Geological setting of the Tverrfjell copper/zinc deposit, Central Norway

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Abstract

The Tverrfjell mine in Central Norway, a volcanogenic exhalative Cu/Zn deposit, occurs within the eugeosynclinal volcanic-sedimentary Early Ordovician Støren Group. This sequence was obducted and translated to the southeast into its present position by Caledonian nappe movements. As a result, two major deformational phases and low to medium grade metamorphic conditions are recognized in the Tverrfjell area. In the working area, the Støren Group is composed of predominantly mafic submarine meta-volcanics with intercalated metamorphosed geosynclinal pelitic sediments, turbidites and volcanic breccias.

The basalts are predominantly tholeiitic, but alkaline types occur, too. Extensive fractionation of olivine and plagioclase in early, and clinopyroxene in later magmatic stages produced highly evolved basalt types and even andesites. High abundances of certain major and trace elements are comparable to those of Type II ocean floor basalts.

Base metal-free exhalative horizons are common in the area, but the copper-zinc ores of the Tverrfjell deposit are strictly confined to an andesitic extrusive body.

On the base of sedimentological and geochemical evidence it is suggested that the Tverrfjell deposit was formed at an intraplate volcanic centre or back-arc spreading centre in a position not too far from the Baltic Shield. Based on petrological consideration, a shallow-seated but extensive magma chamber is postulated to explain the observed extensive magma fractionation, and as a heat source that generated a convective hydrothermal system conductive to the Tverrfjell deposit.

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Introduction

The Tverrfjell mine, one of Norway's major Cu/Zn deposits, is situated in the Dovrefjell area in Central Norway, near the village of Hjerkinn (about 250 km NNW of Oslo and 200 km SSW of Trondheim). Geologically, it lies on the southwestern apex of the Trondheim region which is built up of Caledonian nappes, especially the Trondheim Nappe Complex (fig. 1). The nappes were thrusted from a north-westerly direction over the autochtonous Precambrian basement of western Norway.

The Tverrfjell Cu/Zn deposit belongs to the family of volcanogenic exhalative base metal deposits and was formed in conjunction with submarine volcanic activites in Late Cambrian to Ordovician times. Stratigraphically, it is hosted within the volcanic-sedimentary Støren Group (Tremadocian, Arenigian) of the Trondheim Supergroup defined by Gale & Roberts (1974). Table 1 gives their stratigraphic correlation scheme and it will be noted that the Støren Group, which is interpreted as the lower member of an eu-geosynclinal sequence is correlated with part of the Gula Group (Eocambrian, Ordovician), which is thought to have formed in a miogeosynclinal environment.

Major and trace-element data of Støren-greenstones revealed characteristics of ocean-floor tholeiites (Gale & Roberts, 1974; Furnes et al., 1980), and an ophiolitic suite with gabbros, sheeted dikes and pillow lavas was recognized near the Løkken Cu/Zn-deposit (Grenne et al., 1980). A back-arc basin environment was postulated for the ophiolitic Støren unit by Gale & Roberts (1974) and this was further corroborated by Furnes et al., (1980).

In pre-Middle Ordovician times (Furnes et al., 1980), the eugeosynclinal volcanic-sedimentary pile (Støren Group) was obducted, thereby being juxtaposed with the miogeosynclinal Gula Group rocks. The major nappe unit formed by these processes is the Trondheim Nappe Complex which consists of the lower Gula Nappe and the upper Støren Nappe (Gale & Roberts, 1974). The latter includes rocks of the Støren, Hovin and Horg Groups (table 1). During a later event, renewed movements translated the Støren-Gula-couple further towards the east into its present position. Consequently, and in agreement with observations made by Guezou (1978), the basal thrust plane of the Trondheim Nappe cuts off the older tectonic contact between the Støren and Gula Nappe. In the southwestern part of the Trondheim region (including the area around the Tverrfjell mine) the Trondheim Nappe is underlain by the Andbergshøi Complex (Guezou, 1978) which is intercalated between the Trondheim Nappe and the Precambrian basement in the west.

During nappe emplacement the obducted rocks were folded into large isoclinal recumbent folds (F1)[+] with axial directions varying from NW-SE over E-W to NE-SW (Wolff & Roberts, 1980). A second fold phase (F2), which overprinted the previously formed structures, is characterized by open to tight, slightly inclined folds with wavelenghts of several kilometers and axial directions between E-W and NE-SW. A third, only locally important (i.e. not penetrative) deformation phase (F3) produced tight, strongly inclined folds of mesoscopic scale, which however have no marked effect on geological gross structure. In correspondence with these tectonic events, several metamorphic episodes are recognized within the Trondheim Nappe Complex (Guezou, 1978).

Although an extensive literature exists on the many Scandinavian exhalative massive sulfide deposits, including excellent general descriptions (e. g. Bugge, 1978; Vokes, 1980; Vokes & Gale, 1976) as well as detailed work on particular deposits, not much has been written about the geology of the Tverrfjell deposit so far. However, a short article about the mine was published in Mining Magazine in 1978.

The present study is an attempt to unravel the geology of the area around the Tverrfjell mine and to give an interpretation of the conditions under which the ore deposit originally formed. The area was mapped in detail and for mappreparation additional geophysical data (geomagnetic, electromagnetic) as well as drill cores (courtesy of Folldal Verk A/S) were available. Geochemical studies on metavolcanics (major and trace elements) were carried out in order to determine the geochemical character of the magmas, and hence to obtain some constraints for the geotectonic position during their eruption.

[+]Our fold phase classification corresponds to that most widely used in the literature (e. g. Wolff & Roberts, 1980, page 124f), which is different from that of Guezou.

Structural geology

The geological structure (fig. 3) of the area around the Tverrfjell mine is largely determined by the two major fold phases mentioned above (F1 and F2), as well as by the thrusts between Gula and Støren nappe, and at the base of the Trondheim Nappe Complex. A F3 phase is only locally recognizable. In addition, an important N-S striking normal fault ("main fault") which is paralleled by some minor faults of the same system, dissects the area and also cuts off the Tverrfjell orebody on its eastern side (fig. 2).

F2-fold phase:

The most obvious structural feature in the working area is a F2 syncline with its core in the Hjerkinnhoi-area, east of the Tverrfjell mine. The fold axis strikes N80^{o}E and is roughly horizontal, the axial plane dips toward the south with approximately 70^{o}. On the southern limb of this syncline the S1 foliation and transposed Sø structures dip almost vertically, whereas in the northern flank, the same structures dip towards the south at angles of 35 to 45^{o}. A S2 schistosity is well developed only in phyllitic lithologies, whereas it is usually absent in quartzites and amphibolites. Particularly in the chlorite-sericite-schists of the Hjerkinnhoi-syncline, biotite crystallized on S2 schistosity planes.

F1-fold phase:

A large isoclinal F1-fold is recognized in the block east of the main N-S fault. This fold is believed to originally represent an anticline that is now diving into a southward direction, but as a result of the above described F2-syncline reappears on the southern flank ot the F2-syncline where it forms an upright F1-antiform (fig. 3). The axial plane of this F1-fold forms a symmetry axis for the lithologies north and south of the broad zone of volcanic breccias in the northeastern part of the map area. The breccias form the core of this inferred anticline and thus are thought to represent the oldest rocks in the tectonic block east of the main fault. West of the main fault, essentially the same F1 and F2 structures are recognized, but lithostratigraphic correlation across this fault is virtually impossible because the western block is exposed in a significantly deeper structural level with different lithologies due to rapid lateral facies changes (see fig. 2). The F1-fold phase produced a regionally penetrative schistosity by parallel alignment and recrystallization of metamorphic minerals, which is well developed in most lithologies except some quartzites.

Basal thrust of the Trondheim Nappe:

Along the northwestern margin of the working area, the Trondheim Nappe is bounded by a thrust plane, beyond which a series of apparently higher metamorphic rocks follows. This unit can be correlated with the Bottheim Group of the Andergshøi Complex (Guezou, 1978). The thrustzone represents the basal thrust of the Trondheim Nappe and consists of a several meters thick mylonitic shear zone that dips at about 40° towards SE. F1 and F2 - structures of the Trondheim Nappe are cut off by this thrust and therefore must have been formed prior to final nappe emplacement.

Thrust between Støren and Gula Nappe:

The boundary between the Støren and Gula units is found at the southern margin of the working area. The nature of this boundary is somewhat obscure because it was overprinted by younger deformation and metamorphism. It is, however, generally accepted to be of tectonic nature, i. e. to represent an important shear zone.

The Gula Group rocks at the south end of the map (fig. 2) constitute the margin of the central antiformal zone of the Trondheim region (fig. 1). Because the S2-schistosity is developed continuosly across and strikes parallel to the hypothetical thrust plane between the Gula and Støren Nappes, and because this thrust plane was brought into its steep, slightly overturned position by the F2 syncline mentioned, it appears that the Gula Group rocks in the south were brought upward during this F2-fold phase. Thus it seems likely that the central antiformal zone of the Trondheim region is a F2-structure rather than F1.

North-South-faults:

The main fault is well exposed underground in the Tverrfjell mine where it cuts off the orebody towards the east. Its dip is 45°E and the fault zone is more than 50 meters wide, filled with unmetamorphosed gouche. Slickensides indicate almost vertical movements (M. Motys, personal communication). The precise amount of vertical downward displacement of the eastern block is not known but we estimate it to be well in excess of 1100 m, probably twice that much. No significant horizontal movements occurred. The main fault and its minor parallel faults are considered to be related to the Oslo rift zone which is of Permian age. However, earlier movements can not be ruled out.

