Lithos 114 (2010) 473–489

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

P–T evolution of Glenelg eclogites, NW Scotland: Did they experience ultrahigh-pressure metamorphism?

Krishnan Sajeev [a,*], Takahiro Kawai [b], Soichi Omori [b], Brian F. Windley [c], Shigenori Maruyama [b]

[a] Centre for Earth Sciences, Indian Institute of Science, Bangalore 560 012, India
[b] Department of Earth and Planetary Sciences, Tokyo Institute of Technology, O-Okayama 2-12-1, Meguro, Tokyo 152-8551, Japan
[c] Department of Geology, University of Leicester, Leicester LE1 7RH, UK

ARTICLE INFO

Article history:
Received 6 February 2008
Accepted 6 October 2009
Available online 20 October 2009

Keywords:
Glenelg–Attadale Inlier
Eclogites
Exsolution microstructure
Phase diagram
P–T condition
Scotland

ABSTRACT

Eclogites and their retrogressed equivalents from the eastern unit of the Glenelg–Attadale Inlier in NW Scotland preserve much microstructural evidence that indicates that very high-pressure/temperature eclogite facies conditions were reached, and followed by decompression and hydration during exhumation. Rutile exsolution in garnet and quartz exsolution in omphacite and titanite formed through mineral reactions during high *P–T* peak metamorphism. Isochemical phase diagrams modeled for samples from three different locations indicate that the outer part of the eastern unit preserves a peak metamorphic condition of *c.* 850–1000 °C at 18–25 kbar, whereas the central part has a similar pressure (*c.* 23 kbar), but a lower temperature (*c.* 670 °C). Due to the limitations in the phase diagram calculations the estimated *P–T* conditions represent the minimum conditions attained by the peak metamorphic assemblage, and the pre-exsolved peak assemblage probably stabilized at a higher pressure. This observation is strongly supported by the presence of exsolution microstructures. The present results demonstrate that the eastern unit experienced very high *P–T* conditions during peak metamorphism and a tight clockwise *P–T* trajectory and provide the first indication of possible ultrahigh-pressure metamorphism in the Glenelg eclogites.

1. Introduction

Eclogites or eclogite facies rocks provide key information to understand lower crustal processes especially in orogens that were formed by subduction to collision tectonics (Carswell, 1990). Most studies place emphasis on understanding the high-pressure stability of eclogites and eclogite facies assemblages, and others on retrograde reactions and related exhumation microstructures. Moreover, calculation of the metamorphic temperatures of eclogites is problematic, because of the erratic determination of the Fe^{3+} content of omphacite (e.g., Krogh Ravna and Terry, 2004; Štipská and Powell, 2005). The peak temperatures and later decompression/retrogression temperatures of eclogite facies rocks are hotly debated, because of the variability of assemblages and poorly understood geodynamic settings (e.g., Krogh Ravna, 2000; Arnold et al., 2000; Krogh Ravna and Terry, 2004; Štipská and Powell, 2005; Zack and Luvizottow, 2006). Eclogites or high to ultrahigh-pressure rocks are more common in younger orogenic belts (e.g., the European Alps: Droop et al., 1990; Himalayas: O'Brien et al., 2001; Mukherjee and Sachan, 2001; Variscan orogen of Europe: O'Brien et al., 1990; Su–Lu terrane, eastern China; Wallis et al., 1997; Liou et al., 1998; Sanbagawa belt in Japan: Aoya, 2001), whereas high- to ultrahigh-temperature (UHT) granulites and eclogites are widespread in older orogenic belts (e.g., Antarctica: Harley et al., 1990; Sri Lanka: Sajeev and Osanai, 2004; southern India: Sajeev et al., 2004, 2009). The Glenelg–Attadale Inlier contains some of the oldest known (*c.* 1.1 Ga metamorphic age) eclogites worldwide (Sanders et al., 1984; Brewer et al., 2003; Storey et al., 2005; Storey, 2008a,b). Older examples include *c.* 1.9 Ga eclogites in Tanzania (Möller et al., 1995; Collins et al., 2004), *c.* 1.8 Ga eclogites in the Hengshan region, North China Craton (Zhao et al., 2001) and *c.* 1.0 Ga eclogites from the Grenville Province, Canada (e.g., Indares and Rivers, 1995).

