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RAPID COMMUNICATION

Marble dykes emanating from marble layers in an amphibolite-facies, multiply-deformed carbonate succession, Troms, northern Norway

DAVID ROBERTS* & KLAAS BOUKE ZWAAN

Geological Survey of Norway, N-7491 Trondheim, Norway

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Abstract

In one of the higher nappes of the Caledonides of Troms, northern Norway, rare thin dykes of calcite marble lie subparallel to the axial surfaces of folds in multilayered marble beds. The dykes emanate from pure calcite marble layers mostly in or close to the hinge zones of these flat-lying, tight to sub-isoclinal, F3 folds. In many cases, they appear to penetrate along the axial surfaces of these same folds, and there is an up to 10° angular disparity between dyke orientation and axial surfaces. The dykes are considered to have originated, and been expelled, from parent calcite marble layers either at or shortly after the peak of amphibolite-facies metamorphism between the D2 and D3 deformation phases of the Scandian orogeny. The dykes display a dyke-parallel, dark grey to white, colour banding, the origin of which is uncertain at present. In thin-section, an equigranular texture is dominated by 2–3 mm, equant, unstrained, calcite grains with straight boundaries and low-T twin lamellae, denoting a late-stage recrystallization. A weak, oblique, calcite grain-shape orientation fabric curves into a dyke-parallel alignment along the finer-grained margins, reflecting the simple-shear deformation imposed on the host rock. Regarding the initiation of these marble dykes, it seems likely that a combination of P–T conditions and possibly partial melting processes was conducive to generating extreme ductility/superplasticity, at least locally, and that this led to the sudden expulsion of a partially molten carbonate aggregate which had momentarily attained a critical pressure and intruded preferentially along available, transient fractures prior to the imposition of the D3 simple-shear regime.

Keywords: Caledonides, Norway, marble, dykes, Scandian.

1. Introduction

Metalimestone formations, and marbles in particular, are remarkable for their capability of providing complex folding and fold interference outcrop patterns in diverse, polyphasally deformed, geological terranes. This is largely because of the inherent weakness of calcitic carbonate materials under confining pressures and especially at the range of temperatures encountered at intermediate to high grades of regional metamorphism, as has been shown by a variety of controlled, deformation experiments (Robertson, 1955; Griggs, Turner & Heard, 1960; Heard & Raleigh, 1972; Rutter, Casey & Burlini, 1994; Rutter, 1995). Marble, for example, is much weaker than most silicate rocks over a wide range of temperatures. At the same time, its high degree of ductility allows it to accommodate quite readily into sites of comparatively low or lower strain within a surrounding, deforming, multilayered rock succession.

In the Caledonides of Norway, elaborate fold interference patterns in banded marble sequences have been described from some of the highest nappes in the county of Nordland (Rutland, 1959; Nicholson, 1963; Nicholson & Walton, 1963). In some thrust sheets, the intricacy of fold pattern and non-cylindroidal character of the folds have suggested derivation of the structures during just one deformation phase (Nicholson, 1963). In other cases, fold and cleavage superposition favour a polyphase history, that can even be linked to temporally distinct orogenic events (Roberts, Melezhik & Heldal, 2002). Farther north, in northernmost Nordland and the neighbouring county of Troms, thick successions of banded marbles occur extensively. These, too, show evidence of complex, polyphase folding (Gustavson, 1972; Steltenpohl, 1987; Zwaan *et al*. 2002).

In this contribution we report, from one such carbonate rock succession in southern Troms, the unusual occurrence of dykes of calcite marble emanating from marble layers in or close to the hinge zones of tight folds and lying subparallel to the axial surfaces of these same folds. These features, which, to our knowledge, have not been described earlier, bear witness to the exceptional mobility of marble during optimal temperature and pressure conditions.

