Example of magma mixing from the Kialineq district of East Greenland

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An occurrence of basic pillows enclosed in a syenitic matrix is described from the little-known Kialineq district. Cuspate margins, chilled contacts and long fingers of syenite extending upwards into the basic material are evidence that the two magmas were fluid at the same time. Hybridization between these two magmas has produced a microdiorite. The chemical variation in these rocks is linear and quite dissimilar to that observed in other suites from the East Greenland Tertiary but resembles that observed both in mixed rocks from other parts of the province, e.g. eastern Iceland, and in calc-alkaline rocks from orogenic regions.

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The Tertiary to Recent North Atlantic igneous province is particularly rich in examples of acid and basic rocks in close association with each other and it was this relation in Iceland which led Bunsen (1851) to postulate that all igneous rocks were derived by mixing in various proportions of two primary magmas, one basaltic, the other rhyolitic.

Particularly well-known examples of this intimate association are the composite sills and dikes of the Hebridean region, the net-veined intrusions of eastern Iceland and composite lavas in Iceland. All these types of occurrence as well as others have been reviewed by Walker & Skelhorn (1966). In some cases, hybrid rocks have been produced by magma mixing, as in the well-known marscoite of Skye (Wager et al. 1965) while the chemical aspects of such hybridization has been documented in detail for the Stretishorn composite dike in Iceland by Gunn & Watkins (1969).

[In this paper, I use the term *hybridization* to mean any intermediate rock produced by mixing of two or more end-members, whether liquid, solid, or a mixture of the two. *Assimilation* I use in the sense of hybridization with solid materials as discussed by Bowen (1928, chapter X) and demonstrated in nature by Eichelberger (1975). *Contamination* is roughly synonymous but has a sense in some cases that the mixing process is variable from constituent to constituent, e.g. some trace elements or isotopic ratios may be affected but not the major elements. Where hybridization arises by straightforward mixing of two liquid end-members, I will refer to this as *magma mixing*].

In the East Greenland sector of the North Atlantic province similar phenomena have not been recorded and it is the purpose of this note to describe an isolated example and to examine to what extent the process of hybridization has been important here.

The Kialineq district lies at about 67°N, some 200 km north of Angmagssalik and is an extremely mountainous area, broken up into many steep islands and headlands. Inland it is heavily glaciated. As an example of the extreme topography, the island of Stor Tindholm is 600 m high and less than 1 km wide. The geology is poorly documented, doubtless due to the nature of the terrain and the area's general inacessibility, but consists of a number of syenitic and granitic intrusions together with a large layered gabbro, the Imilik gabbro, which may be as much as 60 km in diameter but is largely concealed by the sea. Extensive areas are occupied by net-veined rocks, called here the "breccia complex". These igneous rocks are Tertiary in age and intrude a basement of Precambrian gneisses. A brief description of the Tertiary rocks, together with a map, has recently been published by Deer (1976) but it is clear that the area is extremely complex.

The samples to be described here were collected at Nûk, which is a headland opposite the steep granitic island of Qajarsak. Nûk is shown on the 1:250,000 map published by the Geodetic Institute (Copenhagen) as an island, but it in fact joined to the mainland by a tombola. It is the only site in the area to have been inhabited in recent years. The relationships displayed at Nûk appear to be typical for the so-called breccia complex as a whole.

Nûk consists largely of a grey microdiorite in which biotite is a conspicuous feature in hand specimen. Unfortunately, the field relations between this rock and those to be described below were not examined in detail although it clearly overlies them, at least at the western end of the headland.