The Glenelg–Attadale Inlier contains the best-preserved and largest occurrence of eclogites in the British Isles, first discovered by Teall (1891). Later detailed studies with geological, geochemical, geochronological and structural data include Alderman (1936), Ramsay (1958), Sutton and Watson (1959), Ramsay and Spring (1962), Barber and May (1976), Sanders (1979, 1988, 1989), Sanders et al. (1984), Temperley and Windley (1997), Brewer et al. (2003), Storey et al. (2005) and Storey (2008a,b). Ramsay (1958) divided the Glenelg–Attadale Inlier into eastern and western Lewisian based on marked lithological differences; these were later termed the eastern and western units of the Inlier (Storey et al., 2005).

For this study we carried out a detailed examination of prograde, peak and retrograde microstructures, pressure–temperature (*P–T*)

* Corresponding author. Tel.: +91 80 2293 3404.
E-mail address: sajeev@ceas.iisc.ernet.in (K. Sajeev).

0024-4937/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.lithos.2009.10.007

evolution, and phase relations of systematically sampled eclogites from the eastern unit of the Inlier. The metamorphic peak *P*–*T* conditions and the evolution path were determined using textural interpretation phase diagram modeling and compositional isopleths. We also report exsolution lamellae microstructures (Zhang and Liou, 2000) in the Glenelg eclogites that provide the first indication of possible ultrahigh-pressure metamorphism.

2. General geology

Northern Scotland is mainly composed of metamorphic rocks of the Paleozoic Caledonian orogenic belt that formed as a result of closure of the Iapetus Ocean and collision between three continental blocks, Laurentia, Baltica and Avalonia. In the Caledonian foreland the Lewisian complex is composed of Archean to Paleoproterozoic, predominantly gneissic rocks overlain by an undeformed cover of Neoproterozoic (Torridonian) and Cambro-Ordovician sediments (Fig. 1). The western margin of the Caledonian orogenic belt is defined by the east-dipping Silurian Moine thrust (Fig. 1) that has carried the orogenic belt, including the Moine Supergroup and the Glenelg–Attadale Inlier, westwards over the foreland. The Glenelg–Attadale Inlier is surrounded and overlain by unmetamorphosed Torridonian sediments and metasediments of the Moine Supergroup (Figs. 2 and 3a). The Moine Supergroup comprises psammitic, pelitic and semipelitic metasediments that have detrital zircon ages of c. 980–900 Ma (Storey, 2008a, and references therein). The metasediments lie above the eastern side of the Glenelg–Attadale Inlier on an east-dipping, probable sheared unconformity (Ramsay, 1958; Temperley and Windley, 1997; Storey et al., 2004; Storey, 2008a). The Moine rocks were deformed and metamorphosed under peak prograde amphibolite facies conditions of 687–707 °C and 12.5–14.4 kbar probably in several compressional events at 820–790 Ma, *c*. 737 Ma and *c*. 670 Ma (Storey et al., 2004; Storey, 2008a). During an early period of deformation the Moine rocks were tectonically intercalated with numerous thrust slices of Lewisian gneissic rocks, the westernmost of which is the Glenelg–Attadale Inlier.

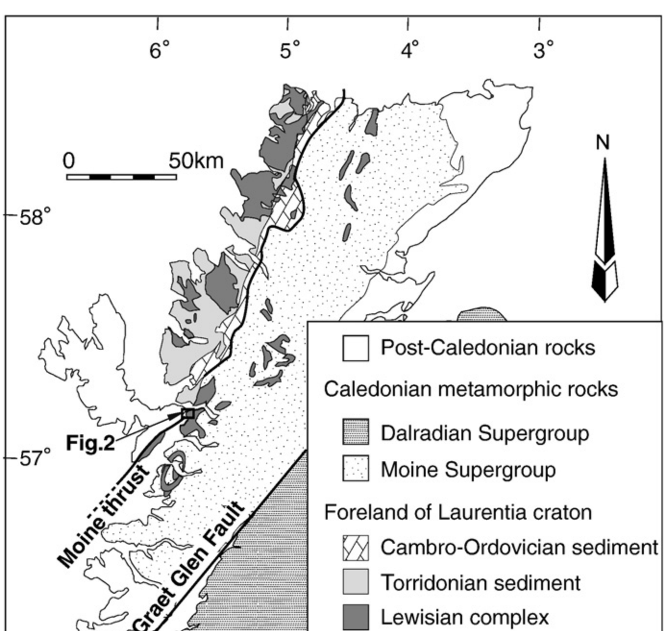

Fig. 1. General tectonic units in NW Scotland, north of the Great Glen Fault, modified from Kelling et al. (1985). Note grid lines are from the UK National Grid and are all prefixed by NG.

