Chicken or egg? Recipes for creating Earth's continental crust

Nick M W Roberts[1,*]

[1]Geochronology and Tracers Facility, British Geological Survey, Nottingham NG12 5GG, UK

*Correspondence: nirob@bgs.ac.uk

Received: May 23, 2024; Accepted: August 12, 2024; Published Online: August 14, 2024; https://doi.org/10.59717/j.xinn-geo.2024.100091

Citation: Roberts N. (2024). Chicken or egg? Recipes for creating Earth's continental crust. The Innovation Geoscience **2(3)**: 100091.

Plate tectonics and strong, emergent, continental crust support Earth's habitability; as such, continental emergence represents a key milestone in Earth's evolution. Early Earth was a water world, with the crust almost entirely covered in water. Once the continents rose above sea-level, the weathering of these landmasses drove irreversible changes to the Earth system. Most estimates for continental emergence fall in the late Mesoarchean to Neoarchean, a time that overlaps with major changes in compositions of magmatism and continental growth rates. The late Archean is therefore recognised as an important period for understanding Earth history. Despite decades of research into the formation of Earth's earliest continental crust and the processes that led to emergent stable cratons, there remain many open questions, with the geodynamic settings of crust formation being hotly debated. A recent study discussed herein, provides fresh debate on the fundamental question, what ingredients are needed to create Earth's long-lasting, stable, continental crust?

