Tectonic setting of the Tronfjell Massif: further evidence for pre-Scandian orogenesis in the Trondheim Nappe Complex, Central Norway

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The Tronfjell Massif consists of a layered mafic intrusion, containing dunites and olivine-bearing to noritic gabbros, lying within metasedimentary rocks of the Hummelfjell Group. The initially more or less flat form of the intrusion is now bowl-like, due to settling of the intrusion under its own weight. Large areas of rock were affected by upper greenschist-facies deformation during the Scandian orogeny. Rare areas of hornfels, wrapped and cross-cut by a Scandian-age foliation, preserve an annealed tectonic fabric which, together with the inferred pre-intrusion form of structures in the metasedimentary rocks, demonstrate a pre-Scandian orogenic event. This is in agreement with the latest tectonostratigraphic model for the area, which places the Hummelfjell Group within the Heidal Group of the Trondheim Nappe Complex.

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Introduction

The Tronfjell Massif lies within the Trondheim Nappe Complex (TNC) of the Upper Allochthon of the Central Norwegian Caledonides (Fig. 1). The massif consists of a layered mafic intrusion surrounded by metasediments which have a complex history of metamorphism and deformation. Detailed mapping has revealed further evidence for pre-Scandian metamorphism and deformation within rocks of the TNC and enabled us to place this intrusion within a tectonostratigraphic framework.

Regional geology

Recent work has established a new tectonostratigraphy for the southern part of the TNC, recognising two distinct rock suites separated by a major unconformity (Sturt et al. 1991, 1995, 1997, Bjerkgård & Bjørlykke 1994) (Fig. 1). The oldest unit (Heidal Group) experienced a phase of deformation and metamorphism prior to an Early Ordovician orogenesis associated with the obduction of the Vågåmo ophiolite. Post-orogenic sedimentation and vulcanism are represented by the Sel Group which is separated from the older rocks by a major unconformity. All units were affected by mid-Silurian Scandian orogenesis which involved polyphase deformation, including the formation of a major recumbent fold structure (Jønndalen syncline). Earlier, the Tronfjell Massif was placed within the Hummelfjell Group, a unit of the

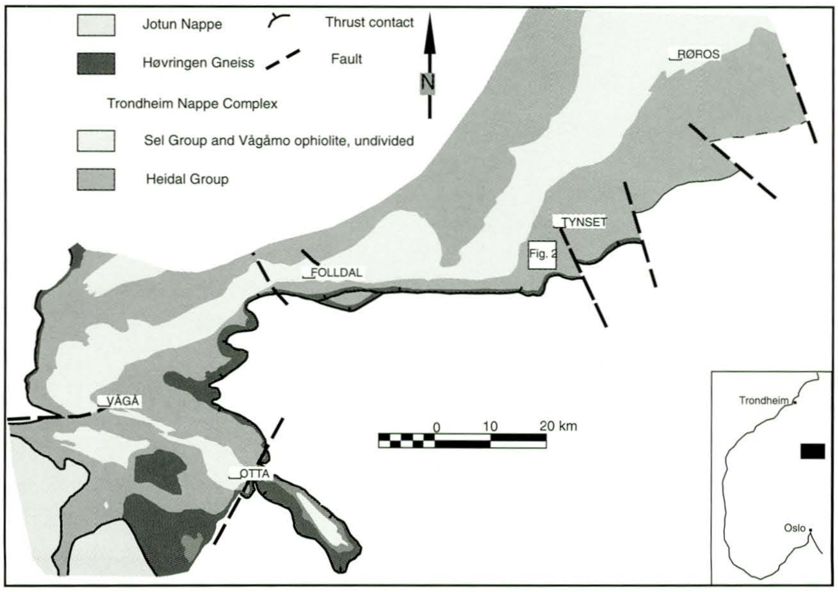

Fig. 1. Map showing the tectonostratigraphy of the southern portion of the Trondheim Nappe Complex, after Sturt et al. (1997). The location of Figure 2 is outlined.

Remsklepp Nappe of the Middle Allochthon (Nilsen & Wolff 1989). Tracing of units from their type-localities in the Otta area (Sturt et al.1997) suggests that the rocks assigned to the Hummelfjell Group (which form the carapace of the Tronfjell Massif) are a direct correlative of the Heidal Group. Structures previously interpreted as thrusts separating these rocks from the TNC are, in our opinion, stratigraphic contacts, thus placing the Hummelfjell Group within the TNC. Given this, the tectonic setting of the Tronfjell massif may shed light on the timing of the polyorogenic sequence of events mentioned above.