Stratigraphy

The miogeosynclinal Gula Group rocks that occur south of the working area are composed of monotonous graphite bearing calcareous phyllites and schists, but in other areas may also contain quartzitic rocks, greenstones and volcanogenic exhalative ores (Nilsen, 1978, Guezou, 1978).

The Andergshoi Complex northwest of the working area is made up of feldspatic gneisses, garnet-mica-schists and amphibolites, with minor occurences of marbles and quartzites. These rocks can be correlated with the Bottheim Group of Guezou (1978) for which a Cambro-Ordovician age is inferred.

The volcanic sedimentary rocks of the Støren Group will be described here in some detail because this is the host sequence for the Tverrfjell orebody.

Establishing a detailed stratigraphy in this area is not an easy task, due to complex folding, extensive primary facies changes and lacking marker horizons. The proposed stratigraphy (fig. 4) therefore depends to some degree on structural interpretation, and vice versa.

Metasedimentary rock types:

Besides the volcaniclastic and pyroclastic rocks, there is only a small variety of metasediments which, however, constitute a significant percentage of the sequence. Most widespread are phyllitic varieties, that grade into one another, in most cases due to primary facies developments. On our geological map (fig. 2), we have differenciated between garnet-mica-schists, chlorite-sericite-schists, quartz-rich chlorite- sericite-schists, dolomite-chlorite-sericite-schists and biotite schists.

The biotite-schists in the northern part of the working area are essentially composed of biotite, muscovite, plagioclase, quartz, zoisite, epidote and carbonates. They are higher metamorphic equivalents of the chlorite-schists and represent originally similar lithologies. Thus, their southern boundary with the chlorite sericite schists is due to the reaction of chlorite with muscovite to form biotite and minor staurolite.

The various chlorite bearing schists and phyllites are made up of chlorite, sericite, quartz, plagioclase, variable amounts of carbonates, and minor epidote, zoisite and amphiboles. The chlorite and biotite-schists are the most common rock types in the upper part of the stratigraphic sequence. They are intimately associated with volcanic breccias and are thought to owe their relatively high contents in ferromagnesian minerals to a finegrained volcan clastic component, i. e. from erosional basaltic debris.

Chemically and stratigraphically intermediate between the chlorite-sericite-schists and the garnet-mica-schists, are the quartz-rich chlorite-sericite-schists. These are of particular interest because they contain some intraformational polymict conglomerate lenses, in part associated with quartzites.

The conglomerate pebbles are up to 10 cm in diameter and are embedded in a finegrained matrix, apparently with a lack of intermediate grain sizes. Most frequent are veinquartz pebbles, but quartzites, limestones, granitoids and probably also keratophyres may occur, too, whereas mafic volcanics are not represented. Although most pebbles are severely strained (flattening up to 20:10:1), some resisted deformation and display well rounded shapes. The mode of occurrence within an essentially pelitic sequence, the well rounded pebble shapes, and the polymict nature suggest similarities with the "pebbly mudstone deposits" from continental margin environments described by Reineck & Singh (1975).

The garnet-mica-schists are essentially composed of muscovite, minor biotite, quartz, plagioclase, and almandine-rich garnet.Their chemical composition (table 2) corresponds to that of typical geosynclinal shales. Garnet-mica-schists occur predominantly in the lower parts of the stratigraphic sequence(in the working area). They also often accompany quartzites.

Quartzites occur as laterally extensive intercalations within the pelitic metasedimentary sequences described so far. They form horizons from one meter up to several tens of meters thickness and generally display sharp contacts towards the phyllitic rocks. However, thicknesses in excess of a few meters are probably due to repetition by isoclinal folding. The quartzites are fairly pure quartz-rocks that range from massive to banded. Sometimes very conspicuous parallel bedded rhythmic alternations of mm to cm thick pure quartzitic layers with thinner pelitic layers are found. The quartzite varieties are gradational into one another and should have been deposited under essentially identical conditions. Although the rhythmically layered types sometimes may resemble varvitic sediments, such an origin is not very likely because individual rhythms may reach thicknesses of several cm (8 cm and more). An alternative explanation for the quartzites is that they were deposited by turbidity currents which brought relatively coarse quartz sands into an environment generally devoid of sandy sediments. The rhythmic varieties then could be regarded as formed during episodes of repeatedly triggered turbidity currents. Because the quartzites occur as intercalations into quite variable sediments or even volcanics and show neither any gradations into these rocks nor any other recognizable genetic relationships, a distant and different source and different depositional mechanism (like turbidity currents) appears very plausible.

Carbonates are widespread as a minor component in many metapelitic rocks, but occur only rarely and locally restricted as thin marble lenses. Absence of the latter is probably evidence for continuous, though not necessarily very rapid clastic sedimentation.

In summary, the bulk of the sediments are thick pelitic sequences with intercalated volcanics. Stratigraphically upward, the amount of ferromagnesian minerals appears to increase and probably correlates with the amount of reworked mafic volcanic materials. Episodic turbidites and pebbly mudstones suggest the proximity of a continental margin.

Volcanic and volcaniclastic rock types:

This chapter includes all types of volcanics and fragmental volcanic rocks, particularly tuffs and volcanic breccias. Mafic and minor felsic volcanics are the dominant lithologies of the Støren Group. In this paper we will also report about an andesite which is a rather uncommon rocktype in this environment.

Pillow structures within the basalts, although rarely preserved, prove their origin as submarine flows. Alteration by seawater is common and sometimes affected complete lava flows such as those termed "calcareous greenschists" in the geological map (fig. 2). The now amphibolitic rocks are frequently banded with carbonates, albite and quartz as a consequence of premetamorphic alteration and redeposition.

Basaltic tuffs are represented as cm-thick amphibolitic layers, alternating with magnetite-rich and magnetiferous cherts, pyritic exhalites and thin marble bands, which demonstrate the contemporaneity of tuff eruptions and submarine exhalative processes.

Very rarely, also felsic tuffs (keratophyre) occur, as meter-thick intercalations, mainly within chlorite-sèricite-schists, but also intercalated between mafic lavas.

An extrusion of andesitic composition was recognized west of the Tverrfjell mine (see fig. 2). Its volume can be estimated to be close to about 10 km^3. Although the bulk composition (see below, table 2) of this rock, which is now a garnetiferous, quartz and fieldspar-rich biotite-chlorite-sericite-schist, is similar to that of typical shales or clays, such an origin is most unlikely because (1) a felsic, genetically related volcanic breccia occurs at its base, (2) there is evidence for hydrothermal alteration within this rockbody, (3) because the rock with its typical appearance is unique in the area and clearly different from that of true pelitic metasediments, (4) because the rock is perfectly homogeneous (besides effects of alteration) and (5) because there is an almost complete series in magma compositions from normal basalts to this andesite. It forms a well defined body in the core of an F1-antiform and is overlain by a mineralized sequence which is laterally equivalent to the Tverrfjell orebody (see below). The basal breccia consists of felsic fragments embedded in a carbonaterich, (altered) schistose matrix of an originally perhaps more mafic material.

Another type of volcanic breccia is found in several places east of the main fault (see map, fig. 2), which consists of mainly basaltic fragments. However, in some stratigraphic levels, felsic fragments can dominate. Because the breccia is a mixture of various rock types, and the components are fairly equally sized (i. e. to some degree sorted) the breccia is thought to represent epiclastic volcanic debris that accumulated to deposits of quite variable thickness.

Exhalative mineralization

Exhalative stratiform mineralizations are fairly common in the working area, most frequently as magnetite and/or pyrite bearing cherts as well as massive to disseminated pyrite and/or pyrrhotite bearing horizons. They invariably occur within or at the boundary of amphibolites. However, these exhalative ores generally do not contain any base metals.

The copper and zinc bearing exhalative mineralizations appear to be strictly confined to the andesite extrusion. Hydrothermal alteration, which can be recognized in the now metamorphosed andesite by the scarcety or complete absence of ferromagnesian minerals, particularly garnet, and by the presence of carbonates and/or excessive silica, has affected large parts of the body. In a number of drillholes, exhalative Cu/Zn ores were encountered in the hanging wall of the andesite. The ores are embedded in a highly variable series of sulfide impregnated, often carbonate-rich sericite-biotite and chlorite-sericite-biotite schists, with locally recognizable felsic tuffs, thin marble layers and pyrite and pyrrhotite bearing cherts. Abundance of carbonates and impregnation with sulfides suggests that these rocks were subject to alteration. The original nature of these schists is not obvious, but they could represent hyaloclastic debris formed from the extruded andesite. The massive exhalative sulfides show ore-grade base metal contents, but are only rarely thicker than a few centimeters. The entire ore bearing series appears to be several meters to several tens of meters thick and is overlain by metabasalts.

The mineralized series is a lateral equivalent of the Tverrfjell orebody which is situated about 4 km further in the east. Unfortunately the footwall of the Tverrfjell orebody is geologically complicated and not well documented. It consists mainly of phyllitic and mafic lithologies. The andesite itself is not known from immediately below the orebody, but a felsic breccia which corresponds to that at the base of the andesite was recognized locally. It appears that the Tverrfjell orebody formed at a site slightly off the andesitic extrusion, probably in a local basin.

The orebody displays vertical zoning in copper and zinc contents, and essentially three distinct ore types can be differentiated. From footwall to hanging wall (i. e. from south to north) these are:

1. Stringer ore. Tectonized matrix rich in chlorite and amphibole with abundant quartz veinlets. Chalcopyrite, pyrrhotite and quartz are metamorphically remobilized; minor idioblastic pyrite. 2.80 % Cu, 0.15 % Zn and 14 % S.