2. Local geology

The marble dykes described here occur in two different thrust sheets (Ramstad and Evenestangen thrust sheets) within the Evenes nappe complex, along the northern coastline of Ofotfjorden in northern Nordland (Fig. 1). All nappe complexes and thrust sheets in this area of the Caledonides form part of the Uppermost Allochthon (Stephens *et al*. 1985; Roberts, Nordgulen & Melezhik, 2007). Both the Ramstad and the Evenestangen thrust sheets are composed almost

*Author for correspondence: david.roberts@ngu.no

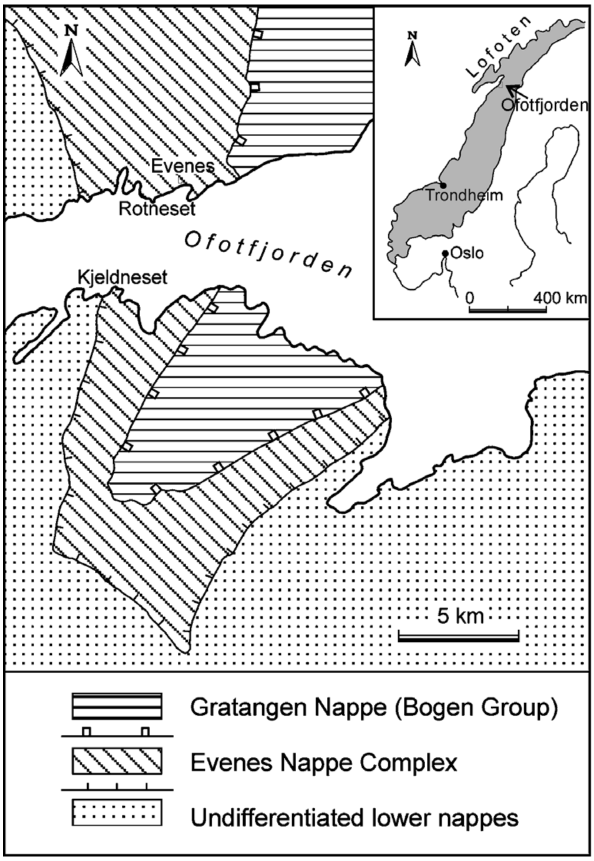

Figure 1. Location map of the Ofotfjorden area, northern Norway, showing the principal tectonostratigraphical units. The basal thrusts beneath the Evenes Nappe Complex and Gratangen Nappe are indicated by the lines with tags. The locality at Kjeldneset referred to in the text is at grid reference 33WWR66959065 (1:50 000 map sheet 'Evenes' 1331–4, edition 4-NOR). In the inset map, the Caledonian thrust belt is shaded.

entirely of varieties of banded, massive or laminated, calcite marbles, but there are also subordinate dolomite marbles and in the Evenestangen unit there are unusual, variegated, thin-banded marbles and rare, thin, calc-schist layers (Zwaan *et al.* 2002). Based on a detailed isotope chemostratigraphical study of the carbonate rocks, the apparent depositional age of the calcite marbles of the Ramstad unit is considered to be Cambrian whilst the depositional age of marbles in the Evenestangen thrust sheet is Silurian (Melezhik *et al.* 2003).

Structural investigations in this area, and in adjacent nappe complexes of the Uppermost Allochthon, have reported a multiphase, Caledonian deformation history (Gustavson, 1972; Steltenpohl & Bartley, 1984; Barker, 1986; Steltenpohl, 1987; Karlsen & Andresen, 1997; Zwaan *et al.* 2002), with the main developments during the Siluro-Devonian, Scandian orogeny. In the Evenes district, the pervasive schistosity in the rocks (S2) is associated with the second deformation phase, D2, and is axial planar to tight to isoclinal, NNE–SSW-trending folds. These structures, denoting an ESE-directed transport (Steltenpohl, 1987), were broadly coeval with the peak of regional metamorphism, in upper amphibolite facies. Both kyanite (Steltenpohl & Bartley, 1984) and, locally, sillimanite (Zwaan *et al.* 2002) have been recorded; and kyanite growth continued into the post-D2/pre-D3 period. *P–T* estimates for the peak of metamorphism in the Evenes area reach up to 688 °C and 10.6 kbar (Steltenpohl & Bartley, 1987). This occurred at around 425 Ma (Coker *et al.* 1995).

