NGU Report 96.112
Geology of the Tronfjell massif:
placing mafic magmatism into a
tectono-stratigraphic framework.

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REPORT

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Summary:

Detailed mapping of a syn-orogenic intrusion and the surrounding rocks provides supporting evidence in favour of a recent re-interpretation of the stratigraphy of the Trondheim Nappe Complex (Sturt et al. 1994). The Tron intrusion lies within rocks of the Hummelfjell group. The preservation of folds within recrystallised hornfels close to the intrusion confirms the presence of an old tectono-metamorphic event in these rocks. This event is predicted by the correlation of the Hummelfjell with the Heidal series of the Otta area (Sturt et al. 1994, B.A. Sturt pers. comm. 1996). Both the intrusion and the surrounding rocks are affected by fabrics correlated, by orientation and metamorphic grade, with the main Scandian orogeny. The intrusion event is therefore placed between c.500Ma (age of post-Heidal-deformation sediments) and c.425Ma (age of main Scandian orogeny). Evidence for poly-phase deformation is seen in the country rocks, with reactivation of pre-intrusion fabrics by post-intrusion deformation. The latest foliations are associated with E-W dipping lineations, and pre-intrusion structures have similar orientations. Three phases of metamorphism are distinguished: a pre-intrusion event, represented by garnet cores; a contact metamorphic event; a late event of upper greenschist facies, similar to Scandian metamorphism in nearby rocks. The latest event overprints all rocks, including the gabbro, where zones of alteration focus deformation into discrete shear-zones. What little is preserved on the contact metamorphism suggests a narrow and low-temperature aureole, implying cool country rocks. The intrusion is a layered mafic body, sheeted along concordant margins with three distinct facies: a lower contaminated layer; a transitional layer rich in dunitic rocks which yield chromite; an upper layer of coarse olivine gabbros. No roof is seen. Magmatic structures are common and include modal layering, igneous lamination and evidence for magmatic deformation. The intrusion has a bowl-like geometry, inferred to have formed due to sinking of the intrusion into hot country rocks. The country rocks had folded planes of weakness during emplacement, yet the intrusion is found within an area of flattish bedding. This suggests that country rock structures may be an important control upon the siting of mafic intrusions.

Keywords: Bedrock geology	Structural geology	Metamorphic petrology
Tectono-stratigraphy	Mafic intrusion	Scientific report

CONTENTS

FIGURES

APPENDICES

1 INTRODUCTION

The Tronfjell massif lies within the Nord-Østerdalen area of Norway, close to the town of Alvdal in Hedmark fylke. The mapped area lies across the 1:50,000 map sheets Alvdal and Tylldalen (1619II and 1619III). Tronfjell itself is a single isolated peak which reaches 1666m in height. The road to the summit is the second highest in Norway. The whole of the mountain is reasonably well exposed, with excellent exposures near the summit. The area at a height of between 1000 to 1300m is less well exposed due to extensive boulder fields of semi-in-situ material. Outcrop in the lower forested areas is best found in stream sections. The Tronfjell intrusion lies within metasediments of the Hummelfjell group. The intrusion is a layered body containing a sequence of rocks varying from altered dunites to olivine-free gabbros. Contact metamorphism has been recognized but the aureole has been largely obscured by later metamorphism and deformation, which also locally effects the intrusion.

This study is based on field work undertaken the author during July 1996. It was made possible by a grant from the European Leonardo da Vinci programme and by logistic and financial support from NGU.

1.1 Previous Work

The study area was covered by the NGU regional studies of Holmsen (1943) and Holmsen & Holmsen (1950) in the east and Marlow (1935) in the west. Modern work on the intrusion itself consists of Kleine-Hering (1969) and Dreyer (1975). The work of Kleine-Hering covered a large area and was only a masters thesis. Its coverage of Tronfjell was largely superceeded by the more detailed and substantial doctoral thesis of Dreyer. Herr Dreyer died in 1978 and so his work was never published. The study area is covered by the NGU 1:250 000 map Røros og Sveg (Nilsen and Wolff 1989).

1.2 Sources of data

This study has drawn heavily on Dreyer (1975) as regards the petrology and chemistry of the intrusion and other data taken from his work will be acknowledged in the text below. Two maps are included in this report: the first is new work, whereas the second is a copy of the map included in Dreyer (1975). There is little disagreement between the two, but the new work contains more structural data whereas Dreyers map has more stratigraphic divisions. Mapping in the immediate area of the Tronfjell intrusion is by the author but the map also includes data taken from mapping by D. Ramsay and B.A. Sturt.

1.3 Regional context: recent changes in stratigraphy

Nilsen and Wolff (1989) interpret the position of the Tronfjell intrusion as lying within the Remsklepp Nappe, an isolated thrust sheet made up of rocks of the Hummelfjell group (figure 1). The Remsklepp Nappe, together with the Røros Nappe lies between the Trondheim Nappe Complex and the Augen Gneiss and Sparagmites of the lower Allochthon. This interpretation of the area has recently been challenged by work started in the Otta area. Papers such as Sturt et al. (1991), Sturt et al. (1995) and Bjerkgård & Bjørlykke (1994) have led to a major reinterpretation of the stratigraphy of the whole area. Rather than forming part of an isolated nappe, the Hummelfjell group is correlated with the Heidal series of the Otta area, (Sturt et al. 1991) and both are regarded as equivalents of the lower part of the Gula Group. The rocks cropping out between the Gula and the Hummelfjell are metasediments of Ordovician age. These various units of Nilsen & Wolff (1989) (e.g. the Dalsbygda, Fundsjø and Aursund groups plus the upper Åsli formation) are now grouped together into the Sel group. This is a single package of Ordovician sediments and volcanics, lying in the core of a major fold structure, of Scandian age. The three thrust planes lying between the Gula and the Hummelfjell units are not recognized.

The tectono-stratigraphy of the area is now thereby greatly simplified. The Røros and Remsklepp Nappes are grouped with the Trondheim Nappe Complex. The oldest parts of this expanded unit are the Heidal / lower Gula / Hummelfjell rocks, which experienced an orogenic event of early Ordovician age. This event was associated with the obduction of ophiolitic material (Sturt et al. 1991) and may be related to the metamorphism seen in the Seve nappes of Sweden (Bjerkgård & Bjørlykke 1994). Post-orogenic sedimentation, coupled with vulcanism gave rise to the Sel series, which lies with major unconformity directly upon the older rocks. All these rock-types were subsequently affected by Scandian orogenic events which metamorphosed and deformed all rock-types.

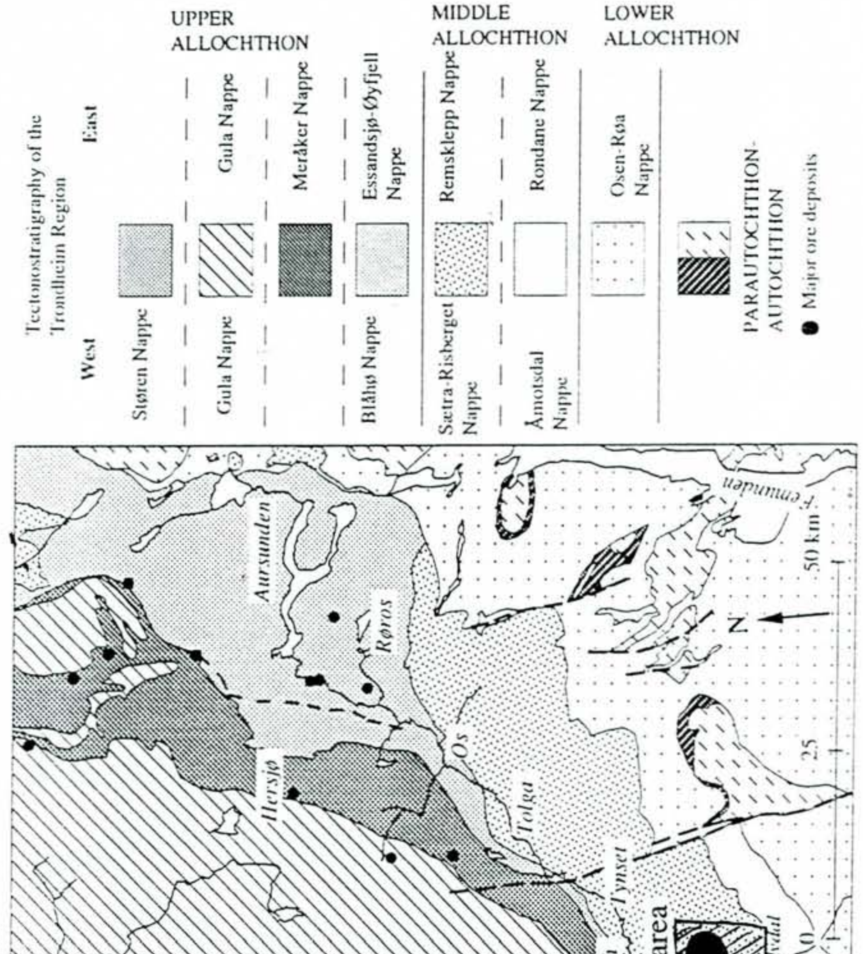

Figure 1. Tectonostratigraphic map of the southern part of the Trondheim region. The study area is indicated. Taken from Bjerkgård & Bjørlykke (1994).

The implications of this reinterpretation, as relevant to this study, are as follows.

1: The Hummelfjell rocks will have experienced two major episodes of deformation, the later one correlatable with fabrics present in the Sel rocks to the east.

2: The Hummelfjell rocks will have experienced two major episodes of regional metamorphism, the latter of likely greenschist facies, as correlatable with the metamorphism of the Sel in the surrounding area.

Any interpretation of the age of emplacement of the Tron intrusion must be compatible with these constraints in order to fit with the new tectono-stratigraphy.

1.4 Aims of the study

The aims of this study were to clarify the relationships between the intrusion and the surrounding metasediments. The following aspects were seen as most important.

1. To confirm the intrusive nature of the body.
2. To confidently place the emplacement event within the regional tectono-stratigraphic framework, thereby testing this framework (see above).
3. To assess the extent of contact metamorphic effects related to the intrusion within the country rocks.
4. To assess the role the solid intrusion played in any subsequent deformation and to describe any deformation of the intrusion, either magmatic or post-magmatic.

2 PETROLOGY OF THE TRONFJELL INTRUSION

2.1 Previous work

Some brief descriptions of the intrusion are given in Holmesen (1943) and Kleine Hering (1969) but the only systematic work is found in Dreyer (1975). Dreyer established the intrusive nature of the body and divided it up into three major facies types, seen as layers parallel to the base of the intrusion (enclosure 2, figures 9 and 10), since the intrusion has a bowl-like geometry and the centre of the intrusion corresponds to the peak of Tronfjell, these zones crop-out in a concentric pattern. Dreyer's facies types have been confirmed and will be used throughout this work. His terms are used, but it is emphasised that the boundaries between the zones are parallel to the base of the intrusion, and that the 'outer' zone lies outermost only in a geographical sense. Its position within the intrusion might best be described as the lowest zone.

Dreyer (1975) also provides much information on minor intrusives and alteration of the intrusion. Where relevant, these will be referred to below.

2.2 Petrology and structure of the unaltered rock

Dreyer (1975) divided the intrusion into three main zones distinguished on the basis of textures, mineralogy and chemistry. They are defined as follows:

1.) 'Outer zone' This lies everywhere at the base of the intrusion and consists of 'fine to medium grained gabbro and gabbronorite with sporadic ultramafics, especially at the base'. Xenoliths of blueish-quartz are found in this zone and quartz may be a phase in the gabbro. Textures are 'often sub-ophitic to intergranular'.

2.) 'Transitional zone' This lies immediately above the outer zone consists of 'medium to fine grained olivine gabbro with scattered ultramafics (dunite)'. The basal contact with the olivine-free rocks of the outer zone is sharp whereas the upper contact is gradational. This zone is especially characterised by the presence of lense forming ultramafic bodies. The olivine gabbros of this zone are similar to the rocks of the core zone.

3). 'Core zone' This forms the summit area of Tronfjell and represents the highest exposed levels of the intrusion. This zone consists of 'coarse grained olivine gabbro, troctolite with subordinate ultramafics (dunite)'.

Field work and study of thin-sections have confirmed this division. Textures within all samples are simple; 120 degree grain boundaries and straight edges are common, especially with plagioclase. No interstitial phases or zoning of minerals was seen, large oikocrysts of greenish clinopyroxene are common in the core zone. These contain laths of plagioclase and occasional olivines and may be seen in samples Tr5 and Tr9.

2.3 Alteration

Dreyer (1975) presents a great deal of information on the style of alteration and readers are referred to him for a thorough listing of the mineralogies involved.

The pattern of alteration throughout the intrusion may be divided up into two types:

1) Minor alteration. This type is alteration of isolated grains within otherwise pristine rock. It is best seen in olivines which may show a little serpentinisation associated with radial cracking. This cracking fractures the surrounding minerals which are unaltered, even along cracks. On sample Tr32 contains olivines in contact within plagioclase. The olivines are mantled by fine grained intergrowth of radiating needles. All these types of minor alteration are related to normal post-magmatic processes within gabbros and are of little importance.

