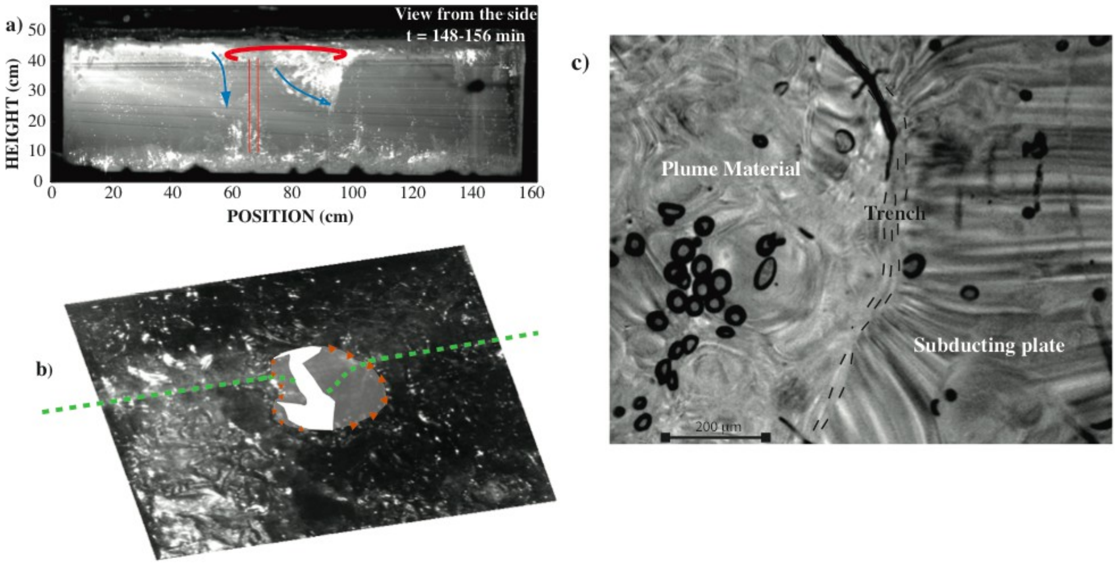

Figure 1. Plume-induced subduction in the laboratory. a) side view. 10 images have been superimposed to show the slab roll-back as the plume spreads. b) 3D view from above where the plume material has been removed. c) close up (1 cm across) on the boundary between plume material and subducting plate. Darker areas are thicker. The outer bulge close to the trench presents cracks and stripes. The trench (black dashed lines) shows faults parallel to it. The small black ovoids are spurious bubbles.

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The transition between rocky and non-rocky exoplanets

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The characterization of exoplanet interiors is key for the understanding of planet diversity. Previous studies have been successful in rigorously analyzing exoplanet interiors while quantifying for the inherent degeneracy. Planets in the mass range below ten M_{Earth} can theoretically have a wide compositional diversity. They may be rocky, rich in ice or gas, depending on planet bulk density. In the solar system, there are no planets with masses and radii intermediate between the Earth and the ice giants. A sample of super Earths and Sub-Neptunes allow the study of the intriguing transition between rocky and volatile-rich planets. Here, we statistically study this transition.

We employ Bayesian inference method for rigorously characterizing the interiors of sampled super Earths and Sub-Neptunes. We employ a full probabilistic Bayesian inference analysis that formally accounts for observational and model uncertainties. Using a Markov chain Monte Carlo technique, we compute how strong constraints on composition and layer thicknesses are based on observations of mass and radius. We include state-of-the-art structural models that use self-consistent thermodynamics of core, mantle, high-pressure ice and liquid water and compute irradiated atmospheres. We calculate the probability distributions for the radius fraction of rocky layers and study their possible correlations with planet radius. We quantify whether the planet samples could originate from two different underlying distributions that represent a separation between rocky and volatile-rich planets.
We present our preliminary results that suggest, (1) a possible transition between rocky and volatile-rich planets around two R_{Earth}, (2) a transition that is likely correlated with stellar irradiation, (3) the location of the transition is sensitive to the quality of the planet samples.
We provide a general methodology of statistically analyzing the intriguing transition between rocky and volatile-rich exoplanets.

Experimentally determined retrograde kinetics of pyrope in mantle peridotites

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Symplectite bearing mantle peridotite xenoliths are commonly found in exhumation zones including the Alps, Bohemian Massif, Canaries archipelago and elsewhere [4].
They show kelyphite corona, a texture associated with the reaction:

$Mg_3Al_2Si_3O_{12} + Mg_2SiO_4 = MgAl_2O_3 + 4\ MgSiO_3$ [3].

This reaction records the re-equilibration of high pressure garnet peridotite to low pressure spinel peridotite at 1.5 – 2 GPa [2].

This reaction is diffusion controlled with growth rate of the spinel-enstatite interface proportional to the square root of time [1]. We are performing a time series of experiments at 1200 – 1600 ü C to constrain the kinetics of the retrograde reaction. Hence this study focuses on the syn-kinematic growth of the spinel interface and not the secondary static overgrowth of deformed structures that has also been observed [2].

Application of our experimentally calibrated reaction kinetics to well preserved natural corona will allow the timing of exhumation of regions with kelyphitic textures to be estimated.

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Plume-lid tectonics, a new paradigm for the Archean Earth

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We conduct 3D petrological-magmatic-thermomechanical numerical modelling experiments of the crust and upper mantle under Archean conditions using a plume-lid tectonics model setup. For varying crustal compositions and a mantle potential temperature increase of ΔTp=250 (compared to present day conditions), a hot lower thermal boundary layer introduces spontaneously developing mantle plumes and after repeated melt removal, depleted mantle lithosphere is formed self-consistently. New crust is produced in the form of both volcanic and plutonic magmatism.

Models show large amounts of subcrustal decompression melting and production of new crust which in turn influences the dynamics. On short-term (10-20 Myr) rising diapirs and sinking basaltic crust lead to crustal overturn and to the formation of the typical Archean dome-and-keel pattern. On long-term a long (~80 Myr) passive phase ‘growth phase’ with strong growth of crust and lithosphere is observed. Both crust and lithosphere thickness are regulated by thermochemical instabilities assisted by lower crustal eclogitisation and a subcrustal small-scale convection area. Delamination of lower crust and lithosphere is initiated by linear or cylindrical eclogite drips and occurs as one ‘catastrophic’ event within a 20Myr ‘removal phase’.

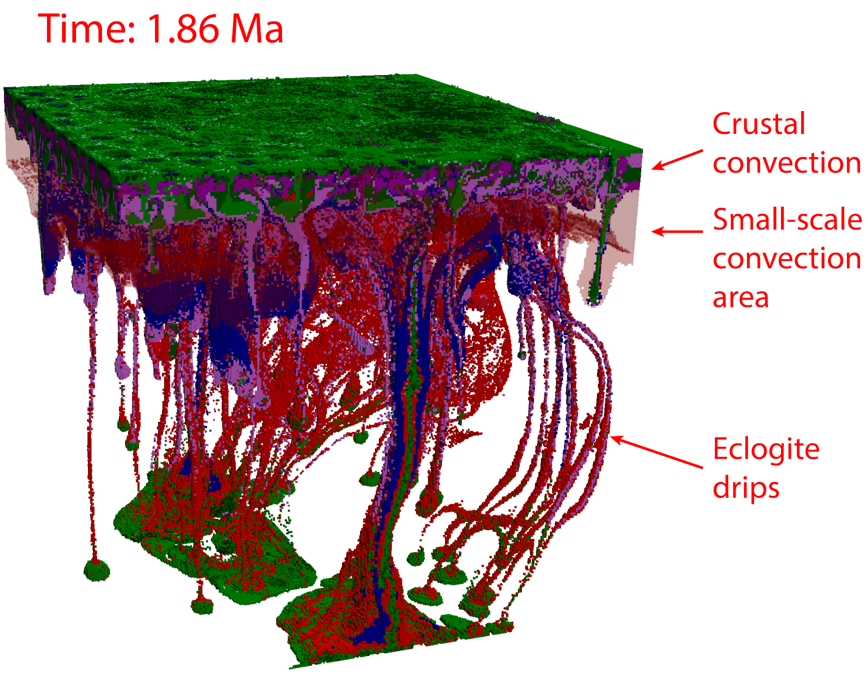

Figure 1. The most important features of plume-lid tectonics are crustal overturn, formation of a subcrustal small-scale convection area and eclogitic dripping.

The Archean orthogneiss complex of eastern Hall Peninsula, Baffin Island, Nunavut, Canada: implications for paleoplate reconstructions

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Eastern Hall Peninsula, Baffin Island is dominated by an Archean orthogneiss complex, which was caught in a two-stage, three-way collision between the Superior, Rae, and North Atlantic cratons at ca. 1860 Ma and ca. 1820-1790 Ma within the greater Trans-Hudson Orogen (Figure 1; St-Onge et al., 2002). The original configuration of these cratons is not well understood because eastern Hall Peninsula, which lies at the triple junction between these plates, lacks detailed geoscience mapping and geochemical data. Consequently, the cratonic affinity of eastern Hall Peninsula remains enigmatic, which has hindered paleoplate reconstructions for this region.

Understanding the evolution of this segment of the Trans Hudson Orogen is important since it has been compared in several aspects to the upper plate Asian continent prior to its early Eocene collision with the lower plate Indian subcontinent (e.g. St-Onge et al., 2006). Consistency between these two large continent-continent orogens in the sequence of plate convergence, subduction, crustal accretion and continental margin arc magmatism along with structural and metamorphic characteristics substantiates the notion of tectonic uniformitarianism for at least the past 2000 Ma of Earth history. This pattern of continental growth is also an integral part of the global amalgamation process that eventually leads to the formation of supercontinents (Hoffman 1992) and may be similar to continental growth during Archean tectonic amalgamation.

New U-Pb and preliminary Hf data from eastern Hall Peninsula shows potential correlation to Archean crust within the Aasiaat domain of West Greenland (Figure 1). Archean crust of West Greenland has a complex and composite nature indicating that it is comprised of a still unknown number of distinct tectonostratigraphic terranes or microplates varying in size from tens of kilometres to hundreds of kilometres (Friend and Nutman 2005). These distinct terranes have independent histories and were then amalgamated at ca. 2700 Ma (Hollis et al. 2006). Orthogneiss units within a small study area on eastern Hall Peninsula yielded U-Pb magmatic crystallization ages ranging from 2976 ±4 to 2720 ±4 Ma and metamorphic ages from ca. 2720 to 2671 Ma. This data closely matches magmatic ages from the Disko Bugt region within the Aasiaat domain and indicates a shared history of Archean amalgamation at ca. 2700 Ma. Archean crust in Northern Labrador also records a history of amalgamation at ca. 2700 Ma following distinct magmatic and tectonic histories for each crustal block (James et al. 2002), however, the extant geochemical data does not demonstrate a positive correlation to eastern Hall Peninsula. Further work with U-Pb, Hf and Sm-Nd isotopes on orthogneiss units across eastern Hall Peninsula will refine a definite crustal correlation and may provide insight into the processes operating during Archean tectonic amalgamation.

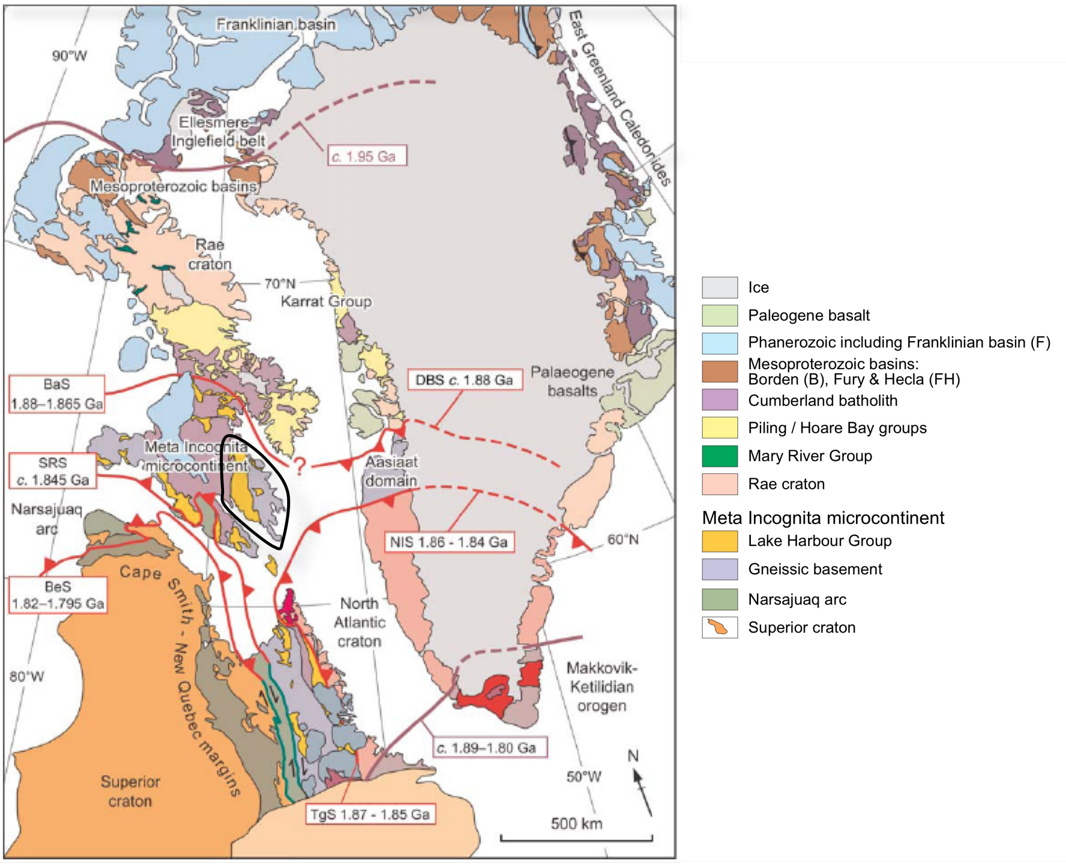

Figure 1. Composite geological map highlighting the main cratonic, supracrustal and tectonic entities in the Northern Labrador – Baffin Island – Greenland segment of the Trans Hudson Orogen. Bounding crustal structures that can be correlated from eastern Canada to West Greenland are shown in red. Hall Peninsula, Baffin Island is outlined with a black line. Ellesmere Island and Baffin Island, are shown in a pre-drift position (pre-late Cretaceous) with respect to mainland Canada. Modified from St-Onge et al. (2009)

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What was before plate tectonics? Destruction of Earth's Hadean crust by Paleoproterozoic magmatism

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Although there is debate about the time at which modern plate tectonics began and the period of time over which it developed, there is little disagreement that different tectonic processes governed the early Earth. The scarce remnants of the Earth's earliest history make it very challenging to describe the processes that operated during this time. It follows that all evidence from this period that survived subsequent tectonism and recycling deserves to be identified and studied closely.

We present a geologic, petrologic, geochemical and isotopic description of previously poorly documented Paleoarchean gneisses in the central Wyoming province, USA. These gneisses are well-exposed on low inselbergs that extend for 75 km east-west within a Tertiary sediment-filled graben. We identify two groups of gneisses: a bimodal TTG and amphibolite assemblage of layered gneisses that are between 3385 and 3450 Ma, and a suite of massive, trondhjemite and granite gneisses that are 3300 to 3330 Ma. Samples from both groups include zircon indicative of older inherited components. In one layered gneiss sample, low U zircon cores give a well-defined age of 3.82 Ga. In addition, three other samples also yielded zircon analyses with $^{207}Pb/^{206}Pb$ ages of 3.47 to 3.83 Ga. These results suggest that Eoarchean age crust probably was present throughout the area in order that Eoarchean zircon could be incorporated into these Paleoarchean gneisses.

Sm-Nd whole rock isotope systematics coupled with O and Hf zircon isotopic compositions further identify the sources of these gneisses. With one exception, initial ü$_{Nd}$ of all samples are negative, indicating that older crust was involved in their genesis. Oxygen isotopic compositions of zircon areas also analyzed for U-Pb and Lu-Hf mainly fall within the range of mantle zircon ü ^{18}O values (5.3 ± 0.6‰ for zircon) but several analyses extend to ~6.5 ‰. The mildly elevated ü ^{18}O in Archean zircons is interpreted to record the incorporation of surface materials into magma with a mantle oxygen isotope signature, creating magmas with mildly elevated ü ^{18}O. Although it is not possible to identify the composition of this crust for certain, the mantle to slightly elevated ü ^{18}O values are compatible with a mafic crust: other workers have proposed that the slightly elevated ü ^{18}O common in Archean zircon reflects the interaction of mafic crust with a nascent hydrosphere. Initial Hf isotopic compositions of 3.82 Ga zircon are negative (between ü$_{Hf}$ -3.6 and -5.3), and require derivation from Hadean crustal sources.

Our data reveal the record of an ancient, 3.82 Ga differentiation event during which Hadean crust was partially melted, and zircon crystallized from those melts. Hadean crust must have persisted in the central Wyoming province until 3.45-3.37 Ga, when mafic crust partially melted to form the TTG layered gneisses, which also incorporated the 3.82 Ga zircons. Thus the central Wyoming province provides a significant addition to the sparse record of evidence of Hadean mafic crust being reworked to form the much more abundant quartzofeldspathic TTG gneisses in Archean terrains worldwide.

Moreover, the central Wyoming province preserves evidence of the episodic nature of crustal reworking and growth in the period of Earth's history prior to plate tectonics. U-Pb geochronology from this area and in the adjacent Bighorn Mountains suggests that zircon crystallization was confined to specific intervals, namely 3.8 Ga, 3.4-3.3 Ga, and 3.0-2.9 Ga. During the latter two episodes, the cycle began with magma contributed from both preexisting crust and mantle sources. This suggests that the mantle supplied both heat and mass to the base of the crust, inducing partial melting. Crustal deformation preceded an intracrustal recycling stage, in which the older gneisses partially melted to produce more silica- and potassium-rich granitic rocks. These magmatic processes reworked the Earth's early crust, effectively transforming the evolving continental crust from mafic to felsic in composition.

