Zircon growth during fluid induced Caledonian/Scandian eclogite-facies metamorphism of the Lindås Nappe, Caledonides of W Norway

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Zircon behaviour during high-pressure metamorphism is studied here in monzonite/monzodiorite of the anorthosite complex of the Caledonian Lindås Nappe, islands of Holsnøy and Radøy, Bergen Arcs, W Norway. This Proterozoic magmatic complex was affected by penetrative Sveconorwegian granulite-facies metamorphism and by eclogite- and amphibolite-facies Caledonian overprinting, the amphibolite-facies overprinting being possibly the youngest. The Caledonian overprinting is spatially restricted along fractures and shear zones and was triggered by fluid infiltration. Along fractures static conversion of the mineral assemblages occurred. Prograde field relationships are preserved, granulite-facies assemblages being metastably preserved where fluid was unavailable (review in Austrheim *et al.* 1997). The objective of the study is to link zircon crystallization and fluid induced eclogite-facies metamorphism, to accurately date high-pressure metamorphism in this Caledonian nappe and analyse the tectonic implications in terms of orogenic evolution.

Sampling and methods. In the monzonite/monzodiorite, the granulite-facies assemblage includes mesoperthite + two pyroxenes + ilmenite + magnetite $\pm$ brown hornblende $\pm$ garnet, the eclogite-facies assemblage garnet + omphacite + rutile + minor blue-green amphibole $\pm$ phengite (>15 kbar), and the amphibolite facies assemblage plagioclase $\pm$ green-amphibole + biotite + epidote + titanite. Five mafic samples variably affected by Caledonian overprinting were selected: a preserved two-pyroxene granulite (BH10, Radøy), a garnet-bearing granulite showing limited eclogite-facies overprinting at grain boundaries (BH5, Holsnøy), a sample showing static amphibolite-facies overprinting (BH8, Radøy), a sample showing amphibolite-facies shearing (BH11, Radøy, close to BH10), and a sample showing static eclogite-facies overprinting (BH2, Holsnøy, close to BH5). A charnockite sample from the island of Lygra was also selected (BH13).

Zircon habitus and internal structure was studied in thin section and polished mount, with backscattered electron and cathodoluminescence imaging. Multigrain fractions were analysed for U and Pb by ID-TIMS, with special emphasis on small grain size (<60 μm).

Zircon structure. Zircon populations of granulite- and amphibolite-facies samples are similar. Crystals are anhedral to prismatic. Cathodoluminescence imaging generally shows a zoned magmatic mantle with a luminescent homogeneous metamorphic overgrowth; common embayement of the magmatic mantle points to secondary replacement during metamorphism; in the garnet-bearing sample (BH5), the luminescent overgrowth is thick (> 80% of the volume). The luminescent overgrowth is attributed to granulite-facies metamorphism. Non-luminescent cores, sometimes observed in the magmatic mantle, possibly represent inherited premagmatic cores.

In the eclogite-facies sample (BH2), zircon occurs as anhedral grains similar to the nearby granulite (BH5) but also as prismatic and multifaceted grains with sharp edges and as flat or ameuboid grains. Cathodoluminescence imaging shows a variably luminescent core with a luminescent overgrowth. The overgrowth is commonly prismatic and oscillatory, and is attributed to eclogite-facies metamorphism.

Zircon coronas. In the samples affected by static Caledonian overprinting, the amphibolite- or eclogite-facies assemblage developed in a corona-like fashion around granulite-facies minerals. A conspicuous feature of these samples is the widespread occurrence of discontinuous coronas of small (typically 10 μm) rounded to flat zircon grains associated with Ti-minerals. In amphibolite-facies overprinted samples (e.g. BH8), ilmenite is surrounded by a corona of titanite; a zircon corona occurs at the outer edge of the titanite corona, commonly in contact with biotite. In eclogite-facies overprinted samples (e.g. BH2), a zircon corona is

observed around rutile; the corona occurs at some distance (20–100 μm) from the rutile crystal and is included in garnet; sometimes it contain larger prismatic crystals (*c.* 60 μm long).
The zircon corona is probably outlining the surface of the former granulite-facies ilmenite crystal. It is interpreted as zircon 'exsolved' from magmatic ilmenite during granulite-facies metamorphism and left intact during Caledonian static breakdown of ilmenite. In granulite-facies samples, small zircon grains situated at the surface of ilmenite are probably present but difficult to detect.