Local geology

The study area was covered earlier by the regional work of Holmsen (1943) and Holmsen & Holmsen (1950) in the east and Marlow (1935) in the west. The only modern work on the intrusion itself is that of Kleine-Hering (1969) and Dreyer (1975). The work of Kleine-Hering covered a large area and formed part of a masters thesis. This particular coverage of Tronfjell was largely superceded by the more detailed and substantial doctoral thesis of Dreyer, who died in 1978. The study area is covered by the NGU 1:250,000 bedrock map Røros (Nilsen & Wolff 1989). The Tronfjell intrusion lies within a metasedimentary rock succession with tuffaceous and 'greenstone' horizons also present. Bed thicknesses are variable, in particular those within a prominent greenstone unit (Fig. 2). Some units host sulphide deposits of volcanic origin (Dreyer 1975).

Petrology and field relationships

Dreyer (1975) divided the Tronfjell intrusion into three, almost concentric zones (Fig. 2). He defined the zones in terms of facies types and rock textures and was able to confirm this division with whole-rock analyses. Our subsequent remapping of the intrusion has confirmed this tripartite division, which is as follows:-

1. *Lower zone (c.250-1300 m thick)*. This is seen everywhere above the contact with the country rocks. It is a fine- to medium-grained (< 2 mm) massive gabbro. Irregular layers of dunite and pod-like blue-black quartz xenoliths occur locally. This zone is interpreted as a contaminated chill-zone formed by interaction between the intrusion and its metasedimentary country rocks.
2. *Transitional zone (c.150 m thick)*. A sharp contact at the top of the lower zone leads into medium- to fine-grained (< 2 mm) olivine gabbro, associated with metre- to decimetre -scale pods and lenses of dunitic material.
3. *Upper zone (>1000 m thick)*. A gradational contact over tens of metres leads into the highest exposed levels of the intrusion which consist of coarse-grained (< 2 mm) olivine gabbro with minor layers of troctolite and dunite.

Mafic sheets are locally abundant in the country rocks immediately beneath the contact with the Tronfjell intrusion, especially on the northern side. These sheets are usually altered, but they resemble the rocks of the lower zone in texture and mineralogy.

Primary magmatic fabrics

Modal layering is common in the upper zone, where it is defined by a variation in the modes of plagioclase relative to mafic phases or, more rarely, clinopyroxene oikocrysts relative to cumulus phases. Although disruption of the layering is rare, slumps and trough-like structures were found which suggest that the intrusion has not been inverted.

An igneous lamination is common in rocks of the upper zone. This may be the only fabric present, but in some cases it is associated with parallel modal layering. Clinopyroxene oikocrysts commonly contain unoriented plagioclase laths yet are surrounded by flattened laths defining an igneous lamination. These relationships suggest that this fabric is due to compaction of a crystal mush, post-dating the growth of the oikocrysts.

Stronger evidence for deformation of the crystal mush is seen within the transitional zone. Isolated pods of dunite are interpreted as boudins of an originally continuous sheet. The pods contain a crude magmatic fabric defined by aligned pyroxene grains. In one case a vein or layer of pyroxene, oblique to this fabric, has been folded within one plane and boudinaged within another. Olivine-poor gabbro surrounding the pod contains a strong magmatic fabric defined by an alignment of centimetre-scale plagioclase-rich patches. This fabric is parallel to other magmatic structures in the intrusion and is interpreted as the consequence of compaction flattening, which perhaps occurred at the time of formation of the bowl-like shape of the massif.

The pod- or sheet-like bodies of *dunite* which occur throughout the intrusion, especially within the lower and transitional zones, sometimes contain small patches or discontinuous veins of chromite.

Alteration

The Tronfjell Massif is cross-cut in many places by areas of greenschist-facies alteration. These vary from discrete cm-wide planes or zones of alteration to a mappable area of largely altered rocks (Fig. 2). This alteration occurred at upper greenschist-facies conditions, and is associated with the breakdown of plagioclase and mafic minerals to chlorite, epidote, albite and amphibole. Alteration is commonly associated with deformation along discrete shear zones which can be seen to offset primary igneous boundaries. Moving into these shear zones, unaltered gabbro passes via undeformed metagabbro into fine-grained amphibole-rich rocks. A zone of hydrous alteration up to 10 m thick is seen along the margins of the intrusion. The large area of alteration along the northwestern side of the intrusion is associated with cross-cutting veins of felsic melt, the emplacement of which was associated with hydrous fluids and associated alteration (Kanaris-Sotirou & Angus 1979) .

