

Geo(Im)pulse

An investigation into the genesis of an erratic (retro) eclogite block from Haren, Groningen, the Netherlands

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Abstract

In boulder clays and glacial deposit sands, exposed in the northern part of the Netherlands, erratic blocks of (ultra)high pressure (UHP) metamorphic rocks may be found that originate from the Baltic Shield (Scandinavia). The occurrence of (U)HP metamorphic rocks in Scandinavia is limited to: (1) isolated occurrences within the Scandinavian Caledonides (Western part of Scandinavia); (2) Sveconorwegian rocks from the Halland area, Southwest Sweden; and (3) Kola Peninsula (Northern Scandinavia). For this reason (U)HP rocks form excellent indicator pebbles/rocks that may be used to trace back the source area from where the erratic blocks, found in the Netherlands, were derived. An example of this, an erratic (retro) eclogite block found in Haren, is investigated in the present study using naked eye, light-optical and electron microprobe (EMP) techniques. EMP mineral analyses were used to reconstruct the PT conditions under which the (retro) eclogite was formed ($T = 756 \text{ }^\circ\text{C/min}$, $P = 16,2 \text{ kb}$). This result, in combination with the mineral chemistry of the major rock forming minerals, provides evidence that this erratic block originates from the upper HP tectonic lens exposed in the Caledonian Seve Nappe Complex of Northern Jämtland, Sweden.

Keywords: indicator rock, glaciation, (U)HPM rocks, Scandinavia.

Introduction

In the last 50 years a few erratic eclogite blocks were found in the Netherlands. G. Dijk from Groningen discovered one of them. In 1965, he found during digging activities, at the corner of the Rijksstraatweg and the Potgieterlaan in Haren (Gr.), an (retro) eclogite (Fig.1) at a depth level of approx. 2 m (pers. comm.).

Haren is situated about 6 km south-south-east of the city Groningen and is lying on a hill range with a length of 70 km existing of glacial deposit sand and boulder clay, called the Hondsrug (Fig. 2). The boulder clay is from Saalian age and includes erratic blocks.

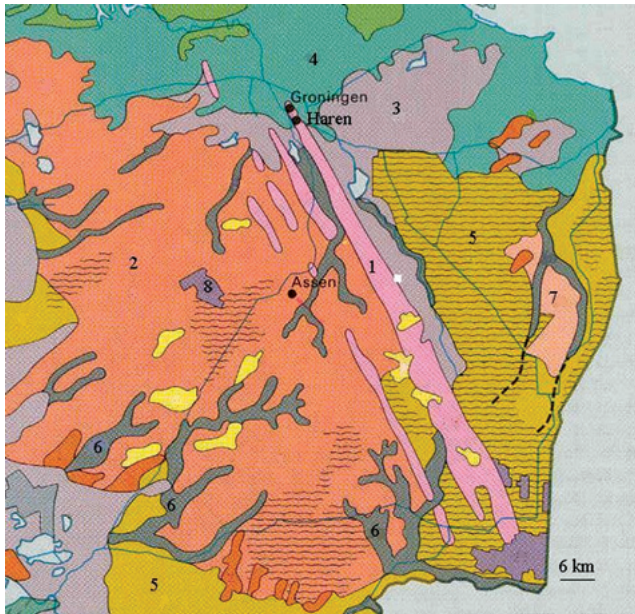
According to Huisman (1982), curator of the Natuurmuseum Groningen, this (retro) eclogite originated from Scandinavia. For more information on erratic blocks from Scandinavia found in the Netherlands, Denmark and Germany, the reader is referred to Zandstra (1988 and 1999) and Smed (1994).

This article describes the results of a detailed light optical and electron microprobe (EMP) study of this erratic (retro) eclogite block. We have made EMP analyses of the major rock



Fig. 1. Erratic (retro) eclogite block from Haren, Groningen.

forming minerals to reconstruct the PT conditions of eclogite formation. These results were used to make a comparative study with similar literature data, described from various (U)HP metamorphic terranes spread out over the Baltic Shield, allowing the source area of this erratic (retro) eclogite block to be determined.



- | | |
|----------------------------------|----------------------------------|
| 1 Hondrug complex (sand deposit) | 6 Creek and river valley deposit |
| 2 Ground moraine | 7 Glacial scouring plain |
| 3 Overflooded moor area | 8 Terrestrial peat plain |
| 4 Diked tidal sediment plain | Removed peat area |
| 5 Wind blown sand deposit | |
| | • City |

Fig. 2. Geological map of the Hondrug complex. The (retro) eclogite block was found in Haren at a depth level of approx. 2 m. Modified after Stichting Wetenschappelijke Atlas van Nederland (1985)

Method

Mineral-major element compositions were determined by EMP analyses at Utrecht University using a JEOL JXA-8600 superprobe. Operating conditions: 15 kV, 20 nA, 30 s counting time in wavelength dispersive spectrometry mode, ZAF routine and external calibrations against international silicate standards.

(U)HP metamorphic terranes in Scandinavia (Fig. 3)

By definition an eclogite is an (ultra) high pressure (UHP) metamorphic (M) rock that consists of garnet and sodium bearing clinopyroxene (omphacite) in the absence of plagioclase (Carswell 1990).

Eclogite is an important rock type of (U)HPM terranes, formed during orogeny when two plates collide with each other. (U)HPM terranes are simply exhumed fossil subduction zones that represent those parts of the colliding plates that

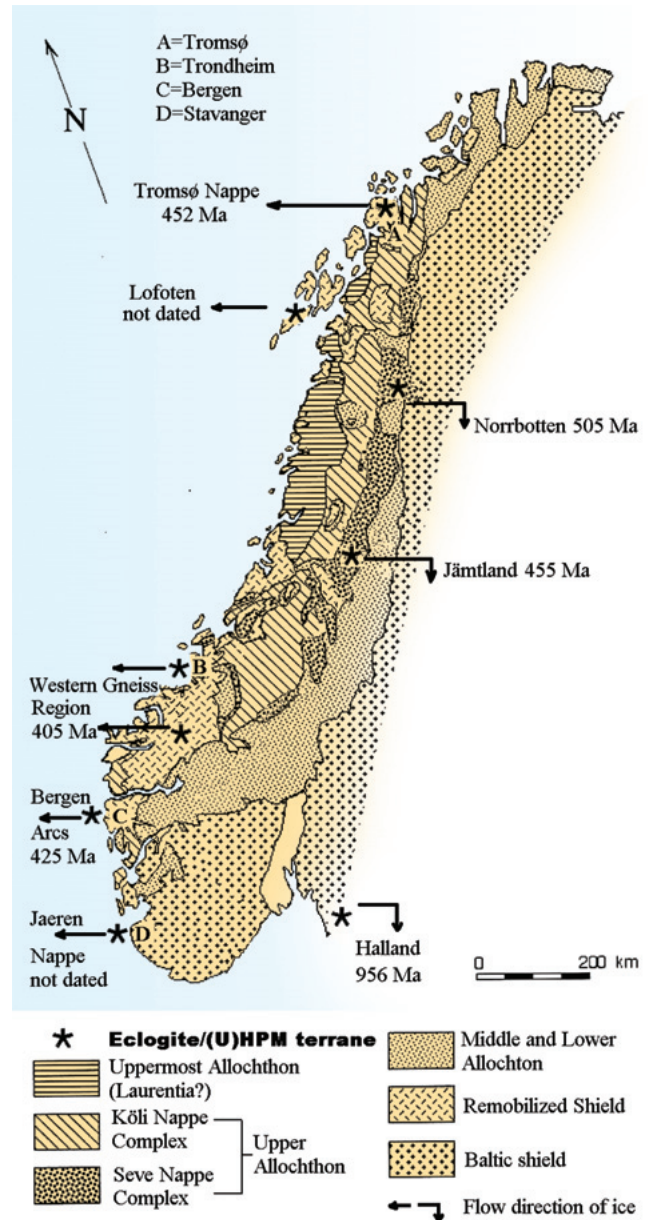


Fig. 3. Terrane map of the Scandinavian Caledonides (Western part of the Baltic Shield). The Scandinavian Caledonides are subdivided into four Allochthons (Nappe Complexes) lying on top of the Baltic Shield. With the star symbol the occurrences of eclogite bearing (U)HPM terranes are indicated. Modified after Brueckner and Van Roermund (2004).

once became subducted below and/or underneath the overriding plate. This subducting plate geometry creates the relatively cold geodynamic environment that is required for the growth of (U)HPM minerals (Carswell 1990).

