

**ANDRADITE GARNET IN ALTERED BASALT FROM  
BORUP FIORD, ELLESMERE ISLAND, NORTHWEST TERRITORIES**

Project 680064

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**Abstract**

*Mineral chemistry and paragenesis of cavity-filling andradite garnet, epidote and prehnite in altered basalt collected from Borup Fiord, Ellesmere Island are described.*

*The garnet is idiomorphic to sub-idiomorphic and dark brown to amber coloured. The ferric garnet part contains more than 30.0 per cent Fe<sub>2</sub>O<sub>3</sub> and less than 1.0 per cent Al<sub>2</sub>O<sub>3</sub>. The birefringent rim of the garnet contains more than 8.0 per cent Al<sub>2</sub>O<sub>3</sub>. Epidote occurs as euhedral to subhedral cavity fillings and a replacement of plagioclase. All analyses of epidote range from Ps<sub>17</sub> to Ps<sub>36</sub>. Euhedral prehnite usually forms overgrowths on epidote in the cavities. The ferric prehnite contains less than 8.0 per cent Fe<sub>2</sub>O<sub>3</sub>. There are two equilibrium temperatures calculated from coexisting garnet and epidote. These results suggest that the various mineralization stages were preserved metastably in the same specimen. The garnet and associated cavity-filling minerals may have been produced during local hydrothermal alteration of the Esayoo basalt in the Borup Fiord region.*

**Résumé**

*Le présent rapport décrit la chimie et la paragenèse de l'andradite, de l'épidote et du prehnite qui remplissent les creux du basalte altéré recueilli au fjord Borup, dans l'île Ellesmere.*

*Le grenat est idiomorphe à subidiomorphe, de couleur brun foncé à ambrée; la partie ferrique contient plus de 30 % de Fe<sub>2</sub>O<sub>3</sub> et moins de 1 % de Al<sub>2</sub>O<sub>3</sub>. Le bord biréfringent du grenat contient plus de 8 % de Al<sub>2</sub>O<sub>3</sub>. L'épidote se présente sous forme de remplissages automorphes à subautomorphes des creux et comme minéral de remplacement du plagioclase. Toutes les analyses de l'épidote varient de Ps<sub>17</sub> à Ps<sub>36</sub>. Des excroissances automorphes de prehnite sont souvent trouvées sur l'épidote recouvrant les creux. La prehnite ferrique contient moins de 8 % de Fe<sub>2</sub>O<sub>3</sub>. Deux températures d'équilibre ont été calculées à partir du grenat et de l'épidote coexistants. Ces résultats suggèrent que les diverses étapes de minéralisation ont été conservées de façon métastable dans le même échantillon. La formation du grenat et des minéraux de remplissage associés a peut-être eu lieu lors de l'altération hydrothermale locale du basalte d'Esayoo dans la région du fjord Borup.*

**Introduction**

Boulders of garnet-bearing, altered basalt were collected by P. Moore, in 1979, from the toe of a glacier near Borup Fiord (lat. 80°55'N; long. 83°00'W), on Ellesmere Island in the Canadian Arctic (Fig. 27.1).

This paper is an analysis of the chemistry of the cavity-filling garnet, epidote and prehnite in the basalt, and presents hypotheses concerning their mode of formation, their mineralization temperature and paragenesis.

The geology of the west central area of Ellesmere Island has been discussed by Thorsteinsson (1974). According to him, this region consists of upper Carboniferous to Triassic sedimentary sequences composed mainly of limestone, chert, siltstone and sandstone (Fig. 27.2). This area is geosynclinally folded and the axis of the geosyncline trends northeast. In the northern part, upper Carboniferous to lower Permian sediments of the Nansen Formation, composed of limestone, minor sandstone, siltstone, chert and dolomite, are overlain by the upper Permian Degerbøls Formation. The latter is composed of limestone, cherty limestone, and chert. These sediments are overlain by Triassic rocks composed mainly of shale and sandstone in the southern part of the area.

