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Earth dynamics and the development of plate tectonics

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Introduction

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This volume brings together contributions from the Royal Society Discussion Meeting on 'Earth dynamics and the development of plate tectonics' held in March 2018. Other planets in the Solar System do not exhibit plate tectonics, so why does it occur on Earth, how did it develop and when did Earth adopt this tectonic regime? In evaluating evidence from the geological record, it is critical to distinguish between local and global phenomena in a discussion of the why, how and when of the transition to plate tectonics on Earth. Thus, evidence of local or episodic subduction in the geological record, for example, does not necessarily provide evidence for the development of a sustainable global network of mobile belts that forms the basis for a mosaic of plates.

The tectonic regime at any point in the evolution of a planet appears to depend on the initial conditions set by crystallization of the last magma ocean. These conditions determine the thermal state—'hot' or 'cold'—at the start of sub-solidus mantle convection, which is subsequently driven by the relative contributions of basal and internal heating to the mantle through time. Plate tectonics is linked to the ability of mantle convection to form plate boundaries, which requires localized weakening of the lithospheric lid. How and when did this become possible? Consideration of the tectonic regime on Venus, which may be an analogue for the early tectonic development of Earth, evidence from the rock record, rock deformation experiments, geodynamic models extrapolated back to the thermal conditions appropriate to the Archaean, and geochemical models for the development and growth of the continental crust have led to the currently popular view that plate tectonics developed from a stagnant lid regime. However, if mantle convection is able to form weak plate boundaries at the higher mantle

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temperatures expected during the Archaean, then plate tectonics may have developed from an earlier more sluggish lid regime with a drip-like style of subduction.

Whatever the earlier regime, the petrological, structural and geochemical evidence from the rock record of the Late Archaean together indicate that a major change in tectonic regime occurred at that time. This has led to an increasing number of contributions in which it is suggested that plate tectonics became the dominant tectonic regime on Earth around 3 billion years ago, although it is likely that the transition to a global network of linked plate boundaries occurred over some time, perhaps extending into the Proterozoic. The development of plate tectonics and the differentiation of the lithosphere into oceanic and continental components that followed were key events in the evolution of the biosphere on Earth, and a similar change in tectonic regime could be crucial for the development of habitability on exoplanets. However, given the stochastic nature of convection in planetary mantles, whether a planet develops plate tectonics or not might just be serendipity.

One consequence of the high degree of heating that occurs during the formation of planets is that they commonly pass through a magma ocean stage. In the first article, Schaefer & Elkins-Tanton [1] review models for the evolution of magma oceans on Earth, the Moon and Mars. In most models, crystallization of a magma ocean commonly leads to a mantle overturn that may set up a stably stratified mantle, which may delay or even prevent the emergence of a plate tectonics regime on some planets. However, as Schaefer and Elkins-Tanton point out, in more recent models the intrinsic stability of a layered mantle is weakened, which may allow an earlier transition to a plate tectonics regime. Clearly, additional modelling is necessary to resolve the uncertainty surrounding the tectonic regime immediately following crystallization of the last magma ocean in planetary mantles. Venus is Earth's sister planet, being similar in density, size, inferred composition and heat budget, and yet the two planets have followed contrasting evolutionary paths. In her contribution on the tectonics of Venus, Vicki Hansen uses geometric analysis of structures and cross-cutting relationships in maps of the Niobe Planitia–Aphrodite Terra area to identify three tectonic domains thought to represent the imprint of different tectonic regimes that record fundamental changes in global conditions over time [2]. She argues that these tectonic regimes provide possible analogue models for the formation of Archaean cratons and continents on Earth prior to the emergence of plate tectonics, and for the subsequent development of plate tectonics. These changes represent an evolution from a mix of exogenic and endogenic controls on the prevailing tectonic regime to a purely endogenic mechanism as Earth transitioned to plate tectonics. In the next article, Lenardic [3] discusses the defining features of plate tectonics, reviews the range of volcanic–tectonic modes that are viable on terrestrial planets and considers transitions between these different volcanic–tectonic modes. In classic models, the transitions between tectonic modes are relatively sharp and determined by the physical and chemical properties of a planet. However, the transition to plate tectonics on Earth could have occurred over a long time during which elements essential for its operation progressively emerged as determined by variations in the temporal evolution. In discussing why Earth has plate tectonics, Lenardic concludes that the answer could include a significant element of chance, which would have implications for the development of habitability on exoplanets.