On the mainland, just behind Nûk, extensive areas are occupied by the breccia complex, which consists of dark blocks embedded in a syenitic matrix. These dark blocks vary from angular to rounded, the latter with cuspate and chilled margins. In the first case, it is clear that the basic material was already solidified sufficiently to fracture in a brittle manner when the syenitic magma was intruded. The latter case, illustrated in figs 1–4, provides an example of intrusion of the syenitic magma while the basic magma was still largely liquid and the basic magma was thereby disrupted into pillows which chilled against the much cooler syenitic liquid in the manner well-known from other occurrences in Iceland and the Hebrides. Exactly similar relationships are described by Walker & Skelhorn (1966) from these places (see, for example, their fig. 1, D and E and fig. 2 B).

At the north-western end of Nûk the syenite can be seen underlying the dark material with a zone of basic pillows between the two and long fingers of syenite reaching upwards into the dark material. Such fingers are also well-known from the other localities (Walker & Skelhorn 1966) and just as in these other cases, the chilled basaltic margins gradually disappear as the finger is followed upwards, indicating the gradual heating up of the syenite as it rose into the hot basic magma. These fingers or pipes apparently arise as a consequence of instability due to viscosity and density contrasts between the two liquids as analysed theoretically by Saffman & Taylor (1958). Their equation shows that if a fluid 2 is injected into fluid 1 with a velocity of W, the interface between the two liquids is unstable if:

$$\left(\frac{\mu_2}{k_2} - \frac{\mu_1}{k_1}\right) W + (\varrho_2 - \varrho_1)\, g < O$$

Where μ and ϱ are the viscosities and densities of the two liquids and k is the permeability.

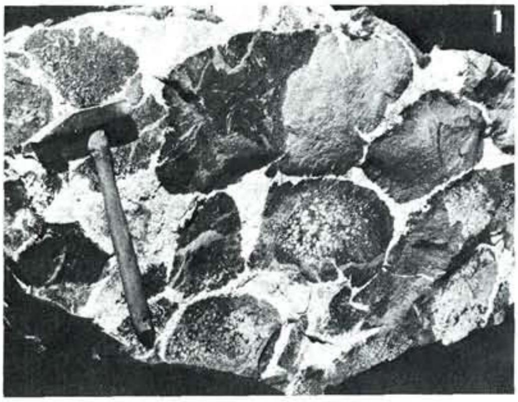
In this case μ_2, refers to the syenite magma and is likely to be less than μ_1, that of the basic magma because the latter is in the process of freezing (as evidenced by the chilled margins) while the former is becoming superheated (disappearance of chilled margins in upper regions of the fingers). In addition the second term, which refers to densities, is also negative as $\varrho_{\text{basalt}} > \varrho_{\text{syenite}}$. Instability will therefore be favoured and longer fingers of syenite will propagate rapidly upwards into the basic magma, becoming superheated in so doing. This situation would appear to be ideal for promoting hybridization by mixing of the two magmas and suggests that the overlying microdiorite has been generated by this process.

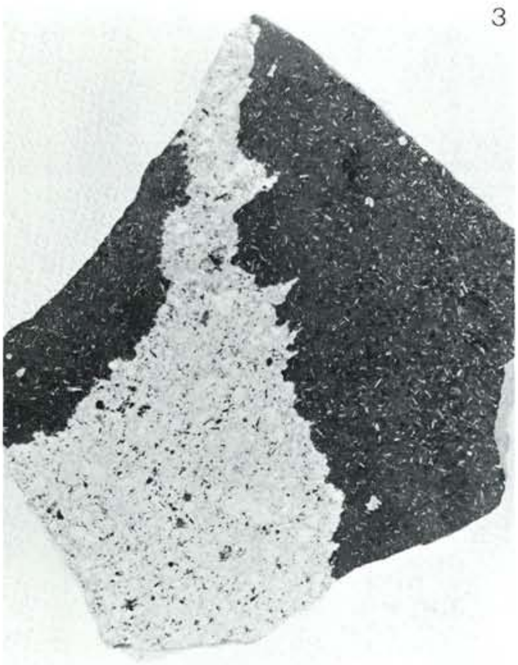
All the above-mentioned rock types in the immediate neighbourhood of Nûk are cut by rocks of granitic composition. Some of these are very fine-grained felsites with a peralkaline chemistry (Brooks & Rucklidge 1976) while others are more coarse-grained and may or may not be peralkaline.