Exposed (U)HPM terranes on the Baltic Shield are relatively scarce (Fig. 3). Most of them are related to the formation of the Scandinavian Caledonides, a mountain belt that was formed 500-380 Ma ago when the two adjacent continents, Baltica and Laurentia, collided with each other after consumption of the Iapetus Ocean that lied in between these two continents (Brueckner & Van Roermund 2004).

The locations of exposed Caledonian and/or Sveconorwegian (U)HPM terranes within the Scandinavian Caledonides are indicated with a star symbol (eclogite/(U)HPM terranes) in Fig. 3. Recently two other (U)HPM terranes were discovered in the northern part of the Baltic Shield: the Salma area, Kola Peninsula and the Gridino area, Northern Karelia (Kaulina and Apanasevich 2005). These locations are not mentioned in Fig. 3. The reason for it will be discussed below.

Potential source areas for erratic (U)HPM blocks

Taking into account the flow directions of the ice during glacial times only locations Halland, Northern Jämtland and Norrbotten can be considered as potential source areas for erratic (U)HPM blocks found in the Netherlands. All other (U)HPM terranes indicated in Fig. 3 can safely be excluded, included the two terranes in the northern part of the Baltic Shield. The ice in the western part of Scandinavia floated westwards into the Atlantic Ocean and the ice in the northern part floated northwards into the Barentsz Sea, consequently the ice from these places never reached the Netherlands. For this reason these terranes were excluded in the present study. The flow directions of the ice are indicated in Fig. 3 by black arrows. Below a summary of the three remaining (U)HPM terranes is given.

The eclogite-bearing terrane in Halland, Southwest Sweden

The eclogites from Halland (Fig. 3) were formed during the Sveconorwegian (Grenvillian) Orogeny around 950 Ma ago. For a review of the geodynamic setting the reader is referred to Bingen et al., (2005) and Berglund & Connelly (1994). The terrane in Halland has roughly N-S trending metamorphic belts of Svecokarelian (1850-1650 Ma), Svecofennian (1890-1750 Ma) and Sveconorwegian (1200 - 950 Ma) age. The Sveconorwegian Belt in the west consists of an Eastern and Western Segment separated by a mylonite zone. In the Southern part of the Eastern Segment, eclogites were found near Ullared (Möller 1998 and Möller 1999). All these eclogites are strongly retrogressed, including widespread plagioclase formation.

Consequently only retrograde PT conditions were determined $T = 750 \pm 45$ °C and $P \geq 10.8 \pm 1.2$ kb (Möller 1998). (U)HPM was dated as 956 ± 7 Ma years old (Möller and Söderlund 1997). In addition to garnet, clinopyroxene and plagioclase, the retrograde eclogites contain kyanite with sapphirine-plagioclase coronas.

The eclogite bearing terranes in Northern Jämtland, Central Sweden

In Northern Jämtland eclogites occur in the Seve Nappe Complex representing the lower part of the Upper Allochthon (Fig. 3) and interpreted to be the continent-ocean transition zone between Baltica and the ocean that opened outboard of it.

In Northern Jämtland/Southern Västerbotten, the Seve Nappe Complex is traditionally divided from top to bottom into a Western, Central and Eastern Belt (Zwart, 1974; Williams and Zwart 1977). However towards the south (Northern Jämtland) the Western Belt is absent. Here Van Roermund (1985; 1989) and Van Roermund & Bakker (1984) recognised eclogite bearing tectonic lenses in the two remaining Belts: the Ertsekey Lens in the Central Belt and the Tjeliken Lens in the Eastern Belt. The Tjeliken eclogites are largely metamorphosed dikes and intrusives associated with unmigmatized quartzofeldspathic gneiss with minor intercalations of garnet-mica schist, amphibolite, marble and garnet peridotite.

The Ertsekey eclogites are associated with migmatitic kyanite/sillimanite potash-feldspar gneiss. Minor intercalations of quartzite, garnet-mica schist, amphibolite, marble and (garnet) peridotite occur. In addition the primary mineral assemblage of the eclogites is (Van Roermund 1985):

- Central Belt: omphacite + garnet + quartz + rutile + zircon + apatite + zoisite;
- Eastern Belt: omphacite + garnet + quartz + rutile + zircon + apatite + phengite.

The following PT conditions for eclogite formation were determined by Van Roermund (1985):

- Central Belt eclogites $P \geq 18,0 \pm 1,0$ kb and $T = 780 \pm 50$ °C;
- Eastern Belt eclogites $P \geq 14,0 \pm 1,5$ kb and $T = 550 \pm 70$ °C, but these PT conditions were recently updated to $T = 650 \pm 50$ °C and $P \geq 16,5 \pm 1$ kb (Litjens, 2002)

The age, determined by Sm-Nd techniques, of (U)HPM in the Central and Eastern Belt is 455 Ma (Brueckner & Van Roermund, 2004; 2006) suggesting both Nappes were subducted/educted simultaneously.

The eclogite bearing terranes in Norrbotten, North Sweden

The Seve Nappe Complex can be followed in northern direction (Fig. 3) from Northern Jämtland through Västerbotten to Norrbotten (Stephens & Van Roermund, 1984). In Norrbotten two eclogite bearing terranes were recognised: in the north the Råvvejaure area, in the south the Grapesvare area. In the Råvvejaure area the Seve Nappe is subdivided into two lenses, Sarek Lens and Tsäkkok Lens (Kullerud, Stephens and Zachrisson, 1990). The Tsäkkok Lens contains eclogites. In the Grapesvare area (Andreasson, Gee and Sukotji, 1985; Albrecht, 2000) the Seve Nappe is subdivided into three nappes, Lower Seve Nappe, Grapesvare Nappe and Maddäive Nappe (the three together were formerly called Vaimok Lens). Eclogites occur only in the Grapesvare- and Maddäive Nappe. In the Råvvejaure and Grapesvare area the lenses/nappes are correlated with the thinned margin of Baltica and the rift-related sediments deposited on this margin (Albrecht, 2000).

The primary mineral assemblage of the Vaimok eclogites is garnet, omphacite, rutile, quartz \pm phengite (Santalier 1988), the Tsäkkok eclogites contain zoisite in addition (Mørk, Kullerud and Stabel, 1988). Estimated PT conditions for eclogites in the Tsäkkok Lens are: $P \geq 14,9 \pm 1,5$ kb and $T = 610 \pm 90$ °C (Stephens and Van Roermund, 1984). For the Vaimok eclogites: $P \geq 19 \pm 1$ kb and $T = 700 \pm 50$ °C (Santalier, 1988; Mørk, Kullerud and Stabel, 1988).

The age determined by the Sm-Nd method is 505 ± 18 Ma. This suggests that the two nappes subducted at the same time (Mørk, Kullerud and Stabel, 1988). The age is corroborated by U-Pb ages from titanites in associated rocks (Essex, Gromet, Andreasson and Albrecht, 1997).

Results

A polished thin section and a scanned image were made of the erratic (retro) eclogite block (Fig. 4). Also indicated in Fig. 4 are the areas that were investigated by EMP analyses. The



Fig. 4. Scanned micrograph of polished thin section from the studied erratic (retro) eclogite block. Outlines refer to investigated areas studied with EMP.

mineralogy of the Haren (retro) eclogite boulder consists of garnet-diopsidic clinopyroxene-orthopyroxene-amphibole-plagioclase-quartz-epidote group minerals-opaque.