2) Intense alteration. This type is geographically restricted. It is ubiquitous within the western 'altered' zone and is common also at the edge of the intrusion. Within the core and transition zones it is found only in discrete zones. These zones often contain shear zones which may offset igneous boundaries (e.g. at G.R.895943), but undeformed altered rocks are common. This alteration is associated with destruction of all igneous mineralogy including the amphibolitisation of pyroxenes and the alteration of plagioclase to zoisite and albite. The restriction of the alteration to discrete zones and the nature of the altering reactions suggests that this form of alteration was related to the ingress of water into the intrusion along fractures. It is notable that the area rich in alteration in the west also contains numerous felsic melt veins. Crystallisation of this felsic magma would introduce large volumes of hydrous fluids in to the area and so aid alteration. Another mineral associated with the alteration is a bright green mica, described by Dreyer as a chrome-rich sodium-mica. A loose block of undeformed altered gabbro revealed that this green mica was found as pseudomorphs after a large oikocryst. Only oikocrysts of clinopyroxene have been observed, suggesting that this mineral is rich in chrome. Sample Tr33 is from an alteration shear zone within the core-zone. It has an intense fabric which in hand specimen is seen to vary in intensity within the zone of alteration. This fabric is defined by small grains of greenish amphibole and of plagioclase. The latter are seen as tails on large porphyroclasts of plagioclase. These porphyroclasts show much evidence of strain, including bent twin lamellae, deformation twins, and intense grain-size reduction along sub-grain boundaries and at the edges of grains. Porphyroclastic grains of

relcit pyroxene are also seen. Small needle-like grains are seen within the plagioclase, especially along sub-grain boundaries, these are probably amphibole. Apart from this there is no alteration of the plagioclase, its composition is not known but they are probably relict igneous grains and so quite calcic. The survival of plagioclase and the lack of zoisite within this rock suggest that the alteration and deformation may have taken place at higher temperatures than for altered rocks with albite and zoisite. This issue will be discussed in the metamorphic section.

2.4 Magmatic fabrics

This study paid especially close attention to the fabrics found in unaltered gabbro. Two fabrics in particular were studied and measured.

1. Modal layering. This is best developed within the coarse olivine gabbros of the core zone. This usually decimetre scale layering is defined by the modal variation of minerals. The most visually striking type is seen with variation in plagioclase content compared with olivine and pyroxene. This layering is best developed on the summit plateau, where it influences the form of the craggy outcrops, for example around the subsiduary peak at G.R. 889947. Other types include layering defined by the presence or absence of large clino-pyroxenes in a medium grained plagioclase, olivine pyroxene matrix (figure 2), for example seen at G.R. 882953. Only rarely, folding of this layering is seen, probably as a result of slumping of a crystal mush. Structures similar to trough layering have been found (figure 3).

2. Igneous lamination. This is seen in all zones but is best developed within the core zone. It is defined by the planar alignment of plagioclase laths within unlatered gabbro. It may be found in rocks with or without modal layering and it is always seen to be parallel to it. Where it is found within rocks with oikocrystic clinopyroxenes (e.g. at G.R. 883953), it can be demonstrated that these fabrics were formed by the flattening of a crystal mush. The clinopyroxenes contain unaligned plagioclase laths whereas outside the laths are flattened and wrapped around the large pyroxene crystals. This indicates flattening of a crystal mush containing plagioclase and clinopyroxene set in a melt matrix. This can be best seen in sample Tr9 where plagioclase laths aligned between two clinopyroxene grains contain bent

Figure 2. Altered olivine gabbro preserving an igneous lamination defined by plagioclase laths parallel to modal layering. G.R. 865936

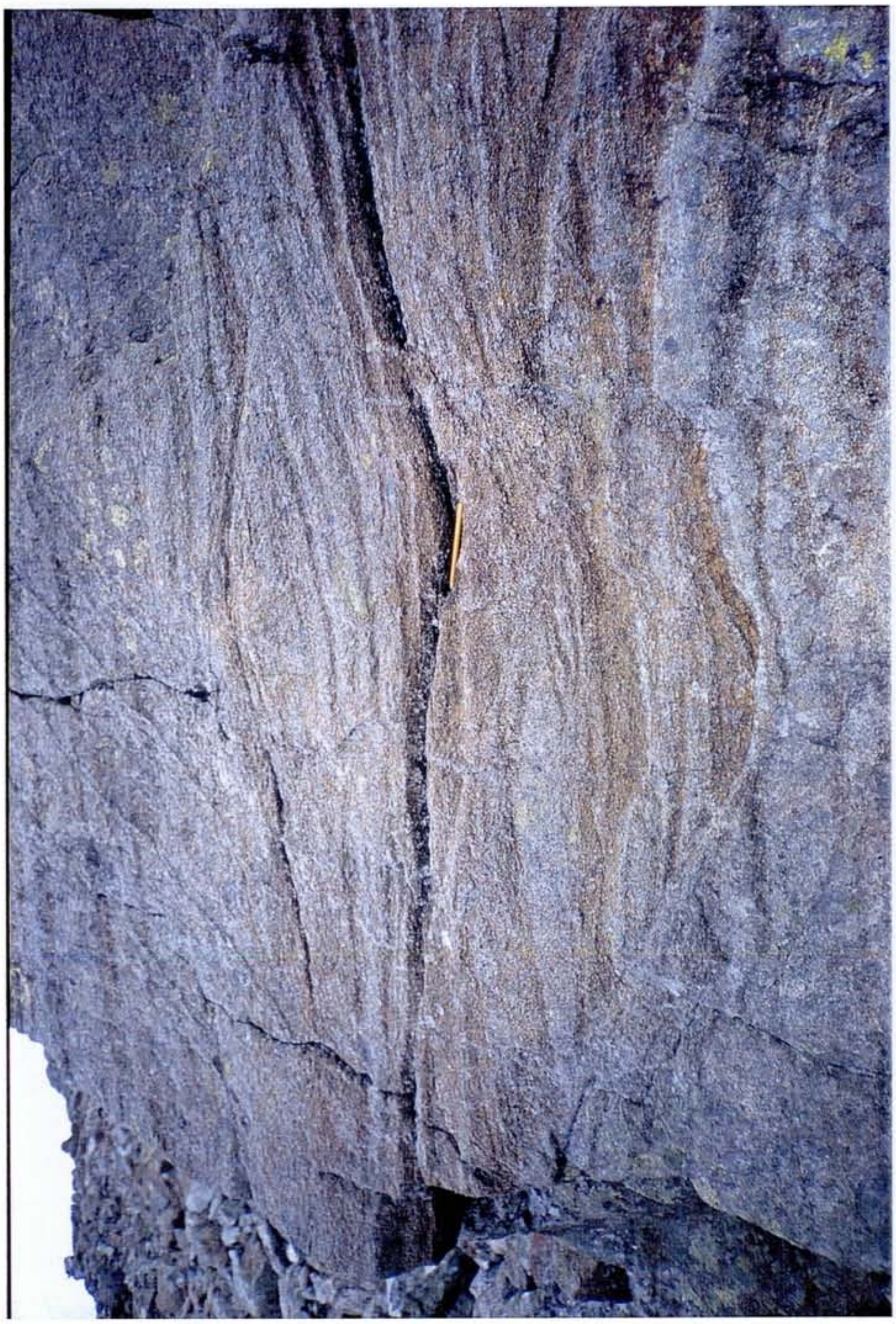

Figure 3. Field photo of trough structure in modally layered olivine gabbro. Pencil for scale. G.R. 883957.

and intersecting twin lamellae, indicative of crystal plastic strains. This fabric is best seen in hand specimen or outcrop (figure 4). Very rarely this fabric can be seen to contain a linear element (see main map).

Other evidence for deformation of crystal mush is seen in a few scattered localities. At one (G.R. 893951) fabrics are seen within olivine poor gabbro and within an isolated pod-like body of serpentinite (figure 5). Within the gabbro, alignment of large areas or laths define a magmatic foliation, with a crude lineation, this may be seen in Tr10. The serpentinite pod is seen to contain a crude magmatic foliation, brought out by pyroxenes. A layer or vein of pyroxene is folded in one face and boudinaged in another (figures 6 and 7.) This is compatible with the pattern of strain inferred from the magmatic fabrics. It is suggested therefore that the pod of serpentinite might represent a boudinaged layer, affected by syn-magmatic deformation. This fabric is not visible in thin section (Tr11) as it was defined by scattered grains of ?pyroxene rather than the groundmass olivine.

2.5 Nature of the magmatic fabrics

Recent work has demonstrated that magmatic fabrics may be recognized within mafic plutonic rocks (Nicolas 1991, Wellings 1996). They may be caused by externally applied strain (syn-tectonic emplacement) or by internal magmatic processes, such as compaction or slumping of a crystal mush. 'Syntectonic'magmatic fabrics are seen to be associated with intrusions with complex internal structure where the magmatic deformation is intense and pervasive (Wellings 1996). The simple structure of the Tronfjell intrusion, coupled with the fact that all magmatic fabrics, modal layering and magmatic contacts are parallel and flat-lying and that magmatic fabrics are sporadic and not intense suggest a non-tectonic origin. Igneous lamination is found in many anorogenic layered intrusions and is thought to be caused by compaction of a crystal mush. Features such as boudinage of ultramafic layers are compatible with this process.

2.6 Ultramafics

A striking feature of the intrusions is the presence of lenses or isolated bodies of serpentinite. These occur throughout the body and are easily spotted because they weather to a bright orange colour (e.g. figures 5, 6 and 7). They consist largely of olivine, weathering to blue-green serpentine with variable small amounts of pyroxene or with veins of talc and other minerals. Chromite has been found on the eastern flank and was sampled by L. P. Nilsson at G.R. (888957).

The most common form of this rock-type is in layers 10-100m thick which can be continuous over hundreds of metres. These are very common in the transition zone, especially on the eastern slopes. One well exposed area around G.R. (895953) reveals two separate layers divided by a screen of typical transition zone gabbro. In addition to the mapped areas it should be noted that the much of the transition zone, where poorly exposed, contains scattered outcrops of serpentinite compatible with the presence of ultramafic layers even where they are not shown on the map. In some localities such as G.R. (893951) and (902944) small pods of a few metres size surrounded by gabbro may be found. The first example was described above, whereas the second is found within sheared amphibolites just above the contact. In both cases boudinage of an orignal sheet due to magmatic or post-magmatic deformation seems likely.

One thin-section of 'serpentinite' showed that unweathered material preserves the original dunite mineralogy. Thin section Tr11 consists largely of unaltered grains of olivine. A variety of altered pseudomorphs exist which contain variable amounts of opaque, white mica (talc), amphibole and serpentine. The hand specimen contains weathering out knots which probably represent weathered pyroxenes, now seen as amphibole rich pseudomorphs. The origin of these bodies is likely a magmatic one, the formation of olivine rich layers by differentiation of the cooling magma is a common feature of layered mafic intrusions. Subsequent deformation of these layers could account for the occurence of isolated pods.

2.7 Geochemistry

No geochemical analyses were undertaken during this study but Dreyer (1975) included 37 major element bulk rock analyses from a variety of rock types. These are not listed here but a plot made from this data is included, since it is of interest. Figure 8 is a discriminatory plot after Irvine & Barangar (1971) plotting data from unaltered rocks of the Tronfjell intrusion and some rocks from the greenstone formation. This plots helps to show the difference between the tholeiitic greenstones and the intrusion and supports the validity of the division of the intrusion into three zones.

Figure 4. Field-photo. Olivine gabbro with modal layering defined by clinopyroxene oikocrysts wrapped by an igneous lamination. G.R. 882953.