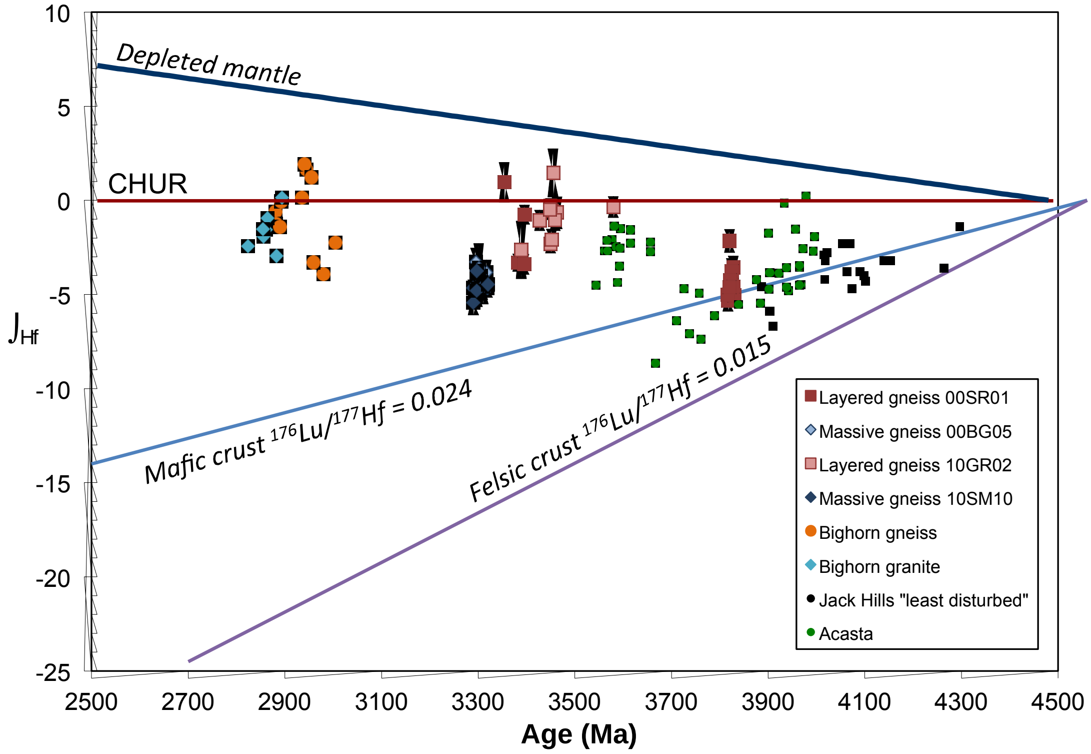

Figure 1. ü Hf of zircon from the central Wyoming province as a function of U-Pb age of the same zircon area. The ü Hf values of 3.82 Ga zircon areas are negative, indicating derviation from Hadean crust. The ü Hf values of ~3.4 Ga zircon areas scatter about chondritic values. Also shown are data from Bighorn Mountains gneisses and granites in the northeastern Wyoming province. Acasta data from Iizuka et al., 2009, *GCA* 107, 96-120; Jack Hills data from Kemp et al., 2010, *EPSL* 296, 45-56.

Plume-induced cratonization

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Archean Cratons (from the Greek “kraton”, strength) are the oldest stabilized parts of Earth’s continents that have remained thick, cool and stable for at least 2500 Myr, as recorded by re-current periods of deep intracratonic magmatism and thick strata of sedimentary rocks in extensive depositional basins. Based on the recent numerical modeling results of Sizova et al. (2015) and Tackley (2011) we propose a new (plume-induced) mechanism for cratonization (gluing) of Archean proto-continental terrains by large ultra-depleted harzburgitic/dunitic mantle plumes generated at the core-mantle boundary as the result of proto-oceanic lithosphere subduction (Fig. 1). The idea that cratonization, i.e. stabilisation of the lithosphere, requires involvement of mantle plumes, which are traditionally considered to be signs of destruction of the lithosphere (i.e., Burov and Gerya, 2014; Gerya et al., 2015), appears paradoxical. However, feasibility of this process seems to be systematically supported by 2D and 3D magmatic-thermo-mechanical numerical experiments. Based on these experiments (Sizova et al., 2015; Fischer and Gerya, 2016) we demonstrate that a distinct Venus-like plume-lid tectonics regime operated on Earth before plate tectonics, which was associated with widespread tectono-magmatic heat and mass exchange between the crust and the mantle. This regime was characterized by the presence of weak internally deformable highly heterogeneous lithosphere, massive juvenile crust production from mantle derived melts, mantle-flows-driven crustal deformation, magma-assisted crustal convection and widespread development of lithospheric delamination and eclogitic drips. Both proto-continental and proto- oceanic domains were formed in this regime by a combination of eclogitic drips and ultra-slow proto-oceanic spreading (Fig.1, Stage 1, 0 Myr). Proto-continental domains were characterized by the growth of hot internally convecting moderately-depleted chemically buoyant eclogite-rich proto-continental mantle layer. Later, this layer could be rapidly cooled by internal convection and consolidated to form eclogite-rich sub-continental lithospheric mantle (SCLM) domains. Proto-oceanic lithospheric mantle forming under thick mafic proto-oceanic crust was colder, more depleted and poorer in eclogite inclusions compared to its proto-continental counterpart, due to higher degree of decompression melting within proto-oceanic spreading centers localized atop hot mantle upwellings. Numerical models show feasibility of short-lived deep subduction of such ultra-depleted proto-oceanic lithosphere (Fig.1, Stage 1, 5 Myr) to core-mantle boundary (CMB). Later slab–CMB interaction was characterized by heating of the slab followed by separation of the eclogite and harzburgite layers, with harzburgite rising in vigorous plumes Fig.1, Stage 2). Rsing and accretion of these chemically buoyant ultra-depleted mantle plumes to the bottom of unrelated heterogeneous crustal terrains may offer a feasible way for plume-induced Archean cratonization associated with eclogite-poor SCLM formation (Fig.1, Stage 3).

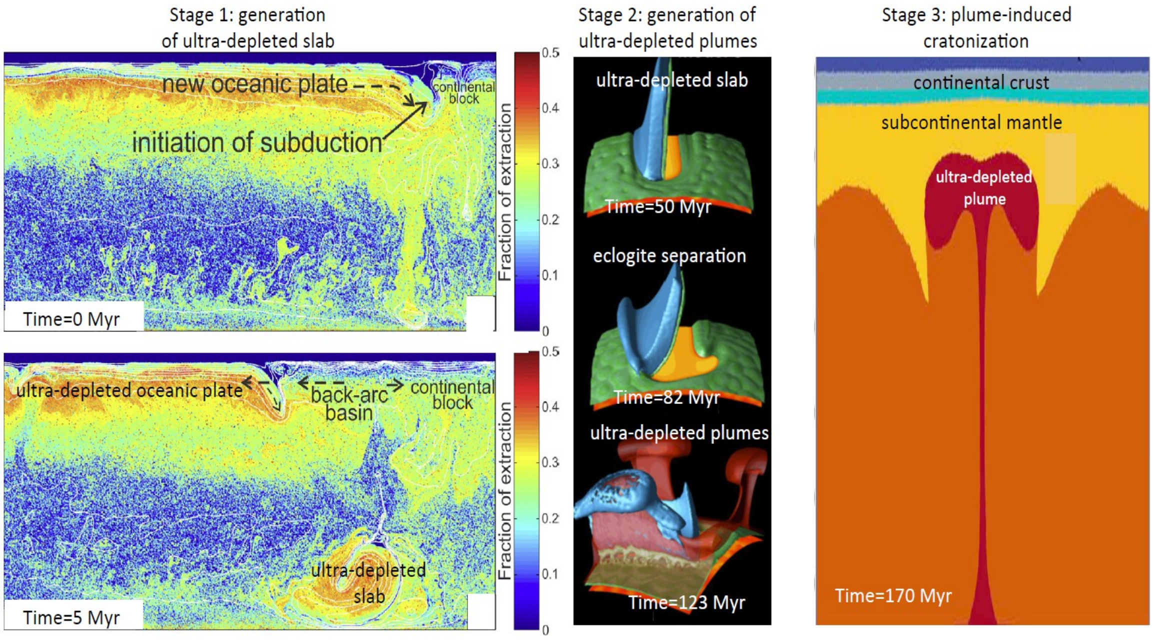

Figure 1. Fig. 6. Conceptual scheme of plume-induced cratonization (not to scale). Modified from: Stage 1 = (Sizova et al., 2015), Stage 2 = (Tackley, 2011), Stage 3 = Burov and Gerya (2014).

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The role of Dynamic flow in the Tethyan closure

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The Eastern Mediterranean, particularly the Ionian domain has had a major role in the Pangean break-up, Tethyan closure and the evolution of the present day Mediterranean Basin. Potentially floored by some of the oldest oceanic lithosphere on Earth, this region is important in understanding the development of ancient subduction systems and the dynamic processes that sustain them.

In this study we develop a density heterogeneity model for the Mediterranean to investigate flow and dynamic topography in the region and attempt to identify surface expressions of dynamic flow.

We analysed the depth-age relationship of the basin, based on the existing CROP M3 seismic line, observed bathymetry data from the GEBCO_08 database and free-air gravity obtained from the EGM2008 database. We computed a residual bathymetry model based on a modern depth-age curve corrected for anomalous seafloor by back-stripping the sediment cover. We computed gravity-topography admittance curves to determine whether the anomalous bathymetry was dynamically supported and augmented our analysis by modelling the mantle flow from regional high-resolution tomographic models.

The depth-age curve reveals the basin to be oceanic. Residual bathymetry, gravity and tomography support the hypothesis that the basin is dynamically supported from within the mantle. Negative dynamic support is observed towards the north and northwest of the region, zones where Ionian lithosphere is subducting under the Calabrian and Hellenic Arcs respectively. These regions are characterised by downwelling mantle flow, negative residual bathymetry and fast s-wave velocity.

We have applied a unique approach in providing detailed insights on residual topography and gravity admittance for this region of the Mediterranean, constraining the local dynamic topography of the Ionian Basin. Our work also indicates that small, inactive, marginal basins such as the Ionian, exhibit the same characteristics and trends as major basins of the Pacific, Atlantic and Indian Oceans.

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Onset and Intermittent Evolution of Plate Tectonics

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The onset of plate tectonics and its further temporal evolution is tightly coupled to the internal dynamics in the mantle and especially to the initial configuration at the onset of solid state convection in the Earth's mantle. One plausible initial scenario would result from fractional crystallization of an early magma ocean, leaving the mantle initially stratified in composition. The stratified mantle was probably subject to heating from below (from the core), from within (by radioactive elements) and, depending on the atmosphere condition , cooled from above. In a series of numerical experiments, spanning a wide parameter range and different geometries, we have explored such scenarios with respect to the evolution of plate tectonics. Typically the models included a strongly temperature dependent viscosity, mostly combined with a pressure and stress-dependence. A well established phenomenon in oceanography appears also here (Hansen and Yuen, 1995) : We observe double-diffusive instabilities to generate distinct layers of virtual uniform composition, separated by sharp diffusive interfaces. In case of a significant heating from below (i.e. the mantle is initially cool relative to the core) , the layer growth progresses from the bottom to the top, resulting in a late destabilization of the top boundary (i.e. lithosphere). Once, destabilization took place , strong downwelling currents (i.e. subduction) occur and global plate tectonics appears. In a scenario, where the initial mantle is much warmer and thus being cooled significantly from the top, we observe layer formation, which is however hindered by the strong dependence of viscosity on temperature. Movement at the surface appears rather early, however being restricted to regions of shallow depth..Under such circumstances one can speculate about a type of local plate tectonics in which, for a certain period, only the upper most part of the mantle would be involved,.

We have further investigated scenarios, characterized by an initially unstable chemical stratification. Such a configuration could arise from the freezing a magma ocean from the top to the bottom. In fact , after an initial phase, during which a Rayleigh-Taylor instability appears which leads to collapse of the unstable gradient, a similar evolution as for the stable cases is observed, i.e the subsequent growth of a stack of layers.
The formation of layers is generic in the “heating from below” cases, in a sense that they appear for all kind of rheologies, in 2D and 3D cartesian, as well as in fully spherical geometry. Besides the meaning for the onset of plate tectonics, many other aspects of mantle dynamics are influenced . At internal boundaries we frequently observe “doming phenomena” (Davaille 1999). Moreover layers typically can break down and merge intermittently leading to episodic variations in heat flow and in the mixing properties of the flow.

Beside the onset, the temporal evolutions off plate tectonics is a matter of controversial discussion. We find that for plausible combinations of parameters

(Rayleigh number, rheological law) a virtually stationary type of plate tectonics can exist , as well as episodic (intermittent plate behavior. (Loddoch et al., 2006)

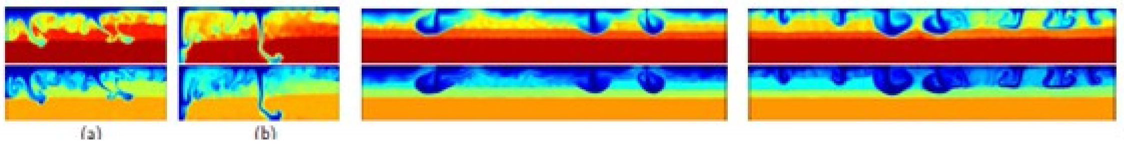

Figure 1. Snapshots of temperature (top) and compositional field. (bottom) displaying the evolution of plate tectonics from a layered state.

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Venus as an analogue for the Archaean Earth without plate tectonics − gravity and radar interpretations

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Field, geochronological, isotopic and geophysical studies do not support plate tectonic models for subduction and arc accretion in Archaean granite-greenstone terrains (Bédard et al. 2013; Bédard & Harris 2014; Harris & Bédard 2014a). For example, geophysical data show Neoarchean granite-greenstone sequences of the southern Superior Province in Canada formed during rifting of an older, composite Superior I craton (Bédard & Harris 2014; Harris & Bédard 2014a) and not as a series of accreted arcs and micro-continents as previously interpreted. Instead of the conventional model of E-W arcs, undoing displacements on conjugate shear zones interpreted from gravity data in the Abitibi Subprovince portrays a N-S to NNE-SSW elongate, mafic-dominated crustal block, interpreted as a > 300 km long oceanic plateau (Harris and Bédard 2015). For the Yilgarn Craton in Western Australia where greenstones are traditionally interpreted as accreted arc terranes, gravity data portrays rifts in which greenstone belts formed that cross older terrane boundaries. Rift margins localized subsequent regional transpressional to transcurrent shear zones. Regional shortening in these and other Archaean cratons is attributed to mantle flow acting upon the deep lithospheric keels of cratons (Bédard et al. 2013; Bédard & Harris 2014; Harris & Bédard 2014a). To confirm that regional shortening and large displacements can occur without plate tectonics and to test the applicability of a mantle flow tectonic model, gravity and radar data for Venus, a planet without plate tectonics, were enhanced and interpreted.

Venus, a planet of similar size to Earth, does not show any evidence for single-sided subduction zones and arcuate volcanic chains that typify plate tectonics. In previous studies, volcanic and deformation features, such as extensional normal faults/graben and contractional ‘wrinkle ridges’ on Venus mapped using Magellan radar imagery have been attributed to upwelling mantle plumes (along with commensurate downwelling plumes and/or mantle ‘drips’) in a stagnant lid or transitional convection regime. Magellan radar imagery alone was used in NASA-USGS mapping projects which focussed on geomorphic interpretations. Whilst radar is used in mapping textures equated to lithological units and surface structures, crustal to lithospheric faults (whose surface expression may also be hidden by younger lava flows) were thus not previously mapped.

Bouguer gravity for Venus (Konopliv et al. 1999), calculated from acceleration and topographic data acquired during NASA’s Magellan mission, separated into short and long wavelength components and enhanced using Geosoft’s Oasis montaj software, provide a new view of our ‘sister planet’ that has significant repercussions in evaluating models for Archaean tectonics on Earth:

- Bouguer gravity lows over highlands (‘plana’), which comprise ca. 10% of Venus’ surface and resemble continents on Earth, require that even where basalt lava flows occur at the surface, basement must contain less dense granitic or other silicic rocks. The presence of silicic rocks on Venus is consistent with petrological modelling by Shellnutt (2013) and near-infrared spectrometry data for highlands (Basilevsky et al. 2012). Correspondence of contacts between short wavelength (i.e. shallow source) gravity lows and highs in Lakshmi Planum with mapped geomorphic boundaries requires that lithological interpretations from radar of 'basalt-only' units be re-evaluated.

- Although transcurrent faults were considered insignificant or non-existent by many Venus researchers, gravity data show that regional transcurrent fault displacements are common. In Ishtar Terra, gravity data support a model for indentation of Lakshmi Planum and lateral escape derived from radar interpretation (Harris & Bédard 2014b). Similarly, transcurrent and associated normal shear zones interpreted from short wavelength gravity gradients and 'worms' dextrally offset the continent-like blocks Ovda and Thetis regiones in Aphrodite Terra. Radar of Ovda Regio also portrays regional fold interference patterns and refolded shears implying superposed deformation.
- Regional linear gravity highs, punctuated by circular lower anomalies that correspond to mapped mantle plumes and offset by transcurrent faults (e.g. south of Lakshmi Planum in western Ishtar Terra) represent lithospheric scale rifts. Other interpreted graben without gravity highs, as in southern Aphrodite Terra, appear as upper crustal structures.

Folding, regional transcurrent shearing, and large lateral translation and offset of continent-like plana on Venus are interpreted to result from mantle flow directed away from upwelling, mantle plume-related rifts interacting with the deep keels of plana, along with lithospheric drips, i.e. similar to the model of Bédard et al. (2013) for Archaean tectonics. Venus shows that plate tectonics is not required to produce deformation features in Archaean terrains on Earth.

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The Known Number of Tectonic Plates Through the Last 55 Years

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The number of tectonic plates on Earth described in the literature has expanded greatly since the start of the plate tectonic era, when only about a dozen plates were considered in global models of present day plate motions. The first global model of pate tectonics was proposed by Morgan (1968), encompassing 14 plates. With new techniques of more accurate earthquake epicenter locations, modern ways of measuring ocean bathymetry using swath mapping, and the use of space based geodetic techniques, there has been a huge growth in the number of plates thought to exist. The study by Bird (2003) proposed 52 plates, many of which were delineated on the basis of earthquake locations. Because of the pattern of areas of these plates, he suggested that there should be more small plates than he could identify. I have gathered together publications that have proposed a total of 107 new plates, giving 159 plates in all. The largest plate (Pacific Plate) is about 20% of Earth's area or 104 Mm^2, and the smallest of which (Plate number 5 from Hammond et al., 2011) is only 273 km^2 in area. Many of the smaller plates have been proposed using data from the Global Positioning System (GPS). The authors of the papers proposing these small plates all (without exceptioon) claim that they are acting as true tectonic plates, defined as areas for which there is no internal deformation (distances and angles are preserved) apart from elastic deformation close to plate edges caused by locked faults at the plate edges. Sorting the plates by size allows us to investigate how size varies as a function of order. There are several changes of slope in the plots of plate number organized by size against plate size which are discussed. The sizes of the largest seven plates is constrained by the area of Earth. A middle set of 73 plates down to an area of 97,563 km^2 (the Danakil plate # 80) follows a very regular pattern of plate size as a function of plate number. For smaller plates, there is a break in the slope of the plate size/plate number plot and the next 32 plates follow a pattern of plate size proposed by the model of Koehn et al. (2008) down to an area of 11,638 km^2 (West Mojave plate # 112). The model of Koehn et al. (2008) suggests that the method of production of these small plates is by fracturing. Smaller plates do not follow any regular pattern of area as a function of plate number, probably because we have not sampled enough of these very small plates to reveal any clear pattern.