The Haren eclogite is heavily retrogressed (Fig. 1 and 4) and basically the rock should not be called an eclogite but a retro-eclogite. This is clearly illustrated by:

1. the kelyphitic rims around garnet (Fig. 1 and 5a) that consist of intergrowths between calcic amphibole (magnesian-hastingsite) and plagioclase. The composition of plagioclase varies from bytownite close to the garnet, to labradorite in the middle, to andesine at the contact with the matrix. In addition, along the outer rim opaques are present (Fig. 8b);
2. the omphacitic matrix of the Haren (retro) eclogite is fully transformed into a symplectitic intergrowth of clinopyroxene-plagioclase (Fig. 6b).

No primary omphacite crystals were found in the matrix. Omphacite occurs only as isolated but subordinate inclusions in garnet (Fig. 6a). Isolated quartz grains in symplectite are always surrounded by clinopyroxene coronas. There are also quartz grains found as inclusions in garnet that are surrounded by orthopyroxene-plagioclase coronas that are later partly replaced by amphibole (mostly magnesian-hornblende) and plagioclase (andesine, Fig.7).

Representative EPM mineral analyses of garnet, pyroxene, amphibole and plagioclase are given in Tables 1 - 5, compositional end-member diagrams of garnet, clinopyroxene, amphibole and plagioclase are given in Fig. 5b, Fig. 6c, Fig. 8c - e and Fig. 9b.

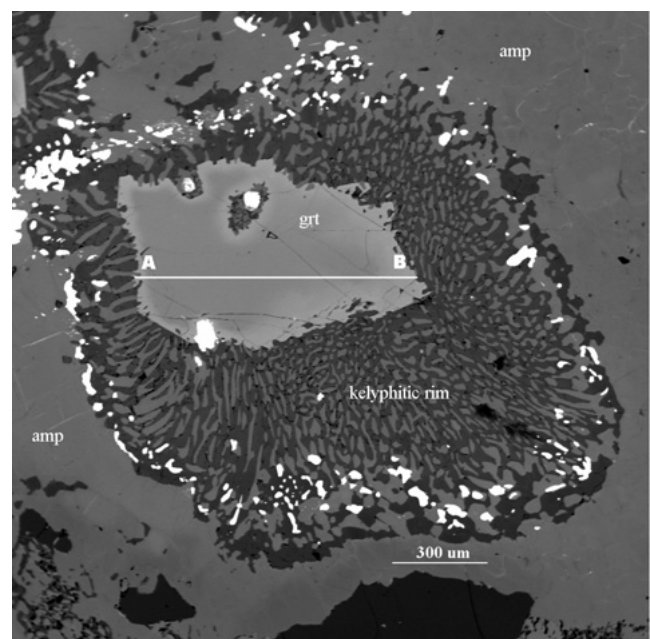


Fig. 5a. Backscattered electron micrograph illustrating a kelyphitic rim around garnet, embedded in symplectitic matrix; dark = plagioclase, white = opaque and grey = amphibole. Location: square 1 in Fig. 4.

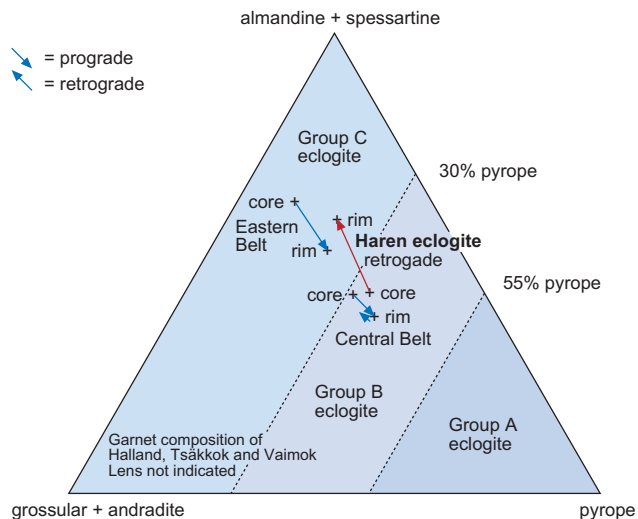


Fig. 5b. Triangular end-member diagram of garnet compositions (analysis number 2y11, Fig. 5a). The change in garnet composition from core to rim is indicated by an arrow. Also indicated is the position of the Haren eclogitic garnet composition (red arrow) with respect to garnet composition from the eclogites of Eastern Belt and Central Belt (blue arrows). Location: square 1 in Fig. 4.

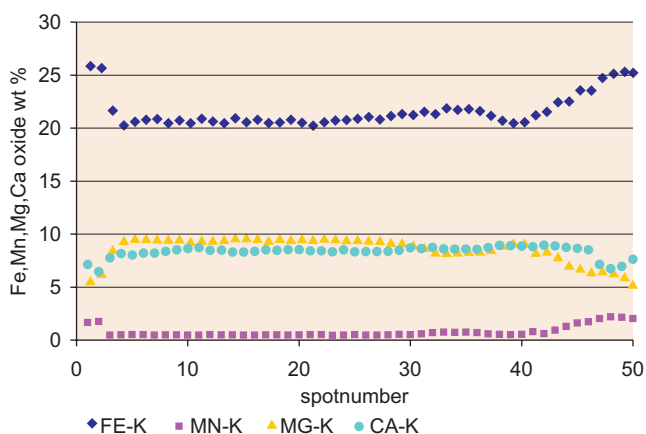


Fig. 5c. Microprobe step scan profile across garnet (analysis number 2y11). The trace A-B is indicated in Fig. 5a. Fe and Mn increase near the rim and Mg and Ca decrease.

Garnet

Representative EMP garnet analyses, a triangular end-member diagram and an EMP step scan profile across garnet (analysis number 2y11) are given in Table 1, Fig. 5b and Fig. 5c. Coleman, Lee, Beatty and Brannock (1965) divided the composition of eclogitic garnets into three groups. Group A: inclusions in kimberlites, basalts, or layers in ultramafic rocks; group B: bands or lenses within migmatitic gneiss terranes and group C: bands or lenses within alpine-type metamorphic rocks. These groups are indicated in Fig. 5b. Also indicated in Fig. 5b is the garnet mineral chemistry of the Haren (retro) eclogite and for comparative reasons garnets from the Eastern and the Central Belt of the Seve Nappe Complex in Northern Jämtland.

Table 1. Representative EMP analyses and calculated structural formulae from rim and core of garnet analysis number 2y11, based on 12 oxygen. Fe^{3+} is calculated following Schumacher (1997). Location: square 1 in Fig. 4.

Analysis number 2y11	Rim, spot-number 1	Core, spot-number 25	Rim, spot-number 50
SiO ₂	38.529	39.332	38.248
TiO ₂	0.020	0.042	0.002
Al ₂ O ₃	21.414	21.747	21.261
Cr ₂ O ₃	0.000	0.039	0.000
FeO	25.566	20.614	25.119
MnO	1.664	0.515	2.036
MgO	5.406	9.303	5.216
CaO	7.124	8.323	7.631
Na ₂ O	0.000	0.017	0.007
Total	99.724	99.933	99.520

Element	No. of cations	No. of cations	No. of cations
Si	3.0315	2.9929	3.0043
Ti	0.0012	0.0024	0.0001
Al	1.9740	1.9504	1.9682
Cr	0.0000	0.0024	0.0000
Fe	1.6722	1.3118	1.6500
Mn	0.1102	0.0332	0.1355
Mg	0.6303	1.0553	0.6108
Ca	0.5970	0.6786	0.6422
Na	0.0000	0.0025	0.0011
Total	7.9984	8.0295	8.0120
Fe ³⁺	0.0000	0.0880	0.036
Fe ²⁺	1.6722	1.2180	1.611

The step scan profile (Fig. 5c) reveals that the Haren eclogitic garnet is chemically zoned. This is also clearly visible in Fig. 5a showing a change in grey-shading of the garnet towards the edge of the grain. Garnet cores are relatively homogeneous in composition with contents of around 42% almandine, 35% pyrope and 23% grossular. Towards the garnet rim Fe and Mn increase while Mg and Ca decrease, resulting in approx. 58% almandine, 21% pyrope and 21% grossular. This mineral-chemical change in garnet composition is indicated by an arrow in the triangular end-member diagram of Fig. 5b and interpreted to be due to decompression postdating eclogite formation.

