

Kaersutite overgrowths on highly aluminous titanaugite in the Quarsut sill

THE type locality for the Ti-rich hornblende, kaersutite, is the 50 m thick alkaline picrite sill at Quarsut, east Greenland (Lorenzen, 1884), in which the amphibole forms either discrete elongate crystals or fringes on augite crystals in late-stage pegmatite veins and segregations of monzonite composition (Drescher, 1932). This note reports overgrowths of kaersutite on exceedingly aluminous titanaugite in the marginal facies of the sill, and contrasts the compositions of this amphibole and pyroxene with those in the pegmatite.

Petrography of the chilled margins. The fine-grained olivine pyroxenite at the sill margins consists of elongate, skeletal titanaugite crystals (up to 3 mm long), which are continuously zoned, subhedral, skeletal olivine microphenocrysts (up to 0.8 mm diameter; Fo_{88}), and euhedral chrome spinels (~ 0.05 mm diameter; $\text{Mg}_{0.62}\text{Fe}_{0.41}^{2+}\text{Cr}_{1.17}\text{Al}_{0.73}\text{Fe}_{0.04}^{3+}\text{Ti}_{0.03}\text{O}_4$). These are set in a pale-green, TiO_2 -poor glass (TiO_2 0.10-0.19 wt. % SiO_2 40-6 wt. %) containing cryptocrystalline material. Kaersutite forms 5-10 μm wide, pleochroic fringes completely, or partially surrounding, the titanaugite crystals. Rock at the sill margin is feldspar-free, whereas several centimetres from the contact it contains radiating plagioclase, but lacks olivine. Fringes of kaersutite occur on augite in some pegmatite veins in the sill, and Drescher (1932) has shown that the *c* and *b* axes of the two minerals coincide. In contrast, a Universal Stage examination of the mutual orientation of titanaugite crystals and their kaersutite fringes in samples from the chilled margins indicates no consistent crystallographic relation between the two minerals. (In the pegmatite samples examined in this study the kaersutite and pyroxene form discrete crystals, with no fringing relations.)

Compositions of kaersutite and pyroxene in the chilled margins and the pegmatite. The compositions of pyroxene and kaersutite crystals (not overgrowths) in a sample of pegmatite and of titanaugite crystals and their kaersutite fringes in a sample from the chilled lower margin of the sill have been determined by electron microprobe analysis (Table I). The kaersutite fringes in the chilled margins contain less Si, Mg, and Ca and more Al, Cr, and Fe than kaersutite phenocrysts in the monzonite pegmatite (Table I, columns 1-5). The Ti content of these fringes is similar to that of kaersutite phenocrysts in the pegmatite analysed in the present study and to those analysed by Kunitz (1930); however, it is approximately half that of kaersutite in the pegmatite samples examined by Gossner and Spielberger (1929) and by Washington and Wright (1908).

The titanaugite crystals in the chilled margins show extensive continuous normal zoning, accompanied by increases in both Ti and Al contents and decrease in Cr and Ca (Table I, nos. 6a and b). The crystals are rich in both Ti and Al in comparison with the augite in the pegmatite (Table I, nos. 6 and 7). The titanaugite is exceedingly silica-undersaturated, having both nepheline and calcium silicate in the norm. Augite crystals in rocks of alkaline affinity are characterized by large Ca, Ti, and Al contents (Kushiro, 1960; Le Bas, 1962; Aoki, 1964; Table II, nos. 1-4). However, the Al_2O_3 contents of the titanaugite in the margins of the Quarsut sill are considerably more aluminous than these. Augites of similar Al_2O_3 content occur in igneous rocks contaminated by limestone or pelitic rocks (Table II, nos. 5-7), but of these rocks only the Vesuvius lava contains augite with as large a $\text{CaAl}_2\text{SiO}_6$ content as the titanaugite in the Quarsut sill margins. The country rock at Quarsut is a siliceous sandstone