2. Banded pyrite-magnetite-ore. Alternating magnetite-rich and pyrite-rich parallel layers of a few mm to several cm thickness in a quartz-rich, calcite-bearing matrix. Chalcopyrite preferentially in pyrite layers. 1.80 % Cu, 0.35 % Zn, 24 % S.

3. Massive pyritic ore. Almost massive pyrite with disseminated chalcopyrite and sphalerite, subordinate quartz and calcite. Upward increase in Zn (0.70-1.60 %) and decrease in Cu (1.60-0.40 %), 40 % S.

In summary, a general upward increase in Zn and total sulfur and a decrease in Cu occurs (compare Mining Magazine, 1978). The upward transition from pyrrhotite over pyrite-magnetite to pyrite appears to be paralleled by a relative and absolute decrease in quartz and a relative increase in calcite.

Geochemistry of the volcanic rocks

Studies on the major and trace element geochemistry of the metavolcanic rocks have been carried out by means of X-ray fluorescence analysis (XRF). Major elements were determined from lithiummetaborate glasses, FeO was measured photometrically, CO_2 and H_2O gravimetrically. Nb, Zr, Y, Rb, Sr, Zn, Cu, Ni, Co, Cr and V were determined from powder tablets by XRF. Results are listed in table 2 and major oxides and trace elements vs. SiO_2 plots are shown in fig. 5.

Although most of our analyzed rocks show high CO_2 contents (>0.5 %), and hence were subjected to alteration, still some significant features can be recognized. The majority of the analyzed rocks are either olivine or quartznormative tholeiites. Two basalts contain nepheline in their norms, and a tendency towards critical silica undersaturation is also observed with some other transitional ol-tholeiites. The rocks display a tholeiitic trend in the AFM triangle (fig. 6), and show an early TiO_2 enrichment trend (1.23-3.71 %) and simultaneously increasing FeO*/MgO ratio[+] (0.95-3.45) with increasing SiO_2 contents. TiO_2, K_2O and FeO*/MgO values are higher than those of normal ocean floor basalts. The olivine-tholeiites are higher in MgO and Al_2O_3 and lower FeO*, TiO_2 and P_2O_5 than the quartz-tholeiites.

When the basaltic rocks are plotted into the Ol-Plag-Cpx-diagram of fig. 7 (according to Cox et al., 1979),one finds that the data follow the olivine-plagioclase cotectic minimum and, therefore, these two minerals were the earliest formed and separated phenocrysts in the melt. It can be suspected that the MgO and Al_2O_3-rich Ol-tholeiites represent more primitive melts, whereas the quartz-tholeiites are more evolved and enriched in FeO*, TiO_2 and P_2O_5 but depleted in MgO and Al_2O_3, due to olivine and plagioclase fractionation. The same fractionation processes are reflected in trace element chemistry. The compatible elements Ni and Cr are highly correlated with MgO and Al_2O_3 because Ni is strongly incorporated into olivine, and Cr tends to be simultaneously precipitated as Cr-spinel in early magmatic stages. Vanadium parallels the behaviour of FeO*, MnO and TiO_2. These elements accumulate in the melt phase until magnetite (Gill, 1981) and/or clinopyroxene (Frey et al., 1974) begin to precipitate. Clinopyroxene is more likely in our case because Ca and Mg become simultaneously depleted.

Compared to normal ocean floor basalts, the mafic volcanics of the Tverrfjell area are significantly enriched in a number of elements, in-

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[+] FeO* = FeO+0.9xFe_2O_3

cluding Ti, P, K, Rb, Sr, Zr, Y and Nb. When plotted into discrimination diagrams (e.g. fig. 8 and 9) the basalts fall predominantly into fields for "within-plate basalts" and "mid-ocean ridge basalts". However, other diagrams (e.g. fig. 10, Zr-Ti-Y, Pearce & Cann, 1973) yield different results. The reasons for this behaviour are thought to lie in the evolved nature of most studied rocks, particularly in their Ti-trends which become reversed as soon as clinopyroxene begins to crystallize. Therefore, the usefullness of such diagrams, especially those using titanium as a discriminant, is not clear in the case of evolved basaltic suites.

The abundances of the anomalously high elements are similar to those found for socalled "Type II ocean-floor-basalts" (Bryan et al., 1976) or "e-MORB (enriched Mid Ocean Ridge Basalt) (Sun & Nesbitt, 1978). This type of tholeiitic basalts is found associated with alkali olivine basalts on volcanic platforms astride mid ocean ridges (e.g. Iceland) and at intraplate volcanic centres like ocean islands and seamounts (e.g. Hawaiian Islands, Mauritius etc.). Basalts of this kind occur above mantle plumes or "hot spots" where deeper undepleted mantle is thought to form the source for these particular basaltic melts. Often tholeiitic and alkaline basalts occur side by side in this type of volcanic environment, and the nepheline-normative and transitional basalts of the Tverrfjell area can probably be interpreted in this sense.

Peculiar types of amphibolites occur near the Tverrfjell mine and are separated in our map (fig. 2) as "Tverrfjell amphibolites" (TV 13 and TV 15, table 2). Macroscopically, these metabasalts can be distinguished by their conspicously high biotite content and their lighter, more greyish colour. Chemically, they are characterized by high SiO_2, K_2O, Nb, Zr, Y and Rb values and are interpreted as very highly evolved basalts which are derived from common basaltic magmas by extensive removal of olivine, plagioclase and additionally clinopyroxene (low V, low normative di). The extrusive andesite (TV 18) west of the mine is probably the result of continued fractionation of this kind.

There is a more or less continuous series of magma compositions which leads from olivine-tholeiites to the andesite. However, between the latter and the keratophyre tuffs mentioned above, no intermediate members are known and it is doubtful whether there is any close genetic relationship between these two rock groups, although keratophyres are commonly thought to form from tholeiitic source rocks. The keratophyre tuff (TV 16) bears features characteristic for trondhjemites (Barker, 1979). Especially the low K_2O/Na_2O ratio is in contrast to the higher evolved basalts and the andesite.

In summary, the volcanic rocks surrounding and hosting the Tverrfjell deposit are tholeiites and minor alkali olivine basalts, that range from more primitive ol-normative to highly evolved quartz-normative rocks. Early olivine and plagioclase and later clinopyroxene fractionation are responsible for the observed variability and evolutionary trends. High abundances of certain major and trace elements indicate primary magmas similar to those of ocean islands and seamounts, or to volcanic platforms on oceanic ridges.

Discussion

As a result of several strong deformational and metamorphic episodes during the Caledonian orogeny, attempts for a geological reconstruction of pre-orogenic conditions must largely rely on geochemical data and on comparison with modern environments.

In the Tverrfjell area, the close association of submarine mafic lavas, pelitic geosynclinal sediments and terrigeneous turbiditic sediments put some constraints on the former geotectonic position and indicate that the Tverrfjell area formed in a geosynclinal basin, but not too far from a continental margin, i. e. the Baltic Shield. Localized accumulation of volcanic debris indicates morphological gradients, and the rapid lateral facies changes of the sediments also suggest a nonuniform and unsteady depositional environment which can be attributed to a submarine volcanic landscape.

The erupted basalts show typical features of ocean island suites or of magmatic associations from volcanic platforms on mid-ocean ridges. Both are localized above uprising mantle plumes. Because of the intercalated terrigeneous sediments, one must conclude that the volcanic eruptions were intermittent and occurred off a major spreading axis. However, a relation to a back-arc spreading centre is also conceivable.

The extensive magma fractionation which is observed in the Tverrfjell area requires a shallow-seated magma chamber to allow for the separation of significant volumes of highly evolved liquids like that conductive to the andesitic extrusion west of the Tverrfjell mine. The high degree of fractionation necessary to form an andesitic liquid from a primary basaltic magma will lead to an amount of residual melt comparable to or larger than that of the andesite itself.

Such a magma chamber on the other hand provides a potent heat source which should be able to induce a large and longlived convective hydrothermal system in the upper few kilometers of the predominantly basaltic crust. Obviously, such a system should be capable of forming exhalative ore bodies like those of the Tverrfjell mine (and the adjacent coeval mineralizations) which formed only very shortly after and immediately above the extrusion of the andesite.

The Tverrfjell ores contain 1.0 % Cu and 1.2 % Zn with minor contents of Au (0.08 g/t and Ag (8 g/t), and in this respect they resemble socalled "Cyprus-type" deposits that form on mid-ocean ridges. The reason for this similarity is the equivalent composition of the underlying crust which provides the metals for the deposits and which controls the composition of the hydrothermal solutions. A genetic linkage of exhalative ore deposits with ocean island type volcanism appears to be uncommon; at least no example is known to the authors. However, from the case of the Tverrfjell deposit it is evident that highly evolved basalts or even further evolved volcanics may serve as an exploration guide, as they are spacially restricted to the epicentres of magmachambers as are potential exhalative ore deposits.

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Figure Captions

Fig. 1 :Location of the Tverrfjell mine and other massive sulfide deposits in the Trondheim region (after Bugge, 1978).

Fig. 2 :Geological map of the area around the Tverrfjell mine.

Fig. 3 :Two north-south sections illustrating the structural interpretation for the Tverrfjell area.

Fig. 4:Schematic representation of the stratigraphic succession and inferred facies relationships.