Clinopyroxene

Representative EMP clinopyroxene analyses and a triangular end-member diagram are given in Table 2 and Fig. 6c. Two types of clinopyroxenes were recognised. The first one occurs as inclusions in garnet (Fig. 6a), its composition corresponds to that of omphacite containing a jadeite component of 32.6 - 33.1% (Fig. 6c). The second type is found in polycrystalline

Table 2. Representative EMP analyses and calculated structural formulae of clinopyroxene type 1 included in garnet, location: square 2 in Fig. 4; type 2 within pyroxene-plagioclase symplectite (or in polycrystalline coronas around quartz grains), location: square 8 in Fig. 4. All analyses based on 6 oxygen, Fe³⁺ is calculated following Schumacher (1997).

Analysis number	Inclusion in grt		In symplectite intermediary			In symplectite coarse		In symplectite fine	
	2y12a	2y12d	2y16-1g	2y16-1i	2y16-1m	2y16-1s	2y16-1u	2y16-3a	2y16-3i
SiO ₂	52.797	52.852	52.464	52.567	50.953	52.337	52.975	53.334	53.900
TiO ₂	0.106	0.401	0.427	0.183	0.747	0.282	0.098	0.082	0.129
Al ₂ O ₃	8.604	8.687	2.801	1.939	3.835	2.395	1.935	1.493	1.644
Cr ₂ O ₃	0.106	0.216	0.059	0.209	0.137	0.032	0.153	0.069	0.157
FeO	7.231	7.284	8.237	7.891	8.517	7.957	7.967	7.620	7.354
MnO	0.000	0.048	0.257	0.326	0.155	0.172	0.227	0.076	0.214
MgO	9.357	9.198	12.519	13.220	12.028	13.030	13.358	13.621	13.887
CaO	16.456	16.033	22.574	22.863	22.488	22.828	22.689	22.966	22.977
Na ₂ O	4.392	4.373	0.895	0.928	1.074	0.918	0.834	0.800	0.743
K ₂ O	0.006	0.000	0.052	0.017	0.063	0.034	0.000	0.016	0.072
Total	99.055	99.091	100.29	100.14	99.998	99.986	100.24	100.08	101.08

Element	No. of cations								
Si	1.9437	1.9433	1.9472	1.9581	1.9053	1.9509	1.9645	1.9796	1.9779
Ti	0.0029	0.0111	0.0119	0.0051	0.0210	0.0079	0.0027	0.0023	0.0036
Al	0.3733	0.3764	0.1225	0.0851	0.1690	0.1052	0.0846	0.0653	0.0711
Cr	0.0031	0.0063	0.0017	0.0062	0.0041	0.0009	0.0045	0.0020	0.0046
Fe	0.2226	0.2240	0.2557	0.2458	0.2664	0.2481	0.2471	0.2365	0.2257
Mn	0.0000	0.0015	0.0081	0.0103	0.0049	0.0054	0.0071	0.0024	0.0066
Mg	0.5135	0.5042	0.6927	0.7341	0.6705	0.7241	0.7385	0.7537	0.7597
Ca	0.6491	0.6316	0.8977	0.9125	0.9010	0.9117	0.9015	0.9133	0.9034
Na	0.3135	0.3118	0.0644	0.0670	0.0779	0.0663	0.0599	0.0576	0.0528
K	0.0003	0.0000	0.0025	0.0008	0.0030	0.0016	0.0000	0.0008	0.0034
Total	4.0220	4.0101	4.0044	4.0250	4.0231	4.0221	4.0104	4.0136	4.0088

Fe ³⁺	0.061	0.030	0.028	0.074	0.077	0.064	0.046	0.040	0.027
Fe ²⁺	0.160	0.193	0.228	0.170	0.187	0.182	0.200	0.196	0.198
Jd	32.6%	33.1%	6.7%	4.4%	7.6%	5.7%	5.1%	4.6%	5.1%
Di	53.3%	53.4%	72.0%	74.9%	68.7%	74.0%	76.8%	77.6%	79.4%
Hd	14.1%	13.5%	21.3%	18.2%	23.6%	19.2%	17.0%	16.4%	15.0%
Ae	0.0%	0.0%	0.0%	2.5%	0.1%	1.1%	1.1%	1.4%	0.5%

coronas around larger quartz grains embedded in symplectite or in pyroxene-plagioclase symplectites (Fig. 6b). It corresponds to a diopsidic clinopyroxene (sodic augite), see Fig. 6c, containing a jadeite component ≤ 8 .

Orthopyroxene

Orthopyroxene was found together with plagioclase as coronas around quartz grains (Fig. 7). Representative EMP orthopyroxene analyses are given in Table 3. Orthopyroxene contains 63.0 - 64.3% enstatite and 35.7 - 37.0% ferro-silite components (Table 3).

Amphibole

Representative EMP amphibole analyses are given in Table 4; amphibole classification diagrams (Leake et al. 1997) are presented in Fig. 8c, 8d and 8e.

Four types of amphiboles were recognised:

- **Type 1** occurs as inclusion in garnet (Fig. 6a and 8a). Different compositions of calcic amphiboles (Fig. 6a) were analysed that correspond to magnesio-hastingsite, analysis number 2y12f (Fig. 8e) and magnesio-hornblende, analysis number 2y12b (Fig. 8d). The optical colour of the amphibole is green or greyish green. Another amphibole included in

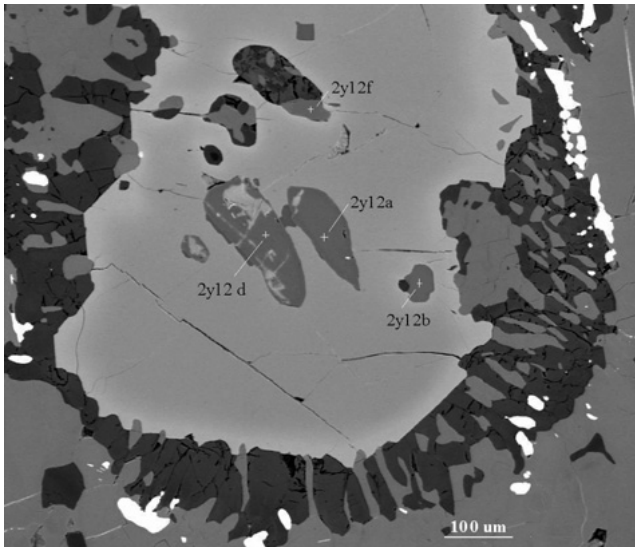


Fig. 6a. Backscattered electron micrograph illustrating type 1 clinopyroxene inclusions in garnet (analyses numbers 2y12a and 2y12d). Analyses numbers 2y12b and 2y12f are amphiboles (type 1). Location: square 2 in Fig. 4.

