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Formation of continental crust by intrusive magmatism

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Abstract

We investigate the creation of proto-continental crust (TTG rocks) employing fully self-consistent numerical models of thermo-chemical convection on a global scale at the Archean, after crystallization of the magma ocean. We show that intrusive magmatism is the key process to reach the pressure-temperature conditions of TTG formation. Full eruptive magmatism produces a too cold lithosphere in our self-consistent models. Our simulations show that the Archean Earth might have gone through various convection regimes before the stabilisation of plate tectonics: eclogite dripping events, stagnant episodes and resurfacings.

Introduction

We solve the equations of compressible mantle convection, employing fully realistic rheological parameters [3] using the convection code StagYY [7] in 2D spherical annulus geometry for a period of one billion years.

Starting from a pyrolytic composition and an initially warm core (6000K), when the temperature exceeds the solidus temperature, our simulations first generate oceanic crust and depleted residue (harzburgite) in the upper mantle. In our model, basaltic material can be both erupted (cold) at the top of the domain and intruded (warm) at the base of the crust following a predefined partitioning. At all times, water concentration is considered fully saturated in the top 10 km of the domain, and it is simply advected elsewhere.

Second, we track the pressure-temperature conditions of the newly formed hydrated basalt and check if it reaches the conditions necessary for the generation of primordial continental crust [5]. We systematically investigate the influence of volcanism (eruption, also called "heat pipe") and plutonism (intrusive magmatism) on the time-dependent geotherm in the lithosphere.

Results

We show that the "heat-pipe" model (assuming 100% eruption and no intrusion) proposed to be the main heat loss mechanism during the Archean [4] is not able to produce continental crust as it forms a too cold and thick lithosphere [6]. We also systematically test different mechanical properties of the brittle domain (friction coefficients). With this parameter study, we are also able to show that an intrusion fraction higher than 60% (in agreement with [1]) combined with a friction coefficient greater than 0.1 can generate the expected amounts of the three main petrological TTG compositions previously reported in field studies [5]. Figure 1 illustrates the impact of intrusion efficiency on the geotherm in the lithosphere.

This result seems robust as the amount of TTG rocks formed varies over orders of magnitude. A fully eruptive model can result in up to 100 times less felsic crust production than in a plutonic simulation using the same rheological parameters. However, our simulations are unfortunately not yet able to produce depleted continental roots, which might significantly modify the thermal profile of the lithosphere.

Despite such limitations, our models might also provide an explanation for the transition in convection regime previously suggested around 3.6 Ga, where mantle activity could have temporarily decreased [8]. Widespread felsic magmatism has been reported over hundreds of millions of year in localised regions, suggesting a possible fixity of mantle upwellings [2]. Our models show that such surprising observation can be reproduced after the initial vigorous stages in which tremendous amounts of eclogite drip from the lithosphere due to extensive melting and crust production. Since this mafic material is denser than the ambiant mantle, it sinks and stabilizes above the core mantle boundary. Hundreds of millions of year of relative convective stability are then often observed in our models. Moreover, massive catastrophic overturns sometimes follow this quiescent phase, which might have a geochemical signature similar to what the onset of plate tectonics could have produced.

1. Summary and Conclusions

We demonstrate that crust production has a major influence on the convection regime on terrestrial planets, as previously reported in [4]. We show that both eruptive and intrusive magmatism are required to form continental material in self-consistent numerical simulations of mantle convection.

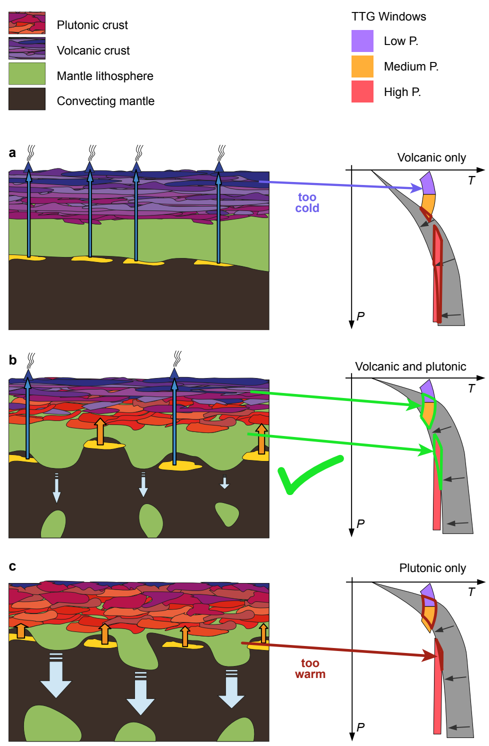

Figure 1: Intrusive vs eruptive magmatism and its impact on the geotherm of the early Earth [6].

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