An eclogite from the Caledonides of southern Norrbotten

ROBIN NICHOLSON

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The eclogite I describe here (N82100) comes from a small basic body enclosed within a marble of the Seve Nappe Complex of the Caledonides of southern Norrbotten. This contribution is written after reading in manuscript from the preceding paper in this journal by Stephens & Roermund (1984), who describe two specimens (BFM S82103 and BFM S82097) collected from some 3.5 Km NNW of N82100. I refer readers interested in details of the shared geological context of these samples to that account. The site from which N82100 was collected is in the lowest marble of the so-called Tsäkkok lens (Stephens & Roermund 1984, Fig. 1), and lies at the extreme right-hand end of that map where the marble is cut off by the map edge.

R. Nicholson, Department of Geology, University of Manchester, Manchester, M13 9PL United Kingdom.

Rock composition

N82100 has the composition of basalt (Table 1), the CIPW norm containing 1% of nepheline. None of the minerals of the probable basic igneous parent rock remain.

Review of petrography

N82100 consists mainly of poikiloblastic clinopyroxene crystals, up to 3 mm diameter and averaging about 43% jadeite. Poikiloblasts are separated from one another by zones rich in much smaller garnet crystals and more or less colourless amphiboles. The latter often have bright green rims and are set island-like in a semi-opaque fibrous green symplectite. Both the groundmass garnets, as well as the minority of garnets included in clinopyroxene crystals, have the same range of sizes and central clusters of inclusions. The pair garnet clinopyroxene obviously is directly comparable with the M2a assemblage of Stephens & Roermund (1984). Pyrope contents in the garnets they describe have a distinctly higher maximum value, however, reaching 42% pyrope rather than the 27% of N82100.

The phases included in garnet are sodic-calcic amphibole + paragonite + epidote + quartz, a list of minerals matching the M1 assemblage of Stephens & Roermund (1984). Calcic amphibole also occurs in reaction rims around garnets as well as in the symplectitic fringes to the deeply corroded clinopyroxene crystals, apparently as in specimen BFM S82103. Albite is known in N82100, as in the former rock, only in these reaction rims. Quartz is a minor but widespread constituent of the groundmass of N82100, as is a relatively Fe-poor epidote. The zoisite of BFM S82103 is classed as part of the eclogite assemblage but I interpret this epidote of N82100 as a by-product of the reaction producing barroisite (Fig. 5). Quartz occurs as clear, strain-free crystals in the groundmass; there are also inclusions in clinopyroxene and garnets, as mentioned above.

No preferred orientation of the clinopyroxene or barroisite has been observed.

Petrological interpretation and analytical results

1. *Pre-eclogite assemblages.* – The assemblage found in the garnets of N82100, and BFM S82103 and 097, has been reported from eclogites of varied ages around the world (e.g. Krogh 1980, Holland 1979). The critical assemblage paragonite + quartz + epidote requires pressures greater than about 8kb for its formation (Franz & Althaus 1976, Krogh 1980, p. 76). The pargasitic to taramitic amphibole I report from N82100 also seems to be typical of such pre-eclogite occurrences (Figs. 1 and 2). For example, it is found in the Pre-Alpine assemblages of the Sesia-Lanzo Zone that show least re-equilibration to Alpine eclogite facies conditions (Ungarotti et al. 1983). According to these authors common paragasitic hornblende, on becoming unstable as pressure increases, gradually transforms into a sodic-calcic amphibole of barroisitic character (see below). The garnet surrounding this inclusion assemblage is the almandine-rich variety characteristic of amphibolite facies conditions of metamorphism (Holland 1983).

Table 1. 1. Rock analysis by XRF (FeO by classical method). 2. Selected mineral analyses. Numbers at heads of columns marked on figures 1 to 3. Amphiboles, 23(0); Garnets, 24(0); Pyroxene, 6(0); Micas, 22(0). i, inclusion, g, groundmass, c, core, r, rim. All iron shown as ferrous except where, for pyroxene and amphiboles, adjustment of cation totals provides positive amounts of Fe^{3+} and Fe^{2+} (negative for most groundmass amphiboles).