As a large layered body, the Tronfjell intrusion might bear

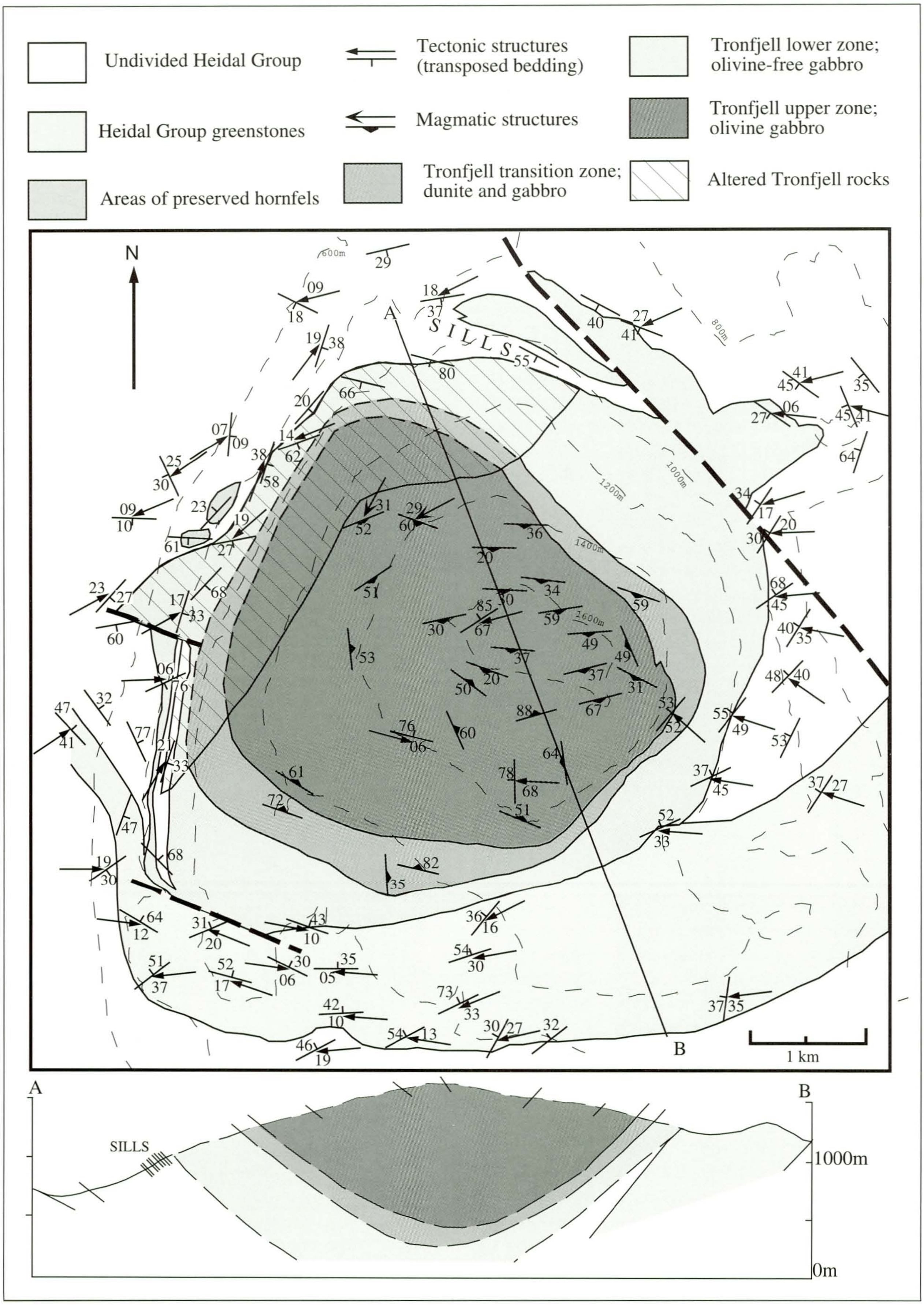

Fig. 2. Geological map of the Tronfjell area, modified after Wellings (1996a) and Dreyer (1975).

comparison with some of the other mafic bodies in the TNC, such as the Fongen-Hyllingen Complex (Wilson et al. 1985). Compared with these, the Tronfjell body is unusual in containing chromite and in having a thick basal layer of contaminated massive gabbro.