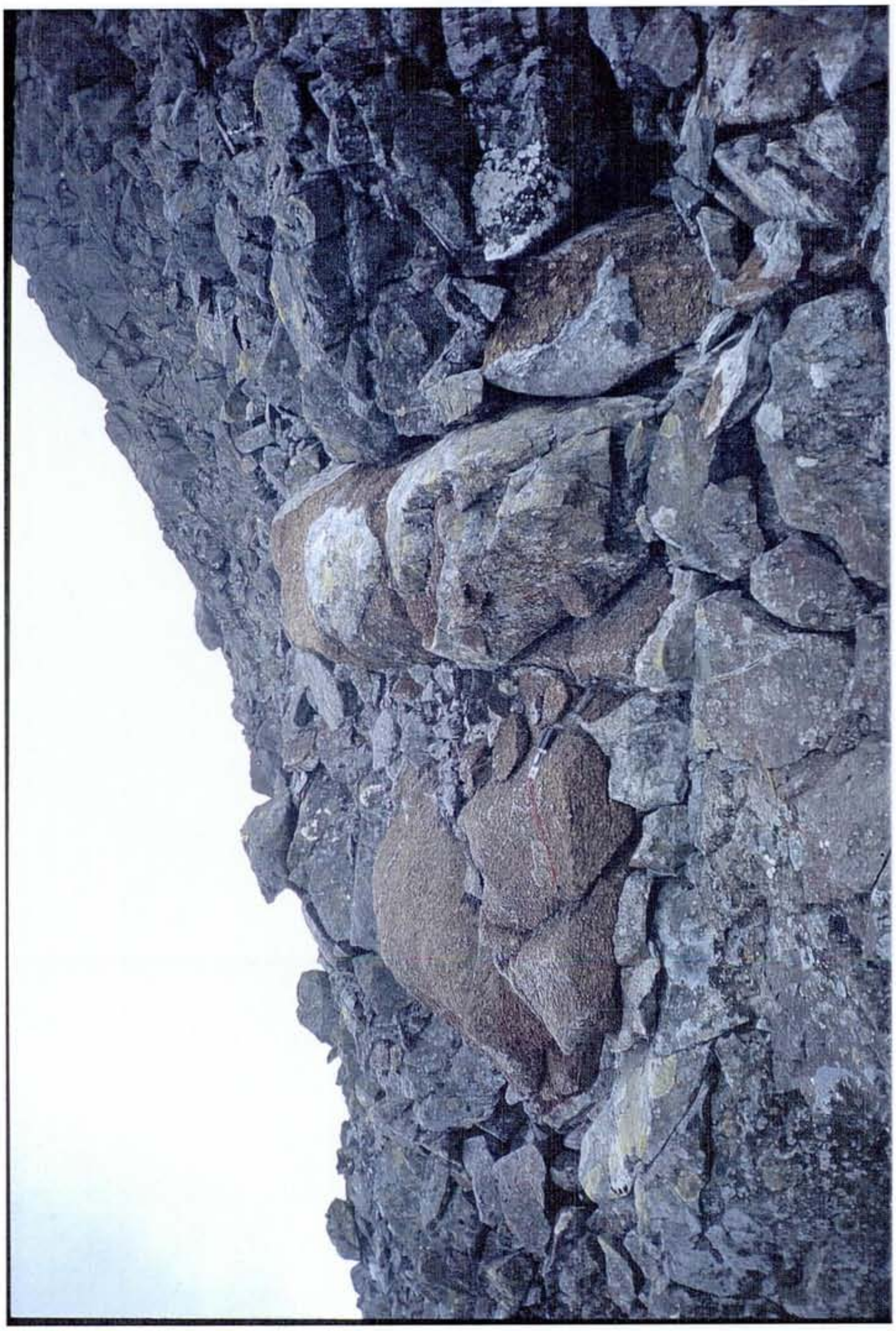

Figure 5. Field photo of pod of serpentinite within gabbro. The pod is rimmed by a white layer of talc-rich alteration products. G.R. 893951

Figure 6. Close up of figure 5, view of face perpendicular to figure 7 showing magmatic foliation (parallel to pencil) and folding of ?pyroxene layer.

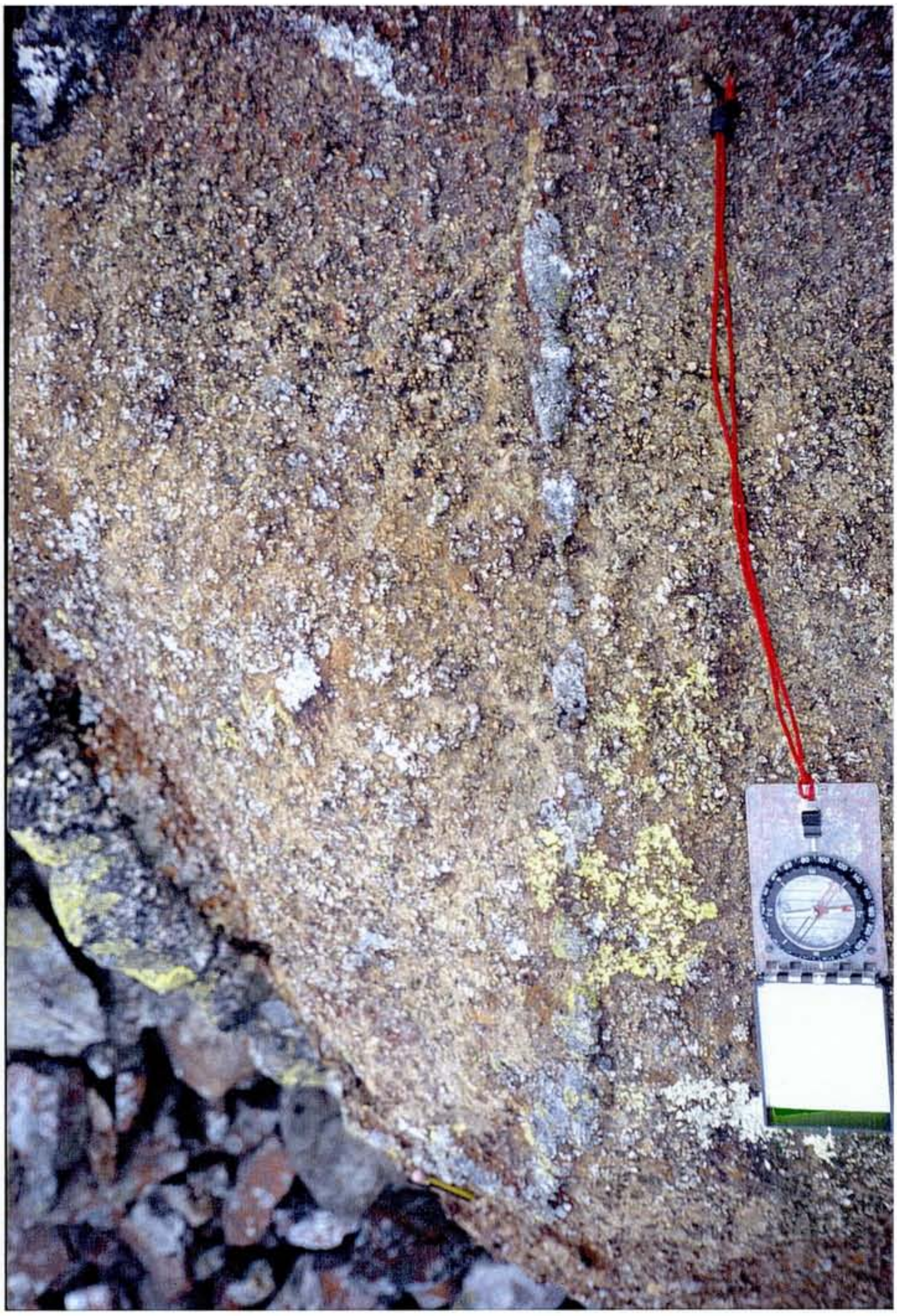

Figure 7. Close up of figure 5 showing crude magmatic foliation parallel to string containing boudinaged ?pyroxene band. G.R. 893951

Key

Greenstone formation	Overturned triangle, green
Ultramafic	Half filled square, blue
Core zone	Empty square
Transition zone	Triangle, red
Outer zone	Filled circle

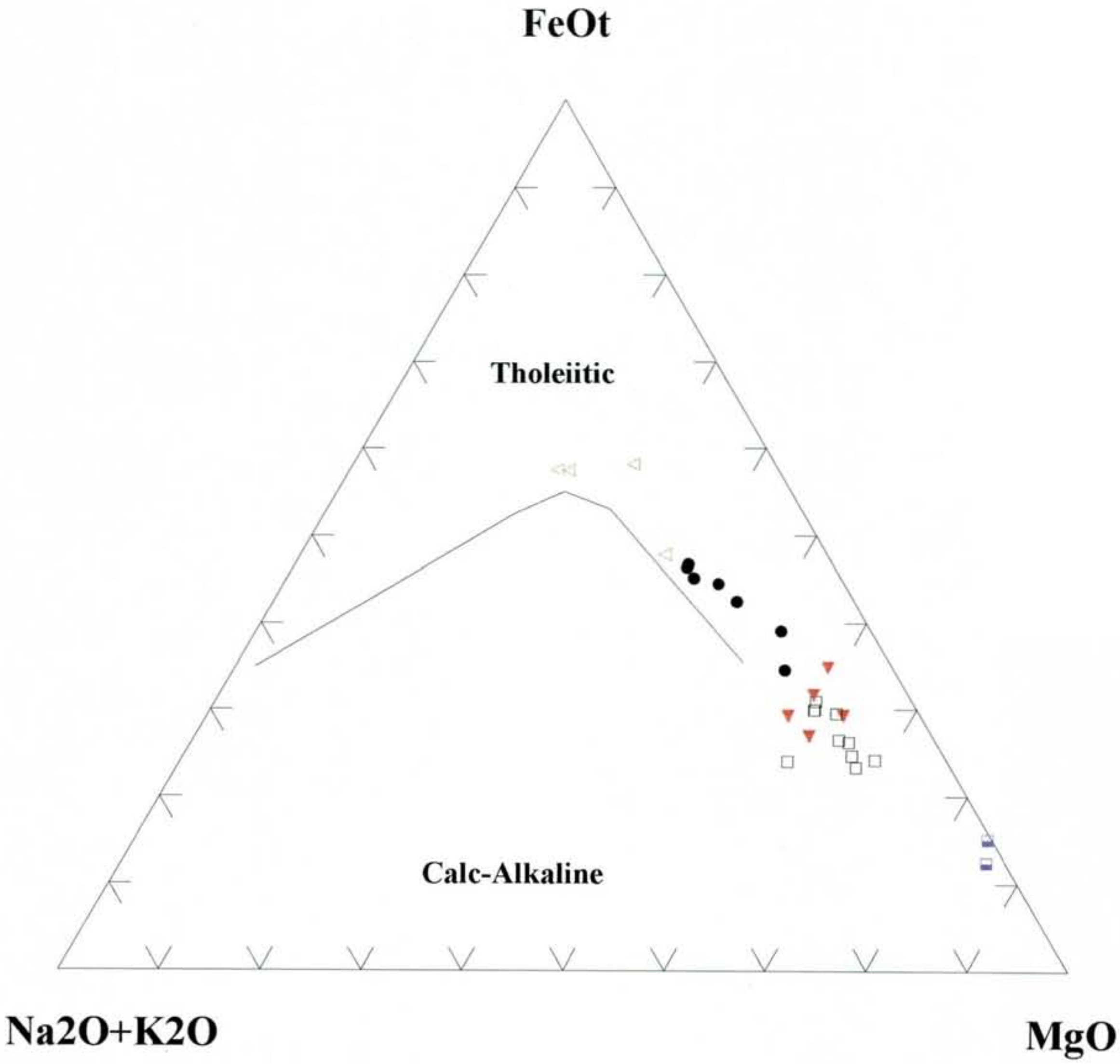

Figure 8. Discriminant plot after Irvine & Barangar (1971). Data is from rocks of the greenstone formations and Tron intrusion.

3 PETROLOGY OF THE COUNTRY ROCKS

3.1 Greenstone formation

The greenstone formation is a varied formation of massive to shistose amphibolites which includes rare pillow structures, banded tuffs (G.R. 877916) and stratabound massive sulphide deposits (see enclosure 2). The vast majority of the formation consists of monotonous foliated amphibolite with a well developed mineral alignment lineation. The likely protolith for this formation is a succesion of lavas and sills of tholeiitic composition. The rocks are now thoroughly metamorphosed. Thin sections Tr1, Tr2 and Tr6a show these rocks to consist largely of aligned green amphibole, often with porphyroclasts of plagioclase or amphibole. Epidote minerals are often seen, either within the matrix or within plagioclase porphyroclasts.

3.2 Metasediments

Sel. Rocks belonging to the Sel group are found on the main map, but were not covered by the authors work. These rocks are low-grade metasediments and volcanics, never containing minerals of higher than greenschist facies. They contain abundant sedimentary structures. Other rock-types include conglomerates and isolated mafic and ultramafic fragments, found at the base of the unit.

Hummelfjell. Rocks belonging to this unit form the envelope to the Tronfjell body. Enclosure 2, the map from Dreyer (1975) divides up these metasediments into 5 units. The author has confirmed these units within the mapped area. Appendix 2 is a stratigraphic column taken from Dreyer (1975). A translation of the rock descriptions in this column provides the best introduction to these rocks:

Tronkalven formation. Quartzite, mica-schist, gneiss with sporadic graphitic schists horizons. 400m thick.

Haugsætra formation. Quartzite and biotite-mica-schists, at the top, graphite schists (meta-greywacke and -pelite). Ca. 300m thick.

Tronfjell Greenstone formation. Greenschist (amphibolite) and greenstone (amphibolite and metagabbro) - volcanic stratiform sulphide bodies; tuffs and metasediments. Up to 1000m thick.

Livangen formation. Quartzite and biotite-mica-schist (meta-greywacke and -pelite) ca. 100m thick.

Tronsvangen formation. Chlorite schists and phyllites (metapelite), subordinate quartzite; quartz-rich mica-schists ('banded schists'); marble horizons: stratiform sulphide bodies. Ca. 500-750m thick.

4. STRUCTURE

4.1 Contact relations

The Tronfjell body is an intrusion. The presence of metasediment xenoliths, of high temperature hornfels and a locally sheeted contact all prove that the Tronfjell rocks were molten when juxtaposed with the country rocks. The layering within the intrusion is broadly parallel to the base of the intrusion which suggests a sheet-like form. Transposed bedding and foliations within the country rocks, as well as mapped sedimentary boundaries are generally parallel to the intrusion base also. The bowl like form of the intrusion is mirrored in the surrounding rocks. This implies intrusion along a flat-lying anisotropy followed by later deformation to give a bowl-like shape (figures 9 and 10).