Petrology

Sample no. CBK 71–11 is illustrated in fig. 3 and was chosen as being typical of the breccia complex. It comes from the steep fellside behind Nûk. The microdiorite (CKB 71–95 was collected at Nûk itself. Chemical analyses of the light and dark portions of CKB 71–11 and of the microdiorite are reported in table 1.

The syenite is hypidiomorphic with a grain size of up to ½ cm. It is a subsolvus type with co-existing perthite and oligoclase, the latter usually rimmed by perthite. Quartz forms interstitial pools and is present to the extent of about 10%. The main ferromagnesian mineral is green hornblende, while accessories are biotite, opaque oxide, zircon and a strongly pleochroic mineral, probably identical to the chevkinite reported by





Figs 1–3. Photographs illustrating the dark pillows enclosed in syenite at Nûk, Kialineq. 1 &2: Note the rounded aspect of the dark pillows and their cuspate and chilled margins. In 2 the chilling is particularly strongly brought out by a clear difference in weathering colours. 3: Polished hand specimen (CKB71–11), ca. 10 cm wide showing the cuspate and chilled margins to the dark pillows, basic inclusions in the syenite and syenitic inclusions in the pillow. Needle-like microphenocrysts of plagioclase are visible in the pillow. The analysed material (table 1, columns 1 and 3) were sawn out of this hand specimen. Fig. 4. Field relationships at the north-western end of Nûk, showing massive basic rock injected from below by a syenite which has broken it up into pillows and penetrated upwards as numerous thin fingers (note hammer for scale at bottom right of exposure).

Table 1. Compositions of the dark pillows, the grey microdiorite and the syenitic matrix from the breccia complex at Nûk, Kialineq district.

	1.	2.	3.		1.	2.	3.
SiO_2	50.95	58.52	66.89				
Al_2O_3	16.30	16.28	15.49	Q	–	6.63	12.91
Fe_2O_3	2.42	2.43	1.23	OR	11.72	16.37	32.99
FeO	7.59	4.89	1.55	AB	39.37	43.07	44.07
MgO	3.94	2.31	0.57	AN	17.13	13.39	3.05
CaO	7.03	3.94	1.41	NE	1.17	–	–
Na_2O	4.85	5.09	5.13	DI	10.75	1.62	2.35
K_2O	1.96	2.77	5.50	HY	–	9.37	1.45
MnO	0.23	0.14	0.07	OL	9.22	–	–
TiO_2	2.74	1.74	0.49	MT	3.55	3.52	1.81
P_2O_5	0.77	0.64	0.18	IL	5.26	3.25	0.94
H_2O^+	0.98	0.93	0.57	AP	1.80	1.48	0.43
sum	99.76	99.65	99.08				
ΣFeO	9.77	7.08	2.66				
Trace elements							
Sr	660	565	295				
Ba	550	820	700				
Zr	290	385	485				
Cr	<10	<10	<10				
Ni	<10	<10	<10				
V	168	66	30				
Co	22	<10	<10				

Major elements by X-ray fluorescence (Geological Survey of Greenland, Sørensen 1975).
Trace elements by optical spectrography (Haldis Bollingberg).

1. CKB71–11, dark pillow, material close to contact with syenite.
2. CKB71–95, grey microdiorite, typical of material forming the majority of the headland at Nûk.
3. CKB71–11, light syenitic matric.

NB: Material for the analyses reported in col. 1 and 3 were sawn from the specimen depicted in fig. 3, taken from the hillside behind Nûk. C.I.P.W. weight norms are calculated on a volatile-free basis without any adjustment to the Fe_2O_3/FeO ratio.