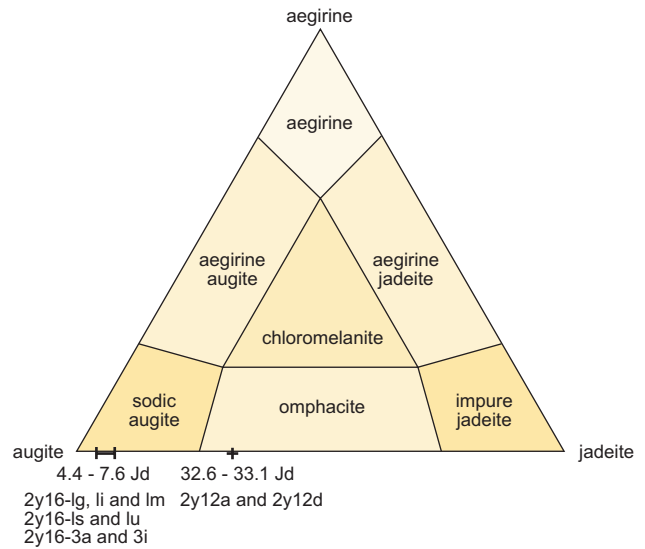
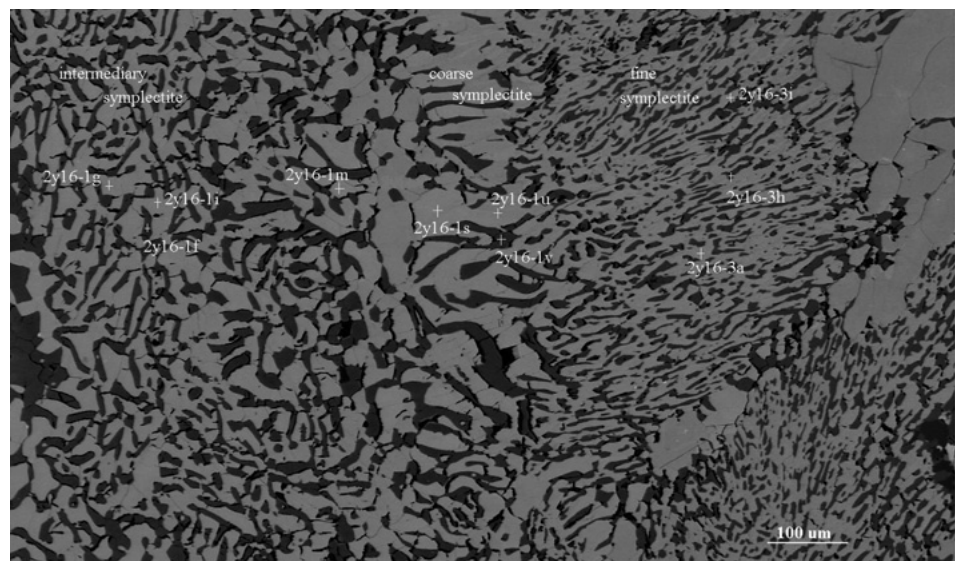


Fig. 6c. Triangular end-member diagram with clinopyroxene compositions. Type 1 (analyses numbers 2y12a and 2y12d) occurs as inclusions in garnet, location: square 2 in Fig. 4; type 2 (analyses numbers 2y16-1g, 1i, 1m, 1s, 1u, 3a and 3i) within pyroxene-plagioclase symplectite. Location: square 8 in Fig. 4.

Fig. 6b. Backscattered electron micrograph showing clinopyroxene (type 2) and plagioclase (type 2) within pyroxene-plagioclase symplectite after omphacite. Analyses numbers 2y16-1f, 1g, 1i, and 1m from intermediary symplectitic area; analyses numbers 2y16-1s, 1u and 1v from coarse symplectitic area; analyses numbers 2y16-3a, 3h and 3i from fine symplectitic area. Location: square 8 in Fig. 4.



garnet is illustrated in Fig. 8a. From this figure it can be seen that the light grey primary amphibole inclusions are surrounded by secondary amphibole-plagioclase coronas that were formed during the retrograde amphibolite facies metamorphic overprint. At the core of this amphibole it is a Mg-Fe-Mn-Li amphibole corresponding to cummingtonite, analysis number 2y13c1 (Fig. 8c), between the core and the rim it is a calcic amphibole: magnesio-hornblende, analysis number 2y13c3 (Fig. 8d). At the rim it is also a calcic amphibole: edenite, analysis number 2y13c4 (Fig. 8e). The optical colour varies from a very pale green core via a green centre to a bluish green rim.

- **Type 2** amphibole is present as matrix grains. The optical colour is brownish green. It is a calcic amphibole correspon-

ding to edenite. Adjacent to matrix quartz crystals, the silica content of the amphibole increases but its composition remains that of edenite.

- **Type 3** amphibole is present within kelyphitic rims around garnet (together with plagioclase, Fig. 8b) but forms also part of the diopside-plagioclase symplectite after omphacite. Its optical colour is bluish green. It may form a rim around type 1 amphiboles and is therefore considered to be younger. Type 3 amphibole is calcic amphibole with different compositions: magnesio-hastingsite, analyses numbers 2y13e5 and 2y13e6 (Fig. 8e) and edenite, analysis number 2y13e8 (Fig. 8e).
- **Type 4** amphibole is present as a rim of amphiboles around a big isolated plagioclase aggregate (Fig. 9a). The optical

Table 3. Representative EMP analyses and calculated structural formulae of orthopyroxene around quartz included in garnet, based on 6 oxygen. Fe³⁺ is calculated in accordance with Schumacher (1997). Calculated is also the percentage enstatite and ferro-silite in orthopyroxene. Location: square 7 in Fig. 4.

Analysis number	T8-16a1na	T8-16a1nb	T8-16a1nc1
SiO ₂	53.126	53.556	53.349
TiO ₂	0.149	0.008	0.000
Al ₂ O ₃	0.881	0.954	0.901
Cr ₂ O ₃	0.076	0.000	0.056
FeO	23.302	23.126	23.651
MnO	0.469	0.436	0.595
MgO	22.202	22.061	21.793
CaO	0.399	0.342	0.319
Na ₂ O	0.344	0.242	0.411
K ₂ O	0.000	0.044	0.000
Total	100.95	100.70	101.08

Element	No. of cations	No. of cations	No. of cations
Si	1.9692	1.9831	1.9775
Ti	0.0041	0.0002	0.0000
Al	0.0385	0.0416	0.0394
Cr	0.0022	0.0000	0.0016
Fe	0.7223	0.7161	0.7331
Mn	0.0147	0.0137	0.0187
Mg	1.2269	1.2178	1.2042
Ca	0.0159	0.0136	0.0127
Na	0.0247	0.0173	0.0295
K	0.0000	0.0021	0.0000
Total	4.0186	4.0055	4.0168
Fe ³⁺	0.055	0.015	0.049
Fe ²⁺	0.664	0.700	0.681
% enstatite	64.3	63.0	63.1
% ferrosilite	35.7	37.0	36.91

colour is pale bluish green. It is a calcic amphibole corresponding to actinolite, analyses numbers 2y17-11a5 and 2y17-12a1 (Fig. 8d).

Plagioclase

Representative EMP plagioclase analyses and a compositional plot are given in Table 5 and Fig. 9b. Three plagioclase-types were recognised.

- **Type 1** occurs within the kelyphitic rim around garnet (together with amphibole, Fig. 8b). The Ca-content of this plagioclase increases towards garnet. Close to garnet it is bytownite, analysis number 2y13e4 (Fig. 9b); halfway the kelyphite the Na-content increases and the plagioclase

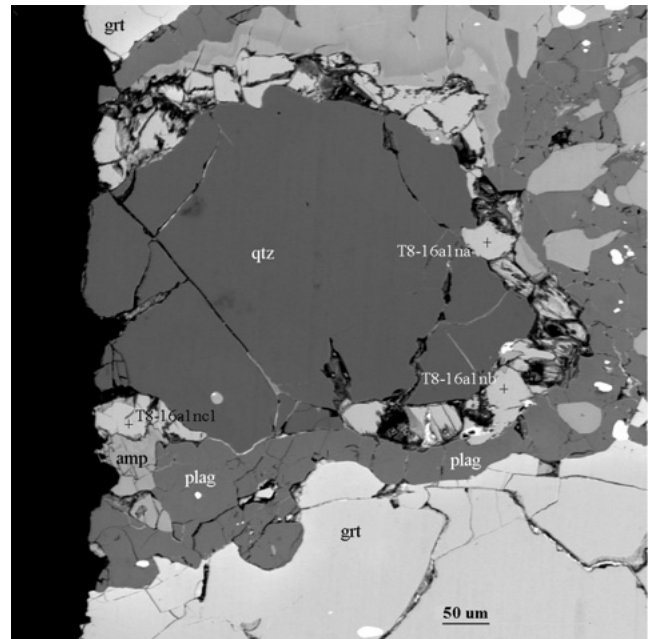


Fig. 7. Backscattered electron micrograph of orthopyroxene-plagioclase corona around a quartz grain included in garnet. Analyses numbers T8-16a1na, T8-16a1nb and T8-16a1nc1, location: square 7 in Fig. 4.