4.2 Structural age of intrusion

The intrusion of mafic magma into the continental crust is a dramatic event which will greatly influence the evolution of the country rocks. Relating traces of this event to deformational fabrics and metamorphic events seen within the surrounding rocks can allow this intrusion event to be linked to a regional tectono-metamorphic sequence. Since radiometric dating is much easier for igneous intrusions than for metamorphic or structural events, such a linkage can help fix orogenic events within an absolute time-scale. Studies of syn-orogenic intrusions are therefore a powerful tool in the unravelling of orogenic events[1]. An intrusion event may be set within a tectono-metamorphic framework by distinguishing pre-intrusion, syn-intrusion and post-intrusion events:

Pre-intrusion Xenoliths within an undeformed intrusion might be expected to preserve evidence of fabrics present within the rock prior to incorporation within the intrusion. However the extremely high temperatures within mafic intrusions result in extensive melting and recrystallisation of metasedimentary material. Xenoliths within the Tronfjell body have been transformed by metamorphism and so preserve little. Rocks within the contact zone preserve pre-intrusion fabrics in areas of hornfels. Within the wider aureole area contact metamorphic mineral growth may be distinguished from other metamorphic events by its geographical distribution and the presence of high-temperature minerals. The timing of the growth of these minerals can then be fixed and used to distinguish pre-intrusion assemblages. Extensive later metamorphism and deformation has destroyed much of the aureole inferred to have surrounded the Tronfjell intrusion, however small areas of hornfels are preserved. These areas are found just beneath the conact along the western edge of the intrusion (see enclosure one). They consist of hard flinty rocks which stand proud from the steep slopes of the Glåma valley. In thin-section these rocks are hornfelsic in texture and contain no mineral defined fabrics. Lithological banding however preserves complex structures of pre-hornfels age. These include tight folding of metamorphic banding (figure 12) and are described in detail below.

Syn-intrusion The form of the intrusion and its magmatic fabrics suggest that the intrusion was not emplaced syn-tectonically. Detailed studies of contact metamorphic assemblages may allow the depth of emplacement to be estimated, however these assemblages are largely destroyed in the Tronfjell area.

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[1] Samples of pegmatitic gabbro facies were collected for zircon dating (see appendix two for location).

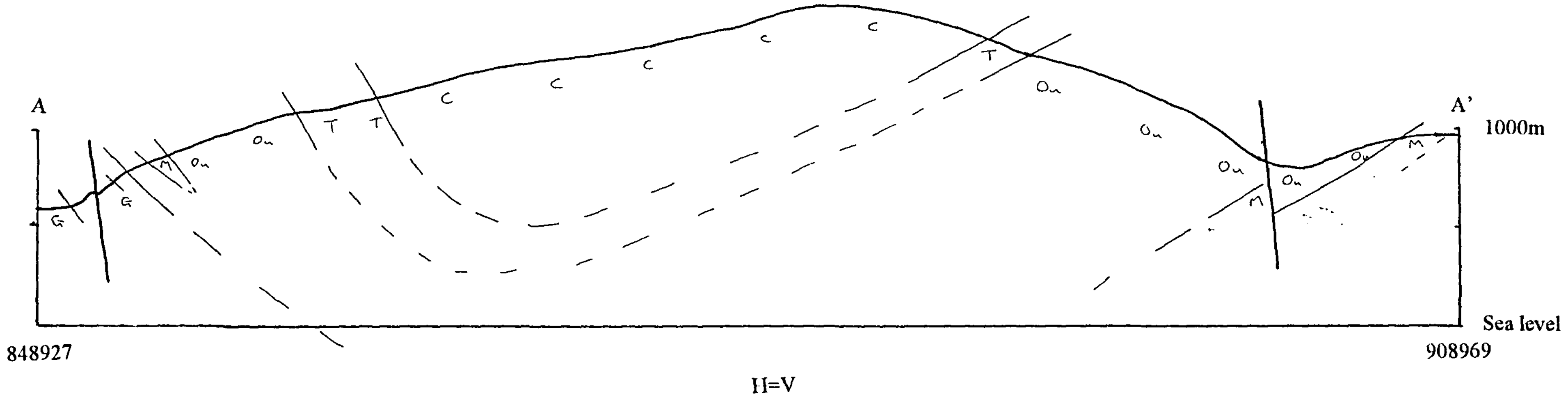

Figure 9. Structural cross-section through the Tronfjell massif. See figure 11 for location.

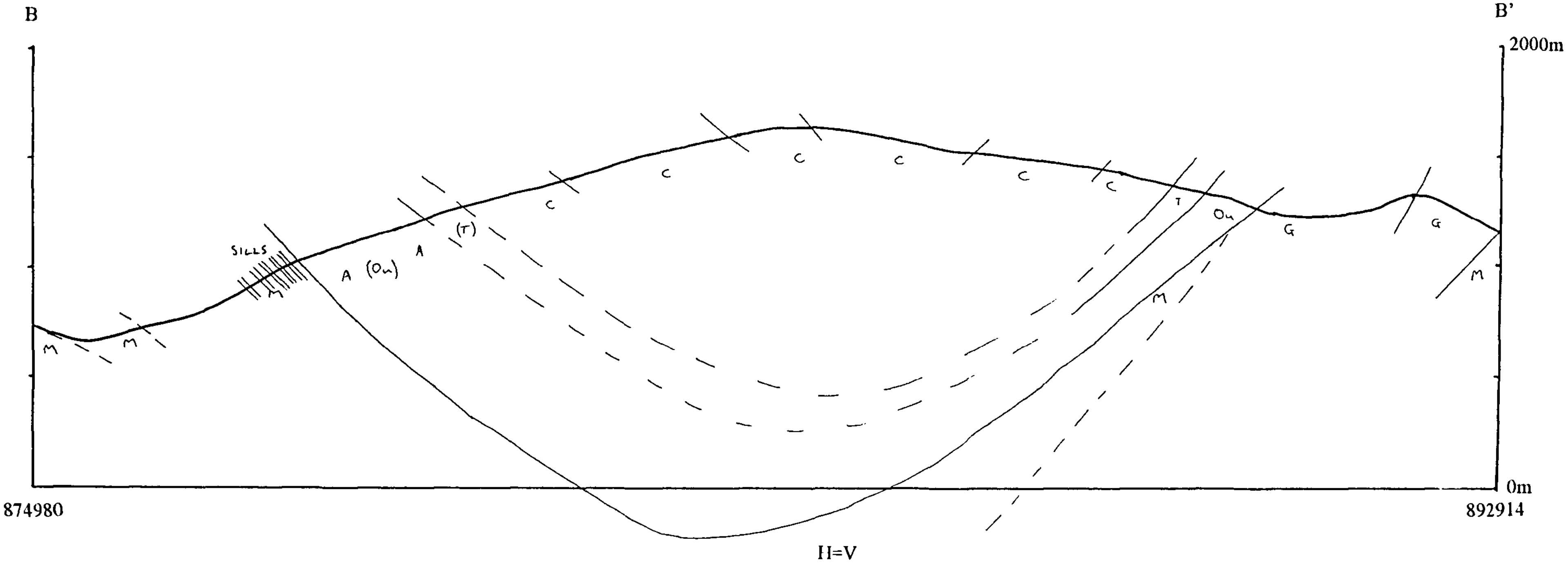

Figure 10. Structural cross-section through the Tronfjell massif. See figure 11 for location.

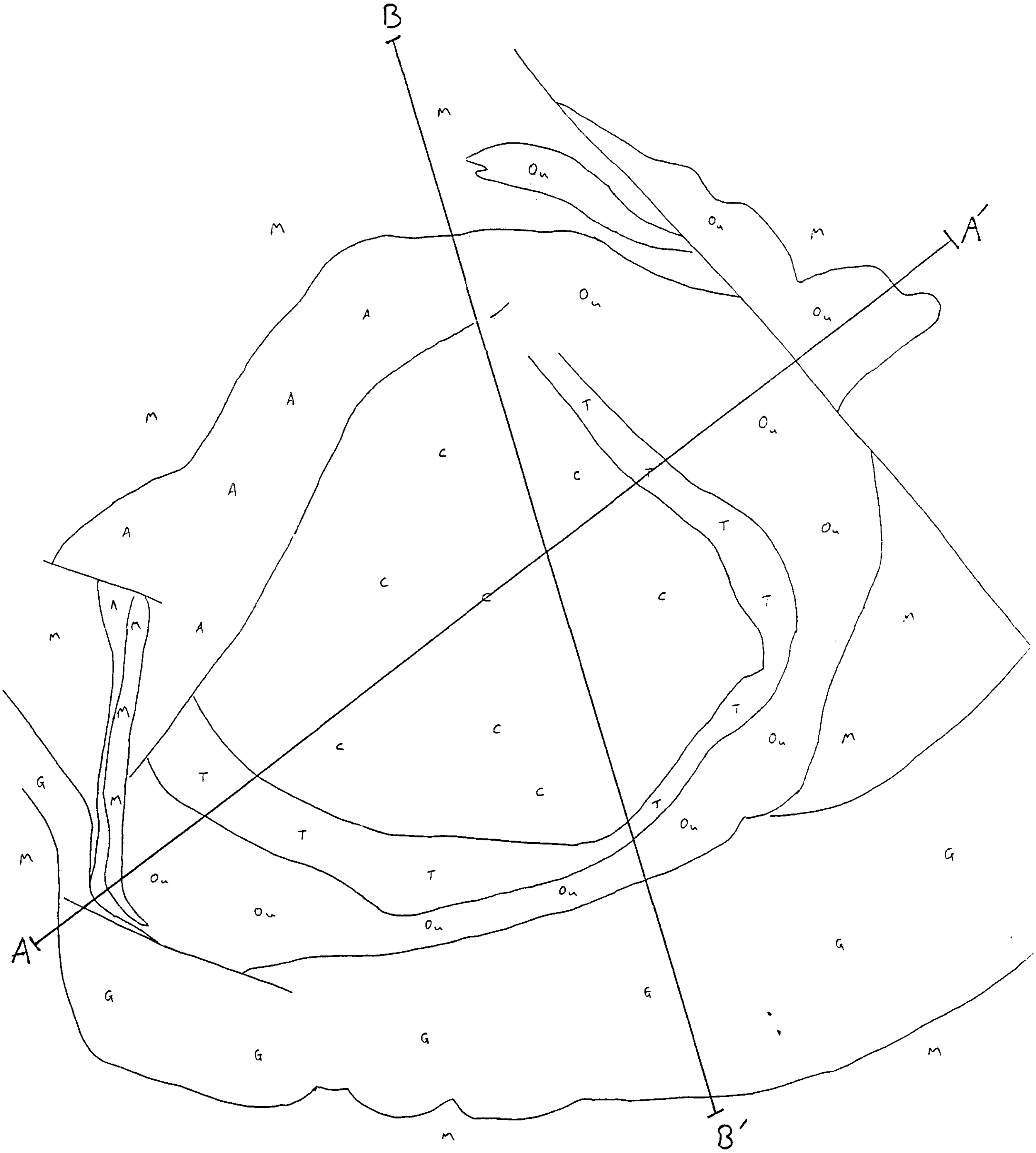

Figure 11. Sketch map of the Tronfjell intrusion showing the location of the sections in figures 9 and 10.

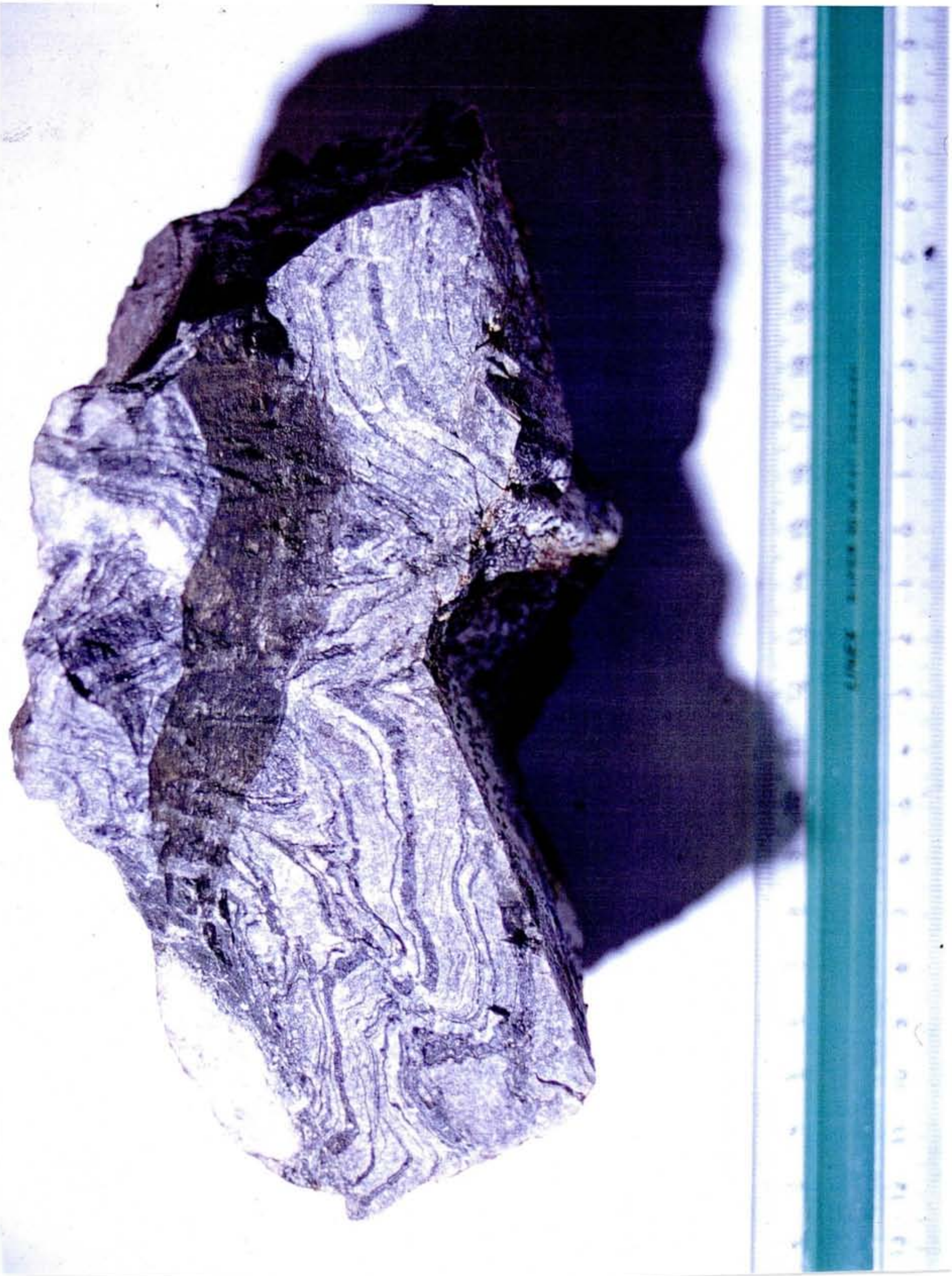

Figure 12. Photo of hand-specimen of hornfels (Tr34) preserving pre-intrusion folding.