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The Hadean: Empirical Evidence vs. Convenient Fiction

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The ubiquity of origin myths among human societies suggests that our species has an innate need to explain how Earth formed and evolved. The controls on myth fabrication include the limitations of the available historical record and the technological capability of the culture in question. Despite our high technology and western cultural bias to watery origins, when the scientific community encountered the limits of its historical record – there are no known rocks older than 4 Ga – it chose the paradigm of a desiccated, continent-free wasteland in which surface petrogenesis was largely due to bollide impact into a basaltic substrate and called it the "Hadean" (hellish time). But the story emerging from investigations of >4 Ga zircons is of their formation in near-H_2O saturated meta- and peraluminous magmas under low geotherms that appear to require weathering and sediment cycling in the presence of liquid water and plate boundary-like interactions. Given general agreement that life could not have emerged without liquid water at or near the Earth's surface, an implication is that our planet may have been habitable as much as 500 Ma earlier than previously thought. Indeed, recent C isotopic evidence obtained from inclusions in Hadean zircons is consistent with life having emerged by 4.1 Ga, or several hundred million years earlier than the hypothesized lunar cataclysm.

Perhaps the most remarkable feature of inferences drawn from >4 Ga zircons is that none were gleaned from theory. Rather, generations of models innocent of observational constraints fed the paradigm of a hellish, uninhabitable Earth. What compelled us to create an origin myth in the absence of direct evidence? While science is distinguished from mythology by its emphasis on verification, its practitioners may be as subject to the same existential need for explanations as any primitive society. In context with high expected Hadean heat production and impact flux, it proved irresistible to explain the lack of ancient continental crust by its non-existence rather than the equally or more plausible notion that it has been largely consumed by the same processes we see operating on the planet today. Does this episode simply represent a scientific anomaly? In fact, such troubling behavior has been a feature of geophysical modelers approach to Earth evolution since Kelvin's "certain truth" that the planet was less than 2% of its actual age, through Jeffreys denial of continental drift, Dirac's belief in a variable *G*, Lamont geophysicists ignoring the significance of seafloor stripes 2 years after publication of the Vine-Matthews hypothesis, Gold's insistence that petroleum is mantle derived, England's explanation for inverted metamorphism, to Gerya's certainty that Venusian tectonics defined early Earth. For reasons that remain obscure, calculations carried out in the absence of observational constraints can take on an edifice-like character in the geo- and planetary sciences that slows progress and distracts the community from fresh, and possibly better, ideas. Perhaps Dave Stevenson said it best when refering to speculations of Hadean dynamics: "Basic physical principles need to be understood but detailed scenarios or predictions based upon them are best regarded as 'convenient fictions' worthy of discussion but not enshrinement".

Bridgmanite Enriched Ancient Mantle Structures Control Plate Tectonics in the Lower Mantle

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The Bridgmanite Enriched Ancient Mantle Structures (BEAMS) hypothesis explores the end-member scenario in which the early Earth's lower mantle had an Mg/Si ratio close to that for the sun. We know that melting of the upper mantle extracted mid-ocean ridge basalt, MORB, and further melting of MORB led to the creation of continents. Continents are rich in Si compared to MORB, so are light and more viscous and thus resist erosion back into the mantle. The mantle left behind after producing MORB, the depleted MORB mantle or DMM is then depleted in Si relative to its initial composition. However, the lower mantle which was not effected by mid-ocean ridge melting could retain relative Si enrichment through time, and due to the higher relative viscosity of Si rich materials, would resist erosion into the convecting mantle. Harzburgite is the olivine rich rock that makes up most of the cold subducting oceanic lithosphere or slabs that enter the mantle in subduction zones and travel through the mantle eventually reaching the core-mantle boundary, CMB. Harzburgite contains around 20% ferropericlase, (Mg,Fe)O, which is two orders of magnitude less viscous than bridgmanite. Thus, as more slab material descends into the lower mantle, it eventually forms channels that allow subducted material to flow more freely. This material is then heated by the core and its positive buoyancy leads to the formation of upwelling channels away from subduction zones. Once this plan form is in place, it remains stable over geologic time.

The BEAMS model explains: 1) The observed change in the dominant tectonics from the surface to the CMB. 2) The discrepancy between geochemical data that indicate the mantle is not fully mixed with seismology and dynamics models which indicate vigorous, full mantle convection. 3) The decreased seismic signal from slab material in the mid mantle. The harzburgite is more sensitive to the iron spin transition and cold slabs have less of a velocity contrast with the higher velocity bridgmanite. 4) The long-term stability of Large Low Shear Velocity Provinces (LLSVP) over geologic time. It has been difficult to explain how this seismically slow, hence soft material could control lower mantle dynamics. We suggest he LLSVP are stable because the BEAMS ambient mantle is strong.

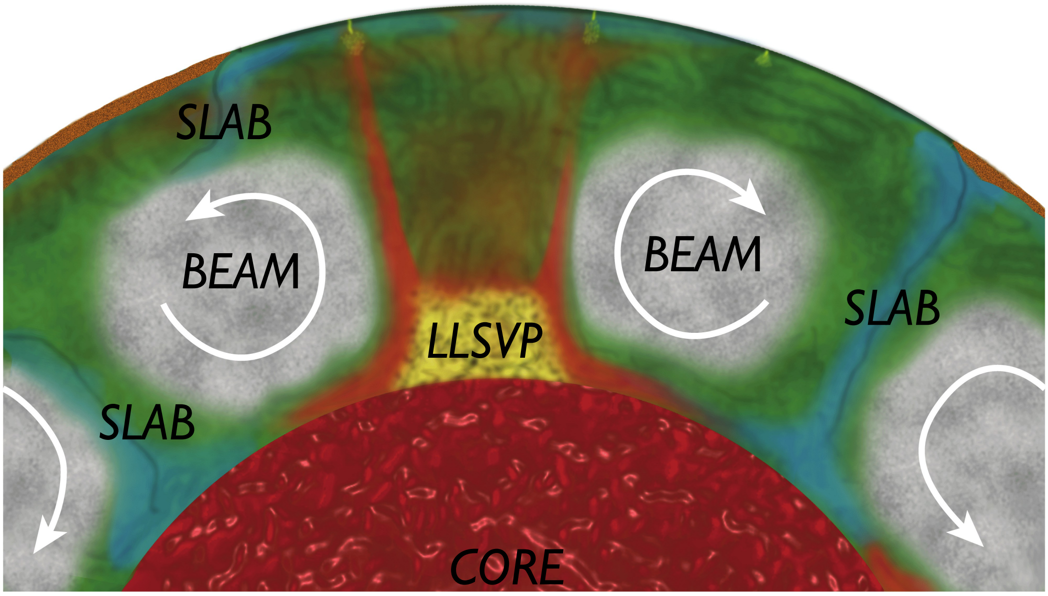

Figure 1. Illustration of BEAMS within the Earth's mantle. BEAMS (light color) are stable, high-viscosity structures that reside in Earth's lower mantle, while pyrolitic-harzburgitic rocks (green) and basalt (black) veneers circulate between the shallow and deep mantle through rheologically weak channels. Also shown are the large low shear velocity provinces near the core-mantle boundary.

Self-consistent generation of continental crust in global mantle convection models

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We present preliminary results of our mantle convection code in which the continental crust is generated self-consistently. The silica-rich continental crust appears to have been formed by fractional melting and crystallisation in episodes of relatively rapid growth from late Archaean to late Proterozoic eras (3-1 Ga) [1] which has also been linked to the onset of plate tectonics around 3 Ga [2]. It takes several stages of differentiation to generate continental crust. First, the basaltic magma is extracted from the pyrolitic mantle. Second, it goes through eclogitic transformation and then partially melts to form Na-rich Tonalite-Trondhjemite-Granodiorite (TTG) which rise to form proto-continents [3, 4]. TTGs dominate the grey gneiss complexes which make up most of the continental crust. Based on the melting conditions proposed by Moyen [5], we parameterize TTG formation and its subsequent melting to generate continental crust. Numerical modeling commonly shows that mantle convection and continents have strong feedbacks on each other, but the continents are always inserted a priori while basaltic (oceanic) crust is generated self-consistently in such models. We aim to implement self-consistent generation of continental crust in global models of mantle convection using StagYY [6]. Continental crust can also be destroyed by subduction or delamination. We will investigate continental growth and destruction history in the models spanning the age of the Earth.

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Is Evidence for Resurfacing on Venus Buried Deep within its Interior?

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The surface of Venus is approximately 500-750 Myr old [e.g., Strom et al., 1994; Herrick et al., 1997; McKinnon et al., 1997; Hauck et al. 1998]. There are two hypotheses to explain the relatively young age of the Venusian surface, progressive volcanic resurfacing or a global lithospheric overturn event [Strom et al., 1994; Herrick et al., 1997; Phillips et al., 1991; Turcotte, 1993]. Mantle-overturn events are controlled by a lithospheric instability whereas volcanic resurfacing events imply a plume-dominated, core-mantle boundary instability. This has significant implications for the mechanism of heat loss from the Venusian interior. The evidence consistent with catastrophic or gradual resurfacing may be buried deep within the planet.

Consider the impact of a global lithospheric instability on the deep mantle of Venus in which the entire lithosphere is subducted over a short time period. If we assume a 100-km thick lithosphere became unstable 500 Myr ago for illustration, such a resurfacing event would have placed approximately $5x10^{10}$ km^3 (4π x 6050 km^2 x100 km) of cold, dense material deep into the Venusian mantle approximately 500 Myr ago. This is 5% of the volume of the planet.

A conductive cooling calculation shows that cold, dense material from a resurfacing event would retain a significant thermal anomaly today unless it sheared and thinned significantly as the resurfacing event unfolded. Using the analytic solution for a cooling slab after 500 Myr at depths greater 120 km beneath the top of the slab, more than half the original temperature anomaly remains. [Turcotte and Schubert, 2002]. A100-km thick lithosphere is quickly displaced to the deep mantle (the essence of the catastrophic resurfacing hypothesis) it would spread out evenly over the entire core-mantle boundary making a 400-km thick layer. If confined to a fraction of the core-mantle boundary, it would be correspondingly thicker.

Such a cold dense pile of material should be evident in the global geoid and topography of Venus. Were the entire surface of Venus to subduct in one location, the cold, dense pile would create a hemispherical (i.e., spherical harmonic degree one) structure unless it spread out evenly over the entire core-mantle boundary. While the geoid has no degree one term by construction, such a hemispherical thermal (hence density) anomaly would be observable in the difference between the center of mass and the center of figure of the planet [Wahr, 1996]. Yet, Venus is remarkable amongst the terrestrial planets for having the smallest offset of the center of mass and center of figure [Wieczorek, 2007; Melosh, 2011]. Thus it is highly unlikely that a single overturn event could have been responsible for the global resurfacing of Venus.
I model the thermal convection problem assuming an incompressible fluid, solving the equations for the conservation of mass, momentum, and energy using CitcomS [Zhong et al., 2000], implementing a temperature-dependent rheology

and lithospheric yield stress to produce stagnant-lid convection with self-generating, punctuated lithospheric instabilities in spherical shell geometry. We follow the method of [van Heck and Tackley, 2008] for implementing an Arrhenius-type viscosity law and lithospheric yield stress. I also include radiogenic heat sources whose concentraction decreases with time and a cooling core boundary condition.

The geoid of Venus differs significantly from Earth and Mars in that the spectral power is not dominated by the longest wavelengths [c.f., Wieczorek, 2007]. Unlike Earth there is a strong correlation between geoid and topography on Venus up to degrees 40 with a notably weaker correlation for degree 2 [e.g., Pauer et al., 2006]. This is reproduced in the numerical experiments. The small offset between the center of mass and center of figure of Venus is inconsistent with the significant dense 'pile' of cold material deep in the Venusian mantle that is expected from a 'catastrophic' resurfacing event.

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Kimberlites through time: new facets on the start of plate tectonics

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The underpinning paradigm in the Earth Sciences is Plate Tectonics, wherein oceanic crust is generated at mid-ocean ridges and subsequently consumed at subduction zones. At subduction zones, at least in their modern context, supply hydrated oceanic crust and overlying sediments deep into the mantle. Subduction and plate tectonics have significant controls over the development and location of a number of types of ore deposits. Kimberlites, the primary source of diamonds, are relatively rare igneous features on Earth. We have analyzed the distribution of kimberlites throughout Earth history and here show that the vast majority of kimberlites are relatively young features (~95% are < 0.75 Ga); rare examples are found as far back as the Archean (> 2.5 Ga). Although there are differing explanations for this age asymmetry (lack of preservation, lack of exposure, lesser mantle plumes or lack of old thick lithosphere in the Archean and Proterozoic), we suggest here that the best explanation is that kimberlite eruptions are a fundamental consequence of modern-style Plate Tectonics i.e., deep subduction of hydrated oceanic crust and sediments deep into the mantle. If this is indeed the case, the age distribution of kimberlites implies that the full development of deep-subduction on a global scale occurred after ~ 1Ga. This recycling of hydrated crust into the mantle since the onset of modern-style Plate Tectonics at ~ 1 Ga has resulted in an increase in the CO_2 and H_2O content of the mantle, permitting the rapid and explosive ascent of diamond-bearing kimberlite magmas. The age distribution of kimberlites, combined with other large-scale tectonic indicators that are prevalent only in the last ~1 Ga (blueschists, glaucophane-bearing eclogites; coesite- or diamond-bearing ultrahigh-pressure (UHP) metamorphic rocks; lawsonite-bearing metamorphic rocks; and jadeitites), therefore provides compelling additional evidence that Plate Tectonics, as observed on Earth today, has only operated for < 25% of Earth history.

Subduction initiation through 2D and 3D numerical models

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Subduction initiation is a hot topic and remains enigmatic (Stern, 2004; Gerya, 2011). Quantitative study is required to shed light on this process (Nikolaeva et al., 2010; Lu et al., 2015; Marques and Kaus, 2016). Here, we use 2D and 3D numerical models to study the subduction initiation of an oceanic plate underneath a continental plate without prescribed kinematic boundary conditions.

In 2D models, spontaneous subduction is produced with a very generic model setup. Sufficiently weak plate boundary at the convergent margin is the most important factor. High model resolutions that facilitate faster strain localization further promote subduction initiation. However, subduction initiation is sensitive to the geometry of the convergent margin.

3D models are influenced by both physical and numerical parameters. The numerical parameter is mainly referred to the pre-specified error tolerance which controls the convergence of the iterative computing on momentum and continuity equations. With relatively large error tolerances (i.e., the commonly used values of 10^{-3} in 3D models with kinematic boundary conditions), extremely fast (less than 1 million year) and thus unrealistic subduction initiation is produced. Therefore, small error tolerances are used to ensure accurate computing. Results of the 3D and 2D models with identical setups are compared and discussed.

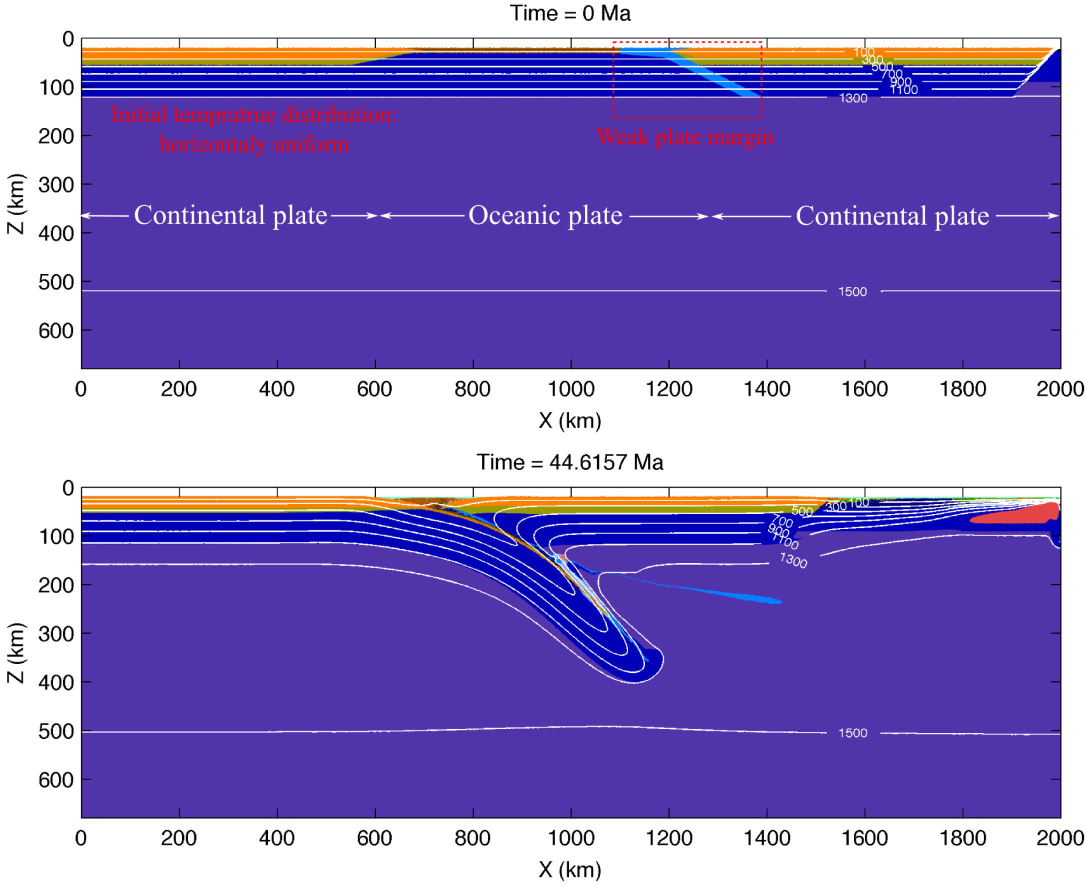

Figure 1. 2D example of subduction initiation without prescribed boundary velocities.

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Melting-induced crustal production helps plate tectonics on Earth-like planets

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Within our Solar System, Earth is the only planet to be in a mobile-lid regime. It is generally accepted that the other terrestrial planets are currently in a stagnant-lid regime, with the possible exception of Venus that may be in an episodic-lid regime (Armann and Tackley, 2012).

Using plastic yielding to self-consistently generate plate tectonics on an Earth-like planet with strongly temperature-dependent viscosity is now well-established, but such models typically focus on purely thermal convection, whereas compositional variations in the lithosphere can alter the stress state and greatly influence the likelihood of plate tectonics. For example, Rolf and Tackley (2011) showed that the addition of a continent can reduce the critical yield stress for mobile-lid behaviour by a factor of around 2. Moreover, it has been shown that the final tectonic state of the system can depend on the initial condition (Tackley, 2000); Weller and Lenardic (2012) found that the parameter range in which two solutions are obtained increases with viscosity contrast.

We present a set of 2D spherical annulus simulations using StagYY (Tackley, 2008), which uses a finite-volume scheme for advection of temperature, a multi-grid solver to obtain a velocity-pressure solution at each timestep, tracers to track composition, and a treatment of partial melting and crustal formation. We address the question of whether melting-induced crustal production changes the critical yield stress needed to obtain mobile-lid behaviour.