ROCK		Amphibole						Garnet				Pyroxene		Mica	
N82100		A1i	A2i	A3g	A4g	A5r	A6r	G1c	G1r	G2c	G2r	P1	P2	M1i	M2g
SiO_2	50.07	40.65	42.54	52.35	51.29	39.67	44.09	38.29	39.44	38.98	39.49	56.79	56.45	46.52	52.16
TiO_2	1.58	0.06	0.20	0.32	0.19	0.11	0.13	0.18	0.00	0.20	0.05	0.15	0.15	0.11	0.75
Al_2O_3	11.61	16.00	16.94	10.90	11.19	16.14	13,77	21.22	22.06	21,86	21.81	11.27	11.40	39.54	28.82
Fe_2O_3	2.96	7.62	7.95	–	4.45	4.17	1.23	–	–	–	–	2.63	1.90	–	–
FeO	7.13	12.40	9.49	7.22	5.86	11.72	12.67	28.30	24.63	23.69	22.04	0.34	1.71	1.08	1.50
MnO	0.17	0.05	0.11	0.08	0.06	0.09	0.07	1.05	0.15	0.51	0.48	0.00	0.10	0.03	0.00
MgO	9.76	6.97	8.90	14.47	14.23	9.54	10.31	2.44	5.04	5.68	6.91	8.01	8.31	0.03	3.32
CaO	10.81	8.63	7.62	7.38	7.87	11.27	10.42	8.22	8.93	8.50	8.55	14.17	13.93	0.41	0.05
Na_2O	3.69	4.07	5.63	4.83	4.25	2.66	2.84	–	–	0.00	–	7.47	7.17	5.06	0.93
K_2O	0.29	0.05	0.00	0.24	0.25	1.08	0.80	–	–	0.01	–	0.07	0.04	1.25	8.15
P_2O_5	0.20														
	99.98	96.50	99.38	97.79	99.64	96.45	96.33	99.70	100.25	99.43	99.33	100.90	101.16	94.03	95.68
Number of cations:															
Si		6.48	6.14	7.30	7.16	5.99	6.56	6.07	6.08	6.04	6.08	1.99	1.98	6.01	6.80
Ti		0.01	0.02	0.03	0.02	0.01	0.01	0.02	0.00	0.02	0.01	0.00	0.00	0.01	0.07
Al		2.67	2.88	1.79	1.84	2.87	2.41	3.96	4.01	4.00	3.96	0.47	0.47	6.03	4.43
Fe^{3+}		0.62	0.86	–	0.46	0.47	0.14	–	–	–	–	0.07	0.05	–	–
Fe^{2+}		1.85	1.14	0.84	0.68	1.48	1.58	3.75	3.17	3.07	2.84	0.01	0.05	0.12	0.16
Ma		0.01	0.01	0.01	0.01	0.01	0.01	0.14	0.02	0.07	0.06	0.00	0.00	0.00	0.00
Mg		1.35	1.93	3.01	2.96	2.15	2.28	0.58	1.16	1.31	1.60	0.42	0.43	0.00	0.64
Ca		1.28	1.18	1.10	1.17	1.82	1.66	1.40	1.47	1.41	1.41	0.53	0.52	0.05	0.01
Na		1.14	1.57	1.30	1.15	0.78	0.82	–	–	–	–	0.51	0.49	1.27	0.24
K		0.00	0.00	0.04	0.04	0.21	0.15	–	–	–	–	0.00	0.00	0.20	1.35

2. *The eclogite assemblage.* – Garnets are all zoned, having almandine-rich cores and relatively pyrope-rich rims, but as noted above the recorded maximum of 27% pyrope in N82100 is notably lower than the maximum of 42% from BFM S82103 and 097. Compositions from N82100 plot in the field of Group C eclogites (Table 1, Fig. 3 and Coleman et al. 1965). With all Fe referred to Fe^{2+}, the Fe^{2+}/Mg^{2+} ratios range from 1.78 to 3.27 in garnet rims, and from 2.38 to 6.51 in cores. The six smallest recorded values are all from rims and average 1.90 ± 0.06.

