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Partial melting in amphibolites in a deep section of the Sveconorwegian Orogen, SW Sweden

Edward Hansen [a,*], Leif Johansson [b], Jenny Andersson [c], Leah LaBarge [a], Daniel Harlov [d,e], Charlotte Möller [b], Stephanie Vincent [a]

[a] Department of Geology, Hope College, Holland, MI, 49423 USA
[b] Department of Geology, Lund University, Lund, Sweden
[c] Swedish Geological Survey, Uppsala, Sweden
[d] Section 3.3, GeoForschungsZentrum, Potsdam, Germany
[e] Department of Geology, University of Johannesburg, P.O. Box 524, Auckland Park 2006, South Africa

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ABSTRACT

Garnet amphibolite metataxites at the Steningekusten Nature Reserve in southwestern Sweden contain tonalitic patches and veins. Whole rock chemistry suggests that the protoliths were mafic igneous rocks with alkaline affinities. Orthopyroxene megacrysts are present in leucosome in parts of these garnet amphibolites but absent in others. Orthopyroxene megacrysts were formed by vapor-absent melting initiated by incongruent melting of biotite followed by the breakdown of hornblende. The net reaction was Bt + Hbl + Pl +/− Qtz ↔ Opx + Melt + Cpx + Gt. Melting occurred at pressures of approximately 1 GPa and temperatures which probably exceeded 800 °C. Pyroxenes are surrounded by hornblende–quartz symplectites, and hornblende in these coronas has distinctly lower concentrations of (Na + K) and Ti than that in adjacent mesosome. The hornblende rims formed upon cooling and reaction with crystallizing melt. This created a barrier to further reaction thus preserving the orthopyroxene megacrysts. Garnet amphibolite metatexites lacking pyroxene megacrysts have features characteristic of vapor-present melting including lack of peritectic phases predicted by vapor-absent melting reactions, larger amounts of leucosome (14 versus 7%), and less distinct melanosomes. The variation in these migmatites reflects open system behavior, either on a regional scale with the migration of aqueous fluids into the amphibolites or on a local scale with the migration of melt within the amphibolites. Zircons from all units have CL-dark core domains that are dated at 1415–1390 Ma. The core zones are cut and overgrown by CL-dark and CL-bright rims that are dated at 975–965 Ma. The zircon rims are thin in the mesosome but are thicker in the leucosome suggesting that they formed during migmatization. New growth of zircon associated with migmatization at ca. 970 Ma corresponds to the timing of crustal scale partial melting in the deep regions of the Sveconorwegian orogen, synchronous with east–west extension and the intrusion of mafic dykes. If partial melting was driven by an influx of aqueous fluids, they were probably derived from a relatively cool source region, which would indicate tectonic juxtaposition of hotter and cooler terranes.

1. Introduction

Granitic melts are produced by anatexis in pelites, metaluminous psammites, and felsic to intermediate igneous rocks under upper amphibolite to granulite facies conditions (Johnson et al., 2008; Tuttle and Bowen, 1958; White et al., 2001). As a consequence, migmatites containing granitic leucosomes are common and there have been many field-based studies of their formation (Sawyer, 2008 and references therein). These studies have had critical implications for our understandings of the evolution of metamorphic terranes and the origin of granites (Brown, 1994).

Experiments have shown that partial melting of mafic metamorphic rocks tends to form trondhjemitic, tonalitic, or dioritic melts (Beard and Lofgren, 1991; Rapp and Watson, 1995; Rushmer, 1991; Selbekk and Skjerlie, 2002; Springer and Seck, 1997; Wolf and Wyllie, 1994). Melting reactions involving amphiboles typically occur at higher temperatures than the melting reactions involving micas that mark the onset of melting in pelites, metapsammites and felsic to intermediate orthogneisses (Weinberg and Hasalová, 2015). Despite this migmatites with amphibolitic hosts and plagioclase–quartz rich tonalitic or trondhjemitic leucosomes are common in upper amphibolite to granulite facies terranes. Tonalitic and trondhjemitic compositions are also an important component of the continental crust (Martin et al., 2005), and are especially abundant in Archean high-grade terrains (Barker et al., 1981). Some models of the origin of these rocks involve the melting of

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[*] Corresponding author. Tel.: +1 616 395 7538.
E-mail address: Hansen@hope.edu (E. Hansen).