The lower-grade D1 phase is represented by rare isoclinal folds of variable trend, and also by tectonic slides. Structures postdating D2, and generated during a composite D3 episode, include crossfolds, backfolds and younger kink bands. In the area considered here, mesoscopic, tight to subisoclinal, NE–SW-trending, post-schistosity folds verging down-dip and with fairly flat-lying axial surfaces are common (Steltenpohl, 1987; Zwaan *et al.* 2002). These F3 folds, which correspond to the backfolds of Steltenpohl (1987), carry a variably developed, axial-planar spaced cleavage, S3, locally approaching a crude schistosity, defined by biotite or muscovite. By this time, metamorphic grade had decreased to upper greenschist facies, probably in the range 350–400 °C, at *c.* 400–395 Ma (Coker *et al.* 1995). The development of these folds, in a broadly extensional regime, is considered by us to relate to an episode of simple shear associated with late-Scandian collapse of the nappe stack. As some of the folds show evidence of excision of both limbs, then an element of flattening was also presumably involved. Such late-stage Scandian structures are similar to those described from areas in central Norway and Sweden (Roberts, 1971, 1979: Zachrisson, 1973).

3. Marble dykes

The dykes of calcite marble described here occur in the banded marbles of the Ramstad and Evenestangen thrust sheets in the well exposed coastal lowland between Evenes and Rotneset, northern Ofotfjorden (1:50 000 map sheet 1331–4 'Evenes'; Boyd *et al.* 1986) (Fig. 1). Along these marble-dominated shore sections, fairly flat-lying, mesoscopic, NNE-plunging F3 folds are common; and there are also slightly larger, intermediate-scale, flat-lying, synforms and antiforms. Mafic dykes, converted to hornblende–biotite schists and strongly boudinaged within S3, are also present.

Calcite marble dykes are easily detected in that they transect the folded compositional layering (banding) at high angles, and lie parallel or mostly subparallel to the axial-planar S3 foliation (Fig. 2). That they are composed of recrystallized marble, rather than representing discrete calcite veins crystallized *in situ*, can be seen by the fact that, in some cases, they are observed to emanate directly from 'beds' or layers of pale blue–grey, coarsely crystalline to finely laminated, calcite marble up to 60 cm in thickness. The dykes penetrate along or at a very low angle to the marked anisotropy represented by S3, and may or may not show boudinage structure. The thickest dykes, 5–6 cm in thickness, show fairly uniform thicknesses, and the longest dyke measured could be followed over 6 m from its root in the parent marble bed, before it tapered out. Thinner marble dykes, on the other hand, 1 cm or less in thickness, are shorter (a few tens of centimetres) and were evidently more prone to boudinage. On the dyke walls, a faint lineation is detectable which is roughly parallel to the F3 fold axial trend. A feature of the thicker dykes is that they display an internal banding, from dark blue–grey to white (shown in grey tone in Figs 2a and 3), paralleling the dyke margins. Up to five such bands have been observed in any one marble dyke. The dykes are evenly medium- to coarse-grained (2–3 mm), irrespective of banding, except that the very marginal, white parts (Fig. 3) are much finer-grained, and the outer walls of the dykes are

Figure 2. Field photographs of the marble dykes. (a) Dyke of colour-banded calcite marble cutting a folded, multilayered succession of calcite marble, micaceous marble and thin laminae of mica schist; looking NE. The dyke lies at a very small angle (5–7°) to the axial surface (S3) of the flat-lying, F3 folds. Locality along the coastal section between Evenes harbour and Rotneset (Fig. 1), looking *c.* NNE; grid reference 33WWR69909445 (1:50 000 map sheet 'Evenes' 1331–4, edition 4-NOR). Pencil for scale, *c.* 16 cm. (b) Another calcite marble dyke, here with an apparent dip of about 15° to the right. Compositional layering, which is coplanar with the regional schistosity, S2, can be followed roughly from bottom left to top right. The purer, coarse-grained, white calcite marble layers, and the marble dyke, show a pitted appearance on weathered surfaces. Coastal section some 200 m SW of Evenes harbour, looking *c.* north; grid reference 33WWR69359480 (1:50 000 map sheet 'Evenes' 1334–4, edition 4-NOR). Pencil for scale, *c.* 16 cm, below the dyke, to the right.

decorated with scattered, small, elongate muscovite grains with their long axes aligned subparallel to the faint lineation.