Fig. 5:Major and trace elements plotted against SiO_2 for the analyzed meta-volcanic rocks of the Tverrfjell area.(Major oxides in percent values, trace elements in parts per million.) Squares = quartz-tholeiites, circles = olivine-tholeiites, triangles = nepheline-normative basalts.

Fig. 6:A-F-M-diagram ($Na_2O + K_2O$, $FeO + 0.9xFe_2O_3$, MgO).Line separates tholeiitic (above) from calc-alkaline (below) rock suites (according to Irvine & Barragar,1971). Symbols as in fig. 5.

Fig. 7:Olivine - plagioclase - clinopyroxene diagram (according to Cox et.al., 1979), displaying low pressure phase relationships for tholeiitic melts. The data scatter around the plagioclase - olivine cotectic line and he ternary eutectic minimum.

Fig. 8:Discrimination diagram (Pearce,1980) using zirconium and yttrium. Symbols as in fig. 5, IAT = island arc tholeiites, MORB = mid ocean ridge basalts, WPB = within-plate basalts.

Fig. 9:Discrimination diagram (Pearce,1980) using chromium and yttrium. Symbols as in fig. 5, IAT = island arc tholeiites, MORB = mid ocean ridge basalts,WPB = within-plate basalts.

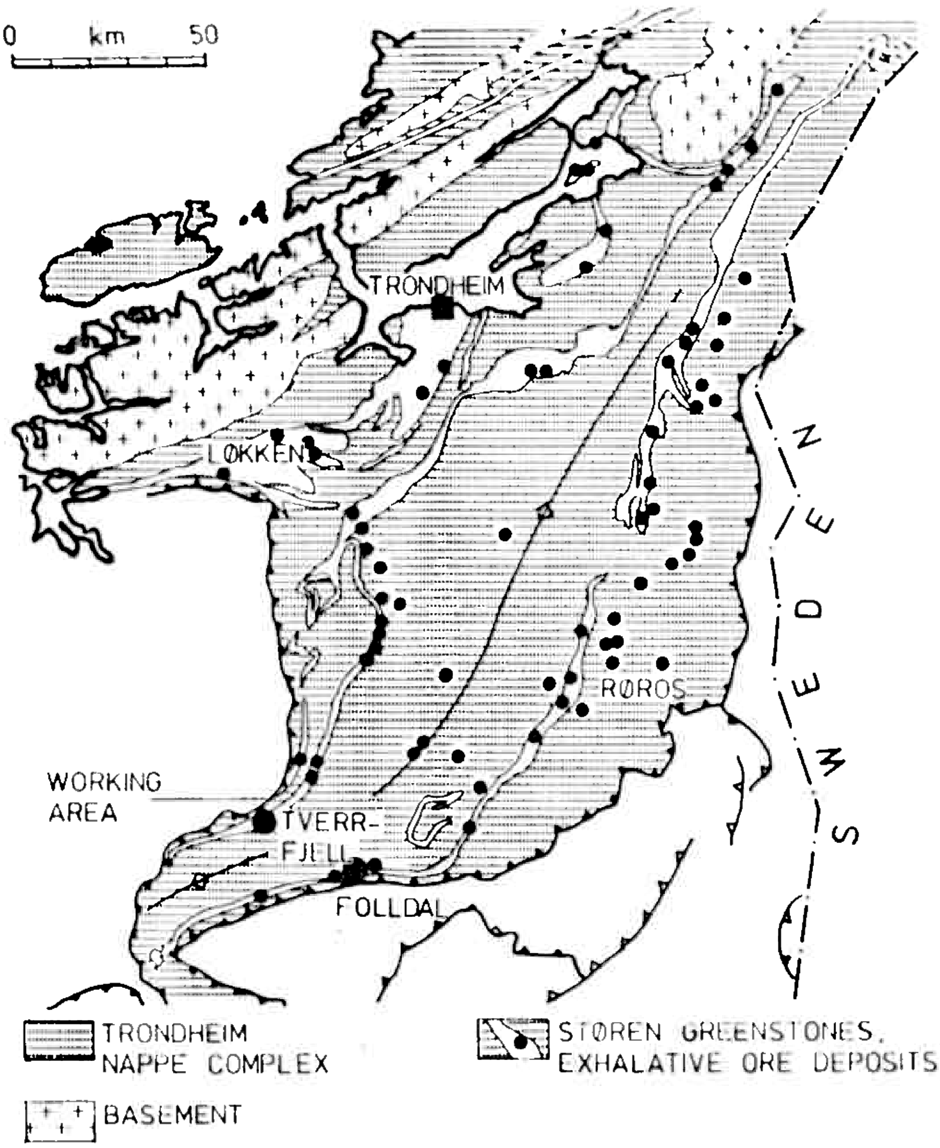
Fig.10:Zr - Ti - Y discrimination diagram (Pearce & Cann, 1973).Symbols as in fig. 5. A = low-K-tholeiites, B = ocean floor basalts, C = calc-alkaline basalts, D = intraplate basalts.