Timing of emplacement

The latest stratigraphic correlations in the area, in particular those based on a tracing of the Sel-Heidal unconformity from type localitites in the Otta area (Sturt et al. 1991), suggest a polyorogenic history for the country rocks surrounding the Tronfjell intrusion. Synorogenic intrusions may act as a useful golden spike, representing a datable event which constitutes a marker within a tectonometamorphic succession (Rogers et al. 1989). Granitic bodies have typically been used but recent work on a synorogenic mafic intrusions has shown that these bodies may be equally useful in this respect (Wellings 1998).

Scandian orogenesis

Bjerkgård & Bjørlykke (1994) described metasedimentary rocks of the Sel Group from the nearby area of Folldal (Fig 1). They considered that upper greenschist-facies fabrics associated with E-W-trending mineral lineations were products of the Scandian orogeny. Similar fabrics and lineations are recognised throughout the area of the Tronfjell massif.

Within the Tronfjell country rocks the main schistosity is generally defined by chlorite or white mica and is associated with an E-W-trending mineral alignment or stretching lineation (Fig. 3a). Close to the country rock/intrusion contact, this foliation is locally more strongly developed and in places it is associated with boudinage of mafic sills. Areas of highly prolate fabrics are seen along the western edge of the intrusion. Rare sense-of-shear indicators, such as shear-bands in well foliated rocks, give a top-to-the-east sense of shear movement.

Within the intrusion itself, such fabrics are associated with alteration of the igneous mineralogy and are variable in orientation (Fig. 3c), especially where the deformation took place in narrow (<10 m thick) zones, but a general pattern of c. E-W lineations is evident. This dominant E-W linear grain strongly suggests that the Tronfjell intrusion was affected by the Scandian orogeny and was therefore emplaced into its host rocks before this event.

Pre-Scandian structures

Xenoliths within the intrusion are generally rounded and have been completely recrystallised, destroying any pre-intrusion fabrics which they may have contained.

Small areas just below the western contact of the intrusion expose undeformed hornfels. These hornfelses are both wrapped and cross-cut by Scandian fabrics, but they also preserve evidence for an earlier phase of deformation. Fig. 4 depicts a sample of hornfelsic material showing a folded tec-