Brooks & Rucklidge (1976). The analysis (table 1) shows that this rock is not peralkaline (as many of the East Greenland syenites are) and it contains ca. 13% normative quartz as opposed to 2% in the average syenite of the area quoted by Brooks & Rucklidge (1976).

The dark pillows contain elongated phenocrysts of plagioclase, 1–2 mm long and about 0.1 mm thick. The groundmass is fine-grained, increasingly so towards the contact with the syenite.

It consists of plagioclase (very strongly normally zoned but with homogeneous cores around An_{50}), green hornblende and biotite. Clots of hornblende, biotite and ore apparently represent original pyroxene phenocrysts. This rock is considerably richer in alkalis than typical East Greenland basalts and the normative feldspar composition is for instance Or_{17} Ab_{58} An_{25}. This combined with the fact that occasional perthite fragments occur indicates that mixing has already occurred to some extent, although data are not extensive enough to calculate the original composition form the amount of xenocrysts derived from the syenite, as shown by Walker & Skelhorn (1966). The small amount of normative NE in this rock cannot be assumed to indicate that it was originally an alkali basalt, as selective diffusion of alkalis may have taken place (see below).

The microdiorite of Nûk is a fine- to medium-grained grey rock consisting of plagioclase, showing very strong normal zoning throughout the entire grains, abundant biotite (showing incipient alteration to chlorite), minor green hornblende and opaque ore. Zircon is a conspicuous accessory while fine needles of apatite occur throughout the rock. This rock is almost exactly

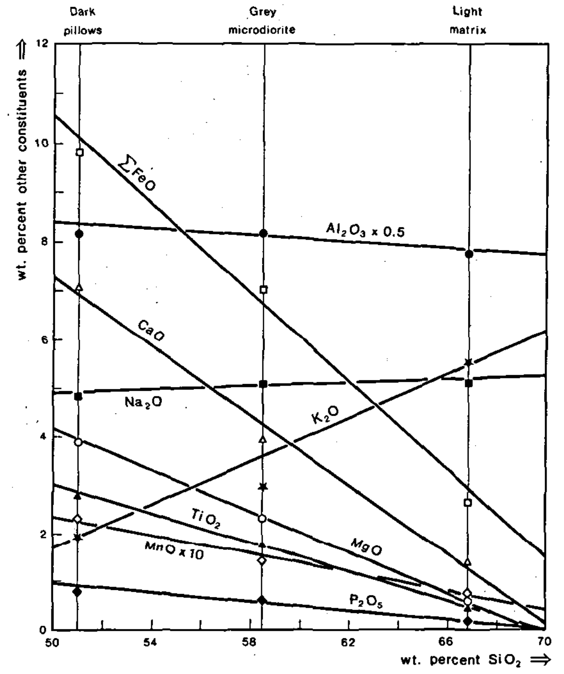


Fig. 5. Silica variation diagram for the three analyses from the Kialineq breccia complex demostrating that the grey microdiorite lies approximately half-way between the two other samples. The only significant departure from straight-line mixing is shown by K_2O.

intermediate in composition between the light and dark part of the breccia complex, thus confirming the field impression that it is a hybrid. Fig. 5 shows a mixing diagram, on which the only significant departure from straight line mixing curves is shown by K_2O.

Table 2 shows a comparison between the composition of the microdiorite and a 1:1 mixture of the two parts within the breccia complex. Again the match is very close although it can now be seen that not only K_2O is abherrent, but also Ba and Sr. The fact that it is only the more labile elements which show this departure from ideal mixing strongly suggests that some selective diffusion was operative which did not affect the bulk of the constituents. An alternative explanation of these divergences may be that the sampled microdiorite was not formed from parents exactly similar to the investigated sample from the breccia complex which came from some 2 km distant.

Table 2. Comparison between a 1:1 mixture of the material forming the dark pillows and the syenitic matrix with that of the grey microdiorite.

