Monazite geochronology and pressure-temperature constraints on Early Neoproterozoic and Caledonian-aged metamorphism in the Shetland Islands

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Abstract

EMPA U-Th-Pb and LA-ICPMS U-Pb monazite data and pressure-temperature calculations on lower to upper amphibolite facies rocks in the Shetland Islands constrain the evolution of Caledonian metamorphism and have identified an early Neoproterozoic metamorphic basement to the Dalradian Supergroup. EMPA monazite and LA-ICPMS data suggest that peak metamorphism occurred at *c.* 460 Ma in the central and northern Shetland Islands, and at *c.* 910 Ma in the basement sequences. These Neoproterozoic age samples have no evidence of Caledonian aged monazite and have been interpreted to be a metamorphic basement to the Dalradian, possibly forming part of the Moine Supergroup. Low-grade rocks immediately beneath the Shetland ophiolite on the island of Unst are characterised by garnet-staurolite-chloritoid-chlorite assemblages with up-P prograde paths culminating in peak conditions of *c.* 550°C and 7-8 kbars. In the slightly higher-grade rocks on Yell, prograde staurolite-biotite-muscovite assemblages have been replaced by peak garnet-kyanite assemblages that formed at *c.* 650°C and 8 kbar. At Lunna Ness on North-eastern Mainland, metapelites had peak assemblages of garnet-sillimanite-biotite-rutile-quartz, which replaced the earlier garnet-biotite-muscovite-kyanite-quartz assemblages. In mafic lithologies, the peak assemblages are defined by garnet-hornblende-plagioclase-quartz. Peak assemblages were associated with partial melting and local granite emplacement and formed at around 700-800°C and 9-10 kbar. Based on available data, the thickness of the Shetland ophiolite is insufficient to have generated the peak metamorphic pressures via obduction. It is therefore likely that peak Caledonian metamorphism predates the ophiolite obduction event.

The Caledonian Orogen (Fig. 1A) marks the collision of Baltica and Laurentia in an event that produced an orogenic belt of Himalayan scale. The products of this orogenic event are preserved in east Greenland (Kalsbeek *et al.* 2000; Watt *et al.* 2000; Watt & Thrane 2001; Gilotti & Elvevold 2002), western Scandinavia (Schwab *et al.* 1988; Daly *et al.* 1991; McKerrow *et al.* 2000; Roberts 2003), the British Isles (Noble *et al.* 1996; Highton *et al.* 1999; Millar 1999; Soper *et al.* 1999; Strachan 2000; Strachan *et al.* 2002) and in the Appalachian belt of the eastern United States (Schwab *et al.* 1988; McKerrow *et al.* 2000; Murphy *et al.* 2004; Murphy *et al.* 2004).

In recognition of the importance of the Caledonian Orogeny in shaping the tectonic architecture of northern Scotland and Ireland (e.g. Highton *et al.* 1999; Soper *et al.* 1999; Strachan 2000;

Strachan *et al.* 2002), there has been an enormous amount of work undertaken to understand the stratigraphic development of the basins and their basement, which were deformed in the Caledonian Orogeny, the timing of events, the structural architecture and evolution and the metamorphic conditions that accompanied deformation (e.g. Schwab *et al.* 1988; Millar 1999; Soper *et al.* 1999; McKerrow *et al.* 2000; Strachan 2000; Strachan *et al.* 2002). In many ways, the early work on the Caledonian marked the birth of modern tectonic analysis and was pivotal in seminal works such as Ramsay (1963).

The Caledonian is defined by two phases of orogenesis. The earliest event is the Grampian Event, which occurred between about 480 to 460 Ma with probable peak metamorphism at *c.* 470 Ma (Soper *et al.* 1999; Oliver *et al.* 2000; Strachan *et al.* 2002). In the Scottish Highlands, the Grampian orogenic event caused deformation in the Grampian Highlands (the region between the Great Glen Fault and the Highland Boundary Fault; (Fig. 1B) an area consisting primarily of Dalradian Supergroup sequences). Deformation in the Dalradian Supergroup consists of the formation of large-scale recumbent folds such as the Kinlochleven antiform. Folding was accompanied by shear zone formation. Several generations of folding occurred, deformation was accompanied by regional prograde metamorphism to amphibolite facies (Phillips *et al.* 1999). The Grampian orogenic event is thought to have been caused by the onset of closure of the Iapetus Ocean, specifically by the collision between an oceanic arc and Laurentia (Dewey & Ryan 1990; Soper *et al.* 1999; Phillips *et al.* 1999; Strachan 2000; Strachan *et al.* 2002).