The continental crust records the history of processes that shaped the outer portions of the Earth, and yet the geological record remains difficult to interpret. No rocks older than *c*. 4 Ga, and relatively few older than *c*. 3 Ga are preserved, so the history is incomplete and potentially biased in favour of what was preserved. While rocks associated with particular tectonic settings, such as subduction, may sometimes be recognized, it is much more challenging to obtain evidence for whether subduction was global, and whether it was continuous or episodic. Thus, it has proven difficult to determine when sustainable plate tectonics may have emerged on Earth. It is perhaps inevitable that geochemical evidence dominates these discussions, and it remains critical that suitable samples are selected. It does not matter how many state-of-the-art analysis may be applied to rock and mineral samples, if those samples have not been carefully selected in the first place the interpretations may be difficult to evaluate. The key steps in the detailed

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interrogation of Earth's oldest crustal rocks are good quality field control and considered selection of samples for analysis. Assuming these steps have been followed, then integrating robust data obtained at multiple scales from well-preserved whole rock and mineral archives with coupled petrological–thermomechanical tectono-magmatic numerical models will allow us to take the next step forward in understanding early Earth processes.

In the first of three related articles, Kemp [4] examines the nature of the Hadean and Archaean geological records to determine the most robust evidence to constrain the prevailing tectonic regime. He considers data retrieved from Archaean gneiss complexes and granite–greenstone terranes, and Hadean detrital zircons, and reviews isotopic proxies of crust–mantle interactions, before concluding that the formation of some of the oldest continental nuclei involved a distinctive mode of geodynamics somewhat dissimilar from modern style plate tectonics. Next, Cawood *et al*. [5] explore the extent to which different aspects of the geological record can be used to evaluate the presence of rigid lithospheric plates and their relative motion. Using a variety of sedimentary, igneous and metamorphic proxies, combined with palaeomagnetic data these authors conclude that a significant change in Earth's tectonic behaviour occurred between 3.2 and 2.5 Ga, consistent with a transition from a non-plate tectonic regime, arguably with localized episodic subduction, to sustained plate tectonics. By contrast, Stern [6] takes a different approach and argues that the preservation of the oldest known blueschist and ultrahigh pressure metamorphic rocks, together with ophiolites indicates that the modern episode of plate tectonics only began in the Neoproterozoic. Before that, there may have been several episodes of plate tectonic (e.g. Mid-Paleoproterozoic) and non-plate tectonic (e.g. the 'boring billion', from around 1.8 to 0.8 Ga) regimes on Earth. Stern argues that the final transition from a sluggish single lid during the boring billion to plate tectonics in the Neoproterozoic, which took *ca* 230 Myr to complete, explains the distribution of kimberlite ages, and caused the Neoproterozoic climate crisis and the Neoproterozoic acceleration of evolution.

The third group of articles marks a shift away from what is preserved in the geological record to experimental and modelling approaches to understanding Earth's geodynamics. Mechanisms of weakening the lithosphere and taking advantage of weak zones are important elements in models for the generation of plate tectonics. Using high-strain torsion experiments on samples consisting of dominantly olivine with 30 vol% ferropericlase, Weisman *et al*. [7] investigate the role of grain-boundary pinning and the mechanisms by which phase mixing occurs during deformation. The results provide evidence for grain size reduction during phase mixing, highlighting a mechanism for the persistent weakening of the lithosphere. Such weakening allows development of the ductile shear zones necessary for the formation of plate boundaries and maintaining plate tectonics. However, when plate tectonics emerged on Earth is intrinsically tied to when mantle convective forces became capable of forming these weak ductile shear zones in the lithosphere to initiate plate boundaries. Foley [8] explores a model for shear zone formation based on grain size reduction. He concludes that thermal conditions on early Earth do not impede their formation, but that high mantle temperatures lead to a more sluggish, drip-like style of subduction. Foley argues that this sluggish style of tectonics can potentially explain enigmas such as the long-term preservation of early formed mantle heterogeneities, as well as allow for the widespread development of the thick 'plateau-like' crust preferred by many for the generation of the tonalite–trondhjemite–granodiorite (TTG) suite. In addition to the initiation of plate boundaries, nascent subduction zones must evolve into long-lived contiguous features. This transition is tackled by O'Neill *et al*. [9], who note that early planetary evolution is dominated by meteorite impacting and volcanic processes, and posit that subduction may be initiated by both large impacts and strong thermal plumes. The geological record includes many instances of episodic or failed subduction, which is consistent with the results of numerical modelling that suggest a nonlinearity in the transition to a plate tectonic regime. In the final article in this group, Nebel *et al*. [10] address the transition from the TTG suites characteristic of the Archaean crust to the more potassic granites that appear as the cratons became stabilized between *ca* 3.2 and 2.5 Ga ago. Numerical modelling by Nebel *et al.* indicates that upper mantle convection drives intra-crustal flow, with partial melting of scattered crustal down-drips generating TTGs.