Except against garnet, clinopyroxene crystals have very irregular margins, directly fringed by a fibrous albite-amphibole seam which merges with the symplectite surrounding the groundmass amphiboles. Clinopyroxenes show undulose extinction and sub-grain development, such as reported by Stephens & Roermund from BFMS82103. Compositions, wherever determined in the crystals, are closely similar to one another (Fig. 4, Table 1) averaging some 43% jadeite (compared with 40% in BFMS82103). The clinopyroxene of N82100 is Fe-poor; Tschermak's molecule does not appear in calculations of end-members (Hutchinson 1974). No sign of compositional zoning has been discovered in them, even in the comparison of analyses from close to included garnets where corrosion of the clinopyroxene is least obvious, with analyses from the cores of pyroxene crystals. When all iron is reported as Fe^{2+}, totals for my 11 analyses average 100.55, which is somewhat high. Otherwise analyses seem perfectly acceptable (Table 1).

In spite of the uniformity of major element composition, clinopyroxenes appear to vary widely in their Fe^{2+}/Fe^{3+} ratios. Where sufficient of the Fe^{2+} content reported in the probe analysis is allocated to Fe^{3+} so as to set the cation total to 4.00, the mean Fe^{2+}/Mg^{2+} ratio, for the examples plotted in Fig. 3, is 0.08 ± 0.06. The average cation excess of 0.026 contrasts with the deficiency reported by Cawthorn & Collerson (1974, Fig. 1, a mean of 3.9747 ± 0.0336 from 91 analyses). The range of values is less if an alternative procedure of setting $Fe^{3+} = Na - Al$ and $Fe^{2+} = Fe_{total} - Fe^{2+}$ is used (Carpenter 1979). The mean val-

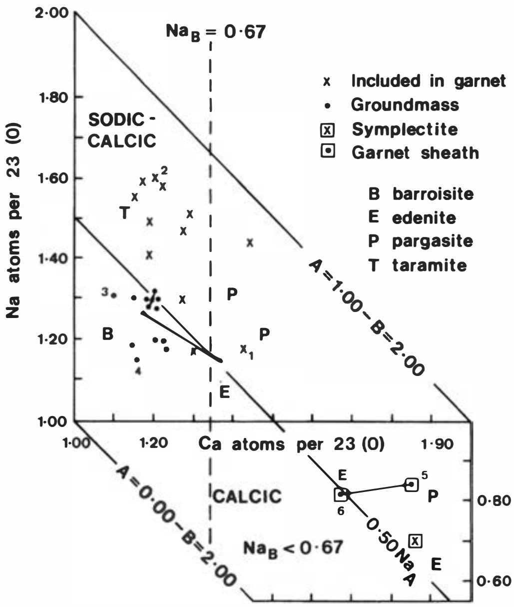

Fig. 1. Amphiboles: plot of Ca per 23(0) against total Na per 23(0). Numbers as in Table 1. 1i and 2i, inclusions in garnet; 3 and 4, groundmass; 5 and 6, inner and outer parts of reaction rim to garnet.

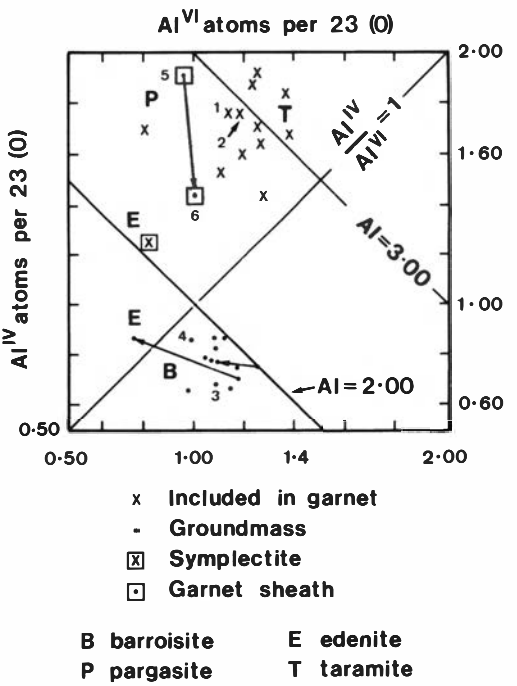

Fig. 2. Amphiboles: plot of Al^{VI} against Al^{IV}. Numbers as in Table 1.