The later Scandian Event (435-410 Ma; Strachan *et al.* 2002; Kinny *et al.* 2003) is thought to mark the completion of closure of the Iapetus Ocean with the collision between Baltica and Laurentia. The Scandian Event principally affected the Moine Supergroup, creating the tectonic form surface within the Moine metasediments (Friend *et al.* 1997; Kinny *et al.* 1999; Strachan *et al.* 2002; Kinny *et al.* 2003) and generating west-vergent basement-cored nappe systems (Friend *et al.* 1997; Rogers *et al.* 1998; Storey *et al.* 2004). It was probably also at this time that most of the movement occurred along the large thrusts and sinistral strike slip faults in the region (Strachan *et al.* 2002; Storey *et al.* 2004). These structures include the Moine Thrust, which transported the orogen for up to 150 km westwards across Cambrian limestones and Palaeoproterozoic basement in the Caledonian foreland (Friend *et al.* 1997; Rogers *et al.* 1998; Strachan *et al.* 2002; Friend *et al.* 2003). It is thought that the strike slip faults have taken up to 2000 km of slip, with the Great Glen Fault taking up to 200 km alone and juxtaposing the

Northern Highland and Grampian terranes. For this reason the effects of the Scandian Event are restricted to the Northern Highland terrane since the two regions were not in close proximity during the Scandian. In the Northern Highland terrain, the Scandian Event was associated with Barrovian metamorphism with the development of garnet-staurolite-kyanite-bearing assemblages that formed at around 8 kbar and 650°C (Strachan *et al.* 2002).

The vast bulk of the work on the Caledonian of the British Isles has focussed on Scotland and Northern Ireland (Highton *et al.* 1999; Phillips *et al.* 1999; Robertson & Smith 1999; Smith *et al.* 1999; Strachan 2000; Strachan *et al.* 2002). In contrast, comparatively little effort has been focussed on the part of the orogen preserved in the Shetland Islands (e.g. Flinn & Pringle 1976; Flinn 1985; Prichard 1985; Fig. 2). This is despite the Shetland Islands containing an equivalent stratigraphic architecture to the Northern Highland and Grampian terranes (Flinn 1985; Strachan *et al.* 2002), which are separated by the interpreted extension of the Great Glen Fault (Flinn 1985; Ritchie *et al.* 1987; Flinn & Oglethorpe 2005). The western margin of the orogen in the Shetland region is bounded by the extension of the Moine Thrust, which carries the orogen across an undeformed Palaeoproterozoic foreland (Ritchie *et al.* 1987). Additionally the Shetland Islands contain a well-preserved ophiolite package sitting at the top of the structural section (Flinn 1985; Prichard 1985; Spray 1988; Spray & Dunning 1991; Strachan *et al.* 2002; Flinn & Oglethorpe 2005). Therefore the Shetlands arguably preserves the best cross section of the Caledonian Orogen in the British Isles. Despite easy accessibility and extensive outcrop there has been comparatively little work done to constrain the timing of tectonic events and the P-T evolution associated with Caledonian deformation.

In this study an integrated approach using metamorphic pressure-temperature calculations and EMPA U-Th-Pb and LA-ICPMS U-Pb monazite dating is used to determine the physical conditions and evolution of metamorphic assemblages in the Shetland Islands, and to constrain the timing of tectonism. This represents one of the few studies of this type undertaken in the Shetland section of the Caledonian Orogeny, and is the first study to directly date the timing of peak metamorphism in that part of the orogen. The results of this study show that Barrovian prograde Caledonian metamorphism at *c.* 465 Ma was associated with up-pressure P-T paths culminating in burial depths of around 30 km under modest geothermal gradients. This metamorphic expression is consistent with crustal thickening in a convergent orogen. The geochronological data has also identified the presence of an early Neoproterozoic metamorphic basement to the Dalradian sequences.