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A differentiated ultrabasic sheet on Sgurr Dearg, Isle of Skye

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SUMMARY. The field relations, mineralogy, and petrography of a small Tertiary ultrabasic sheet are briefly described. Chemical analyses show that compositional variations exist within the intrusion and electron-probe analyses demonstrate that optically undetectable zoning is present in the olivine. Throughout the intrusion, which is composed primarily of forsteritic olivine, calcic plagioclase, and clinopyroxene, there is a differential distribution of olivine. This distribution is attributed to flow differentiation during intrusion followed by gravitative sinking of olivine crystals.

STRADDLING the main ridge of the Cuillin Hills between 50 and 150 metres south of the Inaccessible Pinnacle of Sgurr Dearg is a small complex of Tertiary minor intrusions. This complex (fig. 1) consists principally of four ultrabasic dykes, two basic dykes, and the ultrabasic sheet which is the topic of this paper.

Field relations

The ultrabasic sheet, which intrudes and is chilled against 'gabbro' of the Main Ridge Complex (Hutchison, 1966), is 1·4 m thick and dips gently to the east. At its north end the sheet lies just below the Cuillin ridge, but to the south, the upper surface actually forms the ridge for about 30 m. Apart from a 20 cm thick basic dyke that cuts its north end, a wider one at its south end, and possibly a porphyritic dolerite dyke (fig. 1), the ultrabasic sheet appears to be the youngest member of the complex. For a few cm above the base of the sheet a fine lamination parallel to the lower contact is visible on the weathered surface (fig. 2). The lower and marginal parts of the sheet are relatively rich in olivine phenocrysts but approximately 1 m above the lower contact there is a sudden change to an upper, olivine-poor part, the junction between the two parts usually weathering out as a step. The sheet can therefore be divided into four parts, namely (in ascending order), the lower chilled margin, the olivine-rich zone, the non-porphyritic zone, and the upper chilled margin.

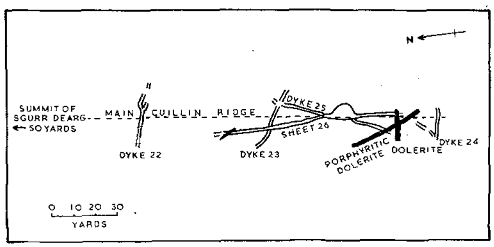
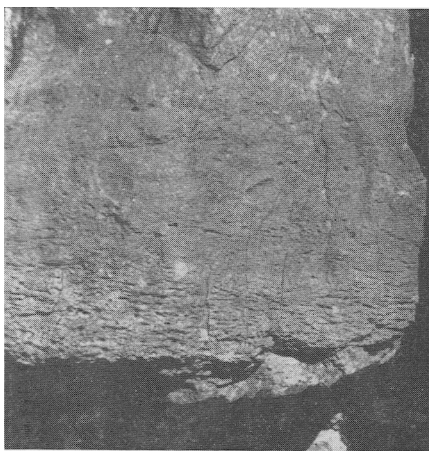