Post-intrusion Fabrics which affect the intrusion are by definition post-emplacement in age. The extreme strength of mafic rocks relative to the surrounding quartz-rich continental crust means that post-emplacement fabrics in a mafic intrusion are associated with alteration. The varied metamorpic facies-types observed in metamorphosed mafic rocks mean that this alteration may be related to P-T conditions. Fabrics in or along the edge of an intrusion can be correlated to fabrics outside, by geometrical arguments, or by observing the deformation of small 'satellite intrusions' such as swarms of sheets near to an intrusion. Fabrics affecting the Tronfjell intrusion are associated with green-schist facies shear-zones which may be correlated with similar grade fabrics within the country rocks. Deformation of sills on the northern and eastern sides of Tronfjell and of hornfels containing pre-intrusion fabrics is also of this form.

4.3 Fabrics in the country rocks

Figures 13, 14 and 15 are stereographic projections of all foliation and lineation data taken from the Tronfjell area and figures 9 and 10 are cross-sections across the intrusion. Figures 9, 10 and 13a confirms that the bowl-like shape of the intrusion is mirrored in the foliations of the surrounding rocks. What is striking about this plot is the absence of any obvious fold axes. Figure 13b shows lineations taken from the same rocks, with the same geographical grouping. The lineation data are much more tightly grouped and the overlap between the different geographical sub-sets is large. The lineations have a mean ENE-WSW plunging, gently dipping orientation

4.4 Age of country rock fabrics

The poly-orogenic nature of the Hummelfjell presents problems for anyone engaged in structural mapping of these rocks. In any given outcrop it is not clear whether the fabrics within the rock are entirely of Scandian age or whether they might represent pristine fabrics of pre-Scandian age. A more likely scenario is that fabrics are composite and represent Scandian re-activation of pre-Scandian fabrics. In support of this contention is the fact that no fabrics oblique to lithological banding were seen.

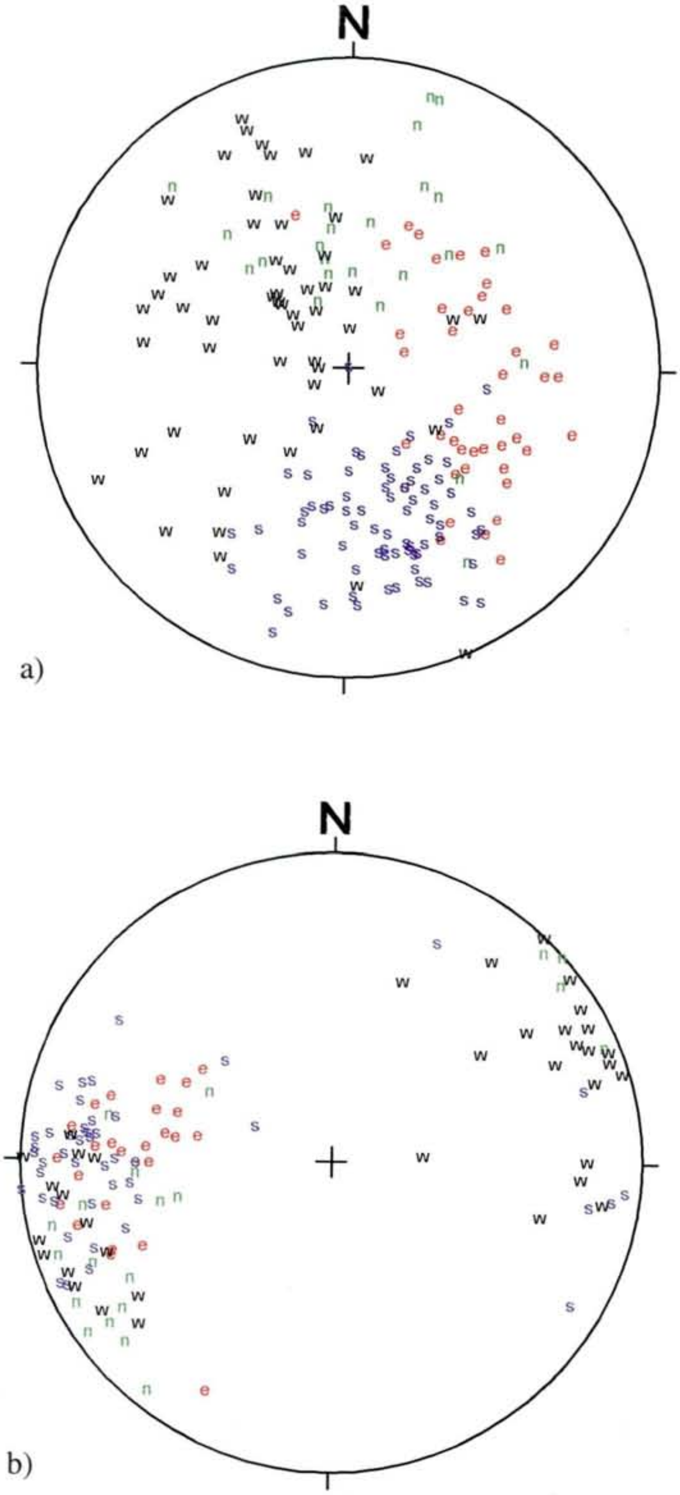

Figure 13. Equal area stereoplot of structural data from country rocks. a) poles to foliations, b) lineations. n, e, s, w correspond to data from north, east, south and west sectors of the study area.

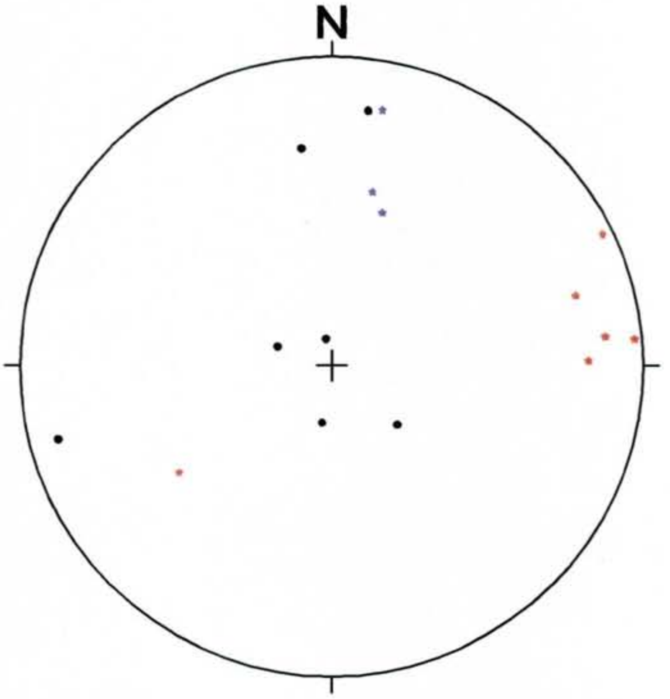

Figure 14. Equal area stereoplot of pre-intrusion structural data from area of hornfels. Dots are poles to banding (foliation), red stars are fold axes and blue stars are poles to axial planes.

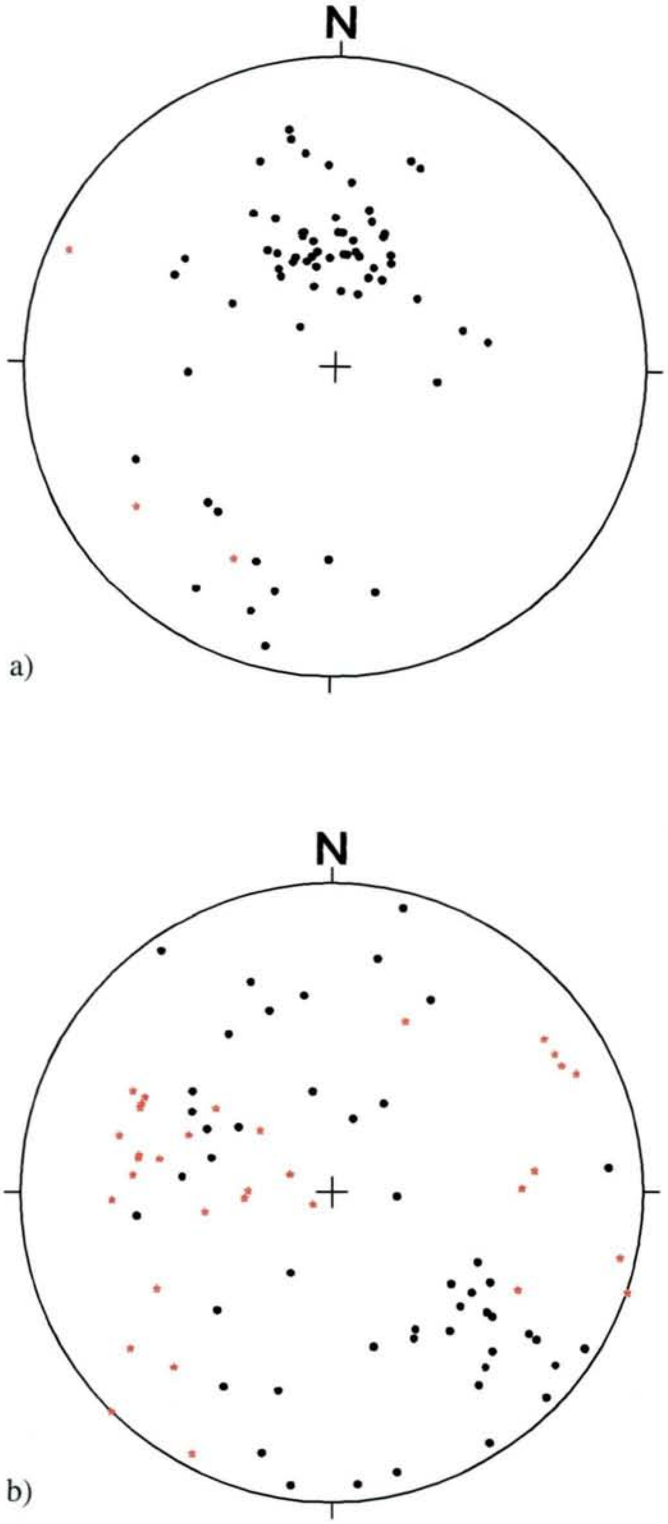

Figure 15. Equal area stereoplot of structural data from the Tronfjell gabbro. a) Poles to magmatic fabrics (layering and lamination). b) Data from alteration shear-zones. Black dots are poles to planar fabrics; red stars - lineations.

Further evidence may be seen in thin-sections from samples Tr6a and Tr6b. These samples come from a single hand specimen which apparently contained one set of fabrics. Tr6a represents mafic material, possibly from a sheeted intrusion related to the Tronfjell body. This material is strongly foliated with a matrix consisting of clino-zoisite, epidote, chlorite and amphibole. This foliation wraps porphyroclasts of plagioclase which is largely altered into epidote group minerals. This broadly greenschist facies deformation is correlated with the deformation affecting the intrusion which is of Scandian age. In contrast sample the quartz-rich metasediments of Tr6b show annealed fabrics. The foliation present in the rock is defined by compositional layering and alignment of biotite, however chlorite and garnet overgrow this foliation. Plagioclase grains are altered, but the alteration products are undeformed. Static growth of broadly greenschist facies minerals over a fabric implies that this fabric is pre-Scandian in age. The presence of fabrics of the same orientation within samples Tr6a and Tr6b therefore provides evidence for the creation of Scandian fabrics parallel to pre-Scandian fabrics.

4.5 Relationship between the contact and country rock fabrics

Evidence from within the gabbro suggests that its form has not been substantially affected by the Scandian events. The assumption that the intrusion was to first approximation flat-lying and sheet-like is a reasonable one. Therefore, the angular relationship between the intrusion edge and fabrics / lithological unit boundaries gives information on the pre-Scandian orientation of fabrics.