Our results show that melting-induced crustal production strongly influences plate tectonics on Earth-like planets by strongly enhancing the mobility of the lid, replacing a stagnant lid with an episodic lid, or greatly extending the time in which a smoothly evolving mobile lid is present in a planet. An interesting observation is that, as our models evolve through time, there is often a transition from a mobile to a stagnant lid, but not the opposite. A long period of stagnant lid followed by mobile lid is never obtained (Fig. 1). This is in contradiction with the conventional proposed idea for the early Earth. Finally, we show that our results are consistent with analytically predicted critical yield stress obtained with boundary layer theory, whether melting-induced crustal production is considered or not.

In the last part of our work we will show the effects of intrusive *versus* extrusive magmatism. We find that high degrees of intrusion greatly increase the mobility of the surface. However, the tectonic regime observed is not always a mobile or an episodic-lid regime. It is a regime where unstable parts of the lithosphere are removed by eclogitic drippings and delamination. This regime has not yet been reported in global models. However, it has been observed in regional models (Fischer and Gerya, 2016) and has been named plume-lid tectonics.

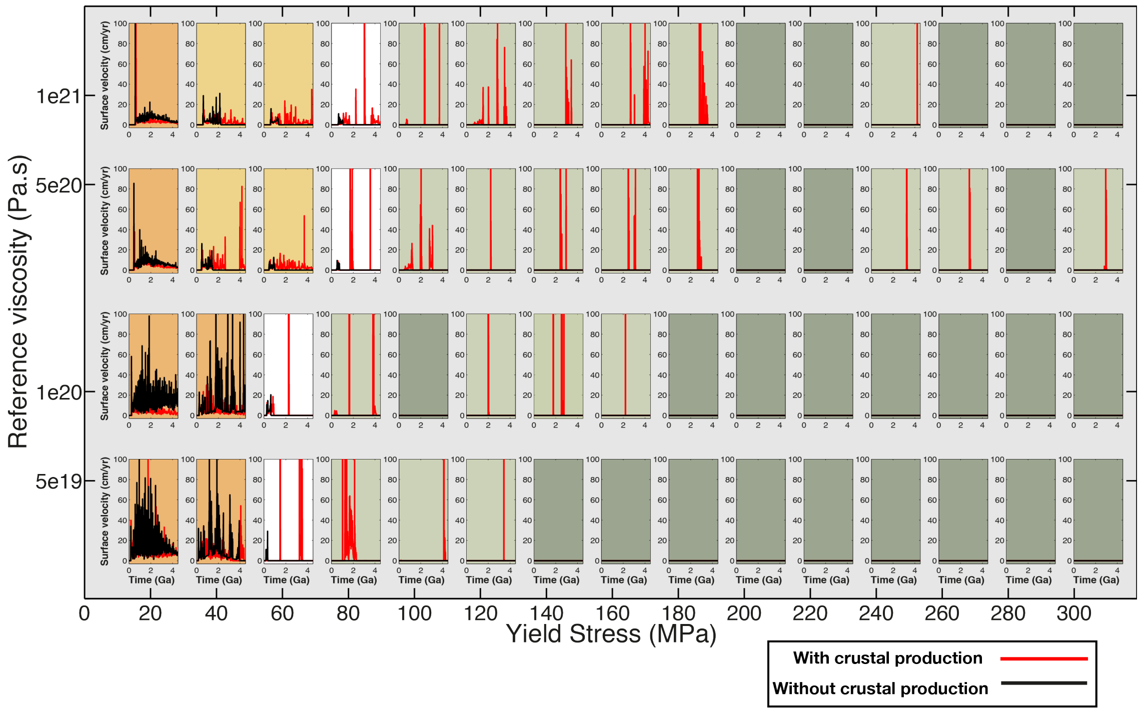

Fig. 1. Surface velocity as a function of time for simulations with different yield stress and reference viscosity. For more information see Lourenço *et al.*, 2016.

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Plate tectonics was initiated by the bombardment of carbonaceous chondrites during 4.37-4.2Ga in Hadean, this event is named ABEL bombardment (Maruyama and Ebisuzaki, submitted). ABEL model explains the formation of the Earth with 2 steps; (1) completely dry Earth formed by enstatite chondrite-like materials at 4.57Ga, and (2) atmospheric and oceanic components (i.e. C, H, O, and N (=Bio-elements)) were delivered by CI chondrites from outer asteroid belts due to gravitational scattering of gas giants (Jupiter, Saturn, and “Black Sheep”) during 4.37-4.20Ga. Latter accretion process is regarded as the Advent of Bio-ELements, therefore this model is called ABEL model and the bombardment event is called ABEL bombardment (Maruyama and Ebisuzaki, submitted).

The estimate of total amounts of bombarded CI chondrites is based on the amount of platinum group elements (PGEs). If the primitive upper mantle (PUM) contains Ir abundance of 3.5 ± 0.4 ng/g, the accreted mass is calculated to be 0.1-0.4% of total Earth mass, corresponding to the 2.1-8.4km increase of Earth’s radius (Becker et al., 2006; Morgan et al., 2001). On the other hand, Walker (2009) estimated the 0.34% increase of the total mass of the Earth, indicating 7.1km increase of crustal thickness. If the period of ABEL bombardment continued over 170 million years, the averaged annual “sedimentation rate” is ca.16mm/1,000year. This is significantly higher tha the modern sedimentation rate on the deep ocean-floor at 1mm/1000years.

Before ABEL bombardment, Earth’s surface was dominantly covered by primordial continents composed of anorthosite which was similar to ancient crust exposed on the lunar surface and KREEP basalt (oceanic crust). The most important result of the ABEL bombardment was to produce primordial atmosphere and oceans on the previously dry Earth. If the total mass of CI chondrite is assumed to contain 20 wt % H2O, the average depth of the ocean is calculated ca. 2,800m. On the other hand, baesd on the geological estimate of ocean thickness, i.e., presence of sedimentary rocks such as sandstone, conglomerate, and mudstone with TTG composition at 3.8Ga in Isua, Greenland (Early Archean terrane), and Li isotopic ratio recorded in Hadean zircons preserves sediment recycling in the Hadean, thus, continental landmass must have been above sea-level by the end of bombardment period ca. 4.20Ga. The geological record of the ocean thickness in the Late Hadean seems to be consistent with estimates by PGEs discussed above.

When the global hydrological circulation began, specifically after the formation of liquid CO2 ocean followed by H2O ocean, sediments from landmasses produced by bombardments would have been transported into the ocean by Hadean rivers. Those sediments capped on oceanic lithospheres would be finally brought to the trenches, to be accretionary complex, or more presumably transported into deep mantle together with tectonically fragmented hanging wall of primordial continental crust. It is speculated that the trigger of plate tectonics was the appearance of ocean with over 2.5km thickness sometime during ABEL bombardment. Prior to the initiation of plate tectonics, pseudo-plate tectonics should have prevailed on the Hadean Earth immediate after the consolidation of magma ocean, which was thought to be similar to on-going Venus’s tectonic movement. With the delivery of volatiles through the ABEL bombardment, ultra-high temperature metamorphism caused the extensive recrystallization under hydrous condition. The mafic lower crust with KREEP composition as thick as 50km or more with anorthositic upper crust would have transformed to eclogite (density over surrounding mantle ca.3.5g/cm3) at less than 50km depth through the infiltration of volatiles due to shock metamorphism. This turned to yield a strong slab-pull force, helped by the ridge push force that generated a curtain-like mantle upwelling.

Onset of solid-state mantle convection and mixing during magma ocean solidification

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Energy sources involved in the early stages of planetary formation can cause partial or even complete melting of the mantle of terrestrial bodies leading to the formation of magma oceans. Upon planetary cooling, solidification is expected to take place from the bottom upwards because of the steeper slope of the liquid adiabat with respect to the liquidus (Elkins-Tanton, 2012; Solomatov, 2015). Fractional solidification, in particular, can lead to the formation of a compositional layering that can play a fundamental role for the subsequent long-term dynamics and evolution of the interior (Tosi et al., 2013; Plesa et al., 2014). In order to assess to what extent primordial compositional heterogeneities generated upon magma ocean solidification can be preserved, we investigate the cooling and solidification of a whole-mantle magma ocean along with the conditions that allow solid-state convection to start mixing the mantle before solidification has completed. To this end, we run 2-D numerical simulations in cylindrical geometry using the finite-volume code GAIA (Hüttig et al., 2013). We treat the liquid magma ocean in a parametrized fashion while we self-consistently solve the conservation equations of thermochemical convection in the growing solid mantle accounting for pressure-, temperature- and melt-dependent rheology. We consider two end-member cases: fractional crystallization, where melt is instantaneously extracted into the overlying liquid leaving beneath a differentiated mantle, and batch crystallization where melt remains in contact with the silicate matrix throughout solidification causing no differentiation. By testing the effects of different cooling rates and Rayleigh numbers, we show that for a lifetime of the liquid magma ocean between 1 and 10 Myr (Lebrun et al., 2013), the onset of solid state convection prior to complete mantle crystallization is possible and that part or even all of the compositional heterogeneities generated upon fractionation can be erased by efficient mantle stirring (Figure 1). We discuss the consequences of our findings in relation to the early and long-term evolution of compositional heterogeneities generated via fractional crystallization of magma oceans in terrestrial bodies with emphasis on Mars' thermochemical history.

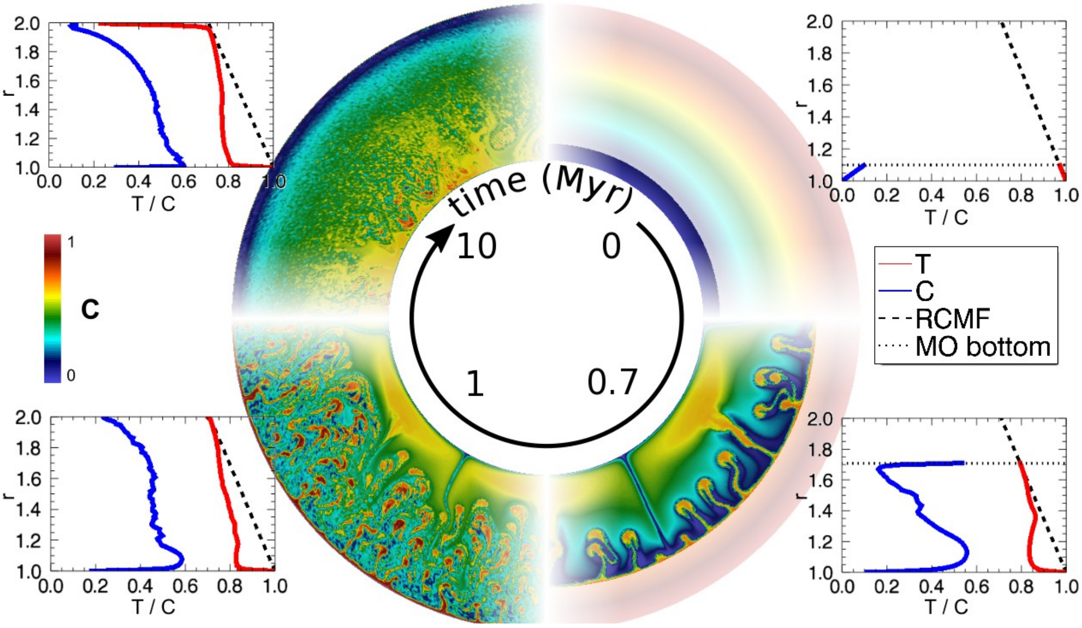

Figure 1. Snapshots of compositional heterogeneities in the solid mantle at different times during magma ocean solidification and after 10 Myr along with the corresponding profiles of temperature (red lines) and composition (blue lines).

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Rcrust: a tool for calculating path-dependent open system processes

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The hot Archean crust was prone to extensive melting which would have greatly influenced the goedynamics of the Archean Earth. Thus studies of Archean tectonics require an understanding of melting processes. A recent study by Yakymchuck & Brown (2014) has shown the impact that melt loss can have on the tectonic system. However, current thermodynamic modelling techniques have limited abilities to handle the bulk compositional changes invoked by melt loss. New software has been developed (Mayne et al., in press) that via a path-dependent iteration approach enables pressure, temperature and bulk composition to act as simultaneous variables. This assists a more in depth study of the consequences of compositional change in an open system. Path-dependence allows phase additions or extractions that will alter the effective bulk composition of the system. Singular paths within Pressure-Temperature-Bulk composition (*P*-*T*-*X*) space give details of changing phase proportions and compositions along a rock's *P*-*T* evolution. The compilation of multiple paths creates path-dependent *P*-*T* mode diagrams.

Figure 1 shows the open-system evolution of a pelite starting composition as it undergoes isobaric heating. The diagram was created by compiling an array of isobaric heating paths all starting with the same bulk composition containing 2 wt.% X_{H2O}. The paths begin at 640 °C over a range of pressures from 2 to 12 kbar. During isobaric heating each path encounters multiple melt loss events that sequentially change the bulk composition of the reactive subsystem (the portion of the chemical system kept in thermodynamic equilibrium). Melt loss events are defined to occur when an interconnected melt network forms and the matrix compacts. This is considered to happen when >80% of grain boundaries become melt bearing at the rheological transition defined by the Melt Connectivity Transition (MCT) of 7 vol.% melt, the upper limit of the accumulation of melt before extraction (Rosenberg & Handy, 2005). Melt retention on grain boundaries is estimated to be 1 vol.% (Yakymchuck & Brown, 2014). This diagram illustrates both the magnitude of compositional change in an open system (large X_{H2O} changes incurred by melt loss especially at low pressures) and the compostional dependence of melt loss events (melting only occuring where sufficient *P*-*T*-*X* criteria are met).

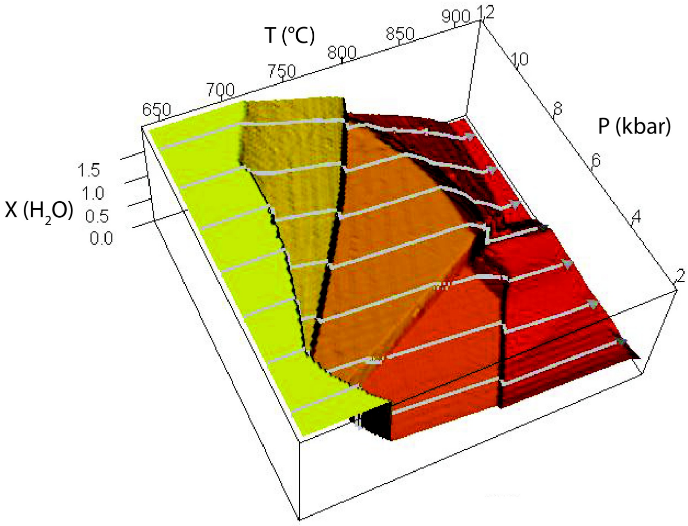

Figure 1. Path-dependent P-T mode diagram for a compilation of isobaric heating paths from 640 to 940 °C ranging 2 to 12 kbar. Melt loss occurs whenever a 7 vol.% threshold is exceeded and leaves behind 1 vol.% melt approximating melt retention on grain boundaries. Grey arrows show the direction of constituent vectors (the isobaric heating paths). *X* scales the amount of H_2O in the bulk composition of the reactive subsystem. Colour shading is applied on the *X* variable with yellow close to 2 wt.% H_2O and red close to 0 wt.%.

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Lithospheric controls on plume magmas through time and implications for crustal growth

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Komatiite lavas of the Yilgarn Craton form within two regions during two distinct periods. The oldest known deposits (3.0-2.9 Ga) occur in the south of the Southern Cross Domain. The youngest (~2.7 Ga) are found in the Norseman-Wiluna belt of the Kalgoorlie Terrane. A small komatiite event occurs at 2.8 Ga in the Kurnalpi/Burtville and Murchison areas, but this is not addressed here due to lack of available istopic data. This study aimed to investigate whether variations in lithospheric architecture could explain the location and timing of komatiite magmatism. An integrated program of U-Pb and Lu-Hf analyses were performed on granitoids and felsic volcanics from the south-central Yilgarn Craton, Western Australia. These data have been plotted as time-resolved Lu-Hf maps (Figure 1) which record the changing architecture of the craton in space and time (Mole et al., 2014).

The 3050-2820 Ma and 2720-2600 Ma Lu-Hf time-slices (Figure 1) both demonstrate key architectural fratures fundamental in the localisation of major komatiite provinces. In both cases, the komatiites (and their host Ni-Cu-PGE systems) occur within juvenile crust (εHf>0) adjacent to an older, reworked crustal block (εHf<0). The margin between these different isotopic terranes is interpreted as a paleo-terrane boundary or ‘craton margin’ i.e. the edge of a relatively mature continent. These older, thicker pieces of crust divert mantle plumes that impinge onto them into the adjacent young, shallow crust, where large-volume decompression melting and komatiite volcanism occurs.

These observations not only explain the timing and location of major komatiite eruptions but also why some regions do not have significant komatiite sequences at all. They also indicate that the evolution of the lithosphere and its subsequent architecture form a major control on komatiite volcanism.

Additionally, peaks in crustal growth and juvenile addition at 3.0, 2.8 and 2.7 Ga broadly correlate with periods of komatiite activity. As komatiites are the signature melt of a mantle plume (ambiant mantle is too cool to produce such high-temperature magmas), this suggests a relationship between plume magmatism and crustal growth in the Archean Yilgarn Craton. Furthermore, this hints a significant role for plume-related magmas and heat (advective) in the reworking of old crust and generation of the first continents.