The Esayoo Formation, which consists of interlayered basalt and agglomerate, is the only volcanic rock formation in this area, and ranges in thickness from 30 to 300 m. As the formation overlies the Nansen Formation and underlies lower Permian rocks, Thorsteinsson (1974) considered the Esayoo Formation to be Early Permian.

Although it is far from any outcrop of the Esayoo Formation, the boulder of garnet-bearing, altered basalt examined in this study is considered to have been derived from the Esayoo, because of its lithologic and petrographic similarity to rocks of that formation exposed near the upper reaches of the boulder-bearing glacier (Fig. 27.2). Also, no other volcanics are known to occur in this region.

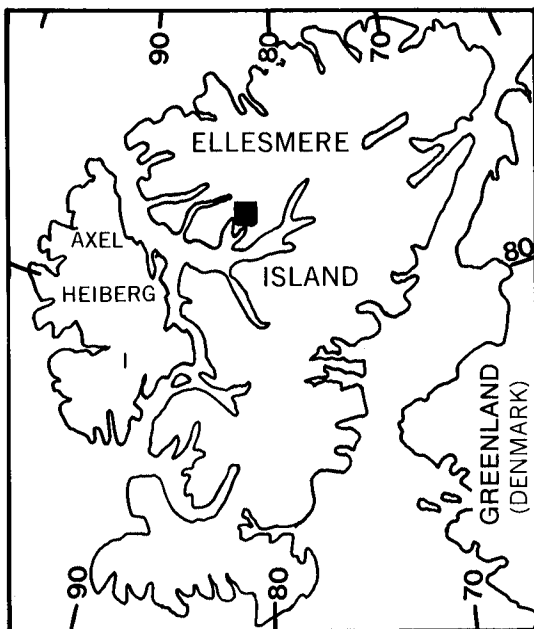
**Petrography**

The Borup Fiord samples are from boulders of dark to light green, fine grained, altered basalt, which have many ovoidal or orbicular cavities ranging up to 3 cm in diameter. The cavities are usually filled with dark brown or amber coloured andradite garnet, epidote, prehnite and calcite, with minor quartz and dusty iron oxides. Chlorite is also rarely present.

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**Figure 27.1.** Locality map of sampling point. The solid square is the area shown in Figure 27.2.

In the weakly altered, dark greyish part, basaltic texture is well preserved. Sparse cavities are also filled with garnet and other Ca-silicate minerals. Metasomatic epidote bands, about 10 mm wide, separate the weakly altered from the heavily altered parts where carbonation predominated.

Thin sections reveal that the weakly altered parts contain a well preserved texture of finely crystalline, aphyric basalt. Laths of plagioclase needles smaller than 0.1 mm are altered to albite. Mafic minerals (presumably originally clinopyroxene) are also decomposed and have recrystallized into iron oxides, chlorite and epidote. In heavily altered parts, basaltic texture is obscure. Calcite and epidote minerals are predominant. Plagioclase laths are altered to albite + calcite, whereas mafic minerals have recrystallized to epidote + calcite + iron oxides.

#### Cavity-filling minerals

Andradite garnet is the main and characteristic mineral filling cavities. Garnet fills not only orbicular, but also large, lenticular cavities up to 3 cm wide. The garnet is idiomorphic to subidiomorphic and dark brown (fresh) to amber (weakly altered) coloured. Garnet cores commonly include epidote, prehnite and calcite. Another common cavity-filling mineral is epidote. Small cavities are, in some cases, essentially filled with epidote.

Calcite, quartz, prehnite and chlorite are subordinate to rare cavity-filling minerals.