The relationship between the contact and lithological boundaries is best seen on the map of Dreyer (1975) (enclosure 2), whereas more structural data is seen in enclosure 1. At the northern and eastern contacts the boundary, measured foliations and inferred trend of lithological boundaries are all effectively parallel (figures 10 and 11). The boundary in the northern region is marked by a wide zone of gabbro sheeting and sills are found to the east also. The southern contact shows an angular discordance. This is reflected both in cutting across of lithological boundaries and in the fact that foliations in the country rocks dip more steeply than the contact (figure 10). The western contact is the most interesting. Starting at GR8797 and tracing the contact counter-clockwise, the angular relationship changes from being parallel to nearly perpendicular at around G.R. 860955. There is then an offset of the contact by a fault. The area to the south of this contains fabrics which are parallel to the contact when close to it, but which swing away from this orientation as one moves west. This swing away is however is not into the same direction as country fabrics to the north. Rocks on the other side of the river dip to the west and so shed no light on these problems. The swing of fabrics into parallelism with the contact, seen best about G.R. 855940, may be an entirely Scandian age feature, related to the focusing of shear along the contact.

These changes in the nature of the contact are best explained by variations in the orientations of the fabrics in the country rocks prior to emplacement. This therefore provides further evidence that the Hummelfjell rocks were strongly deformed prior to the emplacement event. Consideration of the nature of the contact provides some interesting correlations. Most of the contact is sub-parallel, implying a large area of flat fabrics. Given the evidence that these rocks were already deformed, a large area of flat foliations might be more the exception rather than the rule. It is therefore suggested that, given the known importance of sheeting as an emplacement mechanism for mafic magmas, the presence of the intrusion within this flat area is no coincidence. Since flat-lying planes of weakness greatly aid the growth of mafic intrusions, large mafic intrusions are more likely to be found within such planes of weakness, since they may not be able to form elsewhere. Such a phenomena: ascending mafic magma passing through folded or anisotropic rocks but forming large intrusions in flat-layered rocks might explain the pattern of magmatism further north. The large Silurian mafic intrusions found in the Trondheim Nappe Complex further north were all emplaced into the meta-sediments of the Sel. The lack of similar magmatism within the underlying Gula (Heidal) rocks presents a problem for the present interpretation that the Gula underlies the Sel. This may be explained by the fact that the folded Gula was a far less suitable place for large intrusions to form than the flat-lying, weakly or undeformed rocks of the Sel.

4.6 Style of deformation related to degree of concordance of the contact

Where the contact is concordant or slightly discordant, such as around the northern contact, sills are very common. These are often strongly boudinaged, the degree of boudinage increasing towards the contact.

Folding is seen throughout the area, but large scale (outcrop size) folding is only seen beneath discordant contacts (e.g. G.R.8797) These folds have east-west trending axes and axial planes parallel to the contact. They fold a foliation of unknown age and also affect gabbro sills. The formation of these folds is compatible with shear along the contact affecting fabrics lying at an angle to the contact.

4.7 Older fabrics in the hornfels

The small areas of hornfels preserve pre-intrusion fabrics and so give a unique opportunity to discern the style of deformation associated with the pre-Sel orogenic event. The most dramatic sign of this are tight folds which are very common in these areas (figure 12). Figure 14 is a plot of pre-Sel structural data showing the dominance of folding in these rocks. Evidence for the formation of axial planar fabrics seen in outcrop is borne out by figure 14. There is therefore evidence for a least two phases of deformation preceeding intrusion which explains the complex structures seen in the country rocks (figure 16).

4.8 Fabrics in the intrusion

Fabrics within the intrusion consist of two types, magmatic fabrics found within much of the intrusion, and solid state fabrics restricted to zones of alteration, especially at the margins of the body. Magmatic fabrics were discussed above. The solid-state fabrics are restricted to shear zones within altered material. There are large areas of undeformed altered material and the only place where deformation is always seen is at the edge of the intrusion. Even here the thickness of deformed rocks is never greater than a few tens of metres. Figure 15b shows the varied orientations of these fabrics, but with an E-W bias in the dip directions of lineations, providing a link to fabrics of the same age outside the intrusion.

Figure 15a shows the distribution of magmatic fabrics from Tronfjell. It is important to note that due to the pattern of outcrop, data is largely restricted to the summit area. Taking also into account the position of the magmatic boundaries the internal structure of the intrusion appears to be bowl-like with no discernable axis of folding.

4.9 Causes of the bowl-shaped form

Mafic intrusions are often sheet-like in form, this being a function of the low viscosity of gabbroic melt. It is common, however for the sheet to be curved and to form a bowl-like shape. This is seen in many mafic intrusions worldwide (Petraske et al. 1978).

Figure 16. Field photo of complex folding in metasediments close to contact. G.R. 854943.

To a reasonable first-order approximation the base, internal contacts and fabrics of the Tronfjell intrusion were probably flat and parallel during magmatism. The current form cannot be related to folding by a single fold structure but rather is radially symmetrical. This strongly symmetrical nature of the warping of the originally flat intrusion suggests that the bowl shape was not caused by externally applied deformation. Petraske et al. (1978) proposed that a sheet-like intrusion may form a bowl-shape by gravity-induced warping. Loney & Himmelberg (1983) described an intrusion from Alaska and ascribed its form to this process. This warping would be caused by the inability of hot quartz-rich country rocks to support the weight of a dense gabbro body. This warping would be expected to form during or immediately post-intrusion. This process would explain the form of the Tronfjell intrusion, but the only supporting evidence might be found in sample Tr12 which contains a foliation parallel to the edge of the intrusion which formed at sillimanite-grade temperatures. The magmatic deformation described above would also be compatible with such a process, but there is too little data available to be certain.

5 METAMORPHISM

The sequence of events inferred in the structural chapter suggest the Tronfjell metasediments may have experienced three phases of metamorphism: a pre-intrusion event, synchronous with the folding preserved in hornfels; a contact metamorphic event; a post-intrusion event, synchronous with the formation of 'Scandian' whose fabrics may be found in all rock-types. Thin sections from twenty-one metasedimentary and nine meta-igneous rocks were studied. These rocks are described and then evidence for poly-metamorphism is discussed:

5.1 Xenoliths

Xenoliths are restricted to the very lowest levels of the intrusion, near the contact. Two types are recognized:

1) Blue Quartz xenoliths

These are found as diffuse areas within the outer-zone of the intrusion. They range in size from the centimetre to the decimetre but are never large enough to map. Good examples are found at G.R. 855930 and 863926. Small areas may be seen to have curved globular edges, suggesting they co-existed with the magma as a fluid. Quartz may be seen to be blue, black and white (colourless). Normal white quartz can be seen to be intimately connected with areas of black quartz at G.R. 855930, often as veins of white cross-cutting the black. At this locality bands of greenish material are seen with no consistent orientation seen in different outcrops. Samples from this area (Tr 3 and 4) reveal that the black quartz is due to the presence of extremely fine (μ scale)grains or needles scattered within the quartz. These grains are seen to be concentrated near grain boundaries, especially those with a sharp angle. Thin veins containing clear, grain-free quartz are common, especially along grain boundaries exhibiting mortar texture. Fine needles may sometimes show a degree of aligment in several directions, suggesting some connexion with the crystallographic structure of the surrounding quartz grain. This would suggest that an exsolution process might explain the presence of the fine grained material. The greenish bands contain garnet, chlorite, white mica and a variety of other minerals, mostly from the epidote group. The nature of the assemblage as well as the presence of pseudomorphic textures strongly suggest that this does not represent the contact metamorphic assemblage. No relicts of this remain, even the garnet is late. Pseudomorph shapes suggest cordierite but no definite conclusions can be drawn about the (presumably granulite facies) assemblage which incorporation into magma would have caused.

2)Large sheet xenoliths.

These are xenoliths found in areas of sheeting, such as on the northernmost and southwestern contacts. Large sheets of metasediment close to the edge of the intrusion may not be heated to magmatic temperatures. Therefore the metamorphism they experience may be closer to that of rocks immediately below the contact than that of small xenoliths further in the intrusion. These samples (Tr26, 27, 28, 29, 30, 31 and 12) are therefore considered in the next section.

5.2 Contact rocks

Rocks described here are found within c.500m of the contact and so should have been strongly heated by the Tronfjell gabbro. Rocks from the country rock sheet near the south-western corner are included. This sheet is contains areas of gabbroic melt, especially towards its southern end. A number of samples are meta-igneous rocks consisting of biotite, epidote group minerals quartz and plagioclase. They represent either altered gabbro or xenolithic igneous material.

A striking feature of these contact rocks is the scarcity of evidence for high temperatures (upper amphibolite / granulite facies). Minerals associated with high temperatures are rare. This may be because such assemblages were found only within a small area or because they have been destroyed by later metamorphism. Despite these problems there is a lot of evidence for contact metamorphism within these rocks, supporting the observation that Tronfjell is an intrusion.

5.3 Contact metamorphic minerals

The only high-temperature mineral found within the entire area is found in sample Tr12. In this sample, fibrolitic sillimanite is found within porphyroblasts of garnet, muscovite and plagioclase, where it is seen to help define a foliation. Sample Tr12 is from the large xenolithic sheet mentioned above.

5.4 Evidence for poly-metamorphism

Pseudomorphic textures have already been described from the blue-quartz xenoliths. These textures are also found in contact rock samples Tr17 and Tr35. It is not known what the pseudomorphed minerals were.

Further evidence for poly-metamorphism is seen in samples Tr12, Tr26 Tr34 and Tr35. These contain large garnets which preserve evidence for multiple stages of growth. A typical example is seen in figure 17, which shows hornfels garnets with a preferentially altered core. The best example is Tr12 where the stages of growth are visible in hand specimen as a purplish core and a lighter reddish rim. The inner core contains patches of unaligned sillimanite, as well as an internal fabric. A zone rich in quartz inclusions is followed by an middle zone which contains another internal fabric. This middle zone fabric is at an angle to the internal fabric of the corezone and in one garnet parallel, in another oblique to the external fabric. This external fabric is partly defined by the sillimanite preserved in porphyroblasts (see above). The outermost rim, after a sharp boundary, contains more and finer grained inclusions than the rest of the outer zone and unequivocally overgrows the external fabric. It appears to be intergrown with chloritoid porphyroblasts. This may therefore represent a third phase of garnet growth.

5.5 Age of fabrics in relation to contact metamorphism

Samples Tr34 and Tr18 are critical to our understanding of the timing of emplacement of the Tronfjell intrusion. Both samples come from the area of hornfels at G.R.896955. Tr34 is a sample of hornfels, which contains folded lithological banding (e.g. figure 12) but no alignment of minerals. The folded banding, once related to a tectonic foliation, is now defined by unaligned mineral aggregates (figure 17). The recrystallisation event that caused this therefore post-dates the formation of the recrystallised tectonic fabrics. Garnets in this rock also grow after this event. These garnets are striking in having well-defined crystal shapes but often irregular or tabular outlines. The garnet has grown only within phyllosilicate rich bands and the garnet stops sharply against the edges of quartz-rich bands (e.g. garnet in middle-right, figure 17). Sample Tr18 was taken from a shear-zone cross-cutting the hornfels. It came from a well-foliated rock, easily distinguishable from the hornfels. Thin-section analysis confirms that this sample represents later deformation affecting the hornfels. This sample contains the characteristic garnets of Tr34, some showing sharp truncation of their growth. These garnets are here wrapped by the foliation, which is defined by white mica and chlorite (figure 18).

Applying this chronology to other rocks is fraught with difficulty: There are a few rocks which do not show clear evidence of hornfelsing and which therefore are of little use in defining the timing of emplacement. Fabrics in these rocks are pervasive and complex, with the development of crenulation cleavage. A typical assemblage is quartz + garnet chlorite + muscovite + amphibole ± biotite ± zoisite. These minerals are all aligned within the foliation, folded internal fabrics preserved in some garnets suggest a complex history. This assemblage may represent several stages of mineral growth, it is difficult to link these minerals to any of the three inferred metamorphic episodes (pre-Sel, contact and post-Sel).