U–Pb geochronology. Deeply abraded fractions of the preserved granulite (BH10) are almost concordant at 951 ± 2 Ma, and give the magmatic intrusion age of the plutonic suite on Radøy. Five fractions of rounded zircon (40 to 150 μm) in the garnet-bearing granulite (BH5) are concordant at 929 ± 1 Ma and yield the age of granulite-facies metamorphism. The sample showing static amphibolite-facies overprinting (BH8) has a complex age pattern: deeply abraded large zircon (>100 μm) yields a imprecise intrusion age of *c.* 952 Ma (U<10 ppm); small rounded zircon (40 μm), of presumably granulite-facies origin, is concordant at 933 ± 2 Ma; an Archaean inheritance is detected in one fraction. The sample showing amphibolite-facies shearing (BH11) yields a short discordia line with upper intercept age of 951^{+10}_{-4} Ma, similar to the 951 ± 2 Ma intrusion age of the nearby unsheared granulite (BH10), and an ambiguous *c.* 557 lower intercept age controlled by small rounded zircon (50 μm). This pattern can be explained by some granulite-facies overgrowth at *c.* 930 Ma and some Caledonian Pb loss.
Ten fraction of zircon of the eclogite (BH2) define two distinct discordia lines. A six point discordia is defined by prismatic, multifaceted and rounded zircon; the lower intercept of 419 ± 4 Ma is tightly controlled by prismatic zircon and the upper intercept of 917 ± 7 Ma by rounded one. The second four point discordia line, with lower intercept of 423 $^{+16}_{-17}$ Ma and upper intercept of 895^{+19}_{-18} Ma is defined by flat and amoeboid zircon. A positive correlation exists between the Th/U ratio and the $^{207}Pb/^{235}U$ age of fractions. The pattern can be explained by a two stage post-granulite-facies evolution (i.e. post-930 Ma): first a mild Pb loss episode younger than 895 Ma and then a growth episode of low Th/U zircon at 419 ± 4 Ma.

The Lygra charnockite (BH13) yields a 5 point discordia line with an upper intercept age of 1237^{+43}_{-35} Ma and a lower intercept of 932^{+28}_{-36} Ma. The upper intercept is controlled by prismatic zircon fractions; it is interpreted as the intrusion age of the granodiorite whereas the lower intercept as the timing of granulite-facies metamorphism. These data show that the anorthosite-charnockite complex in the Lindås nappe does not correspond to a single magmatic event.

Zircon growth during eclogite-facies metamorphism. Several lines of evidence support that precipitation of zircon occurred during eclogite-facies metamorphism. 1) In eclogites, the morphology of zircon with prismatic oscillatory overgrowth, is specific; 2) well defined Caledonian age signature is observed only in the eclogite-facies sample; 3) the Th/U of Caledonian zircon (0.06) is distinctly lower than the one of Proterozoic granulite-facies zircon (0.85 ± 0.37 at 933–929 Ma); 4) preservation of coronas of small zircon, outlining former granulite-facies ilmenite, indicates that fluid circulation associated with Caledonian overprinting did not result in any dissolution of zircon; in the eclogite, local prismatic overgrowth on the corona zircon is evidence for zircon precipitation after corona formation, i.e. during eclogite-facies metamorphism.
Formation of the eclogite-facies assemblage, i.e. garnet + omphacite + rutile, probably results in a release of Zr and precipitation of zircon, whereas the formation of the amphibolite-facies assemblage, i.e. amphibole + biotite + titanite + epidote, is barren. It is important to note that precipitation of zircon corresponds to the static formation of the eclogite-facies assemblage, triggered by introduction of fluid and fracturation of the protolith, and not to a specific point on the P-T loop. The role of magmatic (hemo)ilmenite as a source of Zr during both granulite- and eclogite-facies metamorphism is outlined.

Syncollision exhumation of subducted crust. The new data presented here have two main tectonic implications. 1) They suggest a Baltica affinity for the Lindås Nappe. The 951 ± 2 Ma magmatic event in Radøy corresponds to the intrusion of minor granite/pegmatite bodies at 951–942 Ma in the Western Gneiss Region. The timing of granulite-facies metamorphism at 933–929 Ma perfectly matches a phase of high-temperature granulite-facies metamorphism in Rogaland (S Norway), and voluminous anorthosite to granite post-kinematic plutonism in the Sveconorwegian Province (S Norway). 2) The 419 ± 4 Ma age of eclogite-facies metamorphism in the Lindås nappe closely corresponds to the accepted age for Scandian obduction.