Thin section observations reveal three major mineral assemblages of cavity filling:

- Ia. Garnet – epidote – prehnite – calcite – quartz – iron oxides ± chlorite
- Ib. Garnet – epidote – prehnite – quartz – iron oxides
- II. Garnet – epidote – calcite – quartz – iron oxides
- III. Epidote – iron oxides

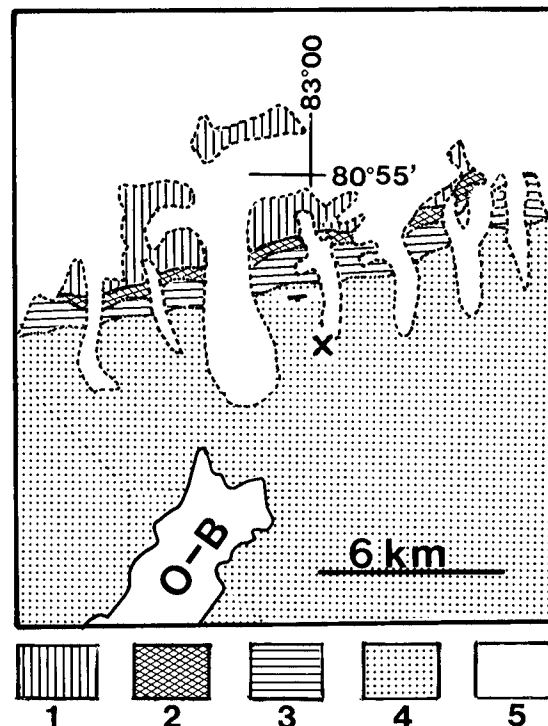
A mineral assemblage of type Ia is illustrated in Figure 27.3. Idiomorphic garnet, about 4 mm in width,

occupies the centre of the cavity. The rim bordering the garnet crystal is less than 200  $\mu\text{m}$  wide and is optically anisotropic and birefringent. The periphery of the cavity is a reaction zone composed mainly of fine grained epidote and dusty iron-oxides. Plagioclase is completely replaced by epidote pseudomorphs. Chlorite is also present sporadically. In most cases, idiomorphic epidote crystals grew from the edge radially towards the centre of the cavity. Clusters of prehnite crystals grew on the epidote layer. Quartz and a small amount of calcite are present in the interstices between the garnet and prehnite crystals.

Electron-backscattering images reveal that the mineralogical composition of the andradite garnet is homogeneous, except for the aluminous birefringent rim. The idiomorphic prehnite is zoned, with a ferric core fringed by an aluminous rim. The idiomorphic to subidiomorphic epidote shows a reverse trend from aluminous in the core to ferric in the rim (Fig. 27.4). The mineral assemblage of type Ib is found in partly resorbed garnet in which the core is replaced by iron-free prehnite.

Figure 27.5 shows an example of the mineral assemblage of type II. In this case, calcite occurs in the core of the garnet. The birefringent rim of garnet is also present. A reaction zone composed of epidote and dusty iron oxides surrounds the cavity. Idiomorphic epidote crystals grew inwards from the edge of the cavity. Interstitial quartz is present between garnet and epidote crystals.

In the type III mineral assemblage, epidote is the main constituent and garnet is not present (Fig. 27.6). An aggregate of dusty iron oxides suggests the decomposition of the garnet into epidote and iron oxides.



**Figure 27.2.** Geological map of the study area, simplified after Thorsteinson (1969). O-B = Oobloyah Bay; X = sampling point; 1 = Nansen Formation (Upper Carboniferous and lower Permian); 2 = Esayoo Formation (Lower Permian, basalt); 3 = Degerbols Formation (Upper Permian); 4 = Triassic formations; 5 = Glacier.

**Mineral chemistry**

The cavity filling minerals, garnet, epidote, and prehnite, were analyzed by electron probe microanalyzer. Representative analyses of these minerals are listed in Tables 27.1 and 27.2.