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garnitiferous amphibolites (Moyen and Martin, 2012) and field-based studies of the melting of garnitiferous amphibolites can potentially contribute to our understanding of the origin of this important rock type.

Despite their potential importance, and with some notable exceptions (Berger et al., 2009; Hansen and Stuk, 1993; Hartel and Pattison, 1996; Johnson et al., 2012; Kunz et al., 2014; Otamendi et al., 2009; Pattison, 1991; Sawyer, 2008; Selbekk et al., 2000; Storkey et al., 2005; Williams et al., 1995), there have been relatively few field-based studies of the formation of mafic migmatites. Thus, a number of important questions on the melting of amphibolites have been only partially answered. What are the sets of reactions responsible for the melting of amphibolites under natural conditions? What products and textures are produced by these reactions? How will these products and textures be modified upon uplift, cooling, and crystallization? What are the conditions (i.e. rock composition, temperature, and pressure) that determine which melting reactions will occur? What are the relative roles of fluid-absent (dehydration melting; Powell, 1983) and fluid-present (water-fluxed melting; Weinberg and Hasalová, 2015) melting in the development of mafic migmatites? What determines the amount of melt generated by anatexis in amphibolites? What techniques are suitable for determining the age of migmatization in mafic systems? Ultimately answers to these questions will allow us to evaluate questions such as which tectonic environments favor partial melting in amphibolites and the importance of this melting for the exhumation of metamorphic terranes.

In this paper we examine migmatitic garnet amphibolites from an upper amphibolite to granulite-facies, polymetamorphic terrane in the Eastern Segment of the Sveconorwegian orogen, southwestern Sweden. We combine field relationships, mineral chemistry, and whole rock chemistry to deduce the reactions involved in migmatization, the modifications of the migmatites upon cooling, the conditions of migmatization, and the relative role of a water-rich fluid. We also use in situ U–Pb analyses of different growth zones in zircon to date zircon growth during migmatization. The results of this study provide key data for modeling the metamorphic evolution of tectonically deeply buried sections of the polyphase Sveconorwegian orogen and incorporated pre-Sveconorwegian orogenic terranes exposed in the southwestern Baltic Shield. The study also provides important insights into the formation of migmatites from mafic compositions in high-grade metamorphic terranes.

2. Geological setting

The Sveconorwegian orogen is a ca. 500 km wide belt extending across the southwestern parts of the Baltic Shield (Fig. 1A). It has a similar age to the Grenville orogen in North America and formed by subduction to collisional orogenesis during the assembly of Rodinia (Bingen et al., 2008). The Eastern Segment (Fig. 1B) is the easternmost of five orogenic segments. It forms a ca. 50–100 km wide N–S trending mobile belt dominated by orthogneisses with protolith ages and chemical compositions equivalent to less reworked and undeformed 1.87–1.66 Ga old granites to quartz–monzonites of the Transscandinavian Igneous Belt in the pre-Sveconorwegian craton to the east (Petersson et al., 2013; Söderlund et al., 1999). Metamorphic grade ranges from greenschist to amphibolite facies along the eastern margin (frontal wedge), to upper amphibolite, high-pressure granulite and retrogressed ecologite facies in the internal section in the west (Möller et al., 2015a). Geothermobarometry applied to amphibolite to granulite facies mafic rocks from the lower internal section of the Eastern Segment yields temperatures of 680–800 °C and pressures of 0.8–1.2 GPa (Johansson et al., 1991; Möller, 1998; Wang and Linh, 1996). Retrogressed eclogites, occurring in a recumbent fold nappe (Möller et al., 2015a) were metamorphosed at pressures exceeding 1.5 GPa (Hegardt et al., 2005; Möller, 1998, 1999). Zircon U–Pb dating yield ages of 0.99–0.98 Ga for the ecologite facies metamorphism (Johansson et al., 2001; Möller et al., 2015a), followed by regional-scale ductile deformation and partial melting at 0.98–0.96 Ga (Andersson et al., 1999, 2002; Möller et al., 2007, 2015a; Piñán Llamas et al., 2015; Söderlund et al., 2002). The southern Eastern Segment records pre-Sveconorwegian regional-scale, high-grade metamorphism and deformation at 1.47–1.38 Ga (Hallandian orogeny: Hubbard, 1975; Christoffel et al., 1999; Söderlund et al., 2002; Möller et al., 2007; Ulmius et al., 2015), followed by intrusions of gabbro, anorthosite, monzonite, charnockite, granite and pegmatite at 1.41–1.38 Ga (Andersson et al., 1999; Brander and Söderlund, 2009; Christoffel et al., 1999; Hubbard, 1989; Möller et al., 2007). The Hallandian migmatitic structures were variably transposed by Sveconorwegian ductile deformation (e,g. Möller et al., 2007; Piñán Llamas et al., 2015).