The dykes were studied microscopically both in normal thin-sections and in ultra-thin (10–15 microns), double-polished thin-sections. In thin-sections cut parallel to the lineation, the dyke shown in Figure 2a displays a fairly equigranular granoblastic texture, except for the finer-grained marginal zone. In the central parts (white in hand specimen), calcite grains show straight or very slightly curved boundaries and are generally 2–3 mm, and only rarely up to 3.5 mm in size. Twinning is quite common in the larger grains, and appears to be closest to the type I twin form of Burkhard (1993), with thin, planar, twin lamellae characteristic of late, low-temperature twins. There is also a faint preferred orientation of twin lamellae parallel to the

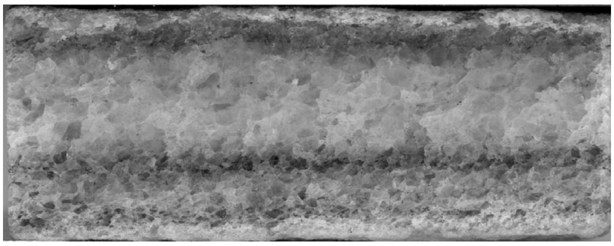

Figure 3. Photo of a polished cut surface of the marble dyke shown in Figure 2a; looking NE, showing the prominent banding; in reality, this is a colour banding from dark blue–grey to white. The dyke thickness (height of the photo) is 2.2 cm.

banding in the dyke that must reflect the presence of some crystallographic preferred orientation (not investigated) in the calcite grains. Outside the central zone (into the dark grey bands) the calcite shows a weak grain-shape orientation fabric which is slightly oblique to the dyke margins, with a grain aspect ratio of *c.* 1:1.5. Twinning here carries features of both type I and type II of Burkhard (1993). Quartz is dispersed throughout as scattered, tiny (0.05–0.3 mm), equant, largely unstrained grains both enclosed within calcite and situated along calcite grain boundaries, and there are a few aggregates of quartz grains with accessory microcline and rare muscovite. There are no visible mineral inclusions, e.g. graphite, that could help explain the dark grey coloration. In the outermost, 1–2 mm-wide, fine-grained marginal zone, which is pure white, the calcite is completely recrystallized in small (0.2–0.3 mm) equant grains and devoid of twins. Elongate muscovite grains are present here, oriented parallel to the dyke margins, and tiny quartz grains are dispersed throughout; these may have pinned grain boundaries and thus retarded calcite grain growth.

In a thin-section cut normal to the faint lineation, parallel to the dyke surface shown in Figure 2a, the grain-shape orientation fabric is slightly more pronounced, at some 26–28° to the dyke margin (Fig. 4). Again, the central white band is more equigranular, with thin, planar, twin lamellae, whereas the zones on either side (which are grey to dark grey in hand specimen) show more elongate, variably twinned, calcite grains with aspect ratios varying from 1:1.4 to 1:2. Scattered quartz grains and some accessory microcline and rare muscovite are also present. Moving from the grey bands toward the dyke margins, the elongate calcite grain fabric shows a perceptible slight swing in orientation into subparallelism with the actual margins (Fig. 4). This curvature is in the opposite sense on the two margins, as would be expected of a simple-shear induced strain gradient adjacent to each dyke wall arising from dyke injection.

4. Discussion

The field relationships and the character of the marble dykes described above leave a clear impression that the carbonate forming these thin dykes has been expelled, possibly quite suddenly in a geological time sense, from one or other host marble layer at some critical stage during the tectonometamorphic evolution of this multilayered, mainly calcitic marble succession. As the dykes are rarely perfectly parallel to the axial surfaces of the flat-lying F3 folds, but usually show angular disparities of 5–10° (Fig. 2a), we infer that they were expelled from the parent calcite marble beds in the interval between D2 and D3, coeval with or shortly after