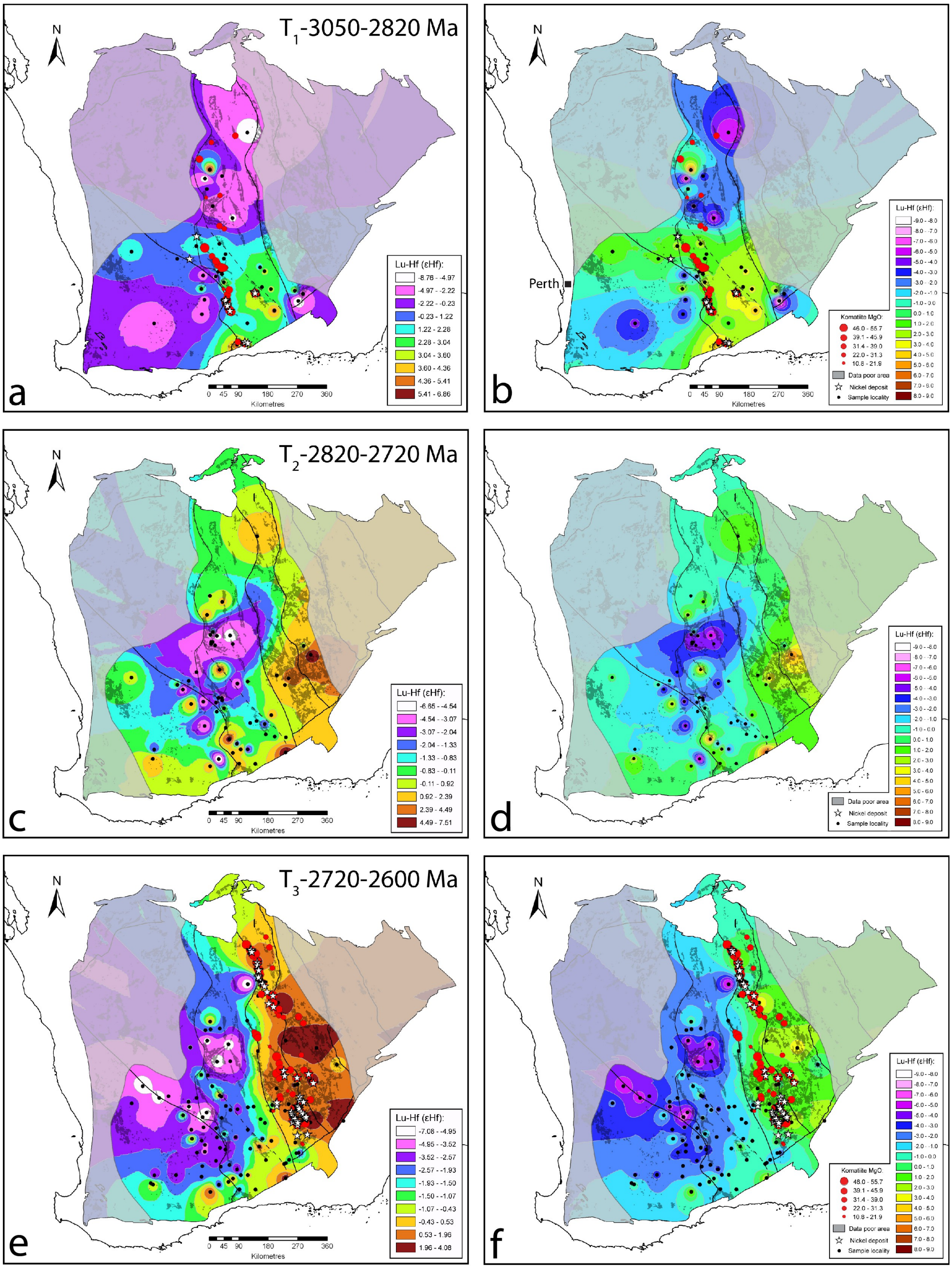

Figure 1. Lithospheric architecture at (a-b) 3050-2820; (c-d) 2820-2720; and (e-f) 2720-2600 Ma (plotted as εHf). (a,c,e) use geometric grouping; (b,d,f) uses custom fixed-size groups allowing maps to be comparable.

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A new view of Plate Tectonics in the Afro-Arabian Rift

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Archaean tectonic systems: a candid geochemist's view

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On a global scale, the geochemistry of common igneous rocks reflects the dominant processes operating on Earth. Therefore, any change in global tectonic patterns should reflect on global geochemical patterns. This work examines the global distribution of Archaean and modern igneous rock's compositions, without relying on preconceptions about the link between rock compositions and tectonic sites (as in "geotectonic" diagrams). Rather, geochemical patterns are interpreted in terms of source and melting conditions; Archaean and modern patterns are compared.

Mafic rocks on the modern Earth show a clear separation between "arc" and "non-arc" rocks, depicting for instance two clearly separated, parallel arrays in a Th/Yb vs. Nb/Yb diagram. This points to the first order difference between "wet" (arc) and "dry" (mid-ocean ridges and hotspots) melting of the mantle. Dry melts are further separated in depleted (MORB, high Zr/Nb) and enriched (OIB, low Zr/Nb) sources. This three-fold pattern is a clear image of the ridge/subduction/plume system that dominates modern tectonics. In contrast, Archaean mafic and ultramafic rocks are clustered in an "intermediate" position, between "arc" and non "arc" and between "enriched" and "depleted" components. The distribution is unimodal; Archaean rocks depict a single, oblique array in Th/Yb vs. Nb/Yb, and cluster between the three main modern types in e.g. Zr/Nb vs. Nb/Th. This suggests that the Archaean mantle had lesser amounts of clearly depleted or enriched portions; that true subductions were rare; and that the distinction between oceanic plateaux and ridges may have been less significant.

Modern granitic rocks are essentially metaluminous (subduction-related), plotting together with mafic "arc" rocks; or peraluminous (collision, plotting near the average continental crust). This close proximity between granites and their potential sources (basalts that differentiate, or crust that melts) emphasizes the role played by the nature of the source in controlling the composition of granitoids. In this light, Archaean granites appear to be connected to different sources. Peraluminous rocks are rare, but granites connected to true basaltic compositions are equally uncommon. Both types tend to appear late in the evolution of any given continental segment. In contrast, the Archaean record is dominated by rocks of the TTG suite, that are connected to an alkali-rich mafic source, comparable to an altered basalt. Details of the geochemistry of the TTG suite are consistent with melting of such protolith at a great range of depths, from ca. 5 to > 20 kbar. This points to the absence of large sedimentary accumulations, again to the paucity of true arc situations, and to the importance played by reworking of an earlier basaltic shell, in a range of settings (some of which consistent with burial of that protocrust in the mantle). In addition, granites witness, for each individual region, a progressive transition towards more modern-looking associations with arc-like and peraluminous granites.

Collectively, the geochemical evidence suggests an Archaean Earth with somewhat different tectonic systems. In particular, the familiar distinction between collision, arcs, ridges and hotspots seems to blur in the Archaean. Rather, the large-scale geochemical pattern reveals a long-lived basaltic crust, altered near the surface and periodically resurfaced. This protocrust is reworked, through a range of processes occurring at various depths that correspond to a progressive stabilization of burial systems and the establishment of true subductions. A punctuated onset of global plate tectonics is unlikely to have occurred, but rather short-term episodes of proto-subduction in the late Archaean evolved over time into longer-term, more successful style of plate tectonics as mantle temperature decayed.

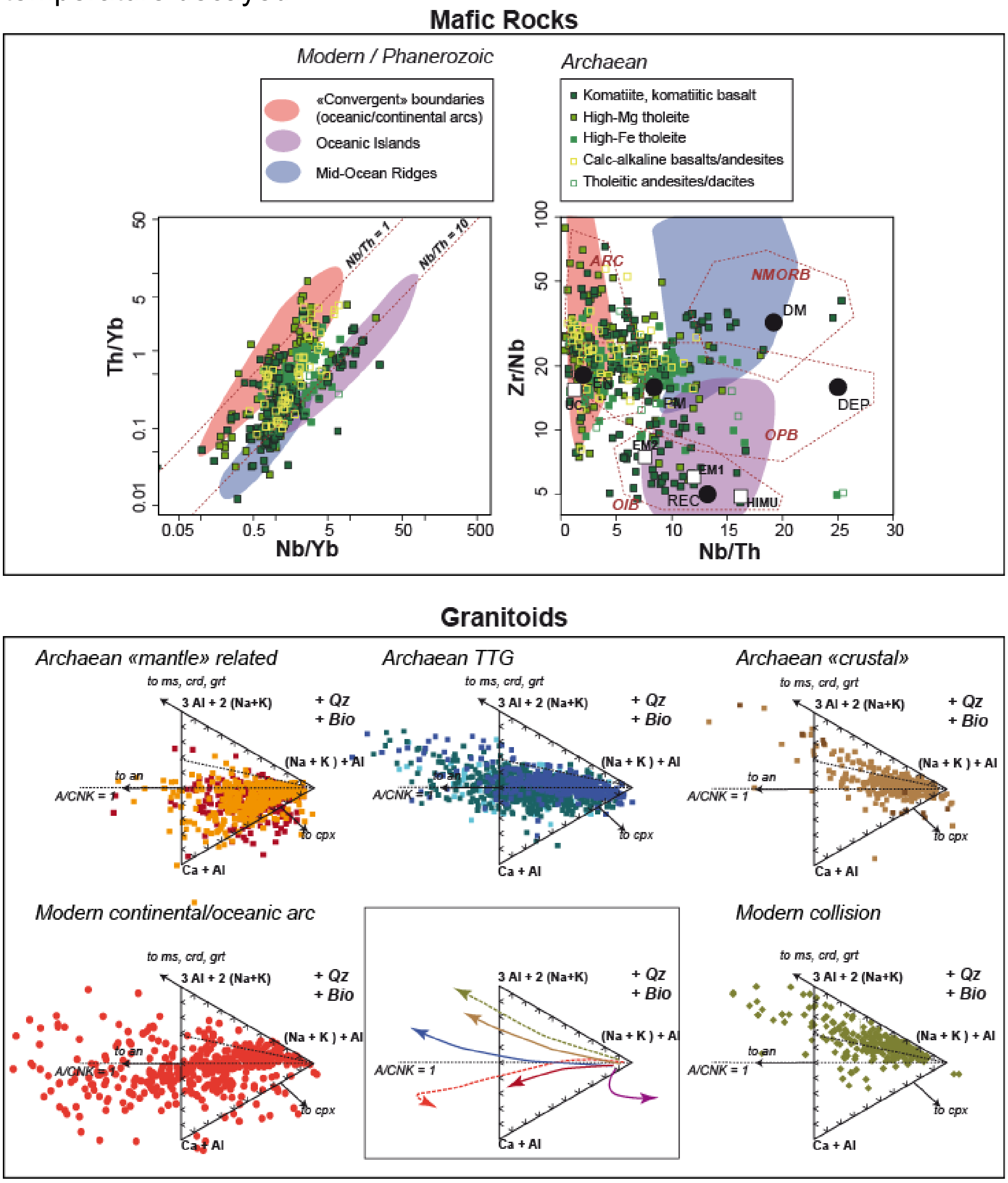

Figure 1. Summary of the main geochemical features of mafic and granitic rocks, modern and Archaean.

On the stability of plate-like behavior and global-scale mantle water cycle in numerical modeling

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The water cycle across the Earth's mantle is crucial for understanding the co-evolution system of deep Earth's interior and surface climate [Tajika and Matsui, 1992; Sandu et al., 2011]. The key issue for such an Earth-system modeling would be a stable plate tecotnics over the geologic time-scale with stable surface water ocean. Using thermo-chemical mantle convection simulations with three water migration processes (regassing, degassing and dehydration) [Nakagawa and Speigeman, submitted], three typical convective regimes (mobile, episodic and stagnant lid) with vayring the friction coefficient of brittle lithosphere are found but the parameter range for boundaries of the mobile lid/episodic lid regime would be shifted for higher friction coefficient compared to the dry mantle model [Nakagawa and Tackley, 2015]. This would be caused by the effects of viscosity reduction caused by the hydrous lithsophere [Nakagawa et al., 2015; Crameri and Tackley, 2015]. On the mantle water circulation in the mobile lid-like regime, two-types of water cycle are found: 1. Regassing-dominated water cycle and 2. Balanced water flux dynamics [Nakagawa and Spiegelman, to be submitted]. These two dynamics are occurred with the rheological control of hydrous lithosphere (amount of visosity reduction caused by hydrous lithosphere). The “Regssing-dominated water cycle” indicates that the mantle water content is gradually increased up to more than 3 Ocean Masses and an order of magnitude faster plate veloicity than the averaged plate velocity at the present time is expected, which suggests that the surface water ocean may not be stable mass over the geologic time-scale. On the other hand, the “Balanced water flux dynamics” may keep 1.5 to 2 Ocean Masses of mantle water content over the geologic time-scale and consisntent surface plate velocity with the observational one. The “Balanced water flux dynamics” can be consistent with current estimte of mantle water content, which is around 1 to 2 OMs [Hirschmann, 2006] and water flux contribution [Hirschmann and Kohlstedt, 2012]. Therefore, the “Balanced water flux dynamics” would be the best-fit scenario for reconcling the evolution of plate-like behavior with the stable surface water ocean.

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Today's Earth plate tectonics : the result of a 4.0 Ga long selection process

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The evolution and the growth of the continental crust is inextricably linked to the evolution of Earth's geodynamic processes. The detrital zircon record within the continental crust, as well as the isotopic composition of this crust, indicates that the amount of juvenile felsic material decreased with time and that in geologically recent times, the generation of new crust is balanced by recycling of the crust back into the mantle within subduction zones (Scholl & von Huenen Hawkesworth *et al*., 2010; Dhuime *et al*., 2012).

Clearly it cannot always have been so; yet the nature of the crust and the processes of crustal reworking in the Precambrian Earth are not well constrained. Here we use both detrital zircon ages and metamorphic pressure-temperature-time (P-T-t) information from metasedimentary units deposited in proposed convergent settings from Archaean, Proterozoic and Phanerozoic terrains (Cawood et al., 2012) to characterize the evolution of minimum estimates of burial rate (km.Ma^{-1}) as a function of the age of the rocks. This burial rate correlates positively with a progressive decrease in the production of juvenile felsic crust in the Archaean and Proterozoic. Burial rates are also more diverse in the Archaean than in modern times. Metamorphic, geochronological, chemical and isotopic information contained in metasedimentary and felsic rocks of current and past lateral shortening sites indicate the evolution of the mechanisms that shape the face of the Earth for the past 4.0 Ga are the direct expression of the competition between new crustal formation and assimilation of the buried supracrustal material. Therefore, rather than to debate the existence/non-existence of lateral tectonics, it seems more appropriate to address the issue of the evolution of tectonic regimes (i.e. the classic "Archaean" type vs. "modern" type consensus), from the point of view of lithospheric processes efficiency. In the Archaean Eon, fast processes indicate low residency time, hence less material in convergent settings and poor assimilation. In the Proterozoic and Phanerozoic Eons, slower burial rates show higher residency time, therefore better assimilation of the supracrustal material in recycling and reworking sites.

Hence, we conclude the modern geodynamic regime is the result of a 4.0 Ga long history that saw convergent plate tectonics progressively became the dominant mechanisms and the emergence of strongly marked modern collisional orogenic signature at the end of the Precambrian. Our work provides material to better constrain numerical models and new hypotheses for a unified theory for the formation and the evolution of the lithosphere.

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Impact-driven subduction in the Hadean

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Impacting was arguably one of the dominant process in shaping planetary surfaces during early solar system evolution, and while its effects on volcanism and crustal evolution of other planetary bodies has been documented, its effects on early Earth dynamics remain poorly constrained. Here we introduce tectonic simulations of an evolving Earth, beginning immediately post-magma ocean, and track their evolution through the Hadean. We include not only waning heat production, and a parameterised core model, but also an evolving impact flux based on solar system accretion models. We find large impacts during the Hadean both weaken the lithosphere, and create a large thermal anomaly in the mantle, capable of driving transient tectonic activity. Our preferred models demonstrate waning tectonic activity with diminishing impact flux from 4.5-4.3Ga, a lull in tectonic activity from ~4.3-4.1Ga, and a resurgence of tectonic activity at ~ 4.1Ga due to the effect of a thick, dense, subductable lithosphere, and increased impact flux at this time. Our calculated magnetic field strength drops to 15-50% of the current field strength from 4.3-4.1Ga, and rises to around current levels with the resurgence in tectonic activity at 4.1Ga – in line with recent paleointensity measurements on Hadean zircons. We also predict a rise in melt flux at 4.1Ga, in line with Hadean zircon age populations. Impact-driven tectonism reconciles evidence from some zircon populations of tectonic activity, with short-lived isotope constraints, which suggest the Hadean to Eoarchaean was largely stagnant.

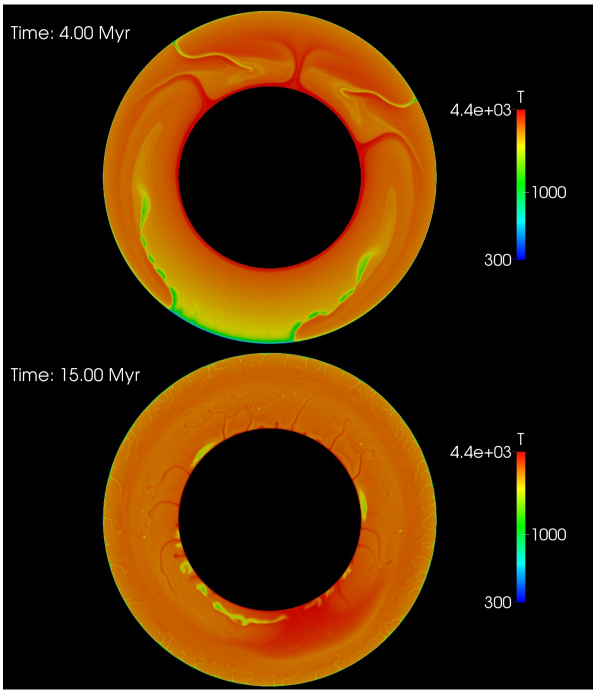

Figure 1. Top panel: Response of the early Earth to an extreme (1700km radius) impact event. The large impact drives wholesale recycling of the pro-

to-lithosphere. Bottom panel: Upwelling induced by large impact event, at 15Myr evolution since the model's inception.

Effects of the differentiation on geodynamic of early Earth

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Archean geodynamic processes are not well understood, and there is an open debate about the mode of convection of the mantle. On the other hand, there are not doubts that the mantle potential temperature was higher than present, and that as consequence significant amounts of melt were produced both in the mantle and in the overlying crust. The differentiation of these melt has likely resulted in the production of a continental like crust and it could had affected the geodynamics of the early Earth (e.g. the depletion of the mantle source could be resulted into a significant compositional changing and thus a density change and viscosity of the depleted mantle). An early attempt to study the relationship between differentiation and mantle dynamics was made by Johnson et al. (2014), who used numerical modelling in conjunction with representative phase diagram to investigate the crust production and its recycle. The results show that there is a positive feedback between the crust production and its recycle. The crust growth induces mineral assemblage changes that create dense material. The dripping of this material into the mantle causes asthenosphere return flow and its partial melting and as a result production of new crust. Whereas the simulations provide useful insight, they were simplified in many aspects: 1) the rheology employed was viscous, and elasticity, pressure dependency of both plasticity and viscous creep law were not considered; 2) the 100 % extracted melt was transformed into volcanic rocks; 3) the effects of the free surface boundary condition were not studied; 4) the effects of the mantle depletion. In order to understand how these simplification affects the development of the experiments, we provide additional simulation to study the effects of these parameters.