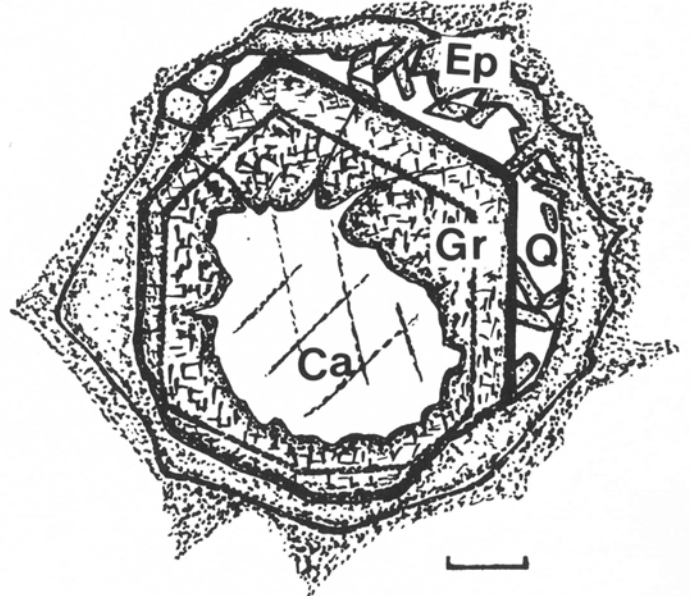
**Garnet** Spot analyses of garnet reveal that the chemical composition of the ferrian garnet is homogeneous, with no distinct zoning. The transitional, birefringent rim shows sharp and abrupt changes in Al and Fe contents.

MgO seems to increase a little in the birefringent zone but this trend is not unequivocal. The ferrian garnet part contains more than 30.0 per cent  $Fe_2O_3$  and less than 1.0 per cent  $Al_2O_3$ . Preliminary analyses suggest that MnO and MgO are less than 0.3 and 0.1 per cent respectively and, therefore, were omitted in routine analyses.

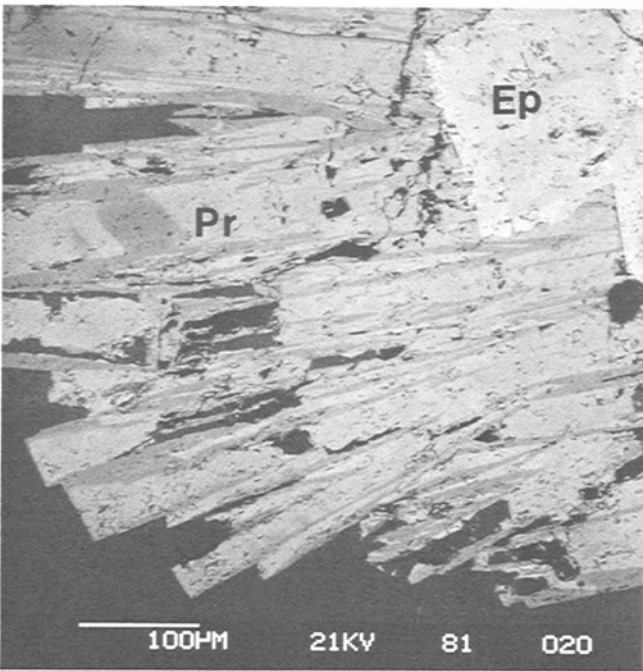
The birefringent zones, less than 200  $\mu m$  in width, are enriched in  $Al_2O_3$  and contain from 8.0 to 10.4 per cent, while the inner parts of exceptionally broad birefringent rims rarely have less than 7.0 per cent  $Al_2O_3$ .