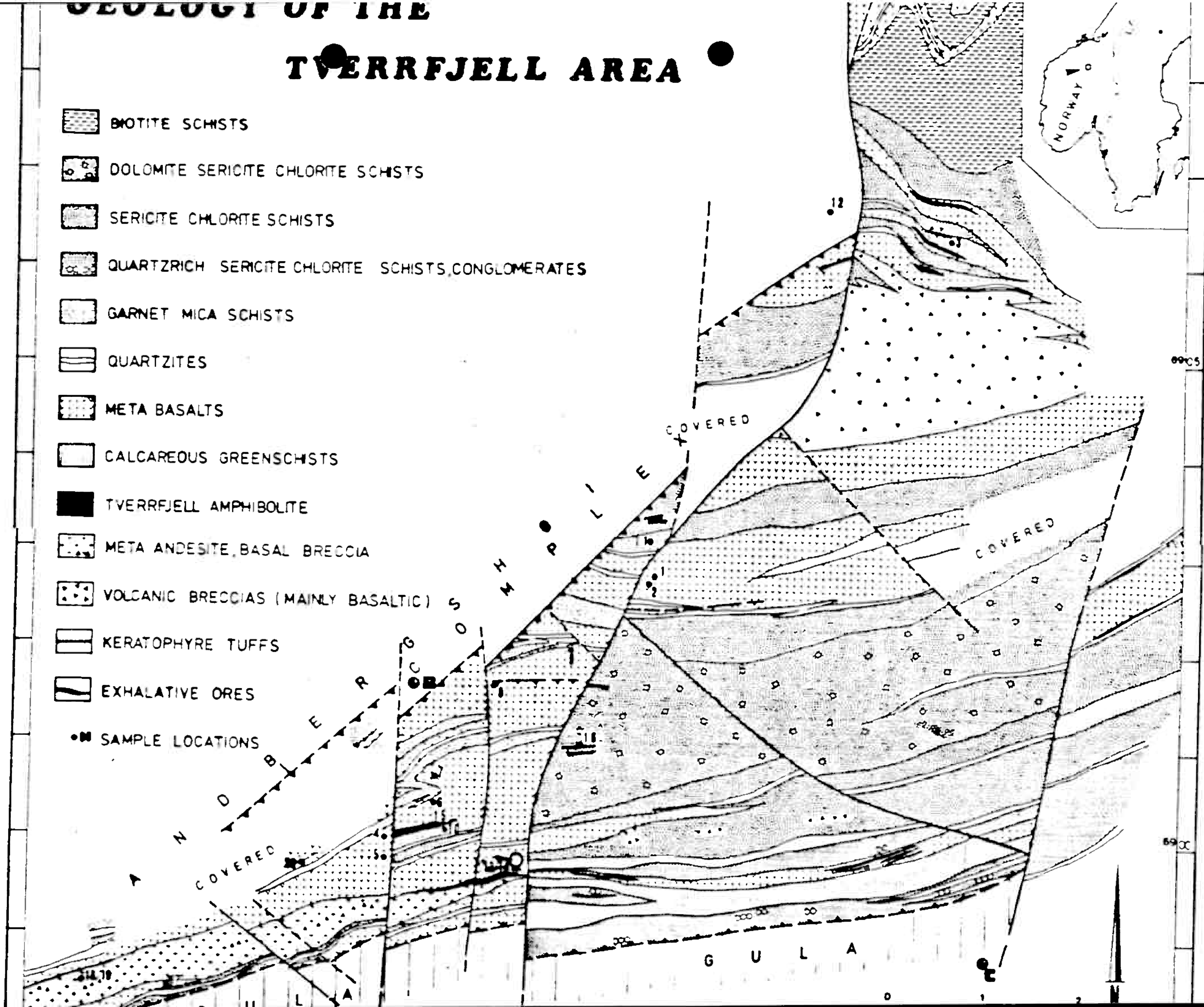
Captions for the tables

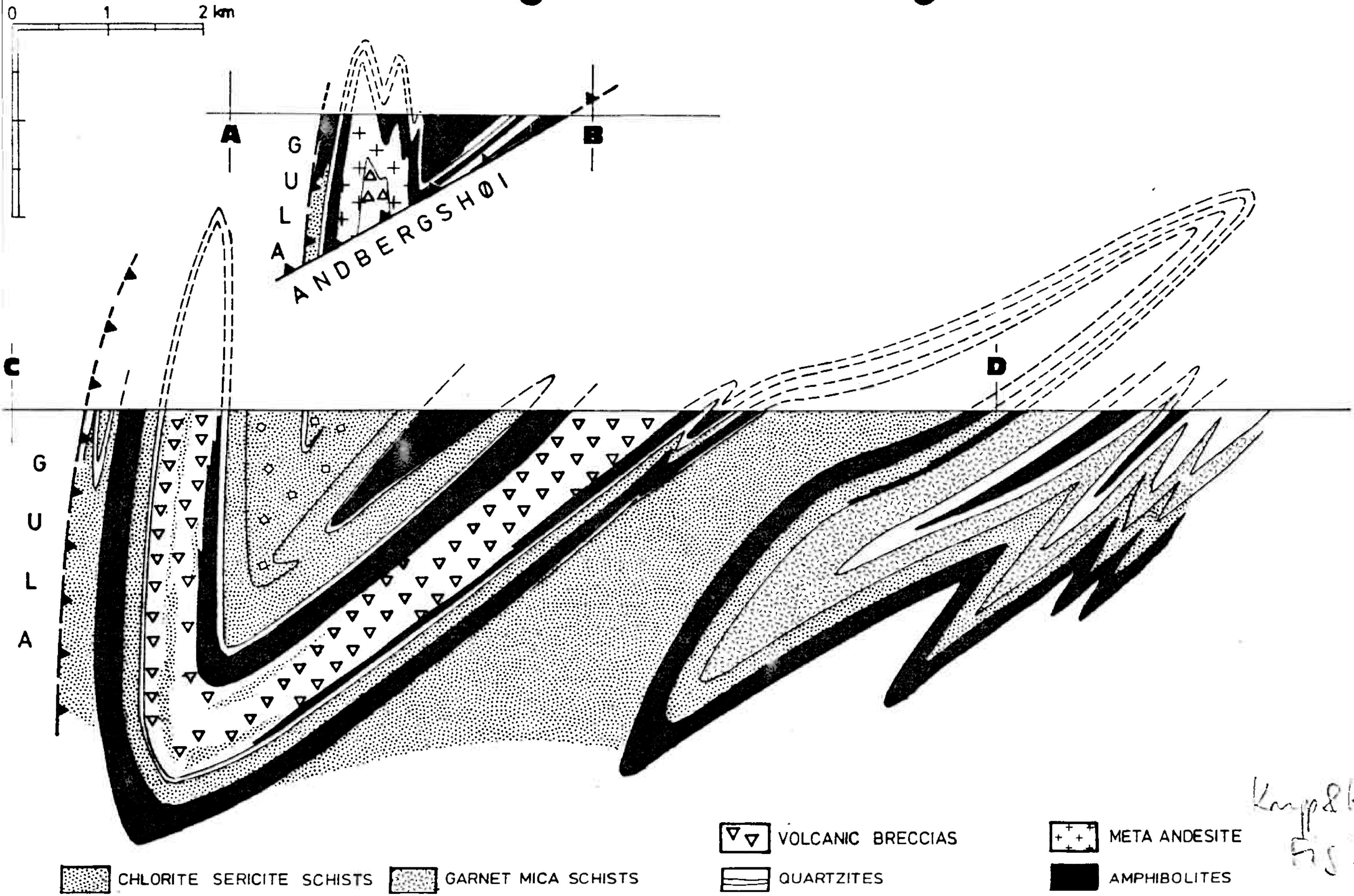
Table 1. :Stratigraphic correlation scheme as proposed by Gale & Roberts,1874.

Table 2. :Major and trace element data for metavolcanic and metasedimentary rocks of the Tverrfjell area,and CIPW norms. Sample numbers correspond to numbers in fig. 2.

Samples tv1 to tv12,tv14 and tv17 are basalts,tv13 and tv15 are highly evolved basalts, tv16 is a keratophyre tuff, tv18 is a "fresh" and tv19 a "hydrothermally altered" andesite sample. tv20 is a meta-pelitic sedimentd (garnet-mica-schist).


0 km 50
TRONDHEIM
LØKKEN
RØROS
WORKING AREA
TVERR-FJELL
FOLLDAL
N
S W E D E N
TRONDHEIM NAPPE COMPLEX
BASEMENT
STØREN GREENSTONES, EXHALATIVE ORE DEPOSITS


GEOLOGY OF THE
TVERRFJELL AREA
BIOTITE SCHISTS
DOLOMITE SERICITE CHLORITE SCHISTS
SERICITE CHLORITE SCHISTS
QUARTZRICH SERICITE CHLORITE SCHISTS,CONGLOMERATES
GARNET MICA SCHISTS
QUARTZITES
META BASALTS
CALCAREOUS GREENSCHISTS
TVERRFJELL AMPHIBOLITE
META ANDESITE, BASAL BRECCIA
VOLCANIC BRECCIAS (MAINLY BASALTIC)
KERATOPHYRE TUFFS
EXHALATIVE ORES
SAMPLE LOCATIONS
NORWAY
COVERED
COVERED
COVERED
ANDBERG COMPLEX
GULA
12
0
1
2