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Generation of TTG rocks in the Archean: insight from numerical simulations

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We study the creation of primordial continental crust (TTG rocks) for the first time employing fully self-consistent numerical models of thermochemical convection on a global scale. Starting from a pyrolytic bulk composition and an initially hot core, we first generate oceanic crust and depleted mantle. In our model, the basaltic material is both erupted and intruded at the base of the crust following a predefined partitioning. Second, we track the pressure-temperature conditions of the newly formed hydrated basalt and check if it matches the conditions necessary for the formation of primordial continental crust. We show that the “heat-pipe” model (assuming 100% eruption and no intrusion) proposed to be the main heat loss mechanism during the Archean epoch (Moore & Webb 2013) is not able to produce continental crust since it forms a cold and thick lithosphere. We systematically test various mechanical properties of the brittle domain (friction coefficients). Using our parameter study, we are also able to show that an intrusion fraction close to 70% (in agreement with [Crisp 1984]) combined with a friction coefficient of 0.2 products the expected amount of the three main petrological TTG compositions previously reported (Moyen 2011). This study represents a major step towards the production of self-consistent convection models able to generate the continental crust of the Earth.

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Extension in Orogenesis: Perspectives from the Tibet-Himalaya Orogen

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The end of a plate tectonic cycle is envisioned with the closure of an ocean basin resulting in the terminal collision of continents. The Tibet-Himalaya orogen is the manifestation of such cycle exhibiting the interaction of deep and shallow structure in the tectonic evolution of the orogen. According to some orogenic life cycle models orogenesis from collision follows a sequence of growth, increase in heat flow, remobilization of fluids, and accumulation of mass culminating in a peak “growth” stage followed by a “decay” phase of crustal thinning associated with extension and/or mantle delamination. This is often viewed as the collapse stage of an orogen and is associated with a phase of extension.

Recent geochronology and field mapping of the Lopukangri Rift in south-central Tibet suggests that the extensional phase for the Tibetan Plateau started in the Mid-Miocene. This is in accordance with research from other Tibetan and Himalayan rifts. The rifting indicates stresses are reconfiguring to allow for a phase of orogenic collapse. Extension can be associated with gneiss dome development, and the Lopukangri Rift has a gneiss dome along its footwall flank. Along the southern boundary of the Tibetan Plateau, parallel to the suture zone between India and Asia, gneiss domes are arranged along strike of the orogen; however, two gneiss domes to the far east <10 km wide and Lopukangri vary in strike. This variation may signify mid-low crustal structure variance. Gravity data across the orogen display clear structure (folds) of the Moho and a slight offset in the vicinity of the domes. Seismic properties of the lower lithosphere/upper mantle regions of the orogen also suggest deeper portions of the orogen manifest topographic/structural variances on the surface matching the wide distribution of deformation. Variance in the strike of the domes and the rifting “zones” may be surface features hinting at the Moho and deeper mechanisms active within the orogen.

The Mid-Miocene time for the Tibet-Himalaya orogen is ubiquitously cited as the emergence of an extension phase visible today in satellite imagery, where 100-kilometer scale conjugate strike-slip systems and north-south rifts dominate the landscape of the Tibetan Plateau (Figure 1). In the Mid-Miocene there were many overlapping events associated with rifting: slowing plate convergence rate, basalt emplacement, rapid cooling/exhumation of gneiss domes in southern Tibet, and rapid sedimentation in the Bengal Fan, and even climate changes.

The interaction between deep structure with shallow/surface manifestations can help us re-organize our views on the operation of tectonic stresses and their timing in active orogenic systems.

The old textbook picture of single delineated boundaries cannot be applied to the continents as we can see from the distributed deformation associated with plate boundaries in collision zones, as in the exemplar case of the Tibet-Himalaya orogen. It is a wide complex zone measuring~4000 km E-W by ~1500 km N-S wide, even wider if we consider the Alpine-Himalayan belt; this zone of distributed stresses constantly accommodates vertical and horizontal stresses.

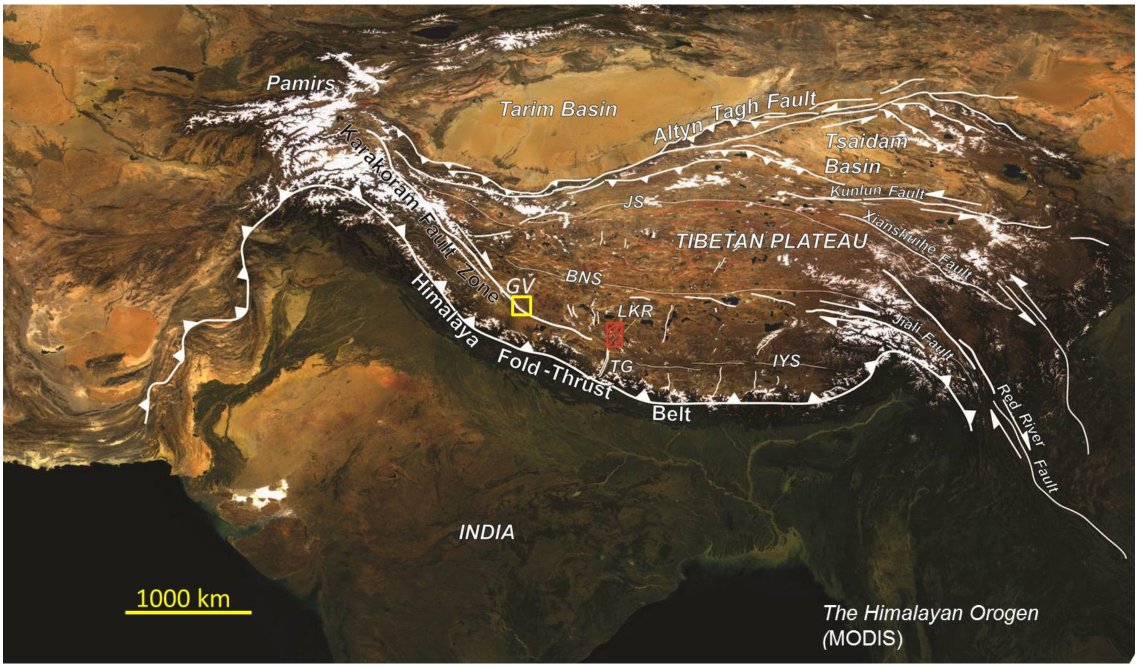

Figure 1. Regional structures of the Himalaya-Tibet orogen on a MODIS scene. Major sutures are indicated by abbreviations: IYS – Indus-Yalu suture (India-Asia suture); BNS – Baggong-Nujian suture; JS- Jinsha suture. GV – Gar Valley – a transtensional site; and LKR – Lopukangri Rift, where we can compare styles of extension associated with active convergence.

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Subduction initiation along arcs: keeping it simple

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Plate subduction along arcs requires four conditions. Two are uncontroversial:

(1) The overlying material must be relatively dense.

(2) The underlying material must be substantially less dense.

In addition,

(3) The underlying material must include a curved 3-D surface of fractured and inherently weak rocks with bowl-like ("craterform") geometry. This condition is furnished by incompletely healed scars of ancient impacts comparable to those that mark the Moon. Figures 1 & 2.

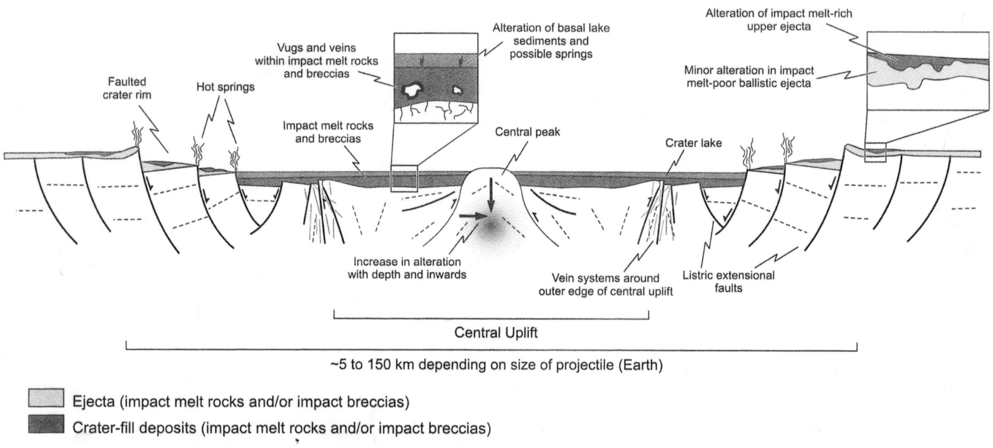

Figure 1. Schematic cross section of a large impact on the Earth's surface, from Osinski & Pierazzo, eds. (2013).

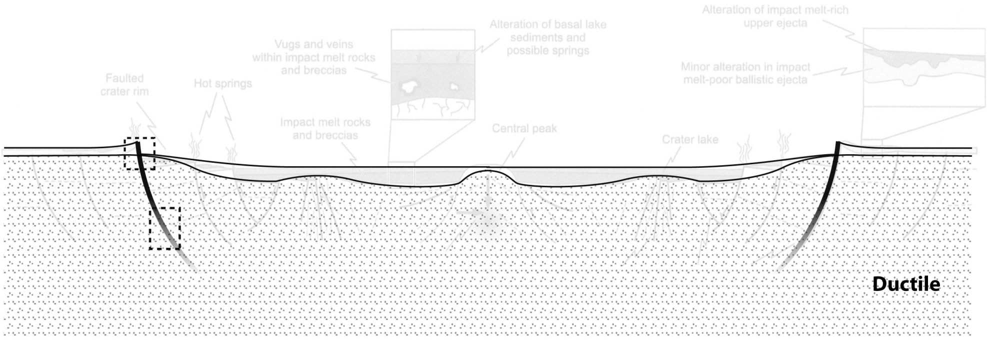

Figure 2. Simplified version of Figure 1. A dotted square has been added to indicate the high angle at which the transient crater intersected the Earth's surface following impact, and a rectangle added to draw attention to the less steep angle of the impact-fractured zone at depth.

(4) The angle at which these surfaces of low-strength impact-fractured rocks intersect the Earth's near-surface must be sufficiently shallow to allow plate descent. This condition is not met until impact-scars have undergone sufficient net erosion (Saul, 2014). Figure 3.

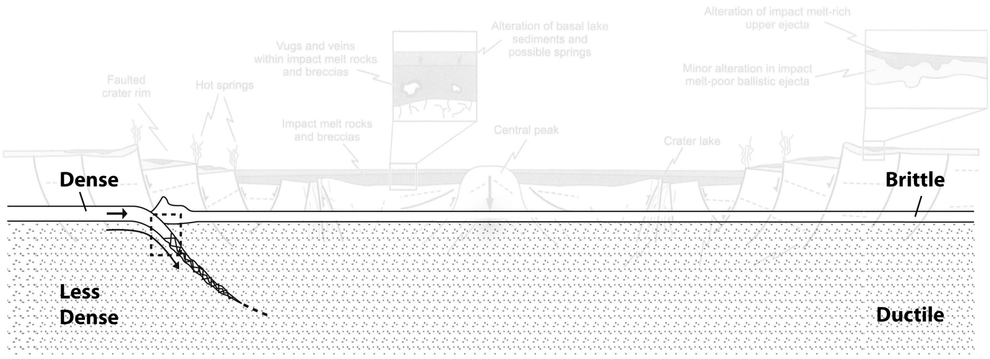

Figure 3: Schematic cross-section of a large impact after net erosion has exposed it to a level at which impact-weakened rock intersects the Earth's surface at a sufficiently low angle to permit subduction.

Arguments that the survival of >3800 Ma impact arcs is incompatible with the workings of plate tectonics must be turned around: the initiation of deep subduction along arcs depends on the existence of these deep fracture-features (Saul, 2014).

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Influence of grain size evolution on the self-consistent generation of LLSVPs from primordial material and subducted MORB: First estimates on possible pile characteristics

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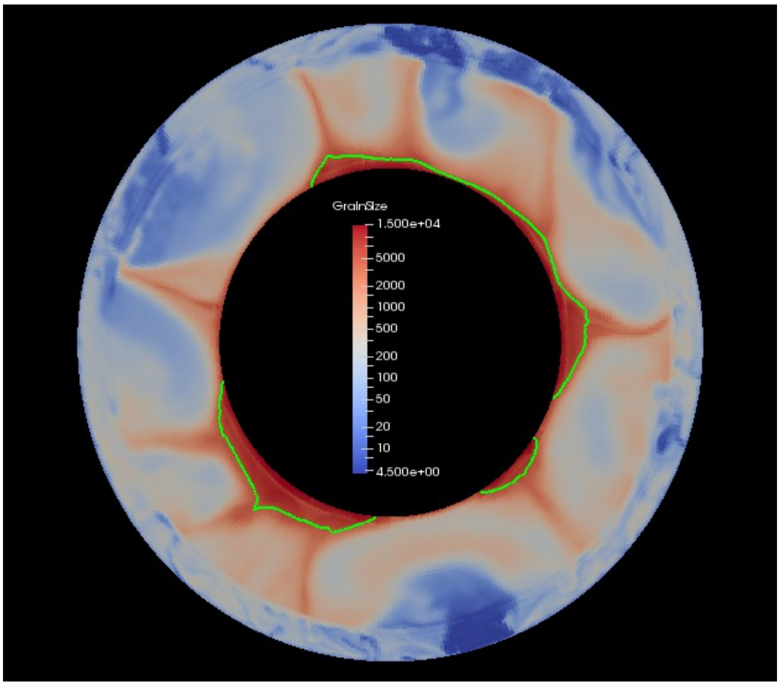
In recent numerical studies using the convection code StagYY, we have been able to reproduce the viscosity profile of the Earth together with a physical model of non-equilibrium grain size evolution. Melting and crustal production (in a simplified system considering a mixture of harzburgite and pyroxene-garnet) is also considered. It helps buffering the internal temperature of the Earth and affects the tectonic regime as it generates compositional heterogeneities such as subducted MORB. The present study focusses on the impact of grain size evolution on the development of large chemical heterogeneities appearing at the core-mantle boundary.

We present a new set of numerical simulations in which we consider both a primordial layer and a time-dependent basalt production at the surface considering to dynamically form the present-day chemical heterogeneities. We test the influence of density and viscosity of both subducted MORB and the primordial layer on the morphology of the LLSVPs and report different pile regimes based on both, the morphology of the LLSVPs and the evolution of the core temperature. Additionally, we calculate the piles' effective viscosity and relate it to their composition (subducted MORB, primordial material, mixture of both).



rain size distribution after a runtime of approximately 4 Ga and the outline (green line) of piles formed from primordial material at the core-mantle boundary

Vertical versus horizontal tectonics in the Archean Barberton Greenstone Belt

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Our knowledge of the Earth's internal processes during the Archean is based on a very limited range of localities in which rocks of this age are exposed.The Barberton Greenstone Belt (BGB) in South Africa and Swaziland is, due to its excellent exposure and good preservation, one of the most important sites for studies of the Archean. Despite decades of intense research, the structural framework of the BGB is still poorly understood. The BGB shows a map pattern, which is characteristic of Archean greenstone belts, expressed by nearly isoclinal synclines with steeply plunging fold axes, separated by isoclinal or broken anticlines. Fold vergence faces towards the interior of the belt. Different approaches have been used to explain this distinctive structure, which can be interpreted as either favoring horizontal or vertical tectonics as the dominant tectonic regime during the final deformation phase of the BGB. Models which favor horizontal tectonics imply that plate tectonics was already established on the Archean Earth. On the other hand, models favoring vertical tectonics claim that plate tectonics was not possible during the Archean due to a higher geothermal gradient and a lower lithospheric density. At present, none of the abovementioned models explains the various features and complex structures of the BGB.

BGB rocks have gone through a long and complex history of deformation and metamorphism, which makes it difficult to reconstruct the tectonic processes related to the formation of the greenstone belt. Crucially, the syntectonically deposited sediments of the Moodies Group, which is the uppermost unit of the greenstone belt fill, contain evidence of the tectonic activity that occurred during its deposition. In models favoring horizontal tectonics, the Moodies Group was interpreted to have been deposited on a stable continental shelf, in a classical foreland foredeep or in a post-collisional basin. All of these settings are known to possess distinctive properties and geometries, which should be preserved within the Moodies Group. On the other hand, the model favoring vertical tectonics would also imply certain patterns, such as sediment wedges that are thinning towards the belt's interior and sourced from the uplifted basin margins (Fig. 1).

Our planned field work will validate or falsify the existing models through detailed field mapping of sediments and age dating of volcanic units and cross-cutting relationships. We will thus explain the structural framework of the BGB and contribute to the resolution of when plate tectonics began on Earth.

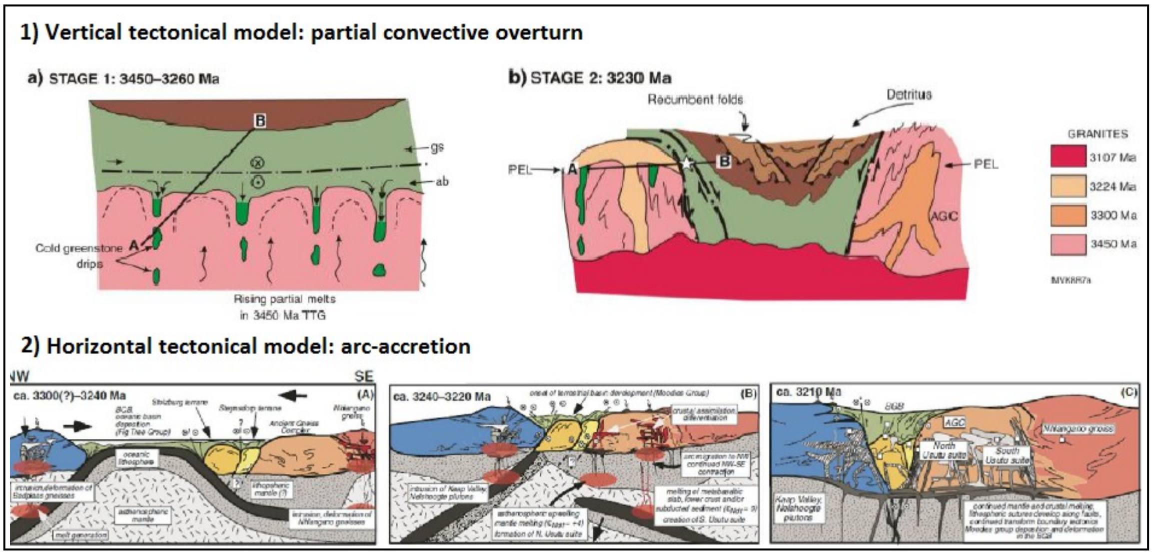

Figure 1. Comparison of the two major tectonical models for the formation of the Barberton Greenston Belt. After van Kranendonk (2011) and Schoene & Bowring (2010).