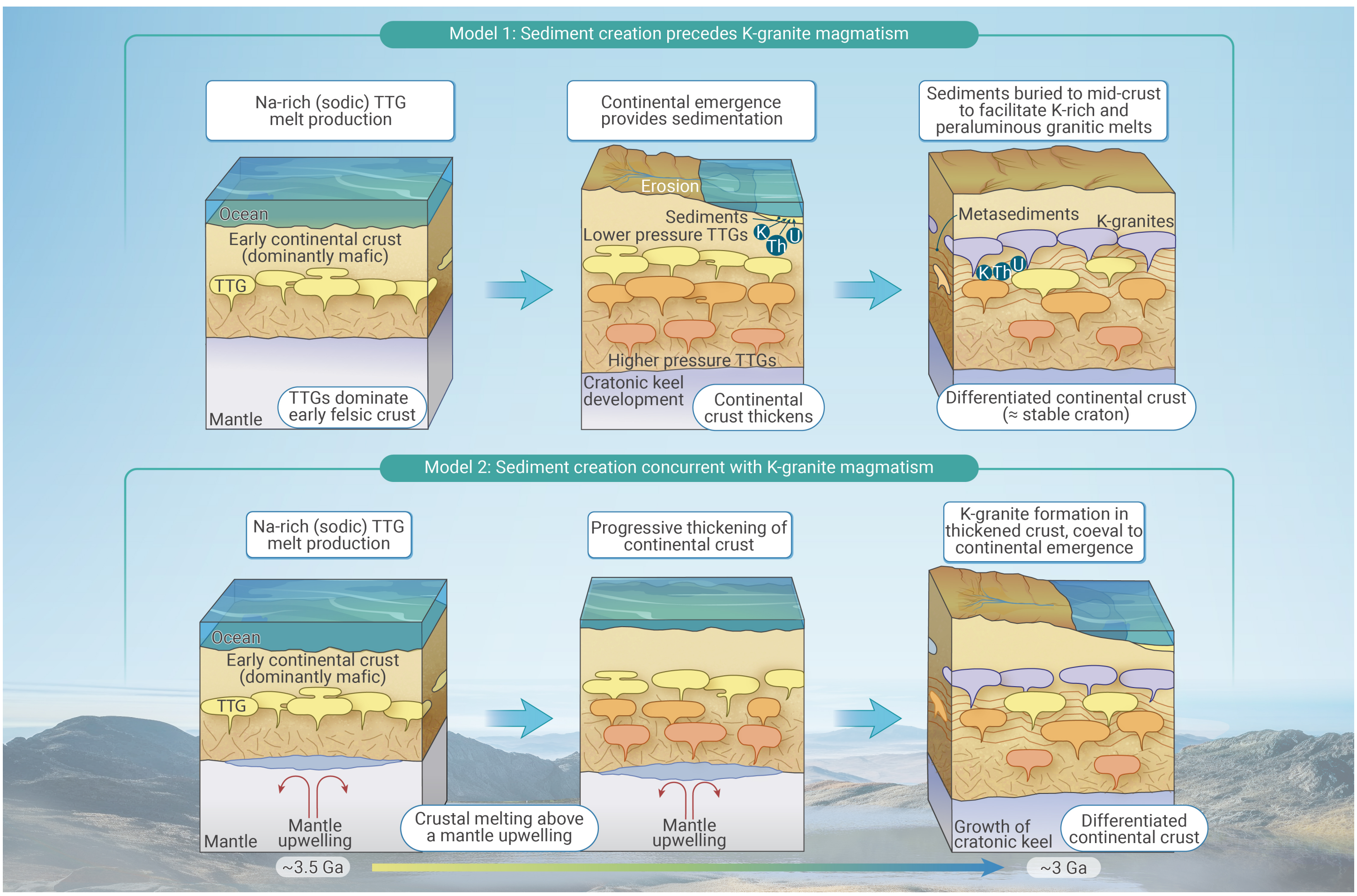

Figure 1. Two contrasting models for creating stable and emergent continental crust Model 1 is based on Reimink and Smye (2024) and Model 2 is based on Chowdhury et al. (2021). TTG = tonalite-trondhjemite-granodiorite. In both models, magmatism evolves through time as a consequence of intracrustal differentiation and increasing thickness of the crustal column. TTG magmatism requires hydrous melting, and the mechanisms to incorporate water into the early formed continental crust remain debated. Both models require burial of sediments into the mid-to lower crust to generate K-rich and peraluminous granites; the mechanisms of this burial likely involve horizontal tectonics (not depicted).

THE BUILDING BLOCKS OF ARCHEAN CONTINENTAL CRUST

It is well established that the composition of felsic magmatic rocks underwent secular changes through the Archean, dominantly comprising Na-rich TTGs in the Eoarchean and Paleoarchean, and involving increasing volumes of K-rich granites through the Mesoarchean to Neoarchean. This pattern occurs diachronously across all of Earth's cratons. The production of voluminous K-rich granites is thought to represent a time when the early continental landmasses would have fully matured into stable cratons – these cratons survive today, and form the continental nuclei to most continents. TTGs form via melting of hydrated mafic protoliths, a process most easily envisaged in subduction-zone settings; however, alternative models include melting at the base of thick piles of basalt that may form above mantle upwellings or plumes,[1] or within dense lower crust that drips into the mantle.[2] The younger K-granites form through intra-crustal differentiation, i.e. melting of pre-existing intermediate composition TTG crust,[1,3] and these are accompanied by minor peraluminous granites that record melting of metasedimentary protoliths. Granulite rocks provide evidence for high-temperature metamorphism of the Archean mid-to lower crust, with the timing of metamorphism commonly overlapping the formation of the K-rich granites.[3] Archean continental crust is associated with thick cratonic keels that stabilise the continents, making them more resistant to deformation and destruction during younger orogenesis.

THE SIGNIFICANCE OF CONTINENTAL EMERGENCE

Continental emergence marked a turning point in Earth history. Once significant landmasses were above sea level, these would have drastically changed the sedimentation into the oceans, and the weathering of the exposed crust would have altered atmosphere and hydrosphere. Arguably, continental emergence does not require specific tectonic mechanisms to occur, but could result from the effects of secular mantle cooling linked to increasing continental volumes, decreasing oceanic crustal thickness, and increasing lithospheric strength, and perhaps also relying on the growth of cratonic keels.[3] Tectonic or magmatic thickening have been argued to contribute to continental emergence,[1] but it is debated whether these processes can lead to early emergence of the crust, or merely act in concert with other long-term secular physical changes.

Chowdhury et al.[1] provide a model for continental emergence specific to the Singhbhum craton in India. The key points of their model are that: (1) the continental crust was thickened as a response to evolving magmatism above a mantle upwelling; (2) magmatism evolved from TTGs to K-rich granites without external drivers; and (3) K-rich granite magmatism was contemporaneous with continental emergence (Figure 1). Reimink and Smye[3] provide an alternative model that relies on calculations of heat production back in time, and associated modelling of geothermal gradients and the conditions and compositions of crustal melts (Figure 1). The key points of their model are that: (1) the heat production of TTG crust is too low to produce voluminous K-rich magmas, and too low to match metamorphic conditions recorded in extant geological record; (2) continental emergence producing abundant continental sedimentation preceded the formation of K-rich granites; (3) burial of sedimentary material with high heat production increased crustal geotherms, thereby allowing the production of K-rich and peraluminous granites; and (4) differentiation of the continental crust, via high HPE granitic magmatism intruding the upper crust, leaving a low HPE residue in the lower crust, led to stabilisation of the continents.