Krupp & Krupp
Fig 3

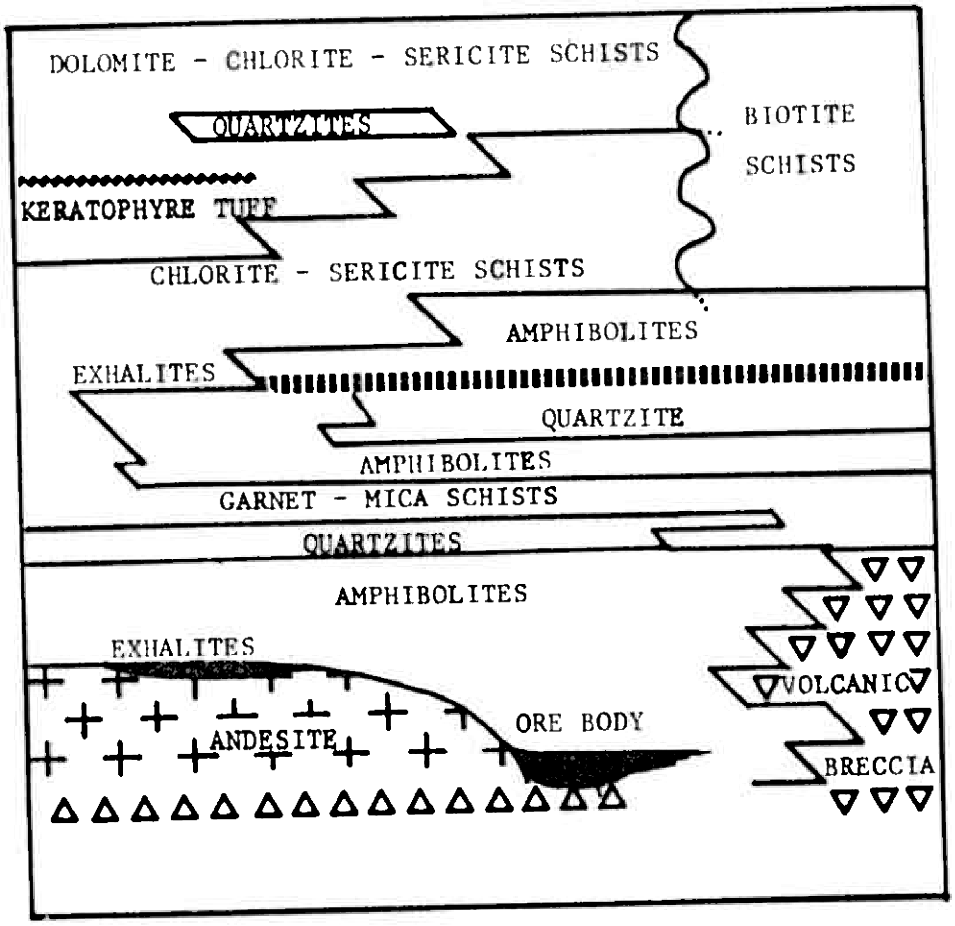
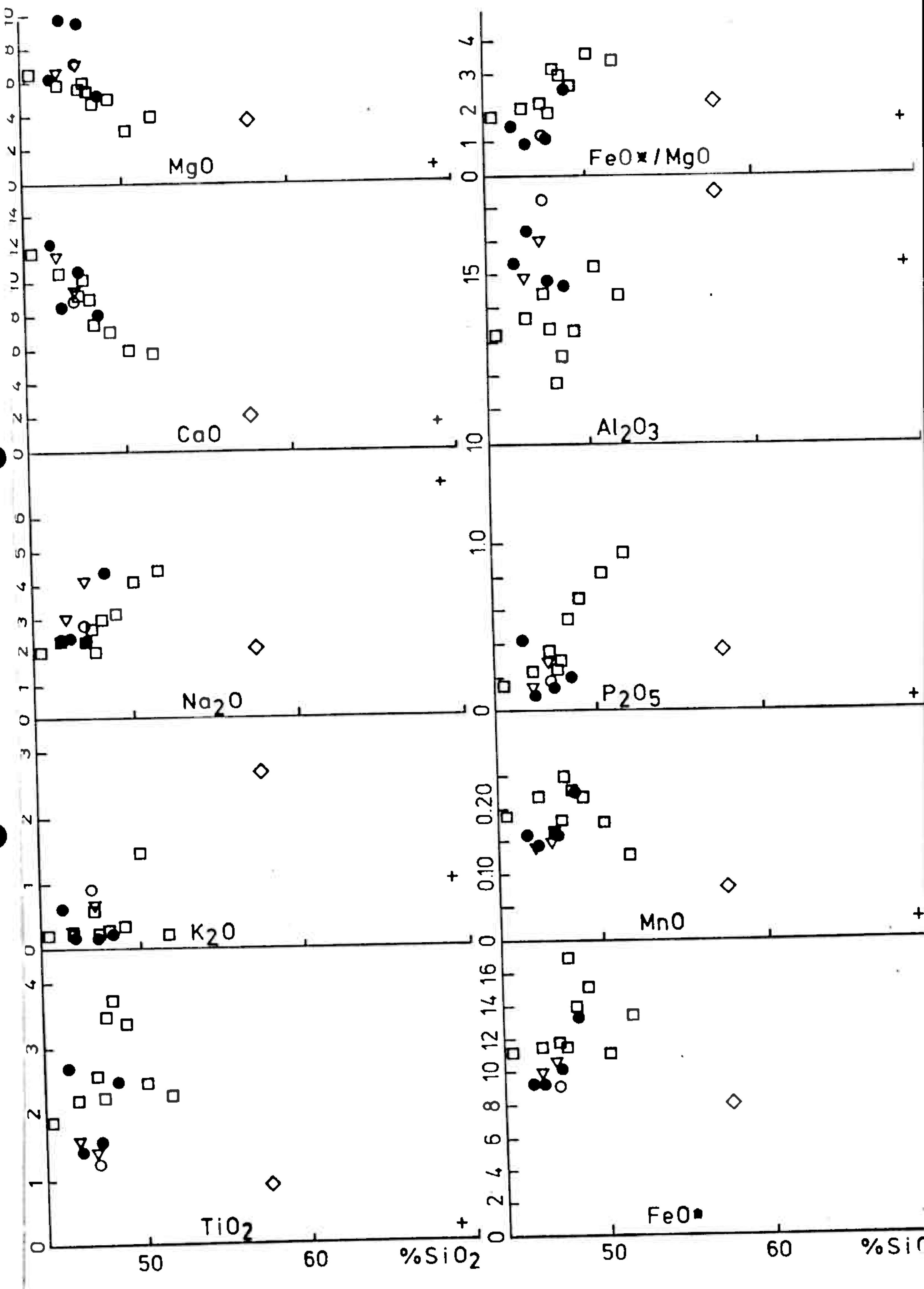
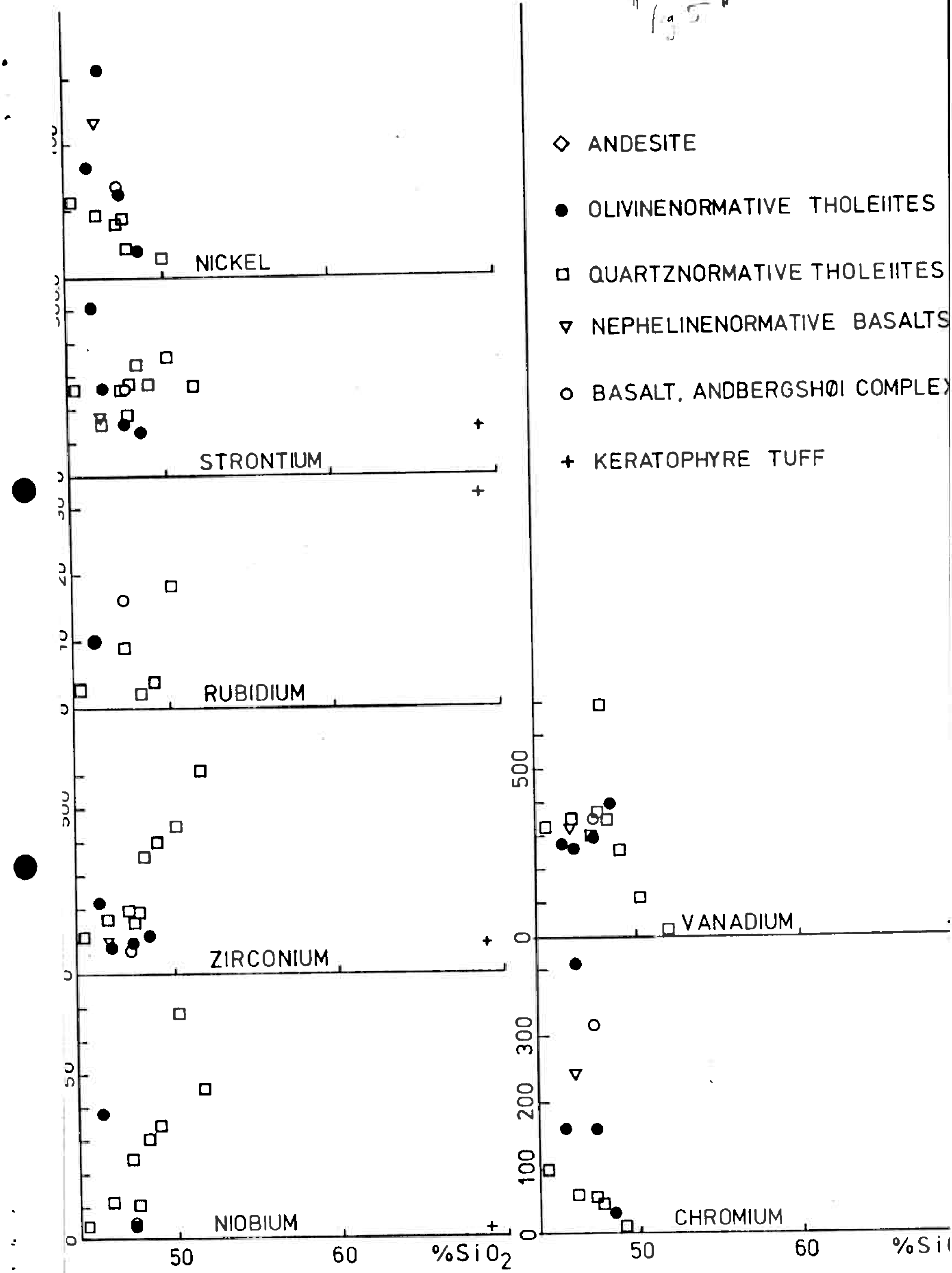

DOLOMITE - CHLORITE - SERICITE SCHISTS
QUARTZITES
BIOTITE SCHISTS
KERATOPHYRE TUFF
CHLORITE - SERICITE SCHISTS
AMPHIBOLITES
EXHALITES
QUARTZITE
AMPHIBOLITES
GARNET - MICA SCHISTS
QUARTZITES
AMPHIBOLITES
EXHALITES
ANDESITE
ORE BODY
VOLCANIC
BRECCIA