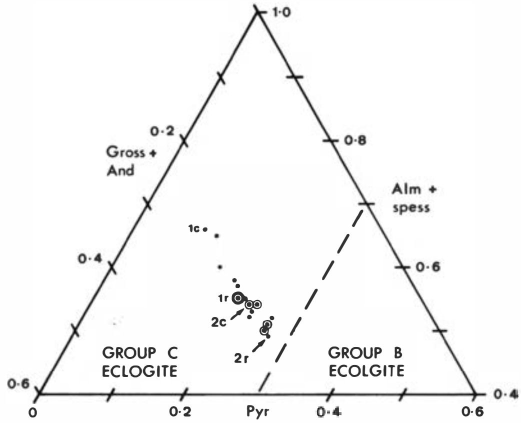

Fig. 3. Garnets: mole% of end members and limits of Group B and C eclogites (Coleman et. al. 1965). Garnet core, c; rim, r. Numbers as in Table 1.

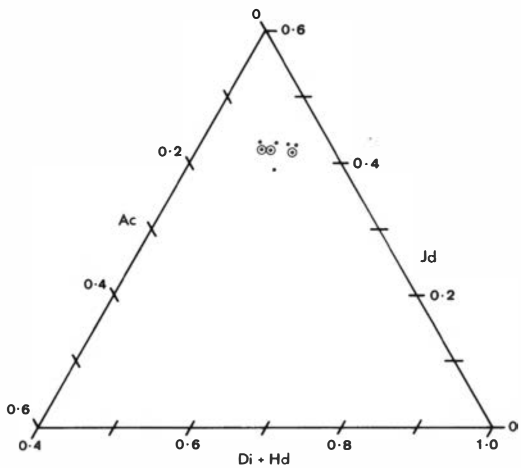

Fig. 4. Pyroxene compositions in terms of end members. Coincidence of several analyses shown here and in other figures, by an open circle with a closed circle at its centre.

ue now becomes 0.16 ± 0.04. Si values are close to 2.00 so that clinopyroxene evidently contains little Al^{IV}; most if not all of it is Al^{VI} as the procedure requires. Ernst, in assigning Fe^{2+} contents to clinopyroxene, adopted the 'somewhat arbitrary procedure' (Ernst 1976, p. 300) of setting the ratio $Fe^{2+}/Fe^{3+} = 1$. If that is done for N82100, the average Fe^{2+}/Mg^{2+} ratio is 0.12 ± 0.01.

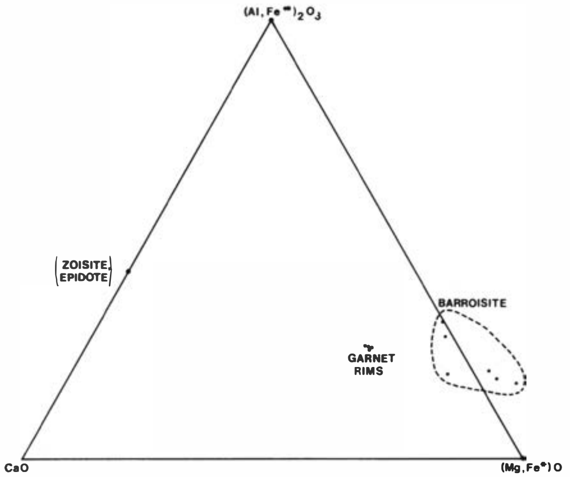

Fig. 5. Projection from omphacite on to the plane A–C–(FM). Omphacite composition $(Di + Hd)_{50}$ $(Td + Ac)_{50}$.