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Subsequently, ascending TTG melts derived from asymmetric drips may interact with overlying asthenospheric mantle to generate high-Mg sanukitoid melts. Heat released by crystallization of these underplated hybrid magmas may promote melting of the lower crust to produce typical potassic granites.

A number of recent geochemical models of continental growth suggest that approximately 60–80% or more of the present volume of the continental crust had been generated by *ca* 3 Ga. Dhuime *et al*. [11] use a box model approach to explore how such estimates can be reconciled with the distribution of crustal formation ages at the surface. They find that the estimated rates of crustal destruction increase dramatically around 3 Ga ago, which may be linked to the widespread development of continuous rather that episodic subduction, and subsequently decrease to levels consistent with a sustainable plate tectonic regime. Jun Korenaga takes a different view. He argues that existing models for continental growth comprise those that are crust-based, corresponding to the distribution of crust formation ages, those that are mantle-based, corresponding to net crustal growth, and those based on other less direct inferences. He points out that the difference between net crustal growth and formation age at any point in time represents crustal recycling related to subduction, whereas the difference between formation age and surface age at any point in time reflects crustal reworking. Korenaga [12] prefers a model in which fractionated $^{142}Nd/^{144}Nd$ ratios are consistent with rapid crustal growth as well as efficient recycling in the Hadean, and the evolution of $^{143}Nd/^{144}Nd$ indicates the declining efficiency of crustal recycling through time. In such models, the present volume of the continental crust is thought to have been established before 4 Ga. Studies of Hadean mantle dynamics would benefit from an integrative treatment of water fluxes, freeboard constraints and the chemical evolution of the lithosphere. In the final article, Zerkle [13] explores how the development of plate tectonics and the generation of stable continents were key events in the evolution of the biosphere on Earth. She focuses on the global cycling and bioavailability of nitrogen and phosphorus over geologic timescales to evaluate the biosphere–geosphere gap. Phosphorus, for example, is generally believed to be the limiting nutrient for global primary productivity, but there is a limit to the supply of phosphorus to the oceans. The input of phosphorus to the marine biosphere relies on riverine delivery from land, and so there are close links to the erosion history of the continents, and on the redox state of the oceans, both of which have changed with time.

The contributions in this volume highlight aspects of the initiation of subduction and the emergence of plate tectonics that may inform future studies. Evidence for subduction in the geological record is not *per se* evidence for sustainable plate tectonics, which is more difficult to establish. However, it is argued that the relative rigidity of the continental lithosphere may be evaluated and that large lateral displacements between cratons can be demonstrated beginning in the Late Archaean. There is increasing evidence that the development of plate tectonics is facilitated by weakening of the lithosphere and localization in shear zones, and the ability of mantle convection to take advantage of these to form plate boundaries. In turn, this requires the development of better, more detailed models of how shear zones develop. Geodynamic models are becoming increasingly sophisticated with increasing emphasis on the development of predictions that can in turn be tested, in addition to demonstrating what is feasible. One goal for future research is the coupling of petrology and geochemistry with geodynamic modelling to better address the growth, recycling and reworking of the continental crust. There is considerable scope for comparison with other planets, a number of which preserve better records of planetary evolution than the Earth over its first 2.5 billion years. There remains a wide diversity in the models of crustal formation and evolution through time, and it is to be hoped that a consensus model can be achieved within the next few years. Plate tectonics is only known to occur on Earth, and that in turn appears to have shaped when life evolved, and perhaps even the nature of that life. It is easy to be impressed by the huge range of analyses on all sorts of scales that can now be undertaken. However, much of the key evidence is anchored in the rock record, and the critical first step remains the careful selection of appropriate samples with clear field control before all those innovative and expensive analyses are undertaken. High-quality fieldwork remains as important as it has ever been.

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