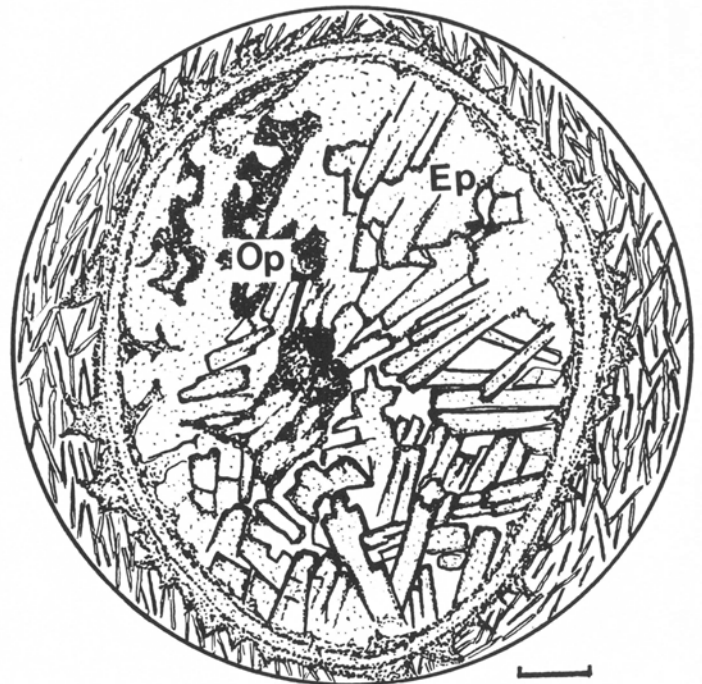
**Figure 27.3.** Occurrence of cavity-filling minerals. Gr = garnet; Ep = epidote; Pr = prehnite; Q = quartz; Ca = calcite. Scale bar is 1.2 mm.



**Figure 27.5.** Occurrence of resorbed garnet. Gr = garnet; Ep = epidote; Q = quartz; Ca = calcite. Scale bar is 0.4 mm.



**Figure 27.4.** Electron-backscattering image of epidote and prehnite. Ep = epidote; Pr = prehnite. Brighter parts of crystals are more enriched in iron.



**Figure 27.6.** Occurrence of epidote. Ep = epidote; Op = opaque iron oxides. Scale bar is 0.4 mm.

$Fe^{3+}/(Fe^{3+} + Al)$  of the ferrian garnet ranges from 0.97 to 1.0, which corresponds to 97 to 100 per cent andradite.  $Fe^{3+}/(Fe^{3+} + Al^{3+})$  of the birefringent rim generally ranges from 0.52 to 0.60, rarely from 0.68 to 0.75. All analyses of garnet, plotted in terms of Al,  $Fe^{3+}$  and Ca ratio in Figure 27.7, are on the low Ca side of the ideal andradite-grossular join, suggesting the existence of minor ferrous iron, possibly in a small component of almandine.

**Epidote** Epidote shows a variety of habits as a constituent in cavity reaction rims. It occurs as euhedral to subhedral cavity fillings and as a replacement of plagioclase crystals. As previously stated, electron backscattering images show the compositional zoning in the relatively large crystals, more than 100  $\mu m$  in length, to be from alumina-rich cores to iron-rich rims. Total iron, as  $Fe_2O_3$  of the analyzed epidote, ranges from 8.5 to 17.6 per cent, whereas  $Al_2O_3$  ranges from 20 to 27 per cent. All analyses of epidote plotted in Figure 27.7 are scattered between  $Ps_{17}$  to  $Ps_{36}$ .

**Prehnite** Euhedral prehnite crystals are up to several 100  $\mu m$  long and usually form overgrowths on epidote crystals in the cavities. In places prehnite occurs in the cores of garnet crystals. Euhedral prehnite shows distinct compositional zoning from iron-rich core to iron-poor rim. This relationship is the opposite to that of epidote. The ferrian prehnites contain from 4.8 to 7.9 per cent  $Fe_2O_3$ , whereas prehnites in the cores of garnet crystals have  $Fe_2O_3$  contents less than 1.0 per cent.