Two contrasting and key facets can be drawn from these models. The first is that the timing of cratonic keel formation is key to understanding continental evolution. Reimink and Smye[3] argue that cratonic keels were already formed by the time of the voluminous K-granite bloom in the Neoarchean. Critically, they argue that these rule out a model whereby mantle upwelling provides the necessary heat for crustal melting and granulite metamorphism, as upwellings would remove any pre-existing mantle keel. In contrast, Chowdhury et al.[1] do not discuss the mechanism of keel formation, but indicate that it formed after continental emergence and the K-granite bloom. Their model of magmatism above a mantle upwelling means a keel would have been unlikely have to have existed *a priori*. The second key facet is that Chowdhury et al.[1] allow for formation of K-granites through intracrustal differentiation, i.e. melting of pre-existing crust. In contrast, Reimink and Smye[3] argue this is unfeasible due to material and condition requirements; firstly, sediments are needed to produce peraluminous compositions of any volume, and secondly, mid-crustal temperatures without the burial of high HPE sediments into the mid-crust would be too low. In short, the model of Reimink and Smye[3] can be distilled into the following recipe for creating stable, differentiated, continental crust: (1) subaerial exposure and weathering of the extant continental crust to produce voluminous continental sedimentation, (2) burial of these sediments into the middle or lower crust, and (3) melting of these sediments and the surrounding meta-igneous crust to produce both K-rich and peraluminous granites. What do these models mean for Archean geodynamics? Chowdhury et al.[1] argue for a specific geodynamic setting - a mantle upwelling, and critically, the lack of a subduction environment. In contrast, Reimink and Smye[3] avoid speculating on specific geodynamic settings. A key point of both models is that both continental emergence and the change from Na-rich to K-rich magmatism, are not linked to specific changes in geodynamic setting.

NO WATER, NO GRANITE?

The two models outlined above discuss the formation of the dominant felsic component to Archean continental crust - TTGs; however, these papers omit one important ingredient - water. Voluminous melt formation from a mafic protolith, without requiring very high melt temperatures, requires the significant availability of water at the site of melting.[4] This requirement for water has been argued[5] to negate any model of TTG formation via vertical tectonic processes, such as melting of crustal drips, or melting at the base of a thick basaltic plateau. Arndt[5] argues that neither process can account for enough water availability, and thus, that subduction-zone environments provide the only plausible geodynamic setting for generation of Archean felsic continental crust. However, there is a possible alternative source of water - komatiites. These high-Mg rocks, most abundant in the Archean, undergo alteration on the seafloor which leads to them being significantly hydrated. If involved in crustal melting, they will release significant water which can then facilitate the melting of basaltic rock to form TTGs.[4] Such a model arguably negates the need for subduction, and thus, the debate on Archean tectonics continues.

FUTURE DIRECTIONS

Understanding the formation of differentiated Archean continental crust is clearly a game of chicken or egg. Did continental emergence and sedimentation precede K-rich magmatism, or did K-rich magmatism in a thickened crust then lead to continental emergence? Furthermore, did cratonic keel formation lead to continental emergence, or result from it? As with all geological science, the answers rely heavily on time. Precise craton-specific timings of cratonic keel formation, continental emergence, sedimentation and K-granite magmatism, will all contribute to answering these questions of chicken or egg, and ultimately, our understanding of how the continental crust came to be.

Based on the salient features of the models discussed, a recipe for creating Earth's stable and differentiated continental crust requires: (1) both mafic and metasedimentary protoliths, (2) deep crustal water availability, and (3) elevated radiogenic heating. However, a recipe needs more than ingredients - how are they mixed together, and in what order? Although Reimink and Smye[1] provide an elegant model, their study stimulates a number of further questions for understanding this key time in Earth's history: (1) Continental emergence is a natural consequence of thickening crust on a cooling mantle, but was emergence of individual cratons stimulated or sped up by tectonic or magmatic processes, and did the timing of this emergence vary significantly from craton to craton? (2) If potassic and peraluminous magmatism require metasedimentary protoliths, how were these incorporated into the mid- or lower crust, and does this incorporation involve plate tectonics? (3) What is the source of water in TTG generation, and does it require subduction?

REFERENCES

1. Chowdhury, P., Mulder, J.A., Cawood, P.A. et al. (2021). Magmatic thickening of crust in non–plate tectonic settings initiated the subaerial rise of Earth's first continents 3.3 to 3.2 billion years ago. Proc. Natl. Acad. Sci. USA 118: e2105746118. DOI:10.1073/pnas.2105746118.
2. Nebel, O., Capitanio, F.A., Moyen, J.F., et al. (2018). When crust comes of age: on the chemical evolution of Archaean, felsic continental crust by crustal drip tectonics. Phil. Trans. R. Soc. A 376: 20180103. DOI: 10.1098/rsta.2018.0103.
3. Reimink, J.R. and Smye, A.J. (2024). Subaerial weathering drove stabilization of continents. Nature 629: 609-615. DOI:10.1038/s41586-024-07307-1.
4. Tamblyn, R., Hermann, J., Hasterok, D., et al. (2023). Hydrated komatiites as a source of water for TTG formation in the Archean. Earth Planet. Sci. Lett. 603: 117982. DOI:10.1016/j.epsl.2022.117982.
5. Arndt, N. (2023). How did the continental crust form: No basalt, no water, no granite. Precambrian Res. 397: 107196. DOI:10.1016/j.precamres.2023.107196.

ACKNOWLEDGMENTS

The author acknowledges the editor and reviewers for their constructive comments, and is partly funded through the UK Natural Environment Research Council (NE/Y005449/1).

DECLARATION OF INTERESTS

The author declares no competing interests.