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Plume tectonics and formation of TTG in the Archean

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The relevance of contemporary tectonics to the formation of the Archean terrains is a matter of vigorous debate. While there is a variety of evidence for Mesoarchean-to-Neoarchean plate tectonics and subduction settings, which was recently maintained numerically, the evidences for early Archean tectonic regime are much more contrasting. As a consequence of secular cooling, there is generally no modern analog to assist in understanding the tectonic style that may have operated in the early Archean. The main lithology of Archean terrains is the sodic tonalite–trondhjemite–granodiorite (TTG) suite. Melting of hydrated basalt at garnet amphibolite, granulite or eclogite facies conditions is considered to be the dominant process that generated the Archean TTGs. Taking into account geochemical signatures of possible mantle contributions to some TTGs, models proposed for the formation of Archean crust include subduction, melting at the bottom of thickened continental crust and fractional crystallization of mantle-derived melts under water-saturated conditions. We evaluated these hypotheses using a 2D coupled petrological-thermomechanical numerical model with initial conditions appropriate to the Eoarchean–Mesoarchean. Based on the result of our experiments, we identify three tectonic processes by which intermediate to felsic melts may be generated from hydrated primitive basaltic crust: 1) delamination and dripping of the lower mafic crust into the mantle; 2) local thickening of the crust; and: 3) small-scale crustal overturns. Based on the P–T conditions in the experiments, many of the melts produced from the hydrated basalt during small-scale crustal overturns or lower crustal delamination likely correspond to the prevalent Archean TTG suites, while other melts could cover the remaining diversity of Archean granitoids. In the context of a stagnant-deformable lid tectono-magmatic geodynamic regime that is terminated by short-lived subduction, we identify two distinct types of continental crust. The first type is a pristine granite–greenstone-like crust with dome-and-keel geometry formed over delaminating–upwelling mantle which is mostly subjected to vertical tectonics processes. By contrast, the second type is a reworked (accreted) crust comprising strongly deformed granite–greenstone and subduction-related sequences and subjected to both strong horizontal shortening and vertical tectonics processes. Thus, a regime of dominantly vertical tectonics is followed by a regime in which both horizontal and vertical tectonics occurs. The results of our reference experiment are in a good agreement with the consensus that the Archean might have been dominated by a stagnant-lid tectonic regime with the possibility of episodic transient subduction and mobile-lid tectonics. Thus, we have provided a conceptual framework for separating different types of continental crust according to the likely tectonic regime.

Plate Tectonics Initiation as Running Hurdles

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Most geoscientists would agree that present-day and perhaps also Phanerozoic Earth is a type example of well functioning plate tectonics Planet. To understand of how and why plate tectonics worked or not worked in Archean it is first necessary to understand why is it so successful presently. This question was investigated in many studies, which demonstrated that mantle convection driven by deep density heterogeneities alone is not sufficient to maintain plate tectonics, and that natural state of such convection would be stagnant-lid rather than mobile-lid convection, a synonym of plate tectonics. It was found that additional conditions should be satisfied for the plate tectonics to work, which are negative buoyancy of the surface boundary layer and mechanically weak plate boundaries, particularly the interfaces between subducting and overriding plates. Global and regional geodynamic models show that typical friction coefficients at subduction interfaces at present Earth are very low, about 0.01-0.03, but they are higher (0.05-0.1), if soft marine sediments, which act as an efficient lubricant, do not supply trenches.

In Archean, the negative buoyancy condition could be satisfied already after less than 100 My of cooling of the solid Earth, despite of the thick (about 30 km) basaltic crust and strongly depleted underlying mantle. Moreover Archean slabs after eclogitization of the basaltic crust became denser than present-day slabs. Therefore it is unlikely that buoyancy of the Archean lithosphere was an obstacle for the beginning of the plate tectonics already shortly after the solidification of the Earth magma ocean.

I suggest that a key obstacle for the subduction initiation and for the sustained and stable subduction in Archean was high friction at subduction interfaces lacking efficient lubrication by the massive sediments eroded from the continents. Additional instability factor, suggested previously, was likely too fast subduction in the hot and low-viscous mantle, which resulted in breaking-off of the young and weak slabs.

The possible scenario is that the first regional and limited “plate tectonics” was initiated some time in early Archean by the large and hot mantle plumes. They episodically broke-up the lid and initiated rolling-back subduction zones opening “plate-tectonic cells”. Mutual collision of such cells and their interaction with oceanic plateaus might have finally resulted in global plate tectonics. However this type of plate tectonics was very unstable with the intensive phases followed by the hiatuses until the increasing supply of the efficient lubricant (sediments eroded from the growing continents) and cooling of the mantle have stabilized it.
I will compare the proposed scenario with geochemical records including recently reported data on the changing water content in the Archean mantle transition zone.

The Spectrum of Subduction

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Mixing in early Earth: influence of self-consistent plate tectonics and melting and crustal production

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It is generally thought that the early Earth's mantle was hotter than today, which using conventional convective scalings should have led to vigorous convection and rapid mixing with a time scale ~100 Myears (Coltice and Schmalzl, 2006). Geochemical observations, however, indicate that mixing in the early Earth was much slower than this expectation (~1-2 Gyears), leading to the suggestion that early Earth had stagnant lid convection (Debaille et al., 2013). Additionally, the mantle's thermal evolution is difficult to explain using conventional scalings because early heat loss would have been too rapid, which has led to the hypothesis that plate tectonics convection does not follow the conventional convective scalings (Korenaga, 2003).

One physical process that could be important in this context is partial melting leading to crustal production, which has been shown to have the major effects of (i) buffering mantle temperature and carrying a significant fraction of the heat from hot mantle (Nakagawa and Tackley, EPSL 2012), (ii) making plate tectonics easier (Lourenco et al., 2016), and causing compositional differentiation of the mantle that can buffer core heat loss (Nakagawa and Tackley, GCubed 2010).

Here, the influence of this process on mantle mixing is examined, using secular thermo-chemical models that simulate Earth's evolution over 4.5 billion years. Mixing is quantified both in terms of how rapidly stretching occurs, and in terms of dispersion: how rapidly initially close heterogeneities are dispersed horizontally and vertically through the mantle. These measures are quantified as a function of time through Earth's evolution.

Results indicate that mixing (as measured by either stretching or dispersal) under simulated early Earth conditions was not very rapid, with some heterogeneities surviving for up to 2 billion years. The explanation for this is that convective velocities were not as high as simple scalings require because much of the heat is transported by a magmatic heat pipe mechanism rather than conductive cooling of oceanic lithosphere. Thus, there is no problem reconciling geochemical and geophysical constraints on early Earth mixing times without invoking a different tectonic mode to today

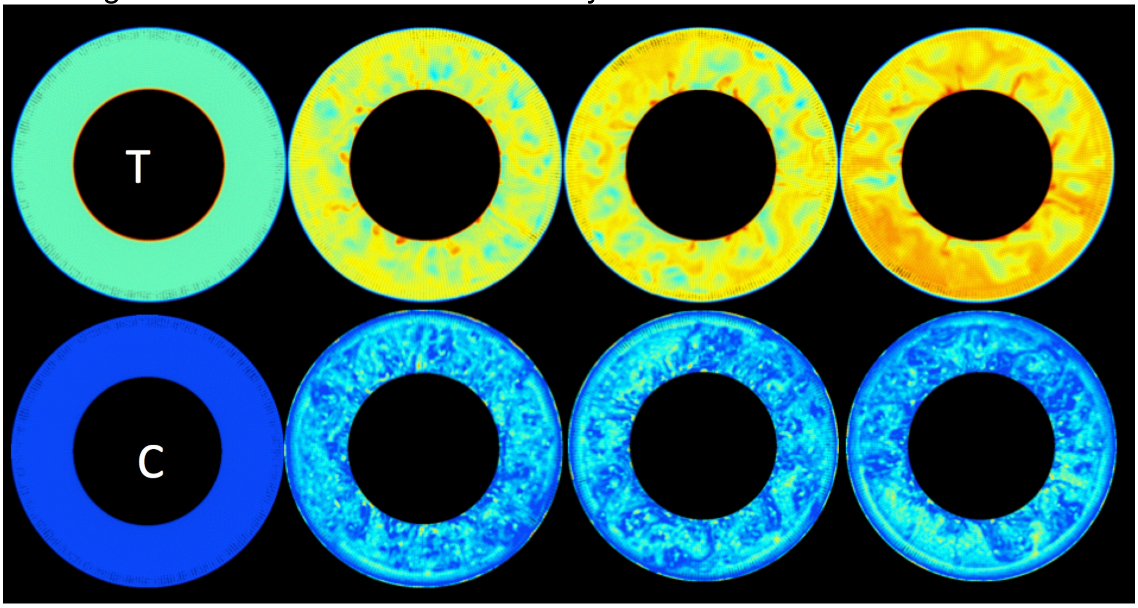

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Figure 1. Simulation of mixing in the early Earth. Top row temperature; bottom row composition with red=basalt to blue=harzburgite.

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Scaling of Plate Tectonics Initiation

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In recent decades, the interest in predicting the existence of plate tectonics on Earth-like planets has been greatly stimulated by the ideas that plate tectonics is important for the evolution and even the origin of life. A better understanding of the conditions for the existence of plate tectonics may eventually inform the search for extraterrestrial life by narrowing down the types of planets that are most likely to harbor life.

One way to think about the existence of extraterrestrial plate tectonics is in terms of how the probability of plate tectonics scales with planetary parameters such as planetary radius, surface temperature, abundance of radioactive elements, etc. Many scaling laws have been proposed to answer this question. The approaches can be classified as heuristic, asymptotic and numerical. The heuristic approaches involve high-level, intuitive assumptions about the convective system, which easily produce scaling laws, bypassing the solution of the convection equations. The asymptotic approaches use the lowest level of assumptions. They reduce the original system of equations to its simplified form and find scaling laws and approximate solutions in certain asymptotic limits. The numerical approaches attempt to determine the scaling laws from a large number of numerical simulations conducted at different values of the controlling parameters. A combination of asymptotic and numerical approaches seems to be the most promising approach.

The major difficulties in scaling plate tectonics initiation include poorly defined constitutive laws for brittle failure, incomplete understanding of convection with realistic parameters, such as pressure-dependent viscosity and phase transitions, and the stochastic nature of mantle convection which may preclude plate tectonics initiation even under favorable conditions. Furthermore, the mechanics of plate tectonics initiation is only one part of the entire process. The modern phase of plate tectonics is known to be a complex phenomenon involving various physical and chemical processes in the interiors and on the surface of the planet. The initiation of plate tectonics is likely to involve similar processes. Thus, scaling of plate tectonics initiation needs to go beyond mechanical considerations to incorporate these complexities. Finally, scaling of plate tectonics initiation depends on the most basic assumptions about how plate tectonics begins. For example, scaling of plate tectonics initiation under the assumption that plate tectonics starts on a completely crystallized one-plate planet is very different from that under the assumption that plate tectonics is a continuation of convection in a magma ocean.

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Initiation of Plate Tectonics in the Presence of Dense Material

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The presence of dense material in the deep mantle, resulting as remnant of the magma ocean phase, strongly interacts with the convective flow in the mantle. Sinking currents sweep up the dense material, that initially covers the core-mantle boundary (CMB), to form piles beneath the plumes. These piles have been widely used to explain the seismologically observed large-low shear wave velocities provinces (LLSVPs) beneath Africa and the Pacific (e.g., McNamara et al., 2010).

However, dense material does not only act passively in mantle convection, it also has a restoring effect on rising plumes. As a consequence deep dense material can have a large impact on the lithospheric plates. Trim et al. (2014) have shown that plate mobility is strongly hindered if the added dense material has a too high density or covers too large a volume. Plate tectonics can even vanish completely.

Rather than adding a dense CMB layer to a system with actively moving plates, we now concentrate on the initiation of plate tectonics. Therefore we utilize a mantle convection code featuring a fully rheological model that allows for plate formation according to the underlying convective flow (cf. Stein et al., 2004). Our starting condition is set after the magma ocean period, i.e. a mantle with a homogenous temperature distribution and an initial dense layer.

To analyse the initiation of plate tectonics in the presence of dense material we conduct numerical mantle convection models with a large parameter setting. We first determine the onset time of plate tectonics in models with a dense layer compared to purely thermal convection models. Then we vary the density of the heavy material and the volume of the dense layer in order to better understand the possible effect of the dense material on plate motion. Additionally, we consider different initial temperatures, and as recent results of magma ocean modelling suggest that the dense particles could have possibly been kept in suspension due to rotational forces (Maas and Hansen, 2015), we investigate how the depth of a dense layer affects the onset time of plate tectonics.

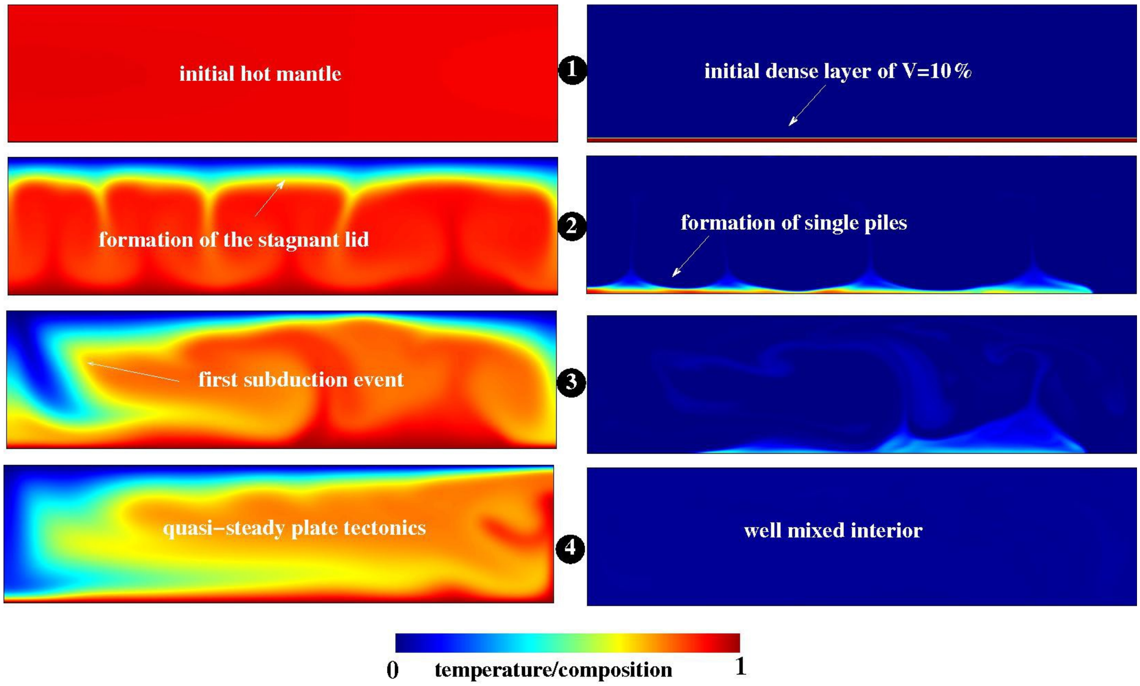

Figure 1. Temporal evolution of the temperature (left) and composition field (right) showing the self-consistent formation of surface plates and dense thermochemical piles. Due to entrainment the density and volume of the piles diminishes so that plate tectonics can initiate.

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When Did Plate Tectonics Begin? On the Nature of Evidence

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There is a wide range of opinions about when Plate Tectonics began, from Hadean (>3.8 Ga) to Neoproterozoic (1000-541 Ma). We need to consider all possible perspectives in the effort to resolve this controversy. One important consideration for constraining when Plate Tectonics began is the quality – the reliability – of the evidence, a discussion that has only just started. At the present (early to intermediate) stage of the "evidence quality" exploration, we should consider all possible lines of evidence. In the future we will need to decide which of the several lines of evidence is most compelling, and the many kinds of evidence complicates this evaluation. Geosciences generally does not have a "philosophy of evidence" but in the case of geohistory like this needs one. This essay explores the nature of evidence about "When did Plate Tectonics begin?"

In the law, there are two kinds of evidence: direct and circumstantial. An example of direct evidence is a witness who testifies to watching a suspect shoot the victim. An example of circumstantial evidence is that the suspect's gun is linked to the shooting or that a witness saw the suspect leave the building where the murder was committed. In the courtroom, direct evidence is more compelling than circumstantial evidence; this should be true for understanding when Plate Tectonics began as well. Examples of direct evidence include ophiolites (direct evidence for seafloor spreading) and blueschist (direct evidence for subduction). Examples of circumstantial evidence include continental crust and trace element signatures in igneous rocks. In addition to discriminating between direct and circumstantial evidence, we should also consider the scale of the evidence and what else does a particular line of evidence for when Plate Tectonics began explain? For scale, big evidence (many meters to kilometers) may be more important than small evidence (invisible to microscopic). Big evidence includes the ~1.95 Ga Jormua ophiolite of Finland (Peltonen and Kontinen, 2004) (exposed ~50 km^2), the ~780 Ma Aksu blueschist in NW China (~750 km^2; Zhu et al., 2011); and the ~620 Ma coesite-bearing UHP metamorphic rocks of Mali (Jahn et al., 2001; 10-100 km^2). The strongest evidence for early (Archean-Hadean) start to Plate Tectonics is microscopic to invisible (isotopic). Invisible evidence includes geochemical (e.g. Tang et al., 2016) and isotopic data in whole rock samples. Thus large, direct evidence should take precedence over small circumstantial evidence.

Regarding the point What else does it explain?, it is likely that the start of Plate Tectonics would have perturbed other Earth systems, especially the climate system and the pace of evolution. We cannot yet predict which of these other Earth systems were most affected, or exactly how they would have been perturbed, but Earth evolved from some sort of a stagnant lid tectono-magmatic style (likely associated with less explosive basaltic "plume" volcanism with modest opportunities for isolation and thus biological speciation) to Plate Tectonics (with more explosive volcanism and more opportunities for speciation), we expect major changes in Earth's climate and evolutionary pace to accompany the transition from stagnant lid to Plate Tectonics. Major changes in both climate and evolution are documented for Cryogenian and Ediacaran time, supporting conclusions based on large, direct evidence that Plate Tectonics began then.