### Discussion

Mineral assemblages of the present cavity fillings are characteristic of low temperature skarns or hydrothermal alteration. The cavity-filling garnet is usually present as subidiomorphic to idiomorphic monocrystals and the chemical composition of the cores is homogeneous, which suggests crystallization from fluid or vapour under stable physico-chemical conditions. Abrupt compositional change from andradite to grandite at the rim may reflect a change in

Table 27.1  
Representative analyses of garnet (per cent oxides)

Sample No.	1	2	3	4	5	6	7	8	9	10	11
Grain	3-1-2	2-2-3	1-1-2	2-1-6	2-1-3	2-3-4	2-3-3	2-1-1	2-2-7	4-1-3	1-1-4
$SiO_2$	35.26	35.19	35.61	35.37	35.46	35.55	35.99	36.65	36.91	36.77	37.36
$Al_2O_3$	0.07	0.16	0.24	0.33	0.55	5.22	7.02	8.93	9.89	9.92	10.41
$Fe_2O_3$	32.26	31.91	32.02	32.18	31.37	25.23	23.34	20.19	18.49	18.36	17.96
CaO	31.94	32.41	32.65	32.21	32.52	32.47	33.00	33.58	33.45	33.71	34.18
Total	99.53	99.67	100.52	100.09	99.90	98.47	99.35	99.35	98.74	98.76	99.91
Structure formula (O = 24)											
Si	5.989	5.972	5.986	5.971	5.987	5.941	5.814	5.929	5.984	5.992	5.993
Al	0.014	0.033	0.046	0.065	0.109	1.028	1.359	1.703	1.890	1.905	1.968
$Fe^{3+}$	4.124	4.075	4.051	4.088	3.985	3.173	2.885	2.458	2.256	2.252	2.124
Ca	5.813	5.893	5.881	5.826	5.884	5.815	5.809	5.821	5.812	5.779	5.875
Total	15.940	15.973	15.964	15.950	15.965	15.957	15.867	15.911	15.942	15.928	15.960
$Fe^{3+}/(Fe^{3+}+Al^{3+})$	1.00	0.99	0.99	0.98	0.97	0.75	0.68	0.59	0.54	0.54	0.52

Table 27.2  
Representative analyses of epidote (columns 1-9) and prehnite (columns 10-13) (per cent oxides)

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Grain	4-1-4	1-1-1	2-1-1	4-1-3	2-1-2	2-2-7	2-2-6	1-1-4	2-2-5	4-1-2	2-1-1	4-1-1	1-1-1
$SiO_2$	37.50	37.68	37.67	37.15	39.23	38.43	37.41	37.66	37.61	41.81	42.11	42.83	44.11
$Al_2O_3$	20.06	21.72	22.87	22.75	22.32	24.51	25.10	21.72	27.23	18.98	19.51	21.44	24.66
$Fe_2O_3$	17.60	15.23	14.81	14.80	13.72	12.26	11.62	10.02	8.46	7.90	6.93	4.78	0.30
CaO	22.58	22.65	22.96	22.51	20.88	23.15	23.33	23.62	23.19	25.85	25.76	26.37	26.77
Total	97.74	97.28	98.31	97.21	96.15	98.35	97.46	93.02	96.49	94.54	94.31	95.42	95.84
Structure formula (O = 12.5)												(O = 22)	
Si	3.034	3.034	2.997	2.989	3.148	3.024	2.972	3.131	2.980	5.982	6.011	5.993	6.033
Al	1.912	2.061	2.145	2.157	2.111	2.274	2.351	2.129	2.543	3.200	3.281	3.536	3.976
$Fe^{3+}$	1.071	0.923	0.887	0.896	0.828	0.726	0.695	0.627	0.505	0.774	0.744	0.504	0.031
Ca	1.957	1.954	1.957	1.941	1.795	1.952	1.986	2.104	1.969	3.960	3.939	3.953	3.923
Total	7.974	7.972	7.986	7.983	7.882	7.976	8.004	7.991	7.997	13.916	13.975	13.986	13.963
$Fe^{3+}/(Fe^{3+}+Al^{3+})$	0.36	0.30	0.29	0.29	0.28	0.24	0.23	0.23	0.17	0.19	0.18	0.13	0.01

these conditions during crystallization. The irregular and complex zoning in epidote and prehnite suggests rapid crystallization under metastable conditions.

Paragenetic relations, therefore, can only be postulated for the surface equilibrium among garnet, epidote and prehnite.