- becomes labradorite, analysis number 2y13e2 (Fig. 9b); at the rim of the kelyphite the plagioclase is an andesine, analysis number 2y13e1 (Fig. 9b).
- **Type 2** plagioclase occurs in the symplectite after omphacite (Fig. 6b). It is an andesine, analyses numbers 2y16-1f, -1v and -3h (Fig. 9b).
- **Type 3** plagioclase is found within isolated aggregates spread throughout the symplectite matrix (Fig. 9a). In the core of the aggregate the plagioclase is bytownite, analyses numbers 2y17-11a2, -13a2 and -13a4 (Fig. 9b); at the rim the plagioclase is andesine, analyses numbers 2y17-11a3, -11a4 and -13a5 (Fig. 9b). The primary HP origin of the aggregate is unknown (but might be zoisite).

Calculated metamorphic conditions

The estimated (minimum pressure) metamorphic conditions for the formation of the erratic (retro) eclogite block is $P \geq 16,2 \pm 1$ kb and $T = 756 \pm 50$ °C. These PT conditions are calculated in the following way (Fig. 10):

1. the $Jd = 33,1$ % isopleth of omphacite is used as a (minimum) pressure indicator (Gasparik and Lindsley 1980). This isopleth line is intersected with
2. the line defined by the results of the two pyroxene thermometer of Brey and Köhler (1990, T_{BK} in Fig. 10) calculated for 10 kb (742 °C) and 18 kb ($T = 759$ °C). The EMP mineral-chemical data, used to calculate T_{BK} , was obtained from lower pressure mineral assemblages but could safely be extrapolated to HP conditions as all Scandinavian eclogites reveal nearly isothermal decompression paths.

Table 4. Representative EMP analyses and calculated structural formulae of amphiboles. Type 1, location: square 2 and 3 in Fig. 4; type 3, location: 3 in Fig. 4 and type 4 location: 9 in Fig. 4. All analyses based on 23 oxygen.

Type	1	1	1	1	1	3	3	3	4	4
Analysis number	2y12b	2y12f	2y13c1	2y13c3	2y13c4	2y13e5	2y13e6	2y13e8	2y17-11a5	2y17-12a1
SiO ₂	51.042	43.200	54.457	52.514	45.224	43.503	42.290	47.113	52.724	53.315
TiO ₂	0.270	0.785	0.000	0.000	0.317	0.187	0.471	0.543	0.000	0.000
Al ₂ O ₃	5.903	14.265	0.286	5.309	11.846	14.088	14.946	17.896	4.312	4.095
Cr ₂ O ₃	0.031	0.000	0.000	0.000	0.000	0.000	0.154	0.226	0.000	0.212
FeO	11.764	11.922	20.000	10.431	12.553	12.802	14.240	10.317	11.452	10.885
MnO	0.054	0.000	0.240	0.163	0.000	0.163	0.008	0.182	0.185	0.283
MgO	16.952	12.380	20.825	17.474	13.110	11.838	11.055	7.446	16.725	16.707
CaO	9.900	11.884	0.844	11.256	11.027	11.845	11.611	10.773	11.493	11.509
Na ₂ O	1.129	2.242	0.373	1.106	2.118	2.337	2.291	3.432	0.915	0.818
K ₂ O	0.046	0.187	0.000	0.000	0.085	0.276	0.137	0.268	0.166	0.060
Total	97.091	96.866	97.025	98.253	96.310	97.039	97.203	98.196	97.973	97.884

Element	No. of cations									
Si	7.344	6.3590	7.8943	7.4347	6.6721	6.4214	6.2737	6.6942	7.5280	7.5857
Ti	0.029	0.0869	0.0000	0.0000	0.0351	0.0207	0.0526	0.0580	0.0000	0.0000
Al	1.001	2.4747	0.0488	0.8859	2.0599	2.4509	2.6132	2.9969	0.7256	0.6866
Cr	0.004	0.0000	0.0000	0.0000	0.0000	0.0000	0.0181	0.0253	0.0000	0.0239
Fe	1.416	1.4677	2.4247	1.2350	1.5488	1.5803	1.7666	1.2259	1.3674	1.2952
Mn	0.007	0.0000	0.0295	0.0195	0.0000	0.0204	0.0010	0.0218	0.0224	0.0341
Mg	3.635	2.7167	4.5004	3.6879	2.8834	2.6049	2.4449	1.5773	3.5601	3.5437
Ca	1.526	1.8743	0.1311	1.7074	1.7431	1.8733	1.8455	1.6401	1.7582	1.7545
Na	0.315	0.6398	0.1047	0.3035	0.6057	0.6688	0.6589	0.9454	0.2534	0.2256
K	0.008	0.0350	0.0000	0.0000	0.0160	0.0520	0.0259	0.0486	0.0303	0.0108
Total	15.286	15.654	15.134	15.274	15.564	15.694	15.700	15.234	15.245	15.160

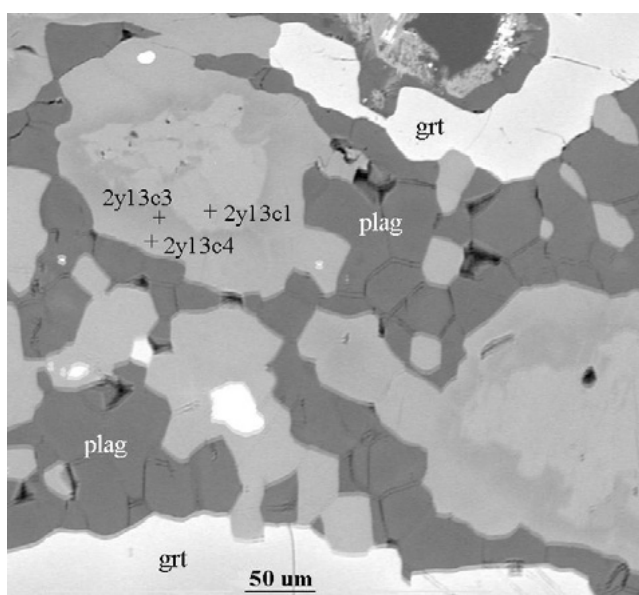


Fig. 8a. Backscattered electron micrograph of type 1 calcic amphibole included in garnet, the amphibole is zoned (light and dark grey) corresponding to cummingtonite (analysis number 2y13c1), magnesiohornblende (analysis number 2y13c3) and edenite (analysis number 2y13c4). Location: square 3 in Fig. 4.

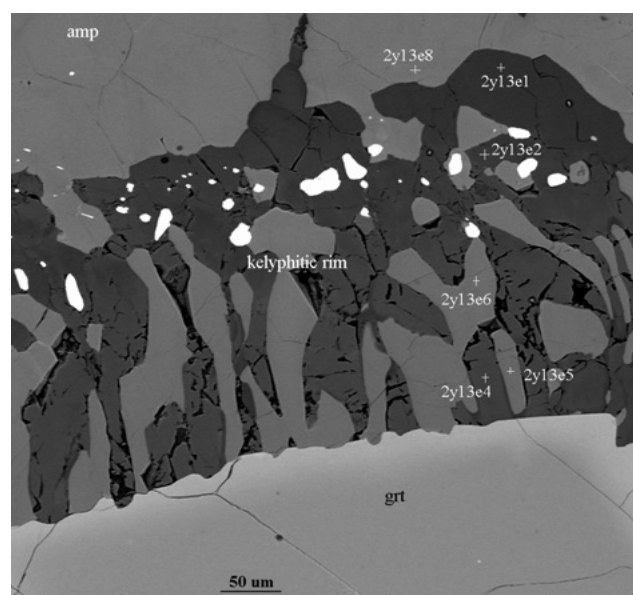


Fig. 8b. Backscattered electron micrograph of type 3 calcic amphibole in a kelyphitic rim around garnet, corresponding to magnesiohastingsite (analyses numbers 2y13e5, e6) and edenite (analysis number 2y13e8). Also you can see type 1 plagioclase analysis number 2y13e1 (andesine), analysis number 2y13e2 (labradorite) and 2y13e4 (bytownite). Location: square 3 in Fig. 4.