TABLE I. *Analyses of kaersutite and pyroxene in the Quarsut sill*

	Kaersutite						Pyroxene		
	1*†	2a*†	2b*†	3	4	5	6a**	6b**	7**
SiO ₂	36.81	41.21	43.32	39.70	39.50	39.52	45.60	40.94	52.33
TiO ₂	5.28	5.79	4.74	6.53	10.33	10.31	2.25	3.29	0.53
Al ₂ O ₃	17.37	11.71	9.24	11.83	11.12	11.12	10.85	13.84	0.64
Cr ₂ O ₃	0.13	0.00	0.00	n.d.	n.d.	n.d.	0.13	0.00	0.00
Fe ₂ O ₃	—	—	—	4.92	0.06	1.22	1.18	1.89	1.66
FeO	19.75	10.86	13.12	5.98	9.44	8.81	5.86	12.31	10.73
MgO	6.38	13.23	12.26	14.72	12.90	13.31	11.48	7.27	13.01
CaO	10.83	11.71	11.31	12.52	10.91	10.93	22.73	20.07	19.81
Na ₂ O	2.39	2.66	2.96	1.84	3.82	2.95	0.30	0.37	0.68
K ₂ O	0.88	0.87	0.99	1.29	1.43	1.07	—	—	—
H ₂ O ⁺	—	—	—	0.85	0.59	0.59	—	—	—
	99.82	98.04	97.95	100.18	100.20	100.00	100.37	100.00	99.43
Si	5.550	6.064	6.429	5.901	5.934	5.921	1.694	1.579	1.985
Al	2.450	1.936	1.571	2.071	1.970	1.981	0.306	0.421	0.015
Al	0.628	0.094	0.045	0.000	—	—	0.169	0.208	0.013
Ti	0.598	0.641	0.529	0.732	1.167	1.160	0.063	0.096	0.015
Cr	0.013	0.000	0.000	—	—	—	0.004	0.000	0.000
Fe ³⁺	—	—	—	0.540	0.008	0.142	0.033	0.049	0.050
Fe ²⁺	2.481	1.337	1.628	0.744	1.187	1.100	0.182	0.397	0.341
Mg	1.431	2.902	2.712	3.260	2.889	2.971	0.636	0.418	0.736
Ca	1.748	1.846	1.798	1.990	1.757	1.752	0.905	0.829	0.805
Na	0.688	0.758	0.852	0.531	1.113	0.864	0.022	0.028	0.050
K	0.164	0.162	0.188	0.242	0.275	0.200	—	—	—
OH	—	—	—	0.841	0.592	0.590	—	—	—
O	23	23	23	24	24	24	6	6	6
Ca	30.9	30.4	29.3	30.5	30.1	29.3	51.6	48.9	41.6
Fe	43.8	21.9	26.5	19.6	20.4	20.8	12.2	26.3	20.2
Mg	25.3	47.7	44.2	49.9	49.5	49.8	36.2	24.6	28.1
mole % CaAl ₂ SiO ₆ in pyroxene**							16.9	20.8	0

* Probe analysis made on ARL-EMX-SM electron microprobe using 15 kV accelerating potential, 0.02μA sample current and mineral standards (Donaldson, 1975).

† All iron reported as FeO.

‡ FeO and Fe₂O₃ calculated assuming perfect stoichiometry and analysis.

** Calculated by method of Kushiro (1962).

1 Average of four kaersutite fringes on pyroxene crystals in chilled margin.

2a,b Core and rim of kaersutite phenocryst in pegmatite.

3 Bulk analysis of kaersutite in pegmatite (Kunitz, 1930).

4 Bulk analysis of kaersutite in pegmatite (Gossner and Speilberger, 1929).

5 Bulk analysis of kaersutite in pegmatite (Washington and Wright, 1908).

6a,b Core and rim of titanite skeleton in chilled margin.

7 Small anhedral fragment of pyroxene in pegmatite.

with a calcite matrix. Absence of vesicles and amygdales in the chilled margin and the low silica content of the residual glass are not consistent with assimilation of the sandstone.

Origin of high Al content of titanite. The titanite crystals in the chilled margins of the sill are uniquely rich in Al for an uncontaminated alkaline rock. Kushiro (1960) has suggested that high crystallization temperature and large Ti content of the parent melt favour entry of Al into augite crystals. However, there is neither field nor petrographic evidence for extreme contact metamorphism at the sill margins (Drever, pers. commun.), nor is the titanite unusually rich in Ti (cf. Tables I and II).