Post-eclogite phases

1. *High pressure hydration.* – The dominant mineral of the first stage of the retrogressive alteration of the eclogite is barroisite. It occurs as a host of small crystals, clustered round the garnets of the groundmass and enclosed in a semi-opaque green symplectite (Table 1 and Figs. 1 and 2). Where barroisite occurs in the clinopyroxenes, such a rim is absent. Often the barroisites have a bright green edenitic rim quite different in texture from the calcic amphibole of the fibrous rims. Both in terms of the ratios Na/Ca and Al^{IV}/Al^{VI} (Figs. 1, 2), the barroisitites form a group distinct from both the earlier taramitic amphibole and the late calcic amphibole (Leake 1978).

It seems likely that a reaction between the rims of garnets and clinopyroxene (Fig. 5), garnet (rims) + omphacitic pyroxene + quartz + water, produced both the barroisite and the conspicuous Fe-poor epidote of the groundmass, a mineral also found in embayments in the pyroxene. However, as we have seen, Stephens & Roermund (1984) regard the zoisite of BFMS82103 as belonging to the preceding eclogitic stage, but give no alternative reaction to produce barroisite.

The relatively large white-mica flakes of N82100 prove on analysis (Table 1) to be phengitic muscovites, typical of many eclogites (e.g. Krogh 1980). Like the barroisites, they too have pronounced reaction rims, which sometimes are shared with the former and must have crystallized early in the post-eclogite hydration of the rock. Like Stephens & Roermund I refer the mica to the barroisite-forming stage of hydration.

2. *Hydration at lower pressures.* – Albite appears in N82100 as very fine fibres in the reaction rims around garnet and clinopyroxene. It is not a phase belonging to the eclogite facies assemblage. In both kinds of rim it is distinguishable and analysable only when viewed on a back-scatter-electron image. The accompanying amphiboles are calcic hornblende instead of the ferroan pargasite reported by Stephens & Roermund from the comparable M3 fabrics of their two specimens (results not separately reported). Amphiboles in the garnet reaction rims of N82100 also include edenite types comparable to the rims on barroisities of the same rock. No actinolite has been discovered in N82100, nor is it recorded by Stephens & Roermund (1984) from the comparable garnet-clinopyroxene rock, BFMS82103, although it is known from the garnet-amphibole rock 097 in which the alkali amphibole crossite-glaucophane also occurs. Unfortunately with the information available it is not possible to judge the influence here of differences in rock composition on mineralogy.

Physical conditions of metamorphism

Some limits have already been recognised to PT path followed by N82100. In particular a pressure of at least 8 km seems to be required for the formation of the pre-eclogite assemblage paragonite + epidote + quartz. Moreover, the amphibole member of this assemblage conforms well to a position as an early member of a series stable at increasing pressure (Ernst 1979, Ungaretti et al. 1983).

Using the average ratio of Fe^{2+}/Mg^{2+} from garnet rims of 1.90, together with the 3 estimates of the same ratio from the clinopyroxene, 0.08, 0.12 and 0.16, allows the calculation of three distribution coefficients, K_D garnet(rims)/pyroxene, of about 24, 16 and 12 respectively. The intersection of K_D curves with the curve for the co-existence of pyroxenes of jadeite 40 with quartz and albite (Droop 1981) provides pressure minima of 12 to 14kb. Employing these values (Ellis & Green 1979), and allowing for the mole fraction of Ca, provides in turn estimates of temperature minima of between 625C and 500C. The wide range of temperature estimates is unsatisfactory, but arises directly from uncertainty over the acceptable Fe^{2+}/Fe^{3+} ratio for the clinopyroxenes. The low Fe total in the clinopyroxene, of course, makes them vulnerable to the effect of analytical error on calculations of Fe^{2+}/Fe^{3+} ratios in a way not possible in minerals with a higher Fe content. However, the average Fe^{2+}/Fe^{3+} ratio of the 11 clinopyroxene analyses of N82100 of 0.48, after the cation total is set to 4.00, is close to the ratio of about 0.41 for the one clinopyroxene analysis given by Stephens & Roermund (1984, Table 1 analyses 5). The K_D value based on the estimates of Fe^{2+} determined in this way is, however, the highest of the three given above, and naturally provides the lowest estimate of the temperature of growth of garnet rims and clinopyroxenes. Moreover, it is one that is substantially below the 610° ± 90°C favoured by Stephens & Roermund (1984). It must be added, of course, that the maximum pyrope value in garnet rims is substantially lower in N82100 than in the rocks the latter describe. This lower concentration of pyrope suggests a lower temperature of transformation, if it does not again express the influence of rock composition.

