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Neoarchean crustal recycling and mantle metasomatism: Hf–Nd–Pb–O isotope evidence from sanukitoids of the Fennoscandian shield

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ABSTRACT

The growing knowledge of the geological record reveals evidence of crustal recycling in the Archean eon. In order to assess the role of recycling of crust into the mantle we have analyzed radiogenic Hf-in-zircon as well as whole-rock Nd and Pb isotope compositions of mantle-derived granitoids of the sanukitoid series in the Neoarchean Karelian province, Fennoscandian shield. Homogeneous initial Hf and Nd values suggest that sanukitoids are derived from well-mixed source(s). Limited scatter in the initial Pb isotope data within intrusions as well as in other radiogenic isotopes point to effective mixing processes in the mantle. O isotope data for zircon from Karelian sanukitoids indicate a dominant mantle source ($\delta^{18}O$ = +5.5–6.1‰) with minor contributions from sources with elevated $\delta^{18}O$ (+7.0‰ to +8.5‰), such as sediments and altered upper oceanic crust. Our results suggest that the parental melts of sanukitoids are mixtures of depleted mantle and recycled crustal components. A slab breakoff at the end-stage of subduction is a plausible trigger mechanism for sanukitoid magmatism and it explains variable contributions from different $\delta^{18}O$ sources.

1. Introduction

The Earth's continental crust to a large extent consists of granitoids. Some compositional characteristics of these rocks are correlated with age, suggesting that granitoids have formed in different tectonic settings at different stages of Earth history. Thus granitoids can provide information on changes in plate tectonic processes. A large fraction of the Archean (4.0–2.5 Ga) continental crust is made up of orthogneisses commonly referred as "grey gneisses". The majority of the "grey gneisses" belong to the tonalite-trondjhemite-granodiorite (TTG) series (e.g., Jahn et al., 1981; Martin, 1987, 1994; Drummond and Defant, 1990), which is almost absent from the post-Archean record. TTG magmas are commonly interpreted as partial melts of metabasaltic rocks, either in a subduction setting (e.g., Martin and Moyen, 2002) or in thickened crust (e.g., Smithies, 2000; Condie, 2005). Melting at pressures ranging from <10 kbar to >25 kbar resulted in significant differences in the residue mineralogy and trace element composition (Moyen and Stevens, 2006; Moyen, 2011). Various subdivisions of the TTG series have been proposed (e.g., Luais and Hawkesworth, 1994; Clemens et al., 2006; Champion and Smithies, 2007; Halla et al., 2009), so the TTG group might in reality include several different series (Moyen, 2011).

Shirey and Hanson (1984) described a minor, but distinct Archean rock group called sanukitoids that also lacks well-defined recent counterparts, although, certain post-Archean granitoid suites share some geochemical characteristics of sanukitoids [e.g., Proterozoic plutonic shoshonites (e.g., Eklund et al., 1998; Conceição and Green, 2004) Caledonian high Ba–Sr plutos from Scottish highlands (e.g., Fowler et al., 2008), and Carboniferous Mg–K granitoids from Corsica–Sardinia (e.g., Rossi and Cocherie, 1991)]. Geochemically the sanukitoid series shows a clear mantle signature with high contents of Mg, Ni, Cr and high Mg#, combined with high LILE; especially K, Ba and Sr at a given SiO_2 content. The sanukitoid series comprises diorites, tonalites, granodiorites, monzonites, and even gabbros that are magnesian, and mostly metaluminous (Stern et al., 1989; Stern and Hanson, 1991; Smithies and Champion, 2000; Martin et al., 2009; Heilimo et al., 2010). Sanukitoid intrusions are variably-sized, even-grained to K-feldspar porphyritic, making up ~1–5% of the exposed Archean crust, and have been emplaced between ~2.95 and 2.55 Ga, typically post-dating a long period of episodic and voluminous TTG magmatism (Heilimo et al., 2011 and references therein).

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The sudden emergence of sanukitoid magmatism indicating presence of an enriched mantle source at the Meso- to Neoarchean transition has caused a debate on the onset of modern plate tectonics, since the enrichment/metasomatism of the subcontinental lithospheric mantle with incompatible elements requires recycling of crustal material into the mantle, which, in turn, is a process attributed to subduction. A process that may have caused the abrupt appearance of sanukitoid magmatism is slab breakoff (Calvert et al., 2004; Whalen et al., 2004; Lobach-Zhuchenko et al., 2008; Halla et al., 2009), following an attempted subduction of buoyant continental lithosphere during continental collision. The slab breakoff hypothesis for sanukitoids is supported by numerical geodynamic modeling on Archean subduction, which suggests frequent events of slab breakoffs (van Hunen and van den Berg, 2008).

The aim of the research reported here is to study and compare the Hf–Nd–Pb–O isotope systematics of the sanukitoids from the Fennoscandian (new data from the westernmost Karelian province) and Canadian (published data from the Superior and Slave provinces) shields to get insight into proposed crustal recycling and mantle metasomatism. The isotope composition of Hf, Pb, and Nd in igneous rocks reflects the relative contributions of mantle and crustal sources in their genesis, and can be used to constrain the tectonic processes causing their formation. Stable O isotopes offer an isotopic tool to distinguish between well-mixed sources, ancient mafic components, and recycled (sedimentary) components.

2. Geological setting

The Fennoscandian shield consists of Proterozoic and Archean domains. Archean rocks cover much of the eastern and northern part of the shield and have been divided into four provinces, Karelian, Kola, Belomorian, and Norrbotten (Fig. 1, inset map), which have been variably affected by Paleoproterozoic reworking (Hölttä et al., 2008).