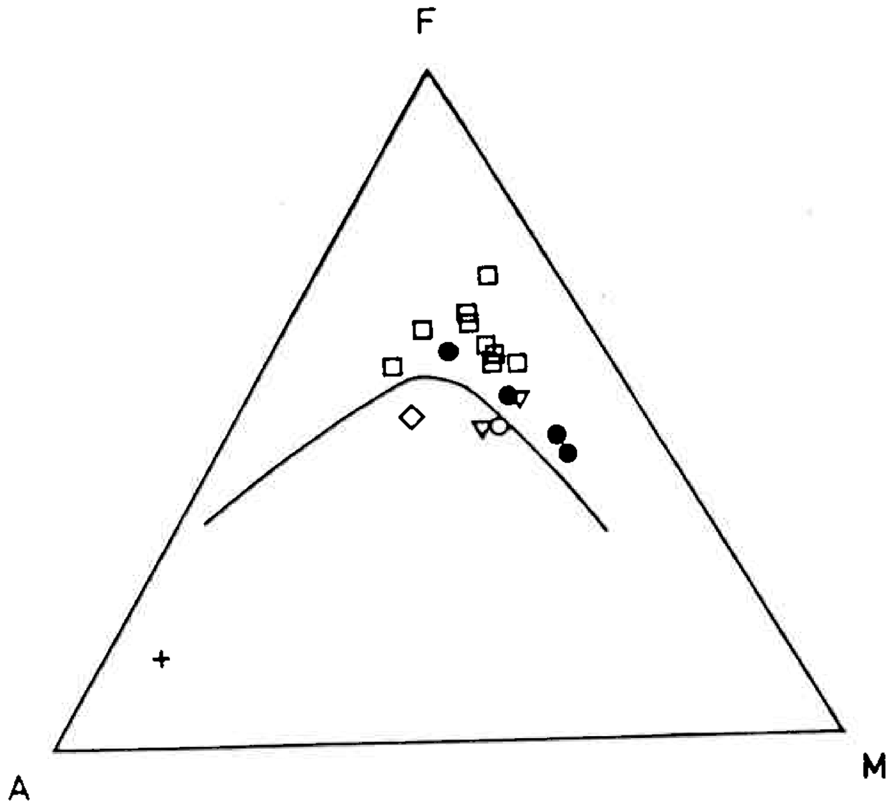
Fig 4



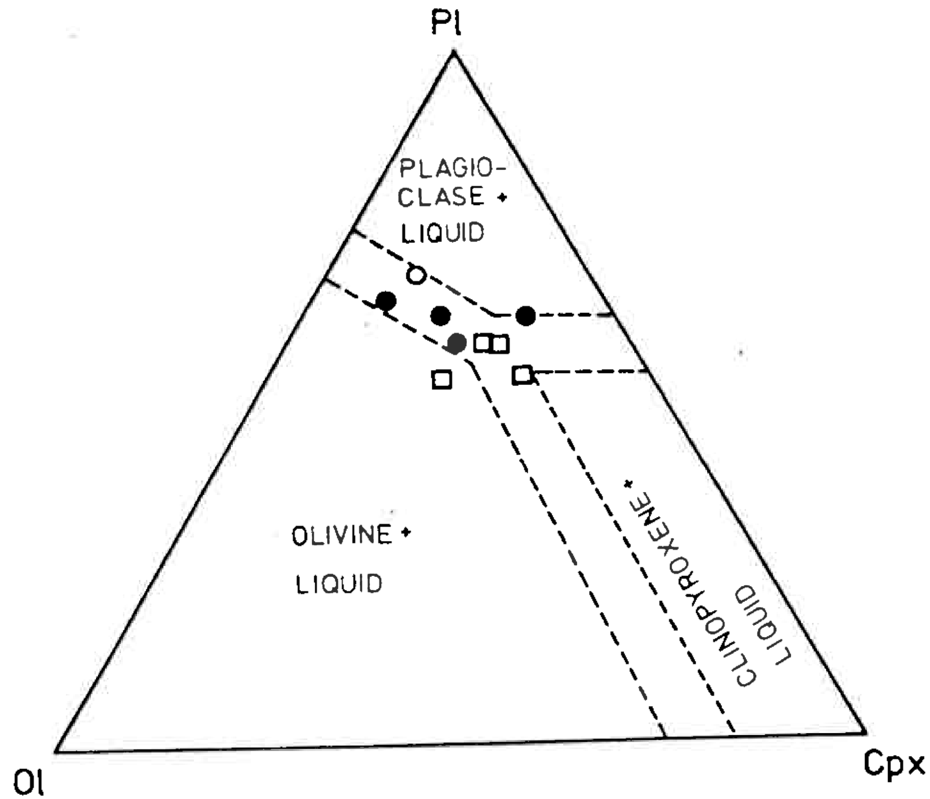
MgO
FeO*/MgO
CaO
Al2O3
Na2O
P2O5
K2O
MnO
TiO2
FeO*
50
60
%SiO2



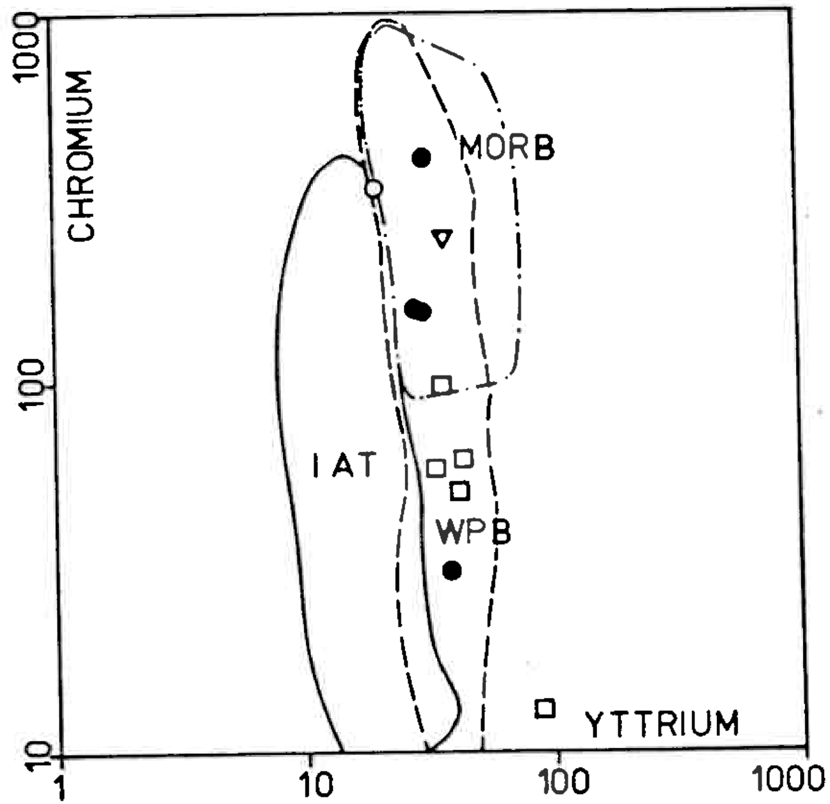
NICKEL
STRONTIUM
RUBIDIUM
ZIRCONIUM
NIOBIUM
VANADIUM
CHROMIUM
ANDESITE
OLIVINENORMATIVE THOLEIITES
QUARTZNORMATIVE THOLEIITES
NEPHELINENORMATIVE BASALTS
BASALT, ANDBERGSHØI COMPLEX
KERATOPHYRE TUFF
500
0
300
200
100
50
60
%SiO2


F
A
M

6


Pl
PLAGIO-
CLASE +
LIQUID
OLIVINE +
LIQUID
CLINOPYROXENE +
LIQUID
Ol
Cpx

7


CHROMIUM
1000
100
10
MORB
IAT
WPB
YTTRIUM
1
10
100
1000

9

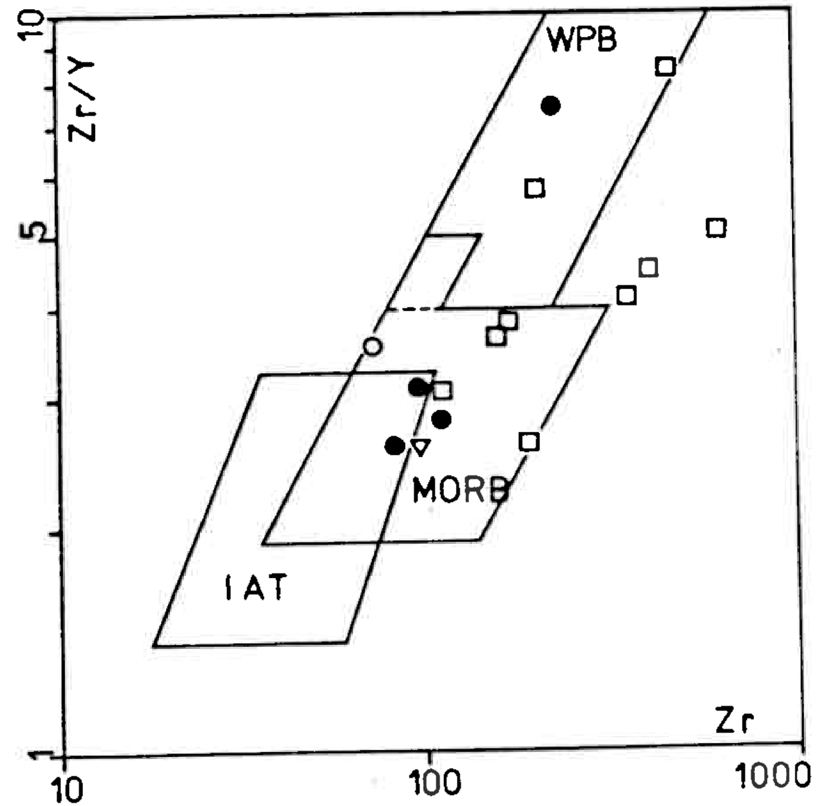
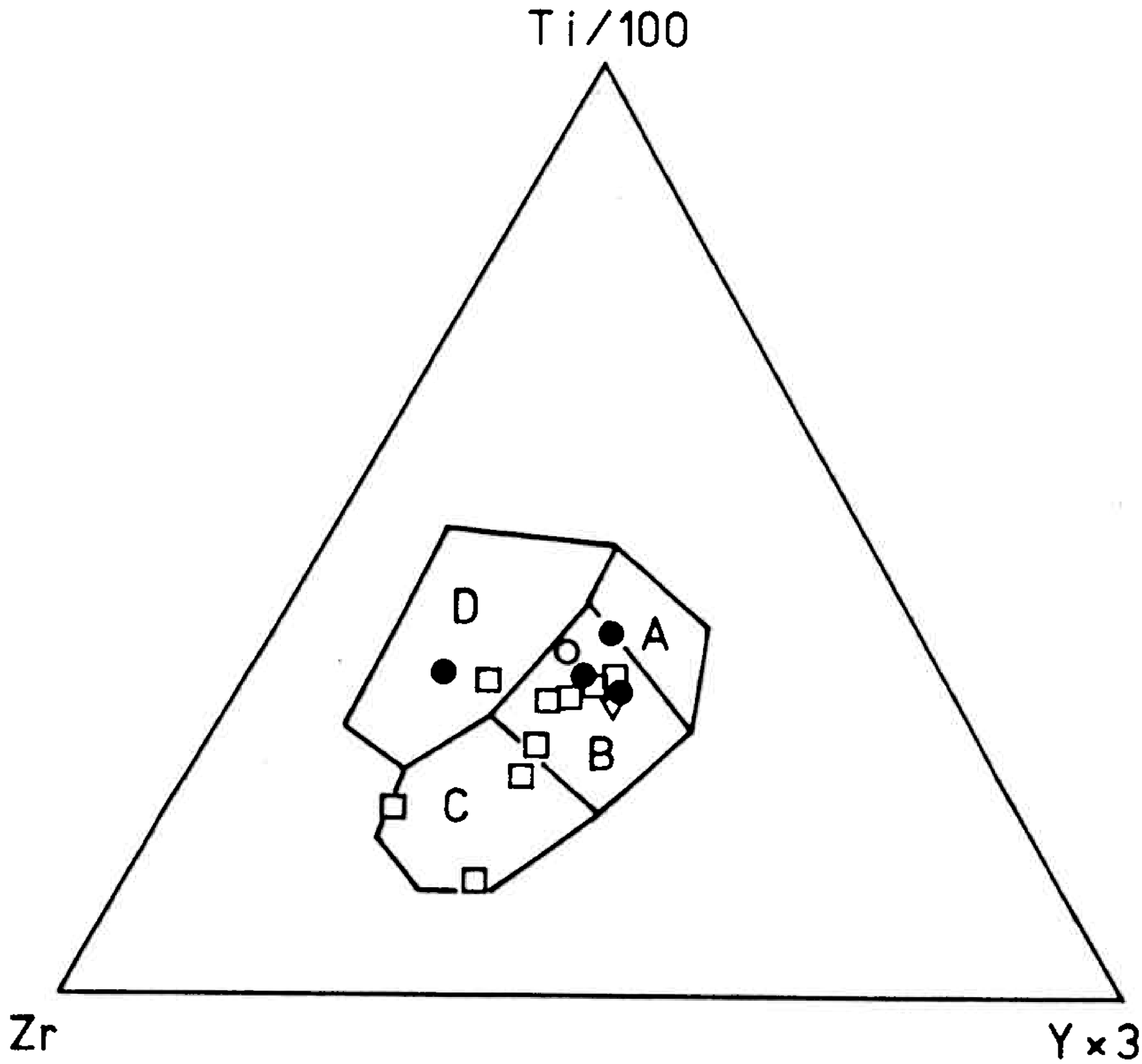