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Petrotectonic indicators for distinctive modern-style subduction zone

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Understanding how and when plate tectonics began on Earth and what came before is paramount for understanding the evolution of the solid Earth as well as its climate and biology. These questions are unresolved, with estimated beginnings that range from >4 Gya to <1 Gya. We were thus very interested to read a recent paper by Palin & White (2016) who argued that blueschist — metamorphic rocks formed during subduction— did not form on Earth until about 0.8 Gya because oceanic basalts were too Mg-rich prior to that time. We agree with their foundation assessment that the oldest blueschists are of Neoproterozoic age. We further agree: 1) presence of blueschists (or glaucophane-bearing rocks) indicate formation by modern-style subduction-driven plate tectonics; 2) importance of understand why these are missing from the first ~3.8 Gyr of Earth history; 3) absence is not a preservation artifact; and 4) that the thermal structure of subduction zones has not changed greatly since plate tectonics began. We question their conclusion that a change in oceanic crust composition was primarily responsible. Our refutation is based on the global inventory of other subduction-related indicators unlikely to be controlled by oceanic crust compositions. These include coesite- or diamond-bearing regional ultrahigh-pressure (UH*P*) metamorphic rocks, lawsonite-bearing rocks, jadeitites, and specific H*P* mineral (or mineral assemblage) in aluminous metasediments and metachert/quartzite, such as carpholite all of which first appear in the geologic record about the same time that blueschists occur. UH*P*s require subduction of continental crust to depths of at least 100 km and return to the surface. The initiation of UH*P* metamorphism near the Precambrian–Cambrian boundary could attest to an abrupt change in the subduction zone geothermal gradient due to large amounts of heat loss from the Earth's interior (Maruyama & Liou 1998), but like the slightly earlier appearance of blueschists could indicate the beginning of subduction and plate tectonics in Neoproterozoic time. Lawsonite formation requires high-*P*/*T* metamorphic conditions, typically blueschist and low-T eclogite facies; lawsonite can also be found in very-low-grade pumpellyite–actinolite facies metabasalts but not in the prehnite–pumpellyite facies metamorphic rocks that dominate Archean greenstone belts. The oldest lawsonite-bearing rocks are latest Neoproterozoic in age, implying that sufficiently cold subduction-zone thermal structures for lawsonite formation had to wait until Late Neoproterozoic time to exist (Tsujimori & Ernst 2014); lawsonite is stable even in a MgO-rich basaltic composition. Jadeitite formation requires the direct hydrous fluid precipitation or the interaction of such fluid and subduction zone metamorphic rocks at a high-P/T condition within forearc mantle wedge. There are no know occurrences of the historically important and economically valuable rock jadeitite for the first ~4 Gyr of Earth history (Harlow *et al.* 2015), which is easily explained if subduction did not begin until Neoproterozoic time. The oldest aluminous metasediments and metachert/quartzite are Archean in age. However, the oldest Fe–Mg carpholite and/or talc+phengite, as indicative of blueschist-facies condition, in those rocks are Late Paleozoic in age. In addition to the aforementioned metamorphic assemblages, we also point out the ophiolite record; ophiolites are indirect indicators of subduction because many of these form during the formation of new subduction zones; the rest are backarc basins and normal oceanic crust (Stern *et al.* 2012). Although a few ophiolites are ~1.9 Gya, nearly all ophiolites are Neoproterozoic or younger. Taken together, the absence of blueschists and the other subduction indicators compels the conclusion that subduction —and modern-style plate tectonics— did not occur until Neoproterozoic time.

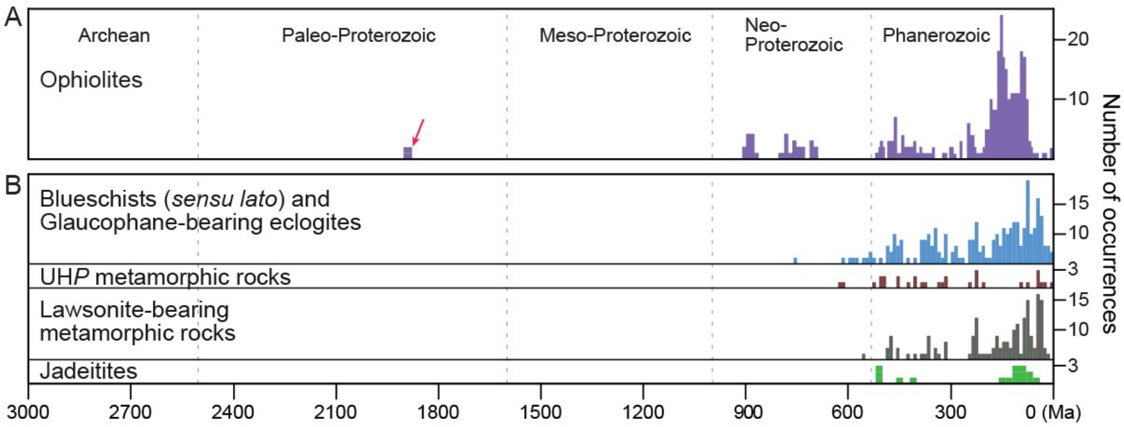

Figure 1. Histograms showing ages of petrotectonic indicators for distinctive modern-style subduction zone products in the last 3 Gyr of Earth history. A: Oceanic lithosphere (ophiolites). B: Subduction zone metamorphic products; blueschists (*sensu lato*) and glaucophane-bearing eclogites, coesite- (or diamond)-bearing ultrahigh-pressure (UH*P*) metamorphic rocks, lawsonite-bearing metamorphic rocks, and jadeitites.

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Where does subduction initiate and die?

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Plate tectonics is a prominent feature on Earth. Together with the underlying convecting mantle, plates form a self-organized system. In order to understand the dynamics of the coupled system, subduction of the lithospheric plates plays the key role since it links the exterior with the interior of the planet. In this work we study how subduction initiates and terminates, following its life span. Using thermo-mechanical numerical calculations we investigate global convection models featuring self-consistent plate tectonics and continental drift using a pseudo-plastic rheology and testing the effect of a free surface. Our calculations indicate that intra-oceanic subduction initiation is favorable compared to the initiation at passive continental margins for most of the studied cases. On the other hand, around 70% of the subductions shut off in the vicinity of the continent after reaching the lower mantle. The time scale of subduction approaching the continent is longer than the life span of the oceanic lithosphere diving back to the mantle close to the continent.

Onset and evolution of plate tectonics in an early Earth: insight from modelling

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The primary source of information to determine whether plate tectonics (PT) was operating in the early Archaean or even the Hadean is the rock record. But this rock record becomes increasingly sparse when going back in time, and deciphering the potential role of PT becomes increasingly complex.
This talk will focus mostly on an alternative way to learn about early Earth tectonics through simulation of PT through time and through studies on its feasibility in an early, hotter Earth and its evolution through time. It will give an overview of how geodynamical modelling has contributed to our knowledge about the onset and evolution of PT.

Earth has cooled by 100s of degrees since the early Archaean (Herzberg et al., 2010), which indicates that surface heat flow exceeded internal heat production, and that the governing tectonics at the time were capable of producing such heat flow. Early parameterized convection numerical models (e.g. , McGovern & Schubert, 1989) and later full 2-D or 3-D models (e.g. Nakagawa & Tackley, 2012, Debaille et al., 2013, Lourenço et al., 2016) provide useful insights.

Other studies focused on the dynamics of subduction or PT in general, how it changes in a hotter Earth regime, and whether PT remains feasible. The increasing buoyancy of plates (Davies, 1992) or decreasing strength of plates in a hotter Earth (van Hunen and van den Berg, 2008, Sizova et al., 2010) have been suggested to limit the viability of PT in the early Earth. But some form of (proto-)subduction might have been viable ever since the solidification of the global magma ocean in the Hadean (Foley et al., 2014). Two main results feature in these studies. First, the role of rheology is very important, and a thorough understanding of rock deformation is essential. Second, plate tectonics may not have suddenly switched on (although plume impacts may have locally kick-started the process, Gerya et al., 2015), but likely evolved from a proto-PT style (with perhaps more diffuse boundaries and less rigid plate interiors and maybe more episodic in nature) to the style PT we know today.

To further constrain the evolution of PT, attempts have been made to link these theoretical models to field observations. Episodicity in theoretical models on timescales from Myrs to 100s of Myrs) has been linked to field observations (O'Neill et al., 2007; Moyen and van Hunen, 2012), and plate dynamics have been linked to the generation of the bulk felsic Archaean crustal material, commonly referred to collectively as TTGs (e.g. Sizova et al., 2015; Maunder et al., 2016, see Figure 1).

To further narrow the range of onset timings and dynamics of early plate tectonics, it is essential to compare models to observations in more detail, using models with self-consistent plate tectonics (e.g. Crameri & Tackley, 2015). To do that, incorporation of more detailed information on rheology, tectonics, petrology and geochemistry will become increasingly important.

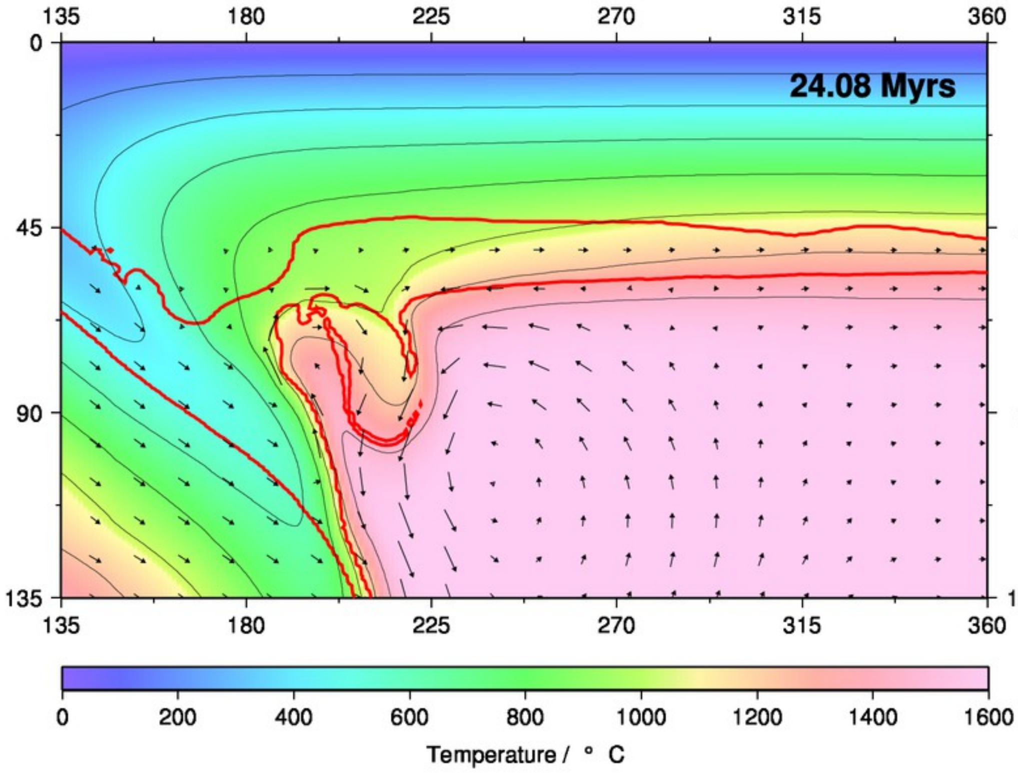

Figure 1. Potential style of Archaean subduction, where most of the thick crust is 'relaminating' to the base of the overriding plate (Maunder et al., 2016).

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Archean accretionary orogen evolution: view from isotopy and thermodynamic equilibrium modelling

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The Archean is the most nebulous Eon of Earth geological recording. This is mainly due to the lack of specimen still present at Earth surface (only ca. 7% of exposed crust consists of Archean rocks, Goodwin (1996)). Unique lithologies (TTGs, komatiites, B.I.F.), the absence of atmosphere, a hotter crust/mantle system, make Archean a highly interesting field of investigation. Despite these unusual features, deciphering early Earth processes brings a better understanding of planetary systems as a whole. The PhD project I'm involved in deals with orogen geodynamics and associated partial melting processes from a natural laboratory: the Archean northern Kaapvaal craton (KC) in South Africa.

Geochronological investigations have shown that KC formed through successive South-North accretionary geodynamics of distinct terranes (Zeh et al., 2009). Geochronological and petro-metamorphic studies of felsic lithologies achieved from this study robustly confirm the genetic link between the northern KC and the immediately northern terrane - the Southern Marginal Zone of the Limpopo Complex - suggested by Ellington and Armstrong (2004). More importantly, the Mesoarchean magmatic event (2.95-2.75 Ga) recorded by zircon U-Pb/Lu-Hf isotopic signature testifies a long-lived accretionary setting (Laurent and Zeh, 2015; Vezinet et al., 2016). This protracted magmatic event matches fairly well with the tectonic switching geodynamics model (advancing and retreating orogens) proposed by Collins (2002).

Partial melting processes are involved in the protracted magmatic event characterizing the northern KC. In order to constrain these processes various intrusive granitoid bodies have been sampled. Field relationship, zircon U-Pb/Lu-Hf isotopic analyses and chemistry links these granitoids with amphibolite facies TTG basement (Vezinet et al., 2016) rather than surrounding granulite facies metasediments (Nicoli et al., 2015; Taylor et al., 2014). Moreover, our dataset point toward a differentiation of the crustal column without external intervention (allochthonous sediments or mantle influx). Therefore, northern KC differentiation is here regarded as a geodynamics achieved through crustal self-refinement, quantified using Theriak-Domino thermodynamic equilibrium modelling software. Finally, this long-lived differentiation results in high producing elements and HFSE accumulation in upper crust granitoids, necessary to stabilize crustal terranes (Sandiford and McLaren, 2002).

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Interior-atmosphere co-evolution: Implications for the long-term evolution of the global carbon cycle

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The climate evolution and habitability of terrestrial planets is governed by both insolation and atmospheric composition [e.g., Noack et al. 2012, Gillmann & Tackley 2014]. The latter may change substantially over time if greenhouse gases (e.g., carbon dioxide) are released into the atmosphere as a consequence of volcanic degassing. Higher concentrations of greenhouse gases lead to an increase in surface temperature, which in turn affects melt production and volcanic activity of the planetary body.

To investigate the complex interplay between interior dynamics and climate evolution, we present a model to calculate the cycling of greenhouse gases. Volatile fluxes from the planet interior to the atmosphere and back again are derived by a combination of parameterisations and fully dynamic simulations. The latter are carried out with StagYY [Tackley 2008], which is a sophisticated code capable of tracking compositional variations within a convecting mantle. To determine surface temperature conditions with respect to time-varying concentrations of greenhouse gases, we rely on a non-grey model of radiative-convection equilibrium that treats the transport of thermal radiation in an evolving atmosphere.

We use the coupled model for studying the long-term carbon cycle operating on Earth-like planets, because of its crucial role in maintaining life-sustaining conditions on the Earth's surface [e.g., Franck et al. 2002, Foley 2015]. In doing so, special emphasis is placed on the effect of different convective regimes on the degassing efficiency. By systematically varying the critical yield stress, our numerical calculations suggest that planets with mobile plates on top of the convecting mantle outgas significantly more CO_2, when compared to their one-plate counterparts. For mobile-lid convection, degassing rates are mainly driven by volcanic activities at regions where cold surface material is transported into the interior. Elevated volcanic activity ensures a steady CO_2 flux from the interior to the atmosphere, which is, in the long run, balanced by removal of atmospheric CO_2 due to silicate weathering. For stagnant-lid convection, degassing is controlled by hot upwellings originating at the core-mantle boundary. Since these mantle plumes need time to rise to the surface, we observe extended periods in which no CO_2 is released into the atmosphere, leading to strong fluctuations in atmospheric CO_2 concentration and surface temperature. To conclude, internally driven processes do play a central role when studying the long-term stability of the global carbon cycle.

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Initiation of subduction along the Puysegur Trench – propogation of the Australia-Pacific collision

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The Puysegur Trench extends south-west off from New Zealand and accommodates the eastward subduction of the Australian Plate beneath the Pacific Plate (Fig. 1.). Subduction related tectonics initiated along the New Zealand Plate boundary at ~23 Ma with westward subduction of the Pacific Plate under the North Island of New Zealand. Subduction similtaneously triggered transpression along the northern Alpine Fault, as the Campbell Plateau was driven westward over the Challenger Plateau. The transition from transtension to transpression slowly moved southward along the Alpine Fault (Furlong and Kamp, 2013) as it rotated into alignment with the Hikurangi Trench (Reyners, 2013). Transpression reached Fiorldand between 12 and 15 Ma (Furlong and Kamp, 2013; Sutherland, 1995; Sutherland et al., 2006) with the Challenger Plateau thrusting over the Resolution Basin and initiating subduction. We present numerical models with free-slip boundary conditions developed in Underworld (Moresi et al., 2007) to mimick the collision of the Pacific and Australian Plates. The model shows that the lateral shear strength of the Pacific Plate is great enough to that shortening driven by the Hikurangi Subduction Zone can initiate subduction as the Campbell Plateau is driven over the Pacific Plate. This result shows that subduction is a naturally propogating feature of collisional boundaries and once initiated can become a self-sustaining process.

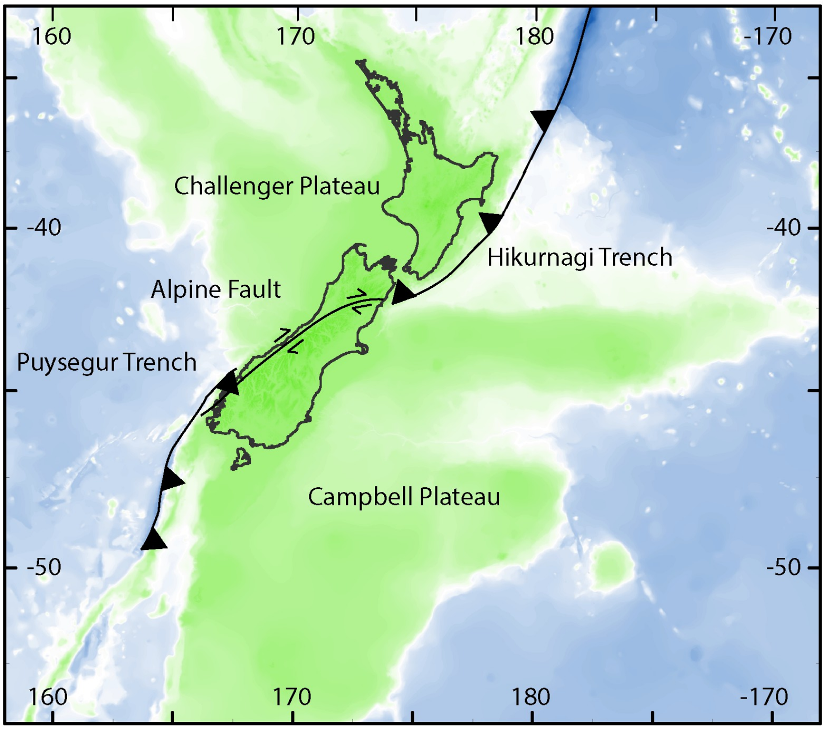

Figure 1. Tectonic setting of New Zealand. Subduction of the Pacific Plate along the Hikurnagi Trench drives shortening southward along the Alpine and has resulted in the initation of subduction along the Puysegur Trench.

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Dynamics of spontaneous intraoceanic subduction initiation: 2D thermomechanical modeling

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Subduction is an important process to understand the global Earth dynamical evolution. In order to obtain better understanding of this process, many numerical experiments have been operated from subduction initiation to mature subduction. However, the dynamical process during (after) subduction initiation remain obscure. The process of suducted slab move from down to downdip is also not revealed clearly. We focus on the process from subduction initiation to the beginning of the true subduction. Using finite difference and marker-in-cell methods, we establish a series of self-sustainable subduction initiation models and explore many visco-elasto-plastic parameters to qualify the dynamical process of subduction initiation. We find that the age of subducted slab plays important roles during subduction initiation. The young subducted slab induces fast trench retreat and then trench begin to advance. For the old subducted slab, it induces relative slower trench retreat and then stop moving. The strength of lithosphere also impacts the backarc spreading and subduction velocity. Stronger subducted plate gives lower subduction velocity and faster trench retreat velocity.