The co-evolution of Earth's continental crust and atmosphere: a Si isotope perspective

University of St Andrews, School of Earth and Environmental Sciences

In partnership with Durham University

Supervisory Team	
	• Paul S. Savage, University of St Andrews • Kevin W. Burton, Durham University • Catherine Rose, University of St Andrews • Tony Prave, University of St Andrews

Key Words	
	1. Great Oxidation Event; 2. Snowball Earth; 3. Silicon isotopes; 4. Continental crust evolution; 5. Glacial diamictites

Overview

The oldest rocks on Earth today are found as parts of the continental crust. These rocks, (i.e. upper continental granitoids, intrusive mafic rocks, sediments and their metamorphic equivalents) record both the petrogenetic processes that formed new crust, and also the processes of weathering and alteration on Earth's surface, over 4.0 Ga of Earth history.

Of particular interest are the times before, leading up to and just after the so-called Great Oxidation Event (GOE; ~ 4.0-2.0 Ga). The rock record from the Hadean, Archaean and Palaeoproterozoic is sparse compared to more recent geological periods, yet this time span – around 50% of Earth's history – is thought to include the establishment of subduction-driven plate tectonics and the rise of atmospheric oxygen and life on Earth [1].

One isotope system that could inform us about the evolution of both of these important phenomena in terms of their effects on the (upper) continental crust is silicon – THE defining element of the silicate Earth. Silicon isotopes behave relatively predictably during igneous differentiation such that Phanerozoic granites without a strong sedimentary component in their source (i.e. I- or M-type) have extremely consistent compositions [2]. It is unclear, however, whether the style of mantle melting during the Archaean (i.e. to form the so-called tonalite-trondhjemite-granodiorite TTG suites; Fig. 1, [3]) would lead to a similar bulk Si isotope composition of the continental crust. Understanding how Si isotopes behaved during the formation of Earth's earliest continental crust has the potential to illuminate the broader petrogenesis of this reservoir over time.

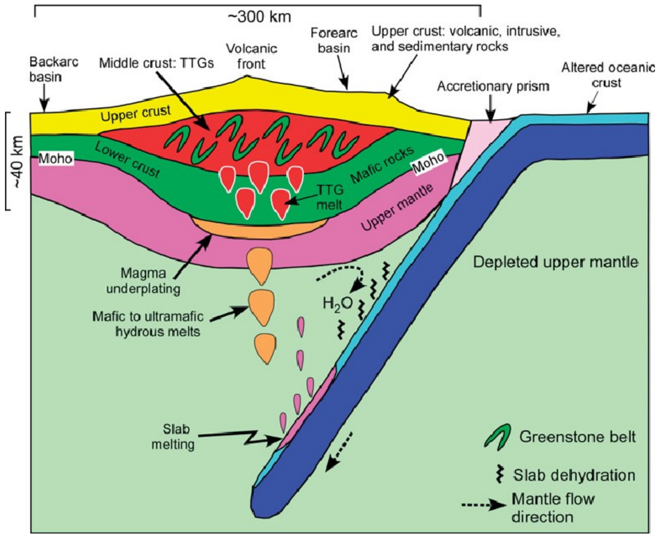

Figure 1. Schematic cartoon of a prevailing view of how formation of TTG crust differs from modern day subduction (from Polat, 2012)

Silicon isotopes also behave relatively predictably during continental chemical weathering – for instance during the formation of pelitic sediments [4, 5]; whereby increasing chemical denudation of the source rock leads to increasing negative isotopic signatures. In simple terms, the more intense the weathering degree, the more fractionated the Si isotopes will become.

Again, however, this is during surface weathering in our modern-day atmosphere, rich in oxygen, and poor in methane and (relatively) poor in CO_2. Can we see a secular effect of the evolution of the composition of Earth's atmosphere on the Si isotope composition of chemical sediments?
This study aims to investigate the question: **Has the average Si isotope composition of the Earth's continental crust varied over time?** In particular, what effect has the evolution of plate tectonics and the atmosphere had on the silicon budget of the continental crust? To do this, the project will focus on two broad lithologies:

1. Cratonic basement rocks – e.g. TTGs – consisting of metaigneous and metasedimentary rock units – from Greenland and Scotland.
2. Glacial diamictites and associated siliciclastic strata deposited at key time intervals sourced globally (Fig. 2).