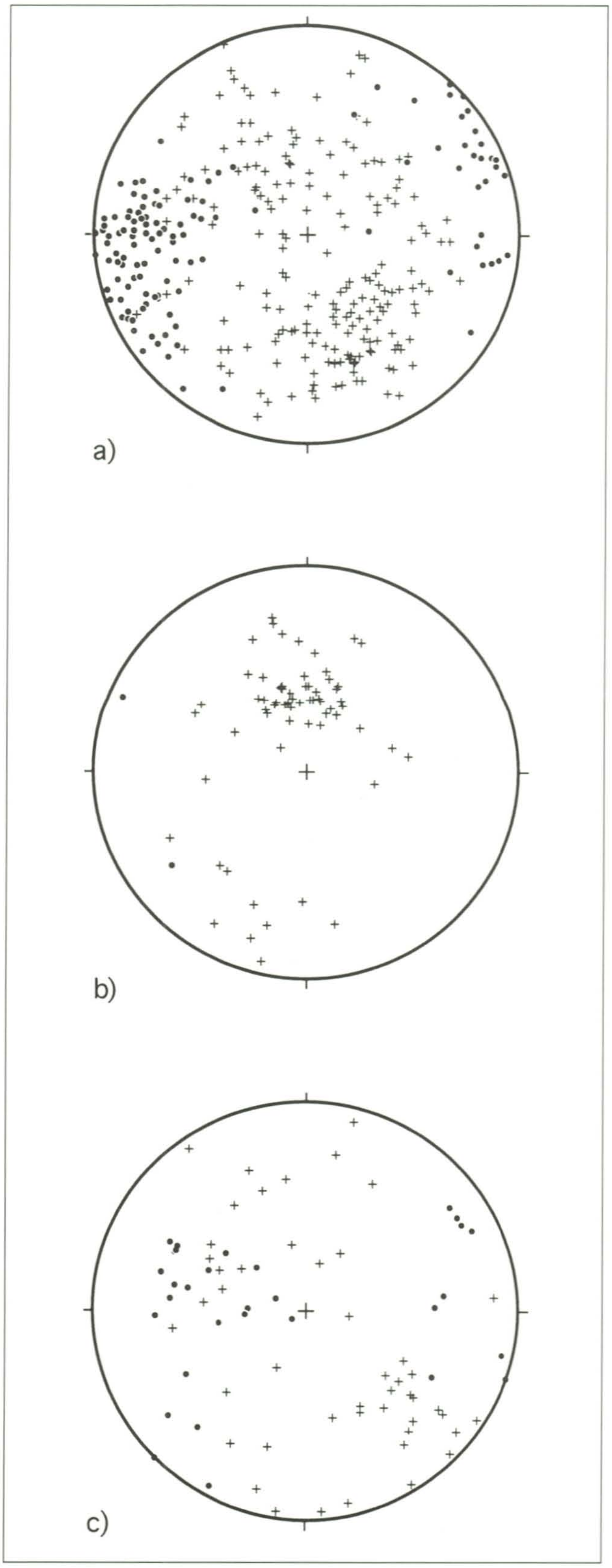

Fig. 3. Stereographic projections of structural data from the Tronfjell massif. (a) Data from the country rocks. Dots are lineations and crosses are poles to foliation. (b) Data taken from unaltered gabbro of the Tronfjell intrusion. Dots are magmatic lineations, crosses are poles to magmatic planar fabrics. (c) Data from deformed metagabbro of the Tronfjell intrusion. Dots are lineations, crosses are poles to foliations.

Fig. 4. Photograph of the polished surface of a block of hornfels, showing a folded foliation. The width of the photograph is equivalent to 15 cm.

tonic fabric. Structures within the hornfelses are complex, with folding common. There is evidence for multiple development of tectonic fabrics, but the limited outcrop hinders a detailed study of these early fabrics. Under the microscope the folds and folded fabric in the hornfelses described above pre-date the contact metamorphism and are now part of a totally undeformed recrystallised mineral aggregate. These hornfelses are preserved in an area where the angle between pre-intrusion fabrics and the contact is relatively high. Where the contact with the underlying rocks is roughly parallel, any pre-intrusion fabrics have been completely destroyed by contact-parallel Scandian deformation. In these areas, both pre- and post-intrusion foliations are parallel to the boundary but are now indistinguishable. West of the intrusion, the fabrics far from the contact are discordant, trending at a high angle to the contact. The swing of these foliations into parallelism with the contact is likely to be the result of Scandian shear deformation. The variation in discordance between the contact and the country rock fabric and the dramatic variation in the thickness of the Heidal Group greenstone horizon, to the south and east of the intrusion, provide further evidence for pre-intrusion deformation. This provides compelling evidence in support of the notion that rocks of the TNC have been involved in polyorogenic Caledonian deformation (Guezou 1978, Lagerblad 1983, Sturt et al. 1991).

The Tronfjell Massif is undated, but this work constrains its age as pre-Scandian and post polyphasal deformation/ metamorphism of the country rocks of the Heidal Group. It is not possible, at this stage, to place the intrusion into a context of Sel Group sedimentation and subsequent deformation. The Øyungen gabbro (Wellings 1996b), which bears many similarities to the Tronfjell intrusion, is emplaced into rocks of the Sel Group. Indeed, it appears to post-date the Scandian D1 schistosity but to pre-date Scandian D2 which produced the main regional foliation. It is tempting to consider the Tronfjell and Øyungen intrusions as being of the same age as the petrologically similar Fongen-Hyllingen Complex (Wilson 1985). This latter has been dated at 426^{+8}_{-2} Ma by U-Pb age determinations on zircon (Wilson et al. 1983). It is hoped that dating of the Tronfjell and Øyungen bodies will be available in the near future.

Emplacement of the intrusion

Mafic intrusions are generally sheet-like bodies (Petraske et al. 1978) and the Tronfjell intrusion is no exception. The crude parallelism of the base, internal contacts and magmatic planar structures suggests that the intrusion took advantage of a flat-lying plane of weakness (metamorphic foliation) during emplacement. The Fongen-Hyllingen intrusion to the north grew by forcing itself along bedding, thickening by forcing its roof and base apart and growing in area by wedging along bedding (Wilson et al. 1987). Areas to the east of the Tronfjell intrusion show abundant sheeting of gabbro just below the contact. This is not seen in western areas, except for in one sheeted xenolith. This absence of sheeting in the west may be related to the inferred pre-Scandian angular discordance between the contact and the transposed bedding. The relatively small thickness of the lower zone in this area may suggest that the angular discordance inhibited expansion of the intrusion at this point.