The skeletal shapes of titanite and olivine crystals and the presence of glass and crypto-crystalline material indicate rapid solidification of the margins of the Quarsut sill. Possible cooling conditions are indicated from the resemblance of the shapes of the titanite crystals to those of pyroxenes grown from a lunar basalt cooled at 10–30°/hr and to others crystallized isothermally from the same basalt at degrees of supercooling ranging from 10–20 °C (Lofgren *et al.*, 1974, figs. 2c and d). Crystallization experiments on basic rock melts at controlled cooling rates indicate that rapid cooling of magmas causes nucleation of feldspar at temperatures much less than the equilibrium crystallization temperature (Lofgren *et al.*, 1974; Walker *et al.*, 1976) and this seems to be the cause of its absence in the chilled margins of the Quarsut sill. In coarser-grained, more slowly cooled rocks several metres from the sill margins, textural relations indicate nucleation of plagioclase before augite; furthermore, this augite contains only 6.4 wt. % Al_2O_3 .

TABLE II. Comparison of the compositions of augites in rocks of alkaline affinity (rows 1 to 4) and in contaminated rocks (rows 5 to 7)

Rock type and occurrence	Reference	CaO wt. per cent	TiO ₂ wt. percent	Al ₂ O ₃ wt. percent	CaAl ₂ SiO ₆ mole percent
Theralite; Square Top Intrusion, New South Wales	Wilkinson, 1966	21.42	2.12	7.33	8.6
Teschenite, Black Jack Sill	Wilkinson, 1957	22.35	3.04	6.61	6.0
Groundmass in alkali olivine basalt, Japan	Aoki, 1964	21.75	3.98	6.65	3.5
Trachyte, Vesuvius	Rahman, 1975	22.88	1.52	7.40	9.4
Trachyte, Vesuvius	Savelli, 1967	16.4	0.97	13.8	22.7
Norite, Haddo House	Dixon and Kennedy, 1933	24.06	5.72	14.29	9.8
Dolerite, Scawt Hill	Tilley and Harwood, 1931	23.57	3.85	10.30	6.0

The evidence therefore indicates that the aluminous nature of the titanite crystals in the chilled margins was caused by rapid cooling, which prevented nucleation of plagioclase. The activity of Al in the melt was therefore larger than during equilibrium coprecipitation of augite and plagioclase, and the pyroxene did not have to compete with plagioclase for available Al. Crystals of aluminous pyroxene in some lunar mare basalts apparently have the same origin (Bence and Papike, 1972); the zoning pattern of these crystals shows an abrupt decrease in Al content, which correlates with the nucleation of plagioclase (Drever *et al.*, 1973).

Kaersutite crystallization. Phenocrysts of titanite are partially, or completely, replaced by kaersutite in trachybasalt lavas of the Iki Islands (Aoki, 1959, 1963) and fringes of kaersutite on augite occur in oligoclase dolerites of the Skaergaard area (Vincent, 1953). Interstitial augite crystals in layered basic and ultrabasic rocks may also be rimmed by kaersutite, e.g. in the Rhum intrusion (Donaldson, 1975). All these occurrences have been attributed to a reaction relationship between pyroxene and melt at temperatures between 950 °C and 1050 °C (Yagi *et al.*, 1975). Assuming that the kaersutite fringes in the Quarsut chilled margins have a similar origin, it is clear that the reaction is an exceedingly rapid one. Alternatively, the absence in the chilled margins of an epitaxial relation between the titanite and kaersutite, which indicates that the latter crystallized rapidly on the former, could reflect passive coating

of the pyroxene by the amphibole, with the amphibole nucleating heterogeneously on the pyroxene.

The more slowly cooled, plagioclase-bearing rock several metres from the sill margins lacks kaersutite, but contains scarce biotite, some crystals of which partially fringe a few of the augite crystals. It is, therefore, possible that the formation of kaersutite fringes on the titan-augite in the chilled margins was favoured by the rapid cooling conditions. Clearly the origin of these fringes is obscure; nonetheless, whichever interpretation of their origin is correct, the low Ti content of the residual glass in the chilled margins points to the efficiency with which the non-equilibrium crystallization of titanaugite and kaersutite depleted the melt in Ti.

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