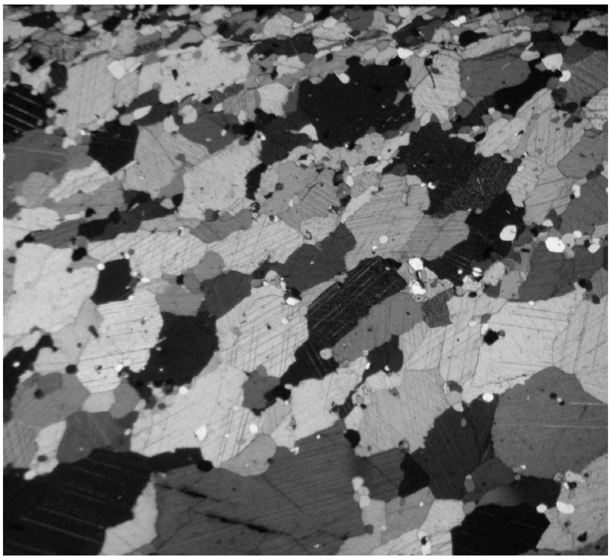

Figure 4. Photomicrograph of part of the marble dyke shown in Figures 2a and 3. The height of the figure measures 7.5 mm, and covers about one third of the actual thickness of the dyke. Calcite dominates the mineralogy, an estimated 99 % of the mode. The tiny, subrounded grains (< 0.05–0.2 mm), either enclosed within calcite or occurring along calcite grain boundaries, are of quartz, rarely microcline. Thin flakes of muscovite appear in the fine-grained marginal zone of the dyke (top). A grain-shape orientation fabric, perceptible in the larger calcite grains, swings into subparallelism with the dyke margin in the finer-grained marginal zone.

the attainment of peak metamorphism. It is likely that the flow of the highly ductile carbonate was focused along transient fractures. The dykes were probably originally oriented at various angles to the developing F3 axial surfaces but have gradually rotated into subparallelism during the pervasive strain that accompanied the F3 folding that characterized this episode of late-Scandian gravitational collapse of the orogen. A terminal stage of this deformation is marked by a component of flattening represented by fold-limb attenuation or excision, isolation of fold hinge zones, and local boudinage of the marble dykes.

In some ways, the dyke–fold relationship described here is not unlike that of 'flanking folds' that develop adjacent to dykes, veins or similar obstacles (Passchier, 2001; Grasemann & Stüwe, 2001), except that, in the present case, the F3 folds are regional in character, occurring widely where marble dykes are usually absent. Moreover, examples of very thin (< 1 cm), short marble dykes that are locally deformed by F3 folds have been found on the Kjeldneset peninsula (Fig. 1) on the southern side of Ofotfjorden. In these cases, the dykes were clearly oriented at a high angle to the developing S3 and were, thus, readily affected by shortening, and folding, during the D3 deformation.

Concerning the initiation of the marble dykes, it is likely that a combination of conditions and processes, and particular mechanical behaviour, gave rise to a rapid expulsion of a locally developed, overpressured, carbonate crystal mush or partially molten aggregate, which is inferred to have intruded preferentially along transient fractures or similar fluid pathways during the changeover between the D2 and D3 deformation regimes. Since muscovite was stable and crystallizing, and as kyanite growth had not yet terminated, temperatures were probably well in excess of 500 °C, which would accord with the thermal conditions estimated to have been obtained prior to D3 (Steltenpohl & Bartley, 1987). The precise reason for expulsion is open to speculation. It may possibly relate to an increasing pore water plus CO_2 pressure in the rock mass which, on becoming sufficiently high, would lead to partial melting around the calcite grain boundaries, allowing expulsion of the hot carbonate 'mush' into and along lower mean-pressure zones (cf. Milsch, Heinrich & Dresen, 2003). Whether or not there has been any true partial melting involved at the time of inception of these dykes is difficult to say, in view of the later static recrystallization, but the microstructure is consistent with the involvement of a high-temperature granular flow mechanism. In a series of experiments, Wyllie & Tuttle (1960) did, in fact, show that calcite begins to melt at 740 °C at 1 kbar in the presence of water vapour. Furthermore, wet calcite, for example, in a high pore water pressure and partial pressure of CO_2 environment, can start to melt at 650 °C (E. Rutter, pers. comm. 2006), which is within the estimated maximum temperature attained by this rock succession as determined by geothermobarometry studies (Steltenpohl & Bartley, 1987). Alternatively, calcite rocks near their melting temperature may in principle become sufficiently weak to display grain-size-sensitive granular flow (e.g. Rutter, 1995), characterized by low flow stresses and linear viscosity, that might explain dyke injection. This mechanism would be favoured by grain-size reduction, although it is unclear whether this has occurred because the present microstructure is dominated by the effects of grain growth and textural equilibrium under low or hydrostatic stress.