The Glenelg–Attadale Inlier is divisible into eastern and western units, based on their lithological differences (Ramsay, 1958; Storey et al., 2005). The eastern unit (the subject of this paper), which lies between a narrow strip of Moine metasediments to the west and the main Moine Supergroup of metasediments to the east, mainly consists of biotite trondhjemitic gneisses that are intercalated with layers and lenses of amphibolite, garnet amphibolite, impure marble, and partly retrogressed eclogite (Figs. 2 and 3b,c,d), together with minor garnet–omphacite–kyanite gneiss, graphite-schist and aluminous, manganiferous and calcareous metapelites (Storey, 2008a and references therein). Up to 25% of the outcrop of the eastern unit is occupied by eclogite. The margins of eclogite lenses have commonly been retrogressed to garnet amphibolite (Fig. 3c). Thin (few mm to 5 cm) veins of amphibolite form networks traversing most eclogites, clearly indicating late, amphibolite facies hydration of the eclogites (Fig. 3d).

The Inlier has undergone at least four major phases of deformation, the earliest of which is related to eclogite facies metamorphism, and later phases to lower grade retrogressive overprints (Storey, 2008a). The boundary between the western and eastern units, occupied by the strip of Moine metasediments, is a major ductile shear zone with a reverse, top-to-the-west sense of motion (Storey et al., 2004). The regional foliation of the eastern unit that has been deformed by megascopic isoclinal folds, generally trends NE–SW, and dips to the SE conformable with metasediments of the overlying Moine Supergroup to the east (Fig. 2).

Sanders (1979, 1988, 1989) reported peak pressure conditions of around *c*. 15–18 kbar and a temperature range of 700–730 °C from eclogites in the eastern unit. Rawson et al. (2001) reported a metre-size lens of garnet-olivine websterite that equilibrated at 20 ± 3 kbar and 730 ± 50 °C, and Storey et al. (2005) estimated a comparable maximum pressure of *c*. 20 kbar at a slightly higher temperature range of 750–780 °C, as well as c. 13 kbar and 650–700 °C for the amphibolite facies retrogression.

Glenelg eclogites in the eastern unit have mineral-whole rock Sm–Nd isochron ages of 1082 ± 24 Ma and 1100 ± 13 Ma, interpreted by Sanders et al. (1984) respectively as close to the peak age of eclogite facies metamorphism and the age of retrogression (Sanders et al., 1984). Brewer et al. (2003) reported a U–Pb (isotope dilution) zircon age of *c*. 995 ± 8 Ma and a discordant rutile age of 416–480 Ma, interpreted respectively as the age of retrogressive amphibolite facies metamorphism and the age of Pb loss caused by reheating by the nearby post-tectonic, 419 Ma Ratagan granite complex (Fig. 2). The consistent age of *c*. 1000 Ma demonstrates that the eclogites formed during the Grenvillian orogeny.

The aim of our study was to make a detailed examination of reaction microstructures in the eclogites and their retrogressed equivalents. Samples were collected systematically along an E–W transect through the eastern unit (Fig. 2).

3. Petrography and reaction microstructures

Detailed petrographic observations were carried out on all collected samples. It is generally considered that inclusion microstructures indicate prograde or pre-peak conditions, that granoblastic minerals probably mark peak equilibrium assemblages, and that symplectites, rims and exsolution lamellae form during retrograde overprinting. Prograde inclusion microstructures in eclogites are rare. Major phases included in garnet are omphacite and minor amphibole and biotite (Fig. 4a,b,c). Minor quartz and apatite inclusions are also observed in some garnet grains. Some omphacites contain minor inclusions of garnet (Fig. 4d). All our samples show granoblastic textures and consist of garnet and clinopyroxene (mainly omphacite) porphyroblasts (Fig. 4a,d,e). Minor quartz grains occur in the matrix (Fig. 4b). A few samples contain titanite (e.g., GN 112; Fig. 4d,e,f), biotite (GN 3; Fig. 4c) and amphibole (e.g., GN 78; Fig. 4c). From these relations we infer that the peak assemblage was garnet–omphacite–