	1.	2.
SiO_2	59.85	59.40
Al_2O_3	16.14	16.53
ΣFeO	6.31	7.19
MgO	2.28	2.34
CaO	4.28	4.28
Na_2O	5.07	5.17
K_2O	3.79	2.81
MnO	0.15	0.14
TiO_2	1.63	1.77
P_2O_5	0.48	0.65
Sr	477	565
Ba	625	820
Zr	387	385
V	99	66

1. Calculated composition of a 1:1 mixture of the dark pillows and the syenitic matrix in sample no. CKB71-11.
2. Composition of the grey microdiorite.

NB: Both analyses have been recalculated to 100% on a volatile-free basis and with all iron as FeO.

Discussion

As shown above, the microdiorite, which makes up the bulk of the headland at Nûk, was apparently formed by mixing of basic and syenitic magmas. These magmas were both available in large amounts throughout the East Greenland Tertiary province and it is natural to enquire if this process has been widespread in the area.

The answer to this must be that it has not. Rocks similar to the microdiorite have not been reported elsewhere, although it is not unlikely that they will be recognized in the future. Intermediate rocks in general are not common in the area although Nielsen (1976) found a complete spectrum of rock types within the coastal dike swarms. Plutonic rocks of intermediate composition also occur in the layered gabbroic intrusions. However, these rocks are chemically quite distinct from the microdiorite in showing iron enrichment, most extreme in the Skærgaard ferrodiorites (fig. 6). Hybridization in East Greenland therefore appears to be process of minor importance, as is the case elsewhere in the North Atlantic Province.