Zr/Y
10
5
1
WPB
MORB
IAT
Zr
10
100
1000

Fig 8


Ti/100
D
A
B
C
Zr
Y×3

	Eugeosynclinal		Miogeosynclinal	
	western areas	eastern areas		
Llandoverian	Horg Group	Slagan Group	Gula Group	Trondheim Supergroup
Upper Ordovician	Upper Hovin Group	Kjølhaug Group		
Lr/Mid Ordovician	Lower Hovin Group	Sulamo Group		
Tremadocian	Støren Group	Fundsjø Group		
Cambrian				
Eocambrian				

Kapp & Kapp
Table 1

	tv1	tv2	tv3	tv4	tv5	tv6	tv7	tv8	tv9	tv10
SiO_2	43.50	46.29	47.91	49.09	46.19	47.26	42.68	44.47	42.43	45.62
TiO_2	2.47	1.43	3.46	3.35	2.20	2.56	2.22	1.88	1.58	2.69
Al_2O_3	14.69	16.31	11.83	13.37	13.73	14.46	13.40	13.26	14.81	15.42
Fe_2O_3	5.21	3.06	5.60	3.11	3.36	4.28	3.22	4.02	2.89	3.13
FeO	8.18	6.52	11.90	10.15	8.44	7.95	8.55	7.61	7.57	6.45
MnO	0.23	0.14	0.25	0.22	0.22	0.16	0.18	0.19	0.16	0.16
MgO	5.21	9.75	5.41	4.9[illegible]	5.81	5.59	5.97	6.48	9.46	6.16
CaO	8.08	8.76	8.97	7.02	10.57	9.27	10.19	11.81	10.61	12.28
Na_2O	4.37	2.44	2.02	3.13	2.39	2.30	2.70	2.03	2.38	2.47
K_2O	0.23	0.15	0.20	0.32	0.23	0.55	0.23	0.21	0.20	0.61
P_2O_5	0.20	0.09	0.30	0.68	0.24	0.36	0.25	0.16	0.14	0.42
CO_2	0.14	0.24	0.06	0.94	1.78	1.04	2.34	2.74	0.48	2.38
H_2O^-	0.04	0.05	0.03	0.03	0.04	0.05	0.04	0.04	0.04	0.02
H_2O^+	1.28	3.62	1.77	3.00	3.66	2.72	3.26	4.25	2.20	3.66
SUM	99.89	98.85	99.71	99.53	98.86	98.55	100.23	99.15	99.95	101.47
Nb	n.f.	n.f.	n.f.	34	11	24	10	4	4	38
Zr	110	83	189	400	165	196	154	111	94	217
Y	39	32	72	89	43	34	42	36	30	29
Rb	n.f.	n.f.	n.f.	4	n.f.	8	n.f.	3	n.f.	10
Sr	130	268	276	280	156	253	183	266	153	508
Zn	102	68	156	142	101	96	99	93	93	87
Cu	36	107	n.f.	n.f.	29	45	80	105	34	36
Ni	16	157	18	13	44	38	42	57	62	81
Co	51	46	66	46	52	51	53	48	58	46
Cr	31	409	n.f.	12	62	58	50	98	159	162
V	392	265	626	255	351	298	220	327	353	270
Or	1.40	0.94	1.21	1.98	1.46	3.44	1.44	1.35	1.23	3.80
Ab	37.28	21.79	17.34	27.74	21.20	20.62	24.21	18.71	20.90	22.01
An	20.30	34.93	23.22	22.51	27.96	29.14	25.19	28.81	30.24	30.73
Mt	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18
Il	4.81	2.86	6.74	6.86	4.48	5.15	4.47	3.89	3.11	5.39
Ap	0.49	0.23	0.73	1.69	0.61	0.75	0.50	0.26	0.25	1.00
Di	16.28	8.33	17.20	7.77	22.02	14.49	22.31	28.28	19.28	25.00
Hy	-----	16.03	27.97	24.95	18.35	22.63	19.64	8.68	12.64	1.35
Ol	16.92	12.73	-----	-----	1.25	-----	0.08	7.84	9.97	8.58
Ne	0.36	-----	-----	-----	-----	-----	-----	-----	-----	-----
Q	-----	-----	3.22	4.37	-----	1.61	-----	-----	-----	-----
Ru	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----

	tv11	tv12	tv13	tv14	tv15	tv16	tv17	tv18	tv19	tv20
SiO_2	46.13	47.25	51.72	48.29	50.28	69.08	47.17	57.66	62.38	59.42
TiO_2	1.58	1.23	2.26	3.71	2.45	0.23	1.43	0.90	0.77	0.92
Al_2O_3	14.96	17.25	14.42	12.68	15.26	15.30	16.05	17.51	11.26	16.70
Fe_2O_3	3.02	2.25	4.27	4.72	4.47	0.95	2.85	1.63	1.11	1.39
FeO	7.09	6.98	9.62	9.74	7.09	0.51	7.74	6.55	4.69	6.84
MnO	0.14	0.16	0.13	0.23	0.18	0.03	0.15	0.08	0.09	0.10
MgO	6.55	7.02	3.90	4.65	3.09	0.81	7.01	3.66	3.37	4.48
CaO	11.59	8.90	5.81	7.58	5.96	1.54	9.44	2.13	4.40	2.14
Na_2O	3.04	2.80	4.47	3.00	4.11	6.92	4.10	2.10	2.57	2.40
K_2O	0.18	0.92	0.19	0.26	1.45	1.00	0.58	2.67	1.26	2.80
P_2O_5	0.14	0.18	0.96	0.55	0.52	0.06	0.28	0.37	0.40	0.10
CO_2	1.80	0.94	0.12	0.74	1.20	1.50	1.65	2.20	6.00	n.d.
H_2O^-	0.03	0.09	0.03	0.04	0.08	0.04	0.09	-----	-----	n.d.
H_2O^+	2.95	3.22	1.79	2.56	2.74	2.16	3.40	2.31	1.31	n.d.
SUM	99.20	99.19	99.69	98.75	97.88	100.13	101.94	100.00	99.70	-----
Nb	-----	5	45	30	68	3	n.d.	n.d.	n.d.	n.d.
Zr	96	70	611	350	445	93	n.d.	n.d.	n.d.	n.d.
Y	37	20	120	85	53	6	n.d.	n.d.	n.d.	n.d.
Rb	n.f.	16	n.f.	2	18	32	n.d.	n.d.	n.d.	n.d.
Sr	186	255	267	337	357	140	n.d.	n.d.	n.d.	n.d.
Zn	78	72	170	138	137	14	n.d.	n.d.	n.d.	n.d.
Cu	19	n.f.	n.f.	n.f.	n.f.	n.f.	n.d.	n.d.	n.d.	n.d.
Ni	116	68	n.f.	n.f.	n.f.	n.f.	n.d.	n.d.	n.d.	n.d.
Co	48	55	27	45	33	30	n.d.	n.d.	n.d.	n.d.
Cr	247	314	n.f.	n.f.	n.f.	15	n.d.	n.d.	n.d.	n.d.
V	327	353	11	345	114	29	n.d.	n.d.	n.d.	n.d.
Or	1.13	5.74	1.15	1.62	9.04	6.13	3.55	16.57	8.06	-----
Ab	24.56	25.00	38.83	26.71	36.67	60.73	25.88	18.66	23.55	-----
An	28.28	33.53	19.22	21.43	19.94	7.92	24.52	8.56	16.75	-----
Mt	2.18	2.18	2.18	2.18	2.18	-----	2.18	2.18	2.18	-----
Il	3.19	2.47	4.41	7.41	4.91	0.21	2.81	1.80	1.58	-----
Ap	0.25	0.25	2.19	1.25	1.00	-----	0.49	0.92	1.03	-----
Di	26.27	10.09	3.70	12.35	4.83	-----	18.55	-----	3.32	-----
Hy	-----	8.25	26.16	23.29	19.55	2.09	-----	19.91	13.87	-----
Ol	12.67	12.52	-----	-----	-----	-----	16.60	-----	-----	-----
Ne	1.48	-----	-----	-----	-----	-----	5.44	-----	-----	-----
Q	-----	-----	2.21	3.79	0.94	21.26	-----	22.86	29.68	-----
Ru	-----	-----	-----	-----	-----	0.13	-----	-----	-----	-----

n.f. = not found

n.d. = not determined

CIPW-norm calculated for Fe_2O_3 fixed at 1.50 %

Table 2
Karpf & Krupp