Kitamura (1975) measured Al-Fe partitioning between grandite garnet and epidote from contact metasomatic deposits. He found that the partition coefficient,  $K' = (Al/Fe^{3+})_{\text{garnet}} / (Al/Fe^{3+})_{\text{epidote}}$  in M3 of epidote, is generally in a range from 1.7 to 10.0 and mineral pairs formed under relatively high temperature have smaller partition coefficients. The compositional relations of coexisting epidote and garnet have also been calculated by Bird and Helgeson (1980). They proposed a tentative temperature-composition diagram.  $Fe^{3+}/(Fe^{3+} + Al^{3+})$  and  $Al/Fe^{3+}$  values for several coexisting pairs of garnet rim and epidote rim in the present cavity-fillings are listed in Table 27.3.  $Fe^{3+}/(Fe^{3+} + Al^{3+})$  values for the garnets range from 0.52 to 0.59 while those of coexisting epidote range from 0.23 to 0.29. The  $K'$  values range from 2.2 to 4.9. It is noteworthy that mineral pairs 4-1-3 and 2-1-1 are accompanied by ferrian prehnite and the temperatures of coexisting garnet and epidote deduced from Bird and Helgeson (1980) are less than 200°C. Meanwhile, mineral pairs 1-1-4 and 2-2-7 are devoid of prehnite and temperatures are estimated to be 500-550°C. Average  $K'$  value is 4.6 in the former and 3.3 in the latter.

The upper stability limit of prehnite defined by Liou (1971) and Strens (1968) is insensitive to pressure and is about 400°C. Recently, Kerrick and Ghent (1978) calculated that the upper stability limit of prehnite has a significant negative slope at higher pressures and the upper stability limit of 1-2 kbar extends up to more than 500°C. Consequently, the upper stability limit of prehnite is still controversial. However, the upper stability limit of ferrian prehnite is suspected to be lower than that of iron-free prehnite (Coombs et al., 1977). It is reasonable that the calculated temperature of mineral pairs without prehnite is higher than that of prehnite-bearing mineral assemblages.

The paragenetic mineral pairs 2-2-7 and 2-1-1, however, coexist in the same thin section.

These contradictions lead to the assumption that there could have been an evolution in the chemistry of the fluid from which the cavity-filling minerals crystallized and that the various mineralization stages were preserved metastably in the same specimen.

In this regard, the mineral assemblage of type III, epidote-iron oxides, suggests decomposition of andradite garnet under lower temperature or higher  $CO_2$  conditions (Taylor and Liou, 1978).

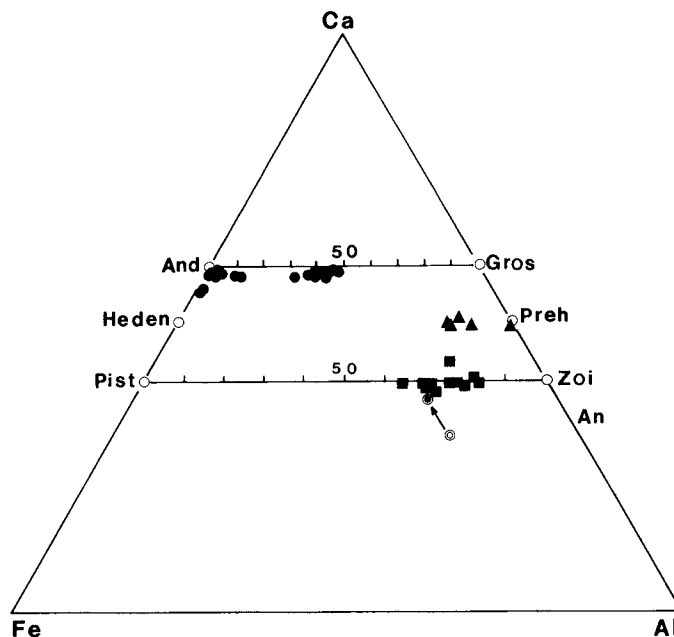


Figure 27.7.  $Fe^{3+}$ -Al-Ca plot of analyses. Solid circles = garnet; solid triangles = prehnite; solid squares = epidote; circle with dot = heavily carbonated basalt; double circle = weakly carbonated basalt.