Mg- Fe- Mn- Li amphiboles

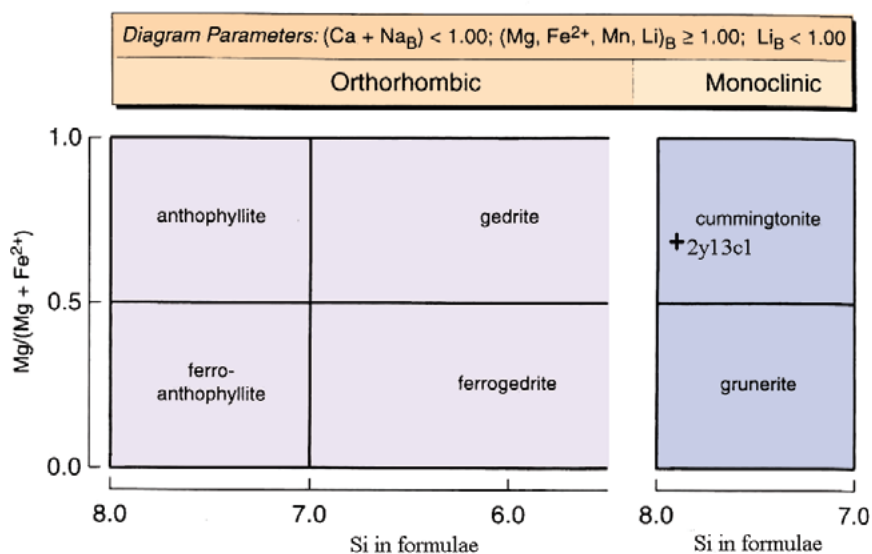


Fig. 8c. Classification diagram Mg-Fe-Mn-Li amphiboles (Leake et al., 1997). Analysis number 2y13c1 is a calcic amphibole included in garnet.

Calcic amphiboles

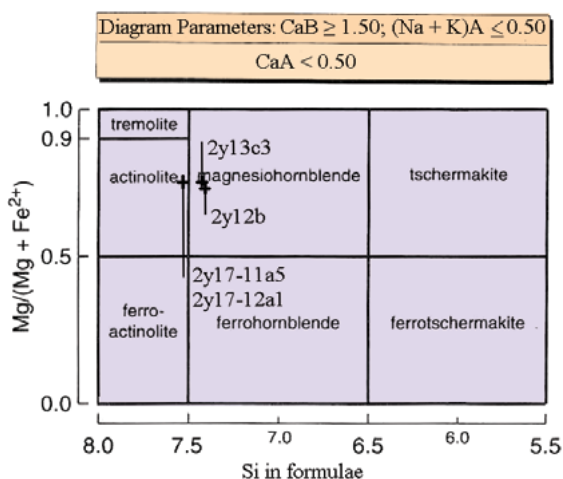


Fig. 8d. Classification diagram of calcic amphiboles $(Na + K)_A \leq 0,50$ (Leake et al., 1997). Analysis number 2y13c3 is a zoned calcic amphibole included in garnet, 2y12b is a calcic amphibole also included in garnet and 2y17-11a5 and 12a1 are calcic amphiboles around an isolated plagioclase aggregate.

Calcic amphiboles

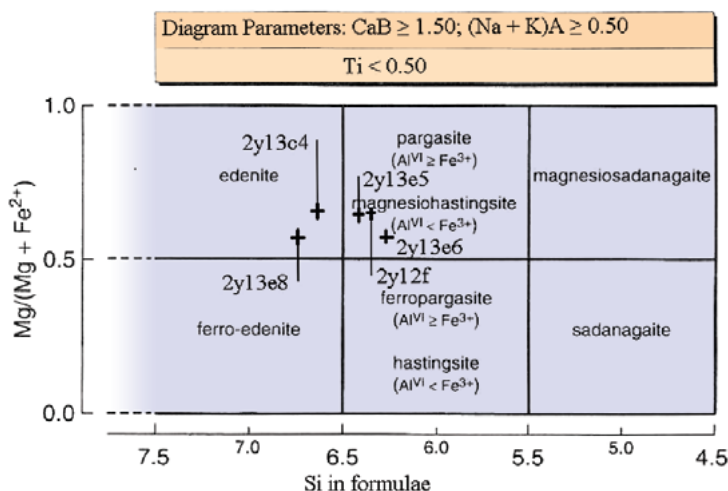


Fig. 8e. Classification diagram of calcic amphiboles $(Na + K)_A \geq 0,50$ (Leake et al., 1997). Analyses numbers 2y13e5, e6 and e8 are calcic amphiboles from kelyphitic rim around garnet, analysis number 2y13c4 is a zoned calcic amphibole included in garnet and 2y12f is also a calcic amphibole included in garnet.

This extrapolation method was preferred above the classical thermometers of Råheim and Green (1975), Ellis and Green (1979) and Krogh (1988) which gave unrealistically high temperatures ($T = 1062 \text{ }^\circ\text{C}$ at $P \geq 20.1 \text{ kb}$). We interpreted the latter as being due to Fe-Mg exchange in omphacite during decompression.

Discussion and conclusion

The calculated PT conditions, the percentage pyrope in garnet and the percentage jadeite in omphacite in the Haren erratic block were compared with those reported in the literature for the three (U)HPM terranes in Sweden (Table 6).

In addition the primary mineral assemblage of the eclogites is:

- Northern Jämtland, Central Belt: omphacite + garnet + quartz + rutile + zircon + apatite + zoisite (Van Roermund 1985).
- Northern Jämtland, Eastern Belt: omphacite+ garnet+ quartz+ rutile+ zircon+ apatite+ phengite (Van Roermund 1985).
- Norrbotten, Vaimok Lens: garnet + omphacite + rutile + quartz ± phengite (Santallier 1988).
- Norrbotten, Tsäckok Lens: garnet + omphacite + quartz + rutile + phengite + zoisite (Mørk, Kullerud and Stabel, 1988).
- Halland, the eclogite is kyanite bearing and contains sapphirine-plagioclase assemblage in a corona around kyanite, no phengite (Möller 1998, 1999).

Table 5. Representative EMP analyses and calculated structural formulae of plagioclase type 1 in a kelyphitic rim around garnet, location: square 3 in Fig.4; type 2 in a pyroxene-plagioclase symplectite, location: square 8 in Fig.4 and type 3 in a big isolated plagioclase aggregate, location: square 9 in Fig. 4. All analyses based on 8 oxygen.

Type	1	1	1	2	2	2	3	3	3	3	3	3
Analysis number	2y13e1	2y13e2	2y13e4	2y16-1f	2y16-1v	2y16-3h	2y17-11a2	2y17-11a3	2y17-11a4	2y17-13a2	2y17-13a4	2y17-13a5
SiO ₂	55.926	51.262	47.505	59.975	59.866	59.300	49.189	56.112	57.700	48.231	47.464	58.371
TiO ₂	0.072	0.000	0.104	0.000	0.043	0.089	0.036	0.000	0.005	0.000	0.133	0.006
Al ₂ O ₃	28.122	30.211	32.639	26.177	26.085	25.792	33.160	28.651	27.786	33.566	33.779	27.106
Cr ₂ O ₃	0.003	0.085	0.262	0.000	0.058	0.053	0.124	0.041	0.000	0.000	0.000	0.000
FeO	0.194	0.429	0.589	0.363	0.288	0.245	0.240	0.127	0.466	0.280	0.315	0.098
MnO	0.053	0.191	0.119	0.000	0.000	0.000	0.056	0.000	0.065	0.034	0.063	0.000
MgO	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CaO	9.381	12.734	15.983	7.365	7.480	7.962	15.225	10.355	8.903	16.353	16.953	8.484
Na ₂ O	6.489	4.380	2.785	7.718	7.829	7.508	2.854	5.974	6.624	2.378	2.046	7.230
K ₂ O	0.000	0.009	0.000	0.034	0.016	0.000	0.050	0.102	0.074	0.001	0.000	0.072
Total	100.24	99.30	99.99	101.63	101.67	100.95	100.93	101.36	101.63	100.84	100.75	101.37

