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GR Focus

An overview of the geochemistry of Eoarchean to Mesoarchean ultramafic to mafic volcanic rocks, SW Greenland: Implications for mantle depletion and petrogenetic processes at subduction zones in the early Earth

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ABSTRACT

This study reviews the geochemical characteristics of Eoarchean to Mesoarchean ultramafic to mafic volcanic rocks (now amphibolites) in SW Greenland and compares them with those of Cenozoic oceanic island arc basalts, to evaluate Archean subduction zone petrogenetic processes. Emphasis is placed on the Th–REE–HFSE (Zr, Ti, and Nb) systematics of the ca. 3800 and ca. 3700 Ma arc suites in the Isua greenstone belt, the ca. 3075 Ma Ivisaartoq–Ujarassuit greenstone belt, and amphibolites associated with the ca. 2970 Ma Fiskenæsset layered anorthosite complex.

On N-MORB-normalized diagrams, the Isua, Ivisaartoq–Ujarassuit, and Fiskenæsset volcanic rocks are all characterized by depletion of Nb relative to Th and LREE, consistent with a supra-subduction (forearc–arc–backarc) geodynamic setting. Similarly, on the Th/Yb–Nb/Yb projection, these suites plot within the field of Cenozoic oceanic island arc basalts. On log-transformed immobile trace element ratio (Nb/Th, La/Th, Sm/Th, and Yb/Th) diagrams, they display a trend projecting from MORB (Mid-Ocean Ridge Basalt) to IAB (Island Arc Basalt) on the IAB–CRB (Continental Rift Basalt)–OIB (Ocean Island Basalt)–MORB diagram, as for Cenozoic oceanic island arc basalts. Accordingly, these trace element compositions are interpreted as reflecting the enrichment of Archean depleted upper mantle (MORB-source) by subduction-derived melts and fluids following the initiation of intra-oceanic subduction and arc migration.

Concentrations of MgO and Ni in SW Greenland Archean basalts overlap with, but extend to 2 to 4 times higher than, those in Cenozoic oceanic island arc counterparts. In contrast, the majority of Archean basalts have REE and HFSE concentrations 2 to 4 times lower than Cenozoic oceanic island arc basalts, consistent with more depleted sub-arc mantle wedge peridotites in the Archean than in Cenozoic counterparts. Such depletion reflects the extraction of large volumes of mafic to ultramafic melts from hotter Archean mantle. We infer that less refractory compositions of the Present-day depleted upper mantle, the source of MORB and conservative HFSE in arc basalts, have resulted from re-mixing with the less depleted to enriched deeper mantle material transferred to shallower depths by mantle convection and plumes in post-Archean times.

Archean basalts in SW Greenland share the negative Nb and Ti anomalies of Cenozoic oceanic island arc basalts. On average, Archean basalts, however, have lower Th/Nb, La/Nb, Sm/TiO_2 and Gd/TiO_2 ratios than Cenozoic oceanic island arc counterparts. Given that rutile controls the Nb and Ti budgets in arc magmas, the lower Th/Nb, La/Nb, Sm/TiO_2 and Gd/TiO_2 ratios in SW Greenland basalts are attributed to the mobility of Nb and Ti in slab-derived melts involving rutile fusion in Archean subduction zones. These elements are less mobile in fluids originating from Cenozoic subducting oceanic crust where rutile appears to be generally stable. Accordingly, it is suggested that higher geothermal gradients in the Archean may have provided optimized conditions for slab melting and metasomatism of the sub-arc mantle wedge by slab-derived melts.

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1. Introduction

The geodynamic origin of Archean greenstone belts, or terranes, has been extensively debated in the literature (Windley, 1993; Condie, 1981, 2005; de Wit, 1998; Kusky, 2004; Cawood et al., 2006; Kerrich and Polat, 2006; Furnes et al., 2009; Ernst, 2009; Herzberg et al., 2010). A number of geological models, including uniformitarian and non-uniformitarian plate tectonic models have been proposed to explain the origin of these greenstone terranes (Windley, 1993; de Wit, 1998; Hamilton, 1998; Kusky and Polat, 1999; Polat and Hofmann, 2003; Cawood et al., 2006; Stern, 2005; Dilek and Polat, 2008; Nutman et al., 2009). Uniformitarian models have invoked Present-day like geodynamic settings including intra-continental rifts, mid-ocean ridge rifts, backarc basins, island arcs, ocean plateaus, plumes in a continental setting, and subduction–accretion complexes, or some combination, to account for the variety of structural, lithological, and geochemical characteristics of Archean greenstone belts. Specifically, the Superior Province, the largest Archean craton in the world, has been interpreted as a series of allochthonous, amalgamated oceanic and continental fragments or tectonostratigraphic terranes, ranging in age from 3700 to 2680 Ma, and accreted from north to south over 40 million years between 2720 and 2680 Ma (Stott, 1997; Percival et al., 2006, and references therein). Similarly, on the basis of detailed field observations, contrasting ages, and metamorphic histories, several studies have shown that the SW Greenland Archean craton is a collage of Eoarchean to Neoarchean oceanic island arcs and continental fragments, assembled in several accretionary tectonothermal events by horizontal tectonics (McGregor, 1973; Bridgwater et al., 1974; Friend et al., 1988, 1996; Friend and Nutman, 2005a,b; Polat et al., 2008; Garde, 2007; Nutman et al., 2002, 2009; Ordóñez-Calderón et al., 2009; Windley and Garde, 2009).