Formation of alkali amphiboles

Perhaps the most interesting aspect of the rocks described by Stephens & Roermund (1984) is the occurrence of crossite-glaucophane in the garnet-amphibole rock BFMS82097. It is the more interesting in the light of recently reported work by Ungaretti et al. (1983, see also Ernst 1979) which indicates a gap between sodic-calcic amphiboles such as barroisite and very glaucophane rich-types. The absence of alkali amphiboles in rims to the barroisites of BFMS82103, as well as N82100 may, however, reveal again the role of rock composition. No doubt there is much yet to be learned of the significance of this development.

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Appendix. – The energy dispersive analyses recorded here were carried out on a CAMECA Camebax electron microprobe fitted with a link systems 860-500 E. D. S. Facility. ZAF-4/FLS Software was used to convert x-ray spectra into chemical data.

References

Carpenter, M. A. 1979: Omphacites from Greece, Turkey and Guatemala: composition limits of cation ordering. *Am. Mineral. 64,* 102–108.

Cawthorn, R. G. & Collerson, K. D. 1974: The re-calculation of pyroxene endmember parameters and the estimation of ferrous and ferric iron content from electron microprobe analyses. *Am. Mineral 59,* 1203–1208.

Coleman, R. G., Lee, D. E., Beatty, L. B. & Brannock, W. W., 1965: Eclogites and eclogites: Their differences and similarities. *Geol. Soc. Am. Bull. 76,* 483–508.

Droop, G. T. R., 1983: Pre-Alpine eclogites in the Pennine Basement Complex of the Eastern Alps. *J. Metamorphic Geol. 1,* 3–12.

Ellis, D. J. & Green, D. H. 1979: An experimental study of the effect of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria controls. *Contrib. Mineral. Petrol. 71,* 13–22.

Ernst, W. G. 1976: Mineral chemistry of eclogites and related rocks from the Voltri Group, Western Liguria, Italy. Schweiz. *Mineral. Petrogr. Mitt 56,* 293–343.

Ernst, W. G. 1979: Co-existing sodic and calcic amphiboles from high-pressure metamorphic belts and the stability of barroisitic amphibole. *Mineral. Mag. 43,* 268–279.

Franz G. & Althaus, E. 1976: Die Paragenese Paragonit + Zoisite + Quartz als Hochdruckindicator. *Forschr. Min. 54(2),* 22–23.

Holland, T. J. B. 1979b: High water activities in the generation of high pressure kyanite eclogites of the Tauern window, Austria. *J. of Geology 87,* 1.27.

Holland, T. J. B. 1983: The experimental determination of activities in disordered and short-range ordered jadeitic pyroxenes. *Contrib. Mineral. Petrol. 68,* 293–301.

Hutchinson, C. S. 1974: *Laboratory Handbook of Petrographic Techniques.* Wiley, New York, 527 pp.

Krogh, E. J. 1980: Geochemistry and petrology of glaucophane-bearing eclogites and associated rocks from Sunnfjord, western Norway. *Lithos 13,* 355–380.

Leake, B. E. 1978: Nomenclature of amphiboles. *Am. Mineral. 63,* 1023–1052.

Stephens M. B. & Roermund, H. L. M. van. 1984: Occurrence of glaucophane and crossite in eclogites of the Seve Nappes. *Nor. Geol. Tidsskr. 64,* (this issue).

Ungaretti, B., Lombardo, C., Domeneghetti & Rossi, G. 1983: Crystal-chemical evolution of amphiboles from eclogitised rocks of the Sesia-Lanzo Zone, Italian western Alps. *Bull. Mineral. 106,* 643–644.