However, as other authors have pointed out,

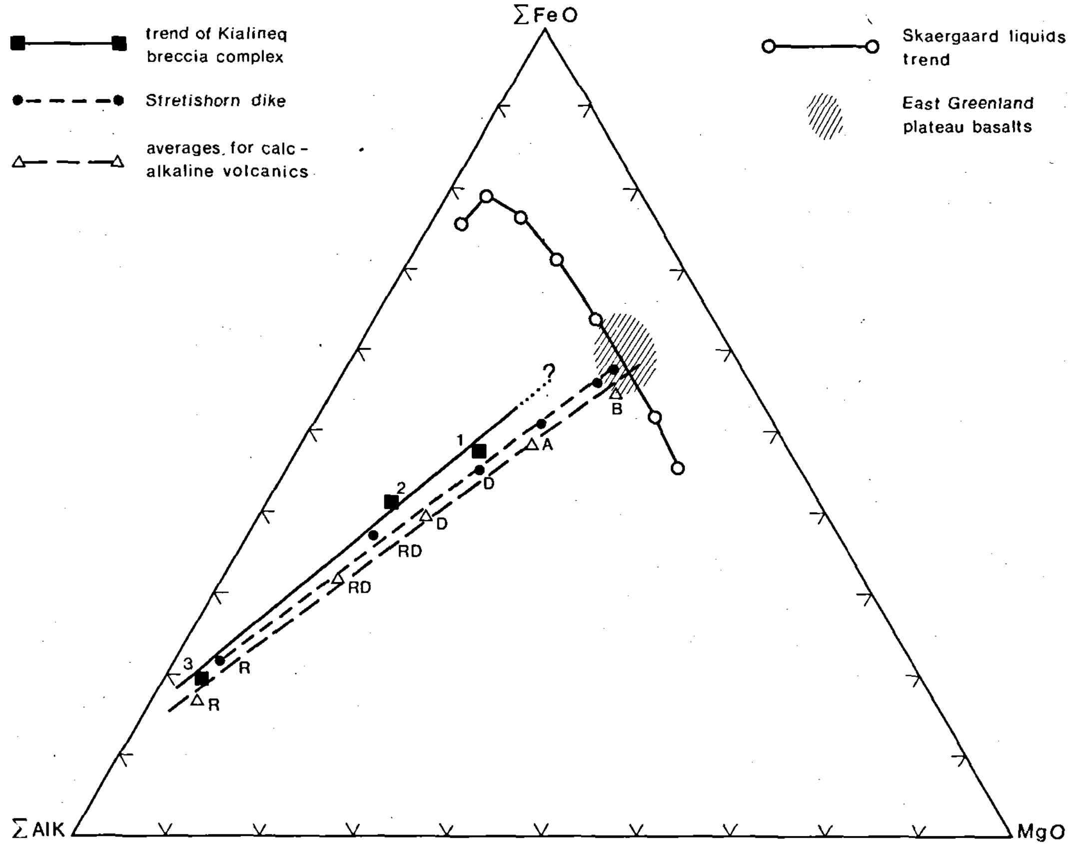


Fig. 6. Triangular diagram showing the trend of the three components of the Kialineq breccia complex in terms of magnesium, total iron and total alkalis. Comparative data are taken from the following sources. Stretishorn dike, Gunns & Watkins, 1969; average calc-alkaline volcanics, Nockolds (1954); Skærgaard liquids trend, Wager (1960) and East Greenland plateau basalts, Brooks et al. (1976). 1, 2 and 3 refer to the dark pillows, the grey microdiorite and the syenitic matrix respectively. B, A, D, RD and R are Nockold's averages for tholeiitic basalts, andesites, dacites, rhyodacites and rhyolites respectively.

the trend of such rocks (e.g. on an FMA diagram, fig. 6) is similar to that observed in calc-alkaline rocks from orogenic regions. This was stressed for example by Gunn & Watkins (1969) in the case of the Stretishorn dike. It appears in the light of recent work, that mixing is an important process in the genesis of intermediate calc-alkaline rocks, either by assimilation of solid materials, as argued by Eichelberger (1975), or by magma mixing, as demonstrated by Anderson (1976).

I suggest that the reason for the frequency of hybridization in orogenic rock suites compared to anorogenic ones is the availability of volatiles. Much evidence (e.g. the abundance of hydrous minerals) suggests that the former are rich in volatiles whereas the latter are poor. A high volatile content affects the relative viscosities leading to the type of instability discussed above and this in turn leads to an intimate mixing of the basic materials with the superheated acid magma. In this connection, the Kialineq microdiorite with its abundant biotite, resembles more closely orogenic rock associations than the intermediate members of the tholeiitic association such as the Thingmuli icelandites (Charmichael 1964) or the Skærgaard ferrodiorites (Wager & Brown 1968), which are composed of anhydrous phases.

Perhaps the most interesting aspect of this study is that it demonstrates that syenitic magmas were occasionally in existance simultaneously with substantial amounts of basic magma in the province. There is otherwise a substantial time gap between the outpouring of the plateau lavas and intrusion of the major gabbroic plutons on the one hand and the emplacement of the syenites on the other. According to radiometric dating this time difference was of the order of 5 m.y. (Brooks & Gleadow in prep.). It would therefore be of great interest if the precise nature of the basic parent could be identified. However, in the samples at present available considerable hybridization has already taken place in the basic pillows and this is not possible.

In conclusion, the magnificiently exposed breccia complex at Kialineq, preserving as it does beautiful examples of contemporaneous magmas of extreme composition and hybrid rocks formed by their mixing, deserves a much more detailed study than that presented here.

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Dansk sammendrag

Et udbredt bjergarts kompleks i Kialineq distrikt, Østgrønland, bestående af basiske »pillows« med finkornede uregelmæssige kontakter til en syenitisk matrix, beskrives. Disse kontakter viser, at der er sket en næsten samtidig intrusion af de to smelter.

Geokemiske undersøgelser viser, at magma blanding mellem det basiske og syenitiske materiale har givet ophav til intermediære bjergarter, svarende til kalk-alkaline andesiter. Bjergarter af denne type er hidtil ukendt fra Østgrønland men velbeskrivede forekomster findes andre steder i den tertiære nordatlantiske magmaprovins.

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