The advantages of using glacial deposits and associated strata to constrain bulk continental crust compositions are numerous:

- Large ice sheets sample large areas of crust
- Glacial milling implies predominantly physical weathering, with limited fractionation as a result of deposition
- There is generally thought to be limited phase sorting during deposition (as opposed to loess or shale)
- Secular changes in a number of elemental and isotopic systems have already been analysed in similar sample sets [6, 7]

Throughout the project there will be opportunities to sample glacial diamictites in the field, which straddle or accompany significant global terrestrial environmental changes such as Snowball Earth events spanning the GOE. The project will further characterise the Si isotope cycle on Earth through time, and has the potential to characterise a new geological proxy for weathering intensity or continental crust formation.

Methodology

The main aim of this project is to constrain the bulk Si isotope composition of the Earth's continental crust over the period from ~4.0 to 0.3 Ga, with an ultimate goal of using variations (or lack thereof!) in Si isotope composition to make broad inferences about early continental crust petrogenesis as well as weathering strength and style. This will be accomplished by measuring a broad range of continental crust-derived materials – this could involve field work, mapping/logging, sample preparation, in collaboration with the Continental Geochemistry Group at the University of California, Santa Barbara, who established the use of tillites as proxies for continental crust isotopic composition [6, 7]. The student will begin by working on the samples collected, prepared and characterised by Gaschnig et al. [7]. In addition, new 'composite' samples will be generated by sampling tillite horizons at different localities, separating matrix from clasts and combining each sampled horizon in equal quantities. These will then be characterised for major and trace element compositions at St Andrews and Durham University, and all samples will require Si isotope analysis - by high resolution multi-collector inductively coupled plasma mass spectrometry (MC-ICPMS) – which will be performed by the student at St Andrews and Durham.

Figure 2. Diamictite from the Varangian glaciation, Norway (from www.sandatlas.org)

The potential for the Si isotope system to be used as a proxy for weathering degree/intensity could be explored in other extreme climatic events on Earth – and following the initial whole-Earth investigation, there is the potential for the student to investigate Si isotope variations in detail in the glacial deposits formed after more recent global glaciation events.

Timeline

Year 1: Literature review and compilation of existing data for ancient and modern continental crust and sampling proxies; identification of localities and sampling strategy; acquisition of extant samples and field work planning; training in rock sampling and characterisation techniques, elemental and stable isotope analysis; fieldwork to take place in summer between Years 1 and 2; write and defend Year 1 Research Proposal.

Year 2: Characterisation of collected samples from field work; continued Si stable isotope analysis of all samples; begin stable isotope modelling of data. Prepare GOE data for presentation/publication; attend Goldschmidt geochemistry conference.

Year 3-3.5: Completion of isotope work and interpretation and modelling of data, writing up. Presentation of results at a national/international conferences; complete thesis.

Training & Skills

- Field sampling of the appriopriate ancient sedimentary deposits; sampling characterisation techniques
- Training in the measurement of Si stable isotopes using high precision MC-ICP-MS at St Andrews and Durham, as well as routine elemental sample characterisation.
- Interpretation and modelling of isotope and elemental data to place new constraints on the terrestrial Si isotope cycle through geological time.
- Participation and presentation of research at both national and international geochemistry conferences.

References & Further Reading

[1] Canfield, D. (2005) The Early History of atmospheric oxygen. Annu. Rev. Earth. Planet. Sci. 33, 1-36.
[2] Savage, P.S. et al. (2014) High temperature silicon isotope geochemistry. Lithos 190-191, 500-519.
[3] Polat, A (2012) Growth of Archaean continental crust in oceanic island arcs. Geology, 40(4), 383-384
[4] Savage, P.S. et al. (2013) The silicon isotope composition of the upper continental crust. Geochim. Cosmochim. Acta, 109, 384-399.
[5] Opfergelt, S., & Delmelle, P. (2012) Silicon isotopes and continental weathering processes: assessing controls on Si transfer to the ocean. Comptes Rendus Geoscience 344(11-12), 723-738.
[6] Gaschnig, R., et al. (2014) Onset of oxidative weathering of continents recorded in the geochemistry of ancient glacial diamictites. EPSL 408, 87-99.
[7] Gaschnig, R., et al. (2016) Compositional evolution of the upper continental crust through time, as constrained by ancient glacial diamictites. Geochim. Cosmochim. Acta, 186, 316-343.

Further Information

For further information please contact Paul Savage (pss3@st-andrews.ac.uk; 01334 464013) or Kevin Burton (k.w.burton@dur.ac.uk; 0191 3344298).