The type III mineral assemblage also coexists with type II or type I mineral assemblages in the same specimen. These occurrences would support the above mentioned assumption.

In carbonate-bearing, cavity-free basalt from the Esayoo Formation, epidote and calcite are ubiquitous in the groundmass but garnet is absent. It is conceivable that, in these rocks, the introduction of carbonate took place prior to the formation of garnet.

One of the weakly altered samples of Esayoo basalt contains 9.0 per cent total iron oxides, 10.4 per cent  $MgO$ , 10.6 per cent  $CaO$ , and 4.5 per cent total alkalis, whereas heavily carbonated basalt contains 9.7 per cent total iron oxides, 8.0 per cent  $MgO$  and more than 13 per cent  $CaO$  (H.P. Trettin, unpublished data).

Carbonation transformed the chemical composition of basalt making it easier to yield the epidote solid solution, as shown in Figure 27.7. Moreover, the formation of andradite is restricted to  $H_2O$ -rich fluid at temperatures below 400°C (Taylor and Liou, 1978).

Table 27.3  
Partition of Elements

Grain No.	Garnet		Epidote		K*
	$Fe^{3+}/(Fe^{3+}+Al^{3+})$	$Al/Fe^{3+}$	$Fe^{3+}/(Fe^{3+}+Al^{3+})$	$(Al/Fe^{3+})_{M3}$	
4-1-3	0.54	0.84	0.29	0.17	4.9
2-1-1	0.59	0.69	0.29	0.16	4.3
1-1-4	0.52	0.93	0.23	0.21	4.4
2-2-7	0.54	0.84	0.24	0.38	2.2

\*partition coefficient =  $(Al/Fe^{3+})_{\text{garnet}} / (Al/Fe^{3+})_{\text{epidote}}$  in M3 of epidote

Coombs et al., (1977) described various occurrences of andradite and intermediate grandite garnet in low grade metamorphic rocks, of prehnite-pumpellyite and pumpellyite-actinolite facies, from southern New Zealand. They estimated conditions of formation involving temperatures of 300 to 400°C, or less, at pressures up to a few kilobars.

In the Borup Fiord region, neither regional metamorphic nor plutonic rocks are known to date.

The infiltration of high temperature, H<sub>2</sub>O-rich fluid may have caused the precipitation of andradite-grandite garnet, and associated cavity-filling minerals, by means of metasomatic reactions between the fluid and the altered basalt, along the rims of cavities, under hydrothermal or shallow burial conditions, where oxygen fugacity was relatively high, although the heat source is uncertain.

### Conclusions

1. There are three major mineral assemblages of cavity filling minerals:
  - Ia. Garnet – epidote – prehnite – calcite – quartz – iron oxides ± chlorite
  - Ib. Garnet – epidote – prehnite – quartz – iron oxides
  - II. Garnet – epidote – calcite – quartz – iron oxides
  - III. Epidote – iron oxides
2. Temperatures calculated from coexisting garnet and epidote are twofold: prehnite-bearing assemblages with temperatures less than 200°C, and prehnite-free assemblages with temperatures ranging from 500° to 550°C. These results lead to the assumption that the various mineralization stages were preserved metastably in the same specimen, as physico-chemical conditions changed during mineralization.
3. Carbonation of basalt transforms the chemical composition of basalt so as to more readily produce epidote solid solution. The subsequent infiltration of high temperature, H<sub>2</sub>O-rich-fluid may have caused the precipitation of andradite garnet.
4. It is concluded that the garnet and associated cavity filling minerals may have been produced during local hydrothermal alteration of the Esayoo basalts, in the Borup Fiord region.

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