2.1. The Stensjö Complex

The Stensjö Complex (Fig. 1C) is an association of amphibolites, sillimanite-bearing quartzo-feldspathic gneisses, and sillimanite-free quartzo-feldspathic gneisses, exposed along 6 km of the coast in the Eastern Segment (Piñán Llamas et al., 2015). The various rock types typically occur in foliation parallel sheets at scales ranging from over 10 cm to ≥10 m in width.

Amphibolites can be subdivided into a darker garnetiferous hornblende–biotite-rich variety and lighter gray types which commonly contain epidote and andradite–grossular bearing calc-silicate lenses. Leucosome, in foliation parallel bands and crosscutting veins and patches, is common in the garnetiferous amphibolite (Fig. 2A), which are metatexites. Orthopyroxene megacrysts are associated with leucosome in about 5% of the exposures of garnetiferous mafic metatexite.

Sillimanite–plagioclase–K-feldspar–biotite–quartz +/− garnet gneisses are intercalated with pink granitic pods and bands. Sillimanite-free quartzo-feldspathic gneisses consist of light gray bands of plagioclase–biotite–quartz–K-feldspar +/− garnet intercalated with granitic bands. The presence of sillimanite-rich gneisses and calcsilicate lenses indicate a supracrustal origin for at least part of the Stensjö Complex. The Stensjö Complex is in tectonic contact with polymetamorphic orthogneisses which make up the bulk of the Eastern Segment.

3. Methods

A glacially smoothed ca 100 meter-long section of mafic metaxite in the Steningekusten Nature Reserve was chosen for detailed study (Fig. 1C). With one exception, all samples were collected in situ using a rock drill. One sample was taken from a loose block within the outcrop.

The proportion of leucosome was estimated for different parts of the outcrop. In each part a representative 2 by 4 m rectangular area was chosen. The leucosome bodies within this rectangle were subdivided into rectangles or triangles and their average dimensions were measured in the field. The total areas of these polygons were summed and divided by the total area of the rectangle. Estimates of the proportion of leucosome were also made from digital images taken from a step ladder. The surface areas of leucosome in the images were calculated using a NIS-elements BR image analysis program.

Thin sections were examined with the JEOL LV-4500 scanning-electron microscope (SEM) in the Department of Geophysical Sciences, University of Chicago and the Hitatchi TM3000 SEM at Hope College. Mineral identification and elemental maps relied on semi-quantitative EDX analyses.

Electron microprobe analyses of amphibole, biotite, feldspar, garnet, and pyroxene were done with the CAMECA SX100 electron microprobe at the GeoForschungsZentrum Potsdam. Analyses were done at a 15 kV acceleration voltage, a beam current of 20 nA and counting times of 10–30 s. Standards were taken from the CAMECA standard set, and the Smithsonian silicate and oxide mineral standard set (Jarsosewich et al., 1980). The Cameca PAP program was used for matrix corrections