The colour banding observed within some of these marble dykes has no visible, microscopic, mineral-compositional explanation, even at SEM scale (K. Brodie, pers. comm. 2006) and may possibly relate to the varying degrees of optical opacity associated with grain size and roughness of grain boundaries, and/or the internal defect state of the grains. The central, greyish-white, coarse-grained calcite zone with low-T twinning shows no trace of optical strain features and is representative of a very late stage of grain growth that followed textural equilibration during the high-T dynamic recrystallization effected by grain boundary migration (E. Rutter, pers. comm. 2006). The orientation of twin lamellae points to a weak preferred orientation of c-axes roughly normal to the internal colour banding, produced by plastic flow at the high-T stage; thus, any earlier textures or grain-shape fabrics were subsequently destroyed during the later stage of subsolidus grain growth. The outermost white zones along the dyke margins appear to have been affected by a more pronounced dynamic recrystallization, notably with grain-size reduction or failure to develop subsequent grain growth, and may be a reflection of continuing shear deformation imposed on the country rock.

Although, to our knowledge, thin marble dykes of this type with a specific relationship to regional folds have not been reported previously, mobilized marbles injecting adjacent, gneissic host rocks in the form of calcitic or dolomitic carbonate dykes up to 20 m thick have been described from a Precambrian basement terrane in the Yemen Republic (Le Bas *et al.* 2004); and carbonate dykes of sedimentary protolith origin are also known from the Moldanubian of the Czech Republic (Drábek *et al.* 1999). Comparable features have been documented from deformed massive sulphide deposits in the form of piercement structures (dykes or veins) penetrating along fractures in the host rock (Maiden, 1976; Maiden, Chimimba & Smalley, 1986, Gilligan &

Marshall, 1987). Such features are ascribed to the flow of highly ductile sulphide rock under varying metamorphic conditions, essentially a solid-state phenomenon, though fluid-state remobilization is also known. Flowage structures of this type have also been recorded in ore deposits in Norway (Vogt, 1952; Vokes, 1969).

5. Conclusions

In part of the Evenes nappe complex, in the Caledonides of Troms, northern Norway, sporadic, thin dykes of calcite marble, up to 6 cm in thickness, transect folded, compositionally layered marble at high angles to the layering. The dykes emanate from white, pure calcite marble layers and lie subparallel to the axial surfaces of flat-lying, tight to sub-isoclinal, Scandian F3 folds. In some cases, the dykes display a dark grey to white colour banding, parallelling their margins, the origin of which is uncertain at present. Thin-sections show a prevalent equigranular texture dominated by 2–3 mm, equant, unstrained calcite grains with mostly straight boundaries and thin, planar, low-temperature twin lamellae, the latter representative of minor late-stage deformation. In the fine-grained marginal zones of the dykes, tiny equant grains of calcite are devoid of twins. Internally within the dykes, a weak calcite grain-shape orientation fabric is considered to reflect an imposed simple-shear regime in the host rock during the D3 deformation.

The dykes are inferred to have originated in, and been expelled from, the parent calcite marble beds either at or shortly after the peak amphibolite-facies metamorphism (*c.* 425 Ma), between the D2 and D3 deformation phases of the Scandian orogeny. It seems likely that a particular combination of *P–T* conditions was conducive to producing extreme weakness and ductility, either through partial melting at grain boundaries or through high-temperature granular flow. One or other of these led to the rapid expulsion of a locally developed, crystal-rich, partially molten carbonate aggregate which intruded preferentially along transient fractures.

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