Element	No. of cations											
Si	2.5103	2.3508	2.1892	2.6373	2.6338	2.6296	2.2288	2.4941	2.5493	2.1936	2.1638	2.5814
Ti	0.0024	0.0000	0.0036	0.0000	0.0014	0.0030	0.0012	0.0000	0.0002	0.0000	0.0046	0.0002
Al	1.4877	1.6328	1.7727	1.3566	1.33526	1.3479	1.7708	1.5009	1.4469	1.7993	1.8149	1.4128
Cr	0.0001	0.0031	0.0096	0.0000	0.0020	0.0019	0.0044	0.0014	0.0000	0.0000	0.0000	0.0000
Fe	0.0073	0.0165	0.0227	0.0133	0.0106	0.0091	0.0091	0.0047	0.0172	0.0107	0.0120	0.0036
Mn	0.0020	0.0074	0.0046	0.0000	0.0000	0.0000	0.0021	0.0000	0.0024	0.0013	0.0024	0.0000
Mg	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ca	0.4511	0.6257	0.7892	0.3470	0.3526	0.3783	0.7391	0.4931	0.4214	0.7969	0.8281	0.4020
Na	0.5647	0.3894	0.2488	0.6581	0.6678	0.6455	0.2507	0.5149	0.5674	0.2097	0.1808	0.6199
K	0.0000	0.0005	0.0000	0.0019	0.0009	0.0000	0.0029	0.0058	0.0042	0.0001	0.0000	0.0041
Total	5.0257	5.0262	5.0404	5.0143	5.0218	5.0153	5.0092	5.0150	5.0091	5.0116	5.0066	5.0240

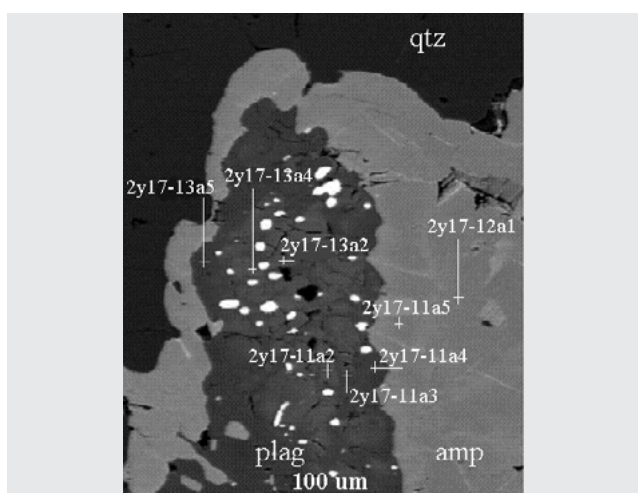


Fig. 9a. Backscattered electron micrograph illustrating a big isolated plagioclase aggregate with a rim of amphiboles. Analyses numbers 2y17-11a5 and 12a1 are actinolites (Fig. 8d). The plagioclase aggregate in the core is a bytownite (analyses numbers 2y17-11a2, 13a2 and 13a4, Fig. 9b) and in the rim an andesine (analyses numbers 2y17-11a3, 11a4 and 13a5, Fig. 9b). Location: square 9 in Fig. 4.

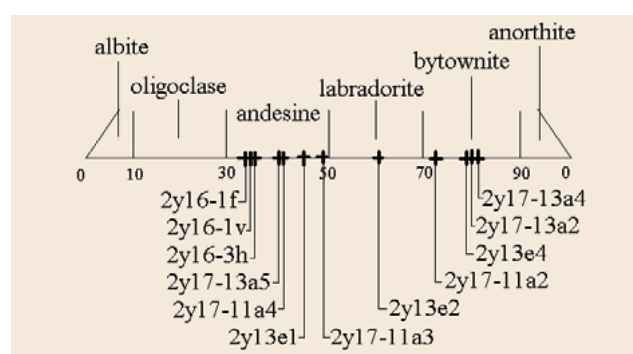


Fig. 9b. Compositional plot of analysed plagioclases. Analyses numbers 2y16-1f, 1v and 3h from a pyroxene-plagioclase symplectite (Fig.6b); 2y17-13a5, 11a4, 11a3, 11a2, 13a2 and 13a4 (Fig. 9a) are from the big isolated plagioclase aggregate; 2y13e1, e2 and e4 (Fig. 8b) are from a kelyphitic rim around garnet.

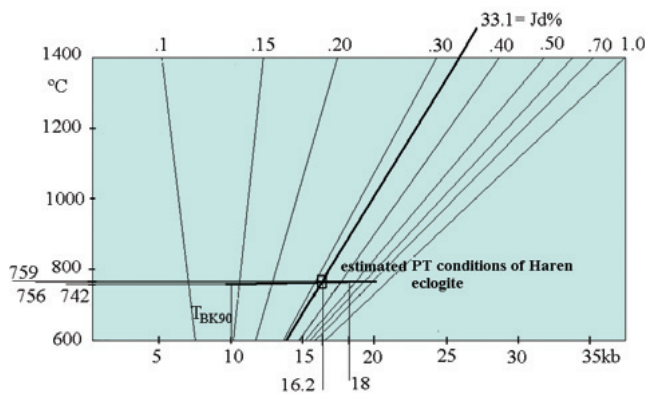


Fig. 10. PT diagram showing the estimated PT conditions calculated using Jd = 33.1% isopleth of omphacite (analysis number 2y12d, Gasparik and Lindsley, 1980) intersected with the nearly isothermal results of the two pyroxene thermometer (T_{BK90}) of Brey and Köhler (1990) at 10 and 18 kb.

- The mineral assemblage of the erratic HP rock from Haren (Gr.) is omphacite + garnet + quartz + rutile + zircon + apatite + zoisite.

Based on the information given above we conclude that the (U)HPM terrane in Northern Jämtland, Sweden, more precisely the Ertsekey (U)HP tectonic lens of the Central Belt of the Seve Nappe Complex, represents the most likely origin of the erratic block found in Haren, Groningen, the Netherlands. This conclusion is fully consistent with results of other indicator pebble counts from the Haren area (Zandstra 1988), which indicates that most of the rocks, found in Haren, originate from the so called Eastern Baltic area.

Based on this study we predict that the age of the Haren erratic (retro) eclogite block will be 455 Ma.

Table 6. This table illustrates minimum pressure (P), temperature (T), percentage pyrope in garnet and percentage jadeite in omphacite from the Northern Jämtland, Norrbotten, Halland metamorphic terranes and the Haren (retro) eclogite.

Terrane	Min. pressure	Temperature	% Pyrope in garnet	% Jadeite in omphacite	Author
Northern Jämtland					
Central Belt	$P \geq 18.0 \pm 1\text{kb}$	$780 \pm 50^\circ \text{C}$	22-35	28-41	Van Roermund 1985
Eastern Belt	$P \geq 16.5 \pm 1\text{kb}$	$650 \pm 50^\circ \text{C}$	8-22	≈ 48	Van Roermund 1985, Litjens 2002
Norrbotten					
Vaimok Lens	$P \geq 19.0 \pm 1\text{kb}$	$700 \pm 50^\circ \text{C}$	18-32	36-46	Santallier 1988, Mørk et al. 1988
Tsäkkok Lens	$P \geq 14.9 \pm 1.5\text{kb}$	$610 \pm 90^\circ \text{C}$	up to 42	33-44	Stephens and Van Roermund 1984
Halland	$P \geq 10.8 \pm 1.2\text{kb}$	$750 \pm 45^\circ \text{C}$	not known	not known	Möller 1998
Haren	$P \geq 16.2 \pm 1\text{kb}$	$756 \pm 50^\circ \text{C}$	21-35	32.6 - 33.1	

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We like to thank Mr. G. Dijk from Groningen, the Netherlands, for allowing us to investigate the (retro) eclogite found in Haren (Gr.). Unfortunately, he could not see the completion of this study. Furthermore, J.L. likes to thank everyone who supported him during this study, more particular Dr. C. Maijer without whom I would never be able to 'read' a thin section; Prof. Dr. B. de Jong, University of Utrecht, the Netherlands for supporting the project financially and Mr. O. Stiekema, IVA, Utrecht, for learning him how to make thin sections.

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