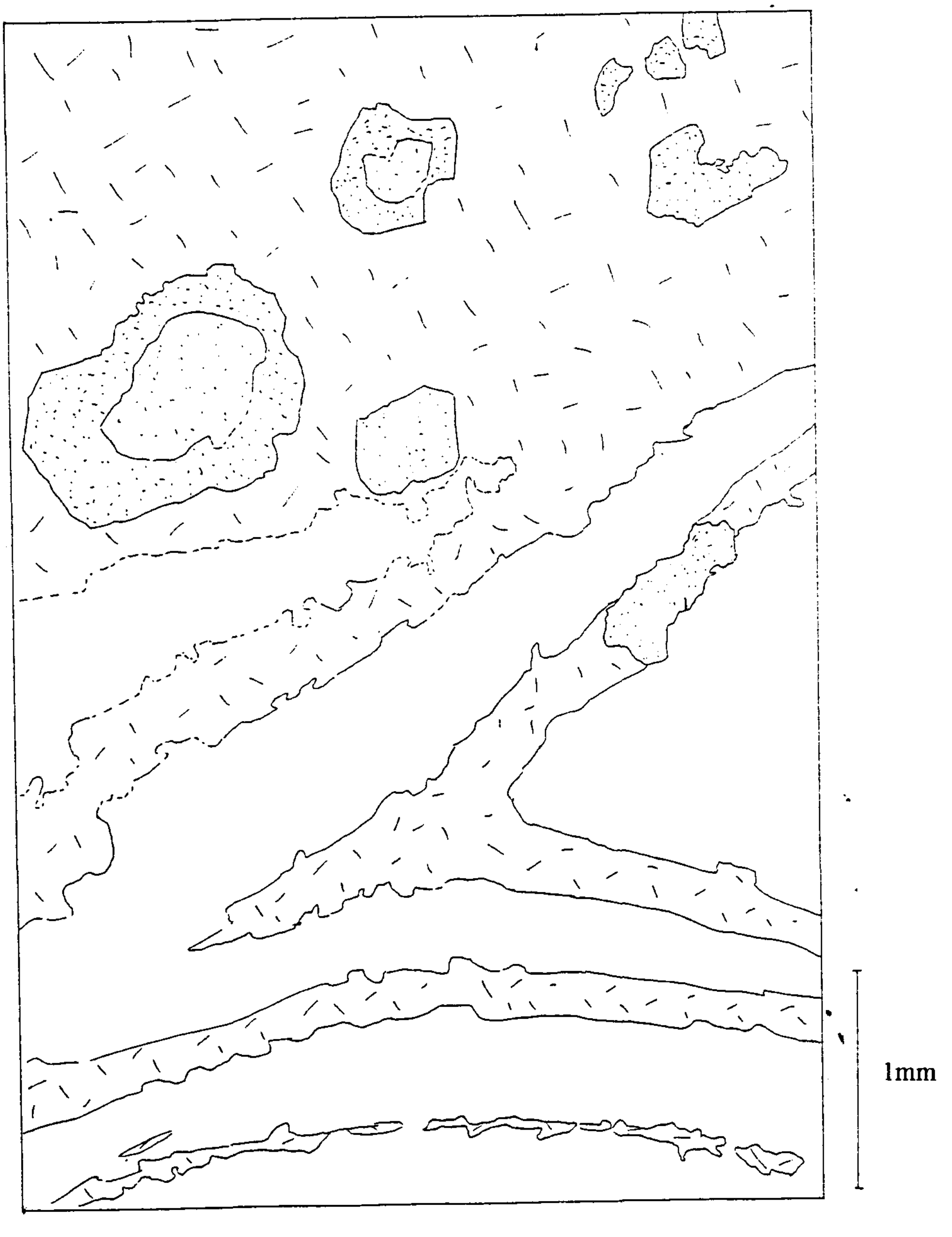

Figure 17. Sketch of microscope image from sample Tr34, showing a folded metamorphic foliation overprinted by contact metamorphism. Cross hatch - areas rich in unaligned phyllosilicates; dotted - garnets some with preferentially altered central areas; unornamented - areas rich in quartz.

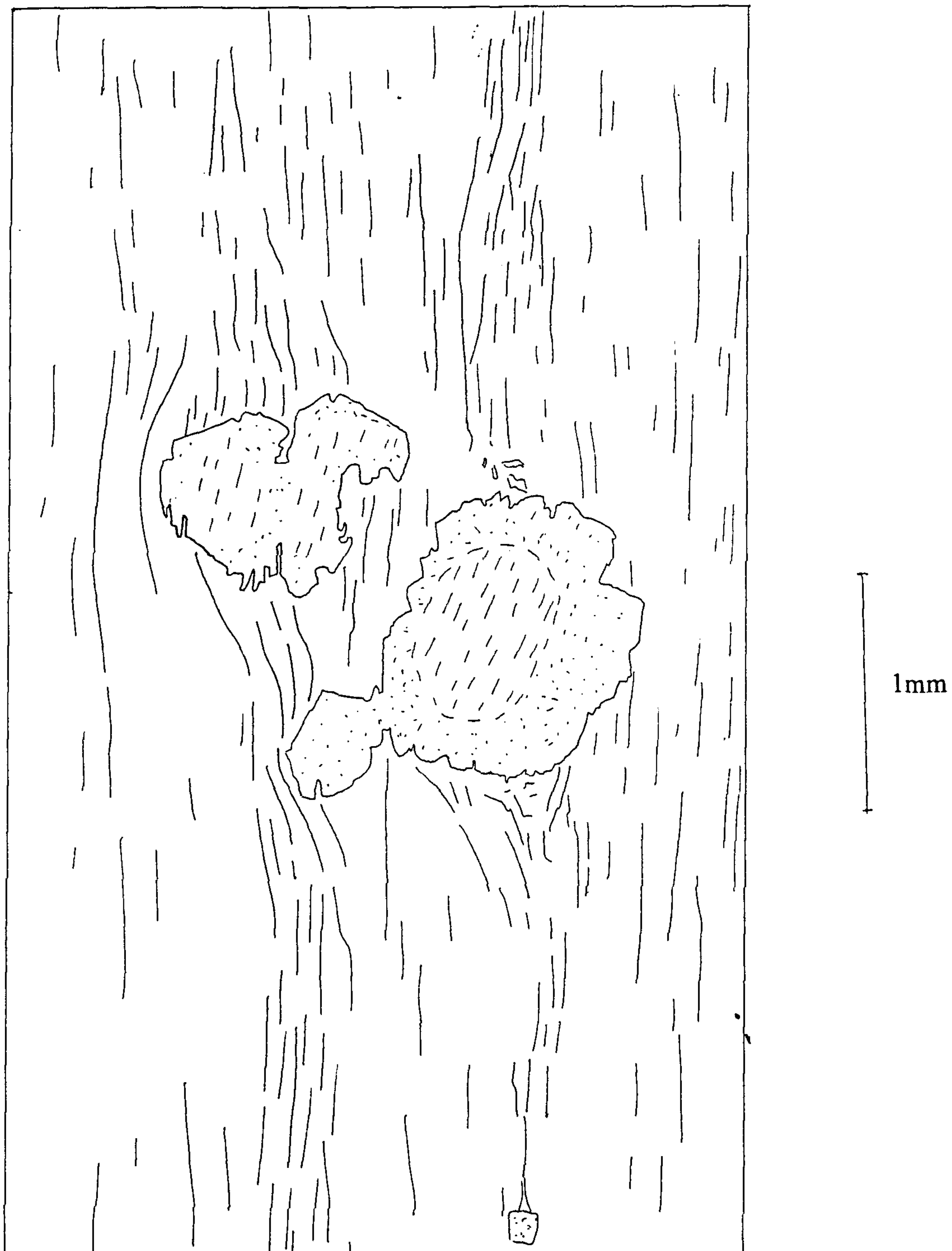

Figure 18. Sketch of microscope image from Tr18, showing tectonic fabrics wrapping hornfels garnets. Dotted - garnets with dashed central areas containing internal fabrics defined by quartz and opaque; Lined - quartz-rich matrix highlighting aligned white mica and chlorite grains which help define the wrapping foliation.

Further complication arises from evidence in Tr12 that there was deformation whilst the intrusion was still hot. The fabric in Tr12 is partly defined by fibrolitic sillimanite, growth of the sillimanite may be mimetic or pre-intrusion, but it is likely that this represents deformation of the metasediment whilst it was at high temperatures. This might be related to the mechanism responsible for the bowl-shaped of the intrusion. This fabric would represent a third phase of fabric formation and so further complicate attempts at correlation between samples.

5.6 Grade of metamorphism

Latest metamorphism. Evidence from elsewhere in the area suggests that the final metamorphic event (Scandian) was in uppermost greenschist facies. Bjerkgård & Bjørlykke (1994) report a typical assemblage of quartz + muscovite + biotite + chlorite ± albite ± garnet from metasediments and one of hornblende + albite + epidote + chlorite + quartz ± calcite ± biotite from metabasalts in Folldal. These are rocks which have only experienced the latest metamorphism. This metamorphic event can be recognised in many samples from the Tronfjell area. All metamorphosed samples show a latest metamorphism of similar grade:

Both the intrusion and the surrounding greenstones yield amphibole and show the alteration of plagioclase to zoisite and albite, suggesting metamorphism under epidote amphibolite facies such as is seen in the Folldal area. The alteration of the gabbro is therefore linked to the Scandian orogeny, a conclusion which is compatible with the structural interpretation made above.

The situation with the metasediments is more complex. Nearly all samples of metasediments show a latest growth of chlorite and white mica. Samples with preserved hornfelsic texture all show a late static metamorphism associated with pseudomorphs. This metamorphism is associated with an assemblage of chlorite + muscovite ± biotite ± chloritoid. Evidence for growth of rims on garnets is seen in some samples (e.g. Tr12), as is alteration of plagioclase (Tr6b). Hornblende may also be seen in such rocks but this may be a relict from an earlier metamorphism. These rocks all escaped the effects of Scandian deformation. Rocks which contain Scandian fabrics invariably have their foliations defined by chlorite and white mica, usually with some biotite.

There is therefore abundant evidence that the Tronfjell area experienced upper greenschist to lower amphibolite grade facies metamorphism and that this metamorphism post-dates the emplacement of the gabbro. Correlation via fabrics further strengthens the correlation of this metamorphism with the post-Sel Scandian orogeny.

Contact and earlier metamorphisms The latest metamorphism, described above is dominant in most samples. However evidence from textures and the existence of hornfels confirms that a contact metamorphic aureole was present at one time. Given the evidence for three phases of metamorphism from samples such as Tr12 care must be taken to distinguish this contact metamorphism from the earliest 'pre-Sel' metamorphism. Weighing the evidence described above suggests the following assemblages:

a) Pre-intrusion metamorphism: This event is represented by garnet. Most garnet bearing rocks contain evidence for more than one stage of garnet growth. Samples Tr12, Tr13 and Tr20 contain garnets or garnet cores which are clearly pre-intrusion and other rocks may have garnets with an earlier history.

b) Contact metamorphic assemblages: Sillimanite, garnet and amphibole are all linked to this event. Sillimanite is seen only in Tr12 whereas garnet is seen in most rocks. The form of most of these garnets; growing only within bands of suitable composition and showing clear crystal faces suggests static growth and fits with the association of these garnets with hornfels rocks. Amphibole is less certain, and may be a pre-intrusion relict, however Dreyer (1975) ascribed hornblende growth to the contact metamorphism on the basis of its geographical distribution. Samples such as Tr22 and Tr20 lie close to the contact and contain large blue-green amphiboles. Fabrics do not allow the age of the growth of these grains to be constrained but if these amphiboles were pre-intrusion it would imply that heating from the intrusion had no effect on these rocks, which is unlikely. What little can be discerned of this contact metamorphism suggests a narrow aureole and very restricted zones of high temperatures. The lack of evidence for partial melting in the aureole further suggests a cool aureole. Since the body is a large one this in turn suggests the magma was emplaced into relatively cool rocks. This would account for the fine grain size of the outer zone, which would represent a large chilled margin. Cool country rocks in turn suggests a shallow depth of emplacement.

6 CONCLUSIONS

6.1 Timing

Greenschist facies metamorphism associated with a major fabric-forming event is seen in all rocks within the mapped area. It is everywhere associated with lineations which have a roughly NW-SE trending orientation. This fabric is associated with the D2 event of the Silurian age Scandian orogeny and represents eastward transport of material onto the Baltic shield. The intrusion of the Tronfjell body pre-dates this main phase of the Scandian orogeny. D1-age fabrics have not been seen in the Tronfjell region so the relative timing of this early Scandian event is not known. The presence of complex fabrics within hornfels is of great significance. These cannot be accounted for by the Scandian-D1 event and therefore demonstrate the presence of pre-Scandian fabrics within the Hummelfjell rocks. This therefore provides supporting evidence for the division into 'Heidal' and 'Sel' and the existence of a pre-Scandian orogenic event within the area.

6.2 Metamorphism

Three metamorphic events are recognized;

1) Pre-intrusion (pre-Scandian) event, represented by relict garnet and garnet cores.

2) Contact metamorphic event, represented by hornfelsing, and the growth of sillimanite, garnet amphibole and other phases now lost. The scarcity of high-grade minerals and the narrow extent of a recognisable aureole all suggest emplacement into relatively cool rocks, probably, therefore at upper crustal levels.

3) Scandian metamorphism, represented by upper greenschist alteration of all rock-types leading to the growth of chlorite, white mica, biotite, chloritoid and garnet in metasediments and amphibole, zoisite and albite in meta-igneous rocks. This is at a similar grade to the equivalent metamorphic event in the Folldal area.

6.3 Form and petrology of the Tronfjell intrusion

The Tronfjell body is a layered mafic intrusion of < 2km thickness. The roof is not preserved. The layered structure is well defined consisting of:

1) A lower fine-grained facies of contaminated gabbro (s.s.) often containing metasediment xenoliths.
2) A narrow zone with a sharp base, rich in olivine-rich cumulate layers (now serpentinites) interlayered with olivine-poor gabbro.
3) A thick zone of olivine rich gabbros.

Substantial layers of dunite, with chromite, have not been described in any other Norwegian non-ophiolitic gabbros, the Tronfjell intrusion appears to be unique in this respect.

Magmatic structures are common, including evidence for magmatic strain. These structures are parallel to the compositional layering, which is inferred to have been flat-lying. The current form of the intrusion is bowl-like, a structure believed to have formed due to sinking of the body into the surrounding rocks.