2.1. The Karelian province

This study concentrates on the Karelian province (Fig. 1) as defined by Slabunov et al. (2006), and Hölttä et al. (2008). The metamorphic peak conditions at 2.7–2.6 Ga in the study area are mostly upper amphibolites to granulite facies. The Karelian province is divided into the Western Karelian, Central Karelian, and Vodlozero subprovinces, which differ from each other in terms of lithology, structure and geochronology. Sanukitoids occur across the Karelian province in two separate zones: The western and eastern zones. Intrusions in the western sanukitoid zone are homogeneous, single phase intrusions, varying in composition from diorite to granodiorite. These intrusions are dated at ~2.72 Ga and are located in the Western Karelian subprovince. The eastern sanukitoid zone is found both in the Central Karelian and Vodlozero subprovinces. These intrusions are ~2.74 Ga old and strongly differentiated, varying from ultramafic to felsic in composition (Bibikova et al., 2005; Lobach-Zhuchenko et al., 2005).

2.1.1. The Western Karelian subprovince

The Western Karelian subprovince in eastern Finland and in the westernmost parts of Russia is the key area of the study. The westernmost (Finnish) part of the province is a diverse mosaic of rocks that has been divided into the Ranua (a.k.a. Pudasjärvi), Iisalmi, Ilomantsi, and Kianta complexes (Sorjonen-Ward and Luukkonen, 2005; Fig. 1). The oldest exposed rocks in the Karelian province and in the Fennoscandian shield are the ~3.5 Ga Siurua gneisses located in the Ranua complex (Mutanen and Huhma, 2003). Hf isotope data from zircon (Lauri et al., 2011) as well as older inherited zircon cores (Mutanen and Huhma, 2003) hint on an even older crustal history for this rock. The Western Karelian subprovince consists mainly of Archean granitoids and migmatites, greenstones and paragneisses of low metamorphic grade and less abundant higher-grade metamorphic rocks. The granitoid rocks in the largest complex in Finland, Kianta, can be divided into: TTG gneisses (2.95–2.75 Ga), sanukitoids (~2.72 Ga), quartz diorites (2.72–2.69 Ga) and anatectic granites and leucogranites associated with extensive migmatization (~2.68 Ga) (Käpyaho et al., 2006, 2007; Heilimo et al., 2010, 2011; Lauri et al., 2011; Mikkola et al., 2011a). The greenstone belts are mainly 2.84–2.79 Ga old, dominated by mafic volcanic rocks and found as N–S trending elongated slivers (e.g., Luukkonen, 1992; Papunen et al., 2009). The best described granulites are exposed in the Iisalmi complex, with protolith ages of 3.2–3.1 Ga (Hölttä et al., 2000; Mänttäri and Hölttä, 2002; Nehring et al., 2009). The southern flank of the Western Karelian subprovince is partly covered by metasedimentary Nurmes-type paragneisses, derived from immature greywackes that were metamorphosed and thrusted eastward during a narrow time interval between 2.72 and 2.69 Ga (Kontinen et al., 2007).

2.1.2. The Central Karelian subprovince

The Central Karelian subprovince is located mostly in Russia with small parts extending into easternmost Finland. It differs from the Western Karelian and Vodlozero subprovinces by a somewhat younger crust-forming period at ~2.76–2.73 Ga. The granitoid magmatism is dominated by the TTG type, with several small intrusions of ~2.74 Ga sanukitoids. Greenstone belts consist mainly of volcanic rocks, with subordinate sedimentary rocks and, like the granitoids, record younger ages and a shorter duration of crust-forming events (~2.75–2.73 Ga), compared with the greenstones in the Western Karelia and Vodlozero subprovinces.

2.1.3. The Vodlozero subprovince

The Vodlozero subprovince, located in the southeastern part of the Karelian province, comprises mostly of ~3.2–2.7 Ga old lithologies. The most abundant rocks are TTGs with ages of 3.2–2.8 Ga. Both homogeneous, and migmatized TTG varieties occur. Also, less voluminous gabbroids are found. The youngest Archean crust forming event was the intrusion of minor granites and mafic dykes at ~2.7–2.6 Ga as well as few sanukitoid intrusions belonging to the eastern sanukitoid zone. The compositionally variable greenstone belts were formed periodically between 3.10 Ga and 2.65 Ga.

2.1.4. Post-Archean activity

The Paleoproterozoic rifting of the Karelian domain is marked by the emplacement of 2.4 Ga, mafic layered intrusions (e.g., Alapieti, 1982; Balashov et al., 1993), and coeval A-type granitoids (Lauri and Mänttäri, 2002; Lauri et al., 2006; Mikkola et al., 2010) into the Archean crust. These were followed by several minor, cross-cutting mafic dyke swarms with ages up to 1.98 Ga marking the final breakup of the Archean nucleus (Vuollo and Huhma, 2005). The Archean crust was reworked during the convergent Svecofennian (~1.9–1.8 Ga; Nironen, 1997) and Lapland–Kola (~1.9 Ga; Daly et al., 2001) orogenies. Evidence from Proterozoic reworking includes the ~1.9–1.8 Ga K–Ar ages from amphibolites and biotites from the southwestern parts of the Western Karelian subprovince (Kontinen et al., 1992).

3. Analytical methods

3.1. Lu–Hf isotope geochemistry of zircon

Zircons were separated by standard methods (Wilfrey-table washing, heavy liquids and Franz magnetic separation) at the isotope laboratory of the Geological Survey of Finland. Selected zircons were mounted on tape, cast in epoxy and polished. Prior to laser