Recent work by one of us (BAS) has suggested that large mafic intrusions in this southern part of the TNC are largely found within the Sel Group. However, this would require the magma to have passed through both Sel and Heidal rocks. The fact that the only major intrusion (the Tronfjell intrusion) recorded within the Heidal Group, on the eastern limb of the Jønndalen Syncline, coincides with an area of flat-lying transposed bedding suggests a structural control upon emplacement. It is suggested that the presence of flat-lying discontinuities was a vital factor controlling the viability of emplacing a large mafic intrusion. For magma ascending from depth in post-Sel Group/pre-Scandian times, such discontinuities were found in abundance only within the Sel sediments. Intrusion growth within the Heidal Group would be inhibited by the lack of suitable discontinuities and magma would perhaps have tended to pond within the Sel. The change in rock properties (such as density or viscosity) at the transition from Heidal metasediments to unmetamorphosed Sel sedimentary rocks might also have acted to inhibit upward dyke propagation and aided the ponding of mafic magma. Such a model would explain the distribution of mafic intrusions within the southern TNC. Magma would still have passed though the Heidal Group, however, and should have left some evidence of its presence, perhaps in the form of small sheets or dykes. Small mafic bodies are common in these rocks, although a large number are undoubtedly not of this age.

Controls on the form of the Tronfjell intrusion

Both the contact with country rocks and planar structures within the Tronfjell intrusion are parallel but now form a saucer shape (Fig. 2). A plot of magmatic structures (Fig. 3b) demonstrates that this saucer is unlikely to be related to later folding, but instead appears to be due to the intrusion sinking under its own weight. This mechanism has been invoked to explain the form of other mafic intrusions (e.g. Loney & Himmelberg 1983). If this sinking was active during crystallisation it may be responsible for some of the magmatic deformation outlined above; however, since the majority of magmatic structures are folded around the structure, they largely formed before this sinking.

Metamorphism

The country rocks in this area are a mixture of metapelites, and meta-igneous rocks. The greenstones have not been studied in detail, but they generally contain greenschist-facies assemblages of green amphibole, plagioclase and epidote group minerals. Meta-pelitic assemblages have been studied in more detail.

Evidence for pre-intrusion metamorphism is largely obscured by later events, but complex garnet morphologies suggest up to three phases of growth, of which the earliest pre-dated emplacement of the intrusion. Contact-metamorphic minerals are also poorly represented, large garnets and rare sillimanite close (< 50 m) to the intrusion being the only definite examples. Xenoliths preserve blue quartz containing sub-microscopic exsolved needles (mineralogy unknown) but are extensively overprinted by later white mica and chlorite. Most studied samples of metapelite are extensively overprinted by Scandian metamorphism, manifested in features ranging from the growth of new garnet rims on garnets through to pervasive recrystallisation at greenschist facies. A common assemblage in metapelites is quartz-plagioclase-biotite-white mica-amphibole and epidote. This metamorphic picture is consistent with the polyorogenic nature of the Hummelfjell / Heidal metasediments and suggests that the contact metamorphism did not affect a large volume of rock.

Discussion and conclusions

The recognition that the Tronfjell Massif was emplaced prior to the main Scandian event but post-dates pre-Sel orogenesis further strengthens correlation with other mafic intrusions within the TNC (Wilson 1985). This correlation will be tested by an ongoing programme of dating and, if correct, is of interest for two reasons: firstly, it strongly suggests that the Tronfjell Massif may be correlated with, and therefore sheds further light upon, other intrusions farther north; secondly, the Tronfjell Massif is the only large mafic intrusion so far recognised within the Heidal portion of the TNC, providing vital evidence that mafic magma passed through these rocks. The fact that all such bodies so far described within the TNC are found within country rocks with flat-lying fabrics suggests a structural control upon their emplacement.

Tectonic fabrics within recrystallised hornfels adjacent to the Tronfjell intrusion provide corroborating evidence in support of the tectonostratigraphic model of Sturt et al. (1991,1995, 1997) and Bjerkgård & Bjørlykke (1994). This confirmation that rocks of the Heidal Group were affected by two tectonometamorphic events, the second related to the Scandian orogeny, is in agreement with this model. A similar bipartite subdivision has been recognised in the northern part of the TNC (e.g. Lagerblad 1983, Tietzsch-Tyler 1989). It is suggested that polyorogenic rock packages may be more common within mountain belts than is currently realised; structural studies of intrusions and their immediate surroundings provide a powerful means of recognising such packages.

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