This intrusion may be equivalent to other large mafic intrusions found further north in the Trondheim Nappe Complex (e.g. Fongen-Hyllingen intrusion; Wilson et al. 1985). This study's conclusions about timing of emplacement does not preclude this possibility. This correlation would be intriguing since the base of the Fongen-Hyllingen is not well exposed whereas the Tronfjell body may currently expose only the lower half of a much thicker body, whose more evolved upper part has been eroded off.

The importance of country rock structures in the siting of mafic magma chambers may explain the relative lack of large mafic intrusions within the Gula (Heidal) part of the Trondheim Nappe Complex and their preponderance within the Sel part.

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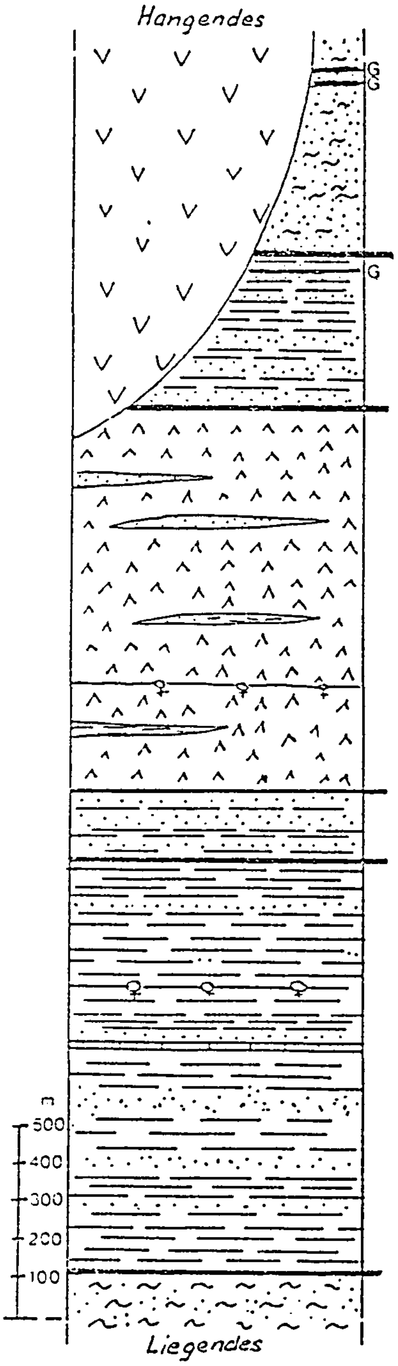
Number	Rock-type	G.R.	Main minerals	Comments
Tr1	Greenstone	881924	Pl, Amp, Ep	
Tr2	Greenstone	868925	Pl, Amp, Qtz, ep.grp	Oriented
Tr3	Xenolith	855930	Qtz, Chl, w.m., ep.grp.	Blue / black quartz
Tr4	Xenolith	855930	Qtz, Chl, w.m., ep.grp.	Blue / black quartz
Tr5	Gabbro, transition zone	864934	Pl, Cpx, Opx, Ol	
Tr6a	Contact metaigneous	904949	Pl, Amp, ep. grp. Chl	Oriented, late fabric
Tr6b	Metasediment	904949	Qtz, Pl, Chl, Bt, w.m. Grt, Amp	Oriented, annealed
Tr9	Gabbro, core zone	882953	Pl, Opx, Cpx, Ol	Igneous lamination
Tr10	Gabbro, transition zone	893951	Amp, Pl	Magmatic foliation
Tr11	Dunite / Serpentinite	893951	Ol, Srp, w.m. Amp.	
Tr12	Metasediment	855944	Qtz, Pl, Grt, Sil, w.m. Chl, Cld	Multi-stage garnet
Tr13	Metasediment	873979	Qtz, w.m. Bt, Chl, Grt, Amp, Zo	Far from intrusion
Tr14	Metasediment	879974	Qtz, w.m. Chl, Grt, Pl, Cld	Hornfelsic
Tr15	Metasediment	875969	Qtz, Grt, Bt, w.m. Cld	Hornfelsic
Tr16	Metasediment	975970	Qtz, Bt, Chl, w.m.	Hornfelsic
Tr17	Metasediment	859958	Qtz, ep.grp. Grt, w.m. Cld, Bt	Hornfels
Tr18	Metasediment	856955	Qtz, Chl, w.m. Grt, Bt, Pl	Oriented, shear zone in hornfels
Tr19	Metasediment	860960	Qtz, w.m. Chl, Grt	
Tr20	Metasediment	862961	Qtz, Grt, Chl, Bt, w.m. Amp, ep.grp.	Complex foliation
Tr21	Gabbro, outer zone	895970	Amp, Qtz, ep.grp. Pl	Strongly altered
Tr22	Metasediment	894971	Qtz, Grt, Chl, Bt, w.m. ep.grp. Amp	Complex foliation
Tr23	Gabbro, core zone	867937	Pl, Opx, Cpx, Ol	Igneous lamination
Tr24	Altered gabbro	867937	Amp, Opx, Cpx, Pl, ep.grp.	
Tr25	Metasediment	873969	Qtz, Pl, Grt, w.m. Grt, Chl	
Tr26	Metasediment	871968	Qtz, Pl, Grt, Amp, ep.grp w.m.	
Tr27	Meta-igneous	854933	Pl, ep.grp. Amp, Qtz	
Tr28	Meta-igneous	854933	Pl, ep.grp. Bt, Pl, Qtz	
Tr29	Meta-igneous	854929	Pl, Amp, Bt, ep.grp.	
Tr30	Meta-igneous	854929	Pl, Opx, Cpx, Amp, w.m. ep.grp.	
Tr32	Gabbro, transition zone	860934	Pl, Ol, Opx, Amp, ep.grp. Srp	Slightly altered, symplectite around Ol.
Tr33	Altered gabbro	891949	Cpx, Amp, Pl	Oriented. Highly strained plagioclase
Tr34	Metasediment	896955	Qtz, Chl, Grt, w.m. Bt	Hornfelsed early structures
Tr35	Metasediment	896955	Qtz, Bt, w.m. ep.grp. Grt, hbl	Oriented, hornfels with early foliation
Tr36	Metasediment	890965	Qtz, Chl, w.m. Cld	
Qtz - quartz. Pl - plagioclase. Bt - biotite. Amp - amphibole. Ep. - epidote. Srp - serpentine. ep.grp. - epidote group.				
Chl - chlorite. w.m. - white mica. Cpx - clinopyroxene. Opx - orthopyroxene. Zo - zoisite. Grt - garnet. Cld - chloritoid.				

Appendix 1. Table of thin-sections

2.211 Übersichtstabelle der lithostratigraphischen Abfolge der Tronfjell-Gruppe



Tronfjell-Eruptivgesteinskomplex

Tronkalven-Formation

Quarzite, Glimmerschiefer, Gneise mit vereinzelten Graphitschiefer-Horizonten
400 m mächtig

Haugsætra-Formation

Quarzite und Biotitglimmerschiefer, am Top Graphitschiefer (Metagrauwacken und -pelite); ca. 300 m mächtig

Tronfjell-Grünstein-Formation

Grünschiefer (Amphibolite) und Grünstein
(Amphibolite und Metagabbros)- Vulkanite
stratiforme Sulfiderz-vorkommen; Tuffe u.
bis 1000 m mächtig; Meta-Sedimente

Livangen-Formation

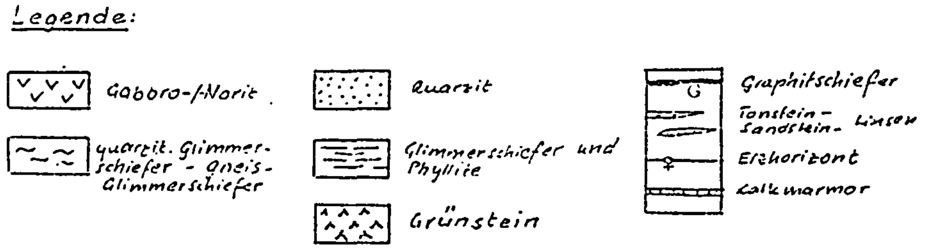
Quarzite und Biotitglimmerschiefer (Metagrauwacken und -pelite) ca 100 m mächtig

Tronsvangen-Formation

Chloritschiefer und -phyllite (Metapelite), untergeordnet Quarzite; quarzreiche Glimmerschiefer ("Bänderschiefer"); Kalkmarmorhorizonte; stratiforme Sulfiderzführung; ca 500 - 750 m mächtig;

Kaldåsen-Formation

Blauquarz-führende, quarzreiche Chloritschiefer und -quarzite; über 200 m mächtig



Appendix 2. Stratigraphic table taken from Dreyer (1975), to accompany map 2.

Tronfjell intrusion

C	Central Zone
Cx	Central Zone(where isotropic)
T	Transition zone
Ts	Transition zone (with serpentinite)
Ou	Outer zone
A	Altered zone
·D	Serpentinite / dunite

Country rocks

Hummelfjell group

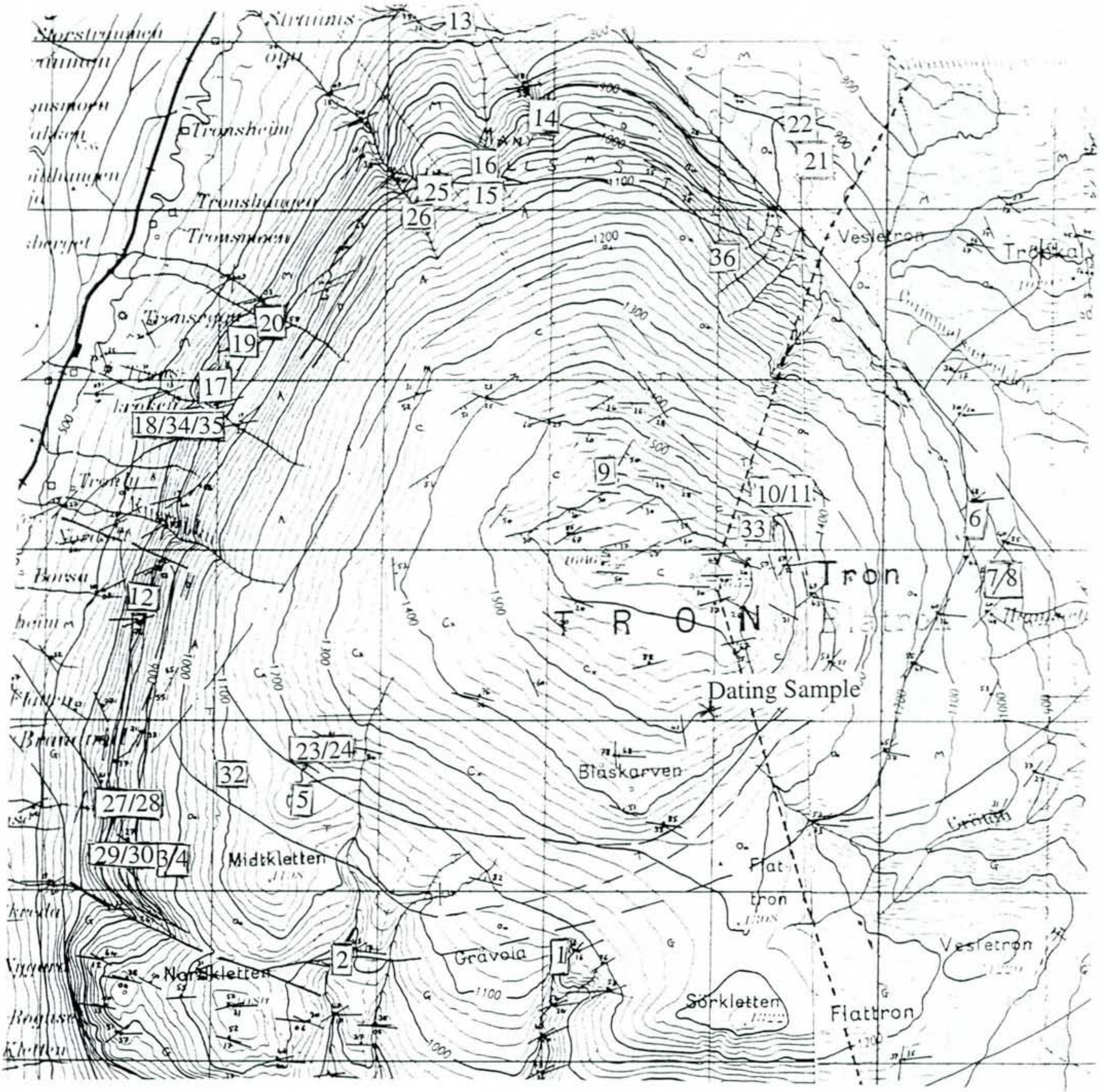
H	Hornfels
G	Greenstone
M	Undivided metasediments

Sel Group

S	Undivided Sel

╲	Geological boundary
↖	Lineation
╱	Foliation
╱	Igneous fabric
↖	Magmatic lineation

Appendix three. Key to map one.
Grid lines are old form (ED50). Grid references in text are given in new form (WGS84).
Grid references may be converted from text to enclosure one by adding 81m to eastings and 207m to northings. E.g. G.R.(500500) in text plots at c. 501502 on enclosure one.
Base map taken from 1:50 000 maps Dalsbygda and Haltdalen.



Appendix 5. Map showing localities of samples Tr1 to Tr36 and sample collected for dating.