Over the last two decades, numerous geochemical studies have used trace element data to interpret the geodynamic origin of Archean greenstone belts, specifically associations of volcanic rocks to circumvent ambiguities of geodynamic interpretations arising from single lithotypes that may erupt in a variety of settings (e.g., Xie et al., 1993; Dostal and Mueller, 1997; Polat et al., 1998, 2002, 2005, 2006; Kerrich et al., 1998; Wyman et al., 2000; Parman et al., 2001; Wilson, 2003; Hollings and Kerrich, 2004, 2006; Sandeman et al., 2004; Smithies et al., 2004, 2005, 2007; Garde, 2007; Manikyamba et al., 2008; Said et al., 2010, and references therein). Geodynamic interpretation in these studies is mainly based on normalized trace element patterns of the volcanic associations.

A number of lines of isotopic evidence from Archean rocks and Hadean zircon grains are consistent with the early differentiation of the mantle (Wilde et al., 2001; Boyet et al., 2003; Caro et al., 2003, 2006; Harrison et al., 2005, 2008; Bennett et al., 2007; Blichert-Toft and Albarède, 2008, and references therein). However, the consequences of early differentiation of the mantle on the trace element compositions of Archean ultramafic to mafic volcanic rocks have not adequately been addressed. In addition, Th–REE–HFSE (Nb, Ti, and Zr) fractionations in Eoarchean to Mesoarchean subduction zones have, so far, been poorly understood.

In this review, we summarize the geological and geochemical characteristics of the Eoarchean Isua greenstone belt (ca. 3800 and ca. 3700 Ma arcs), Mesoarchean (ca. 3075 Ma) Ivisaartoq–Ujarassuit greenstone belt, and amphibolites associated with the Mesoarchean (ca. 2970 Ma) Fiskenæsset layered anorthosite complex, SW Greenland (Figs. 1–3). New major and trace element data are also reported for eighteen samples from amphibolites associated with the ca. 2970 Ma Fiskenæsset layered anorthosite complex. The geochemical characteristics of Archean volcanic rocks in SW Greenland are compared with those of Cenozoic oceanic island arc basalts, using extensive major and trace element data (>700 analyses) from the Aleutian, Kuril, Mariana, Kermadec, Tonga, Vanuatu, and Scotia arcs. The main objectives of this study are: (1) to assess the geodynamic significance of Th–REE–HFSE systematics of Archean ultramafic to mafic volcanic rocks (now amphibolites) in SW Greenland, using N-MORB-normalized patterns, Nb/Yb–Th/Yb projection, and recently developed log-transformed trace element ratio (La/Th, Nb/Th, Sm/Th, and Yb/Th) discrimination diagrams (Agrawal et al., 2008); (2) to evaluate the degree of trace element depletion in Eoarchean to Mesoarchean upper mantle, as sampled by arc magmas, and its implications for mantle differentiation processes in the early Earth; (3) to address Th–Nb–REE–Ti fractionations in Archean subduction zones; and (4) in the light of this extensive database revisit the model of Pearce (2008) in which Archean arc volcanic sequences, that otherwise have intra-oceanic characteristics, are viewed as recording contamination by felsic crust.

Given that all Archean supracrustal rocks in SW Greenland are metamorphosed, the prefix 'meta' is implicit. Notwithstanding the fact that Archean supracrustal rocks in the Nuuk region were metamorphosed under amphibolite facies conditions, they are called "greenstone belts" to be consistent with the terminology used in our previous publications. Accordingly, the term "greenstone" used in this contribution does not imply greenschist facies metamorphism.

2. Regional geology and field relationships

The Archean craton of SW Greenland largely consists of Eoarchean to Neoarchean (ca. 3800–2700 Ma) orthogneisses with TTG (tonalite–trondhjemite–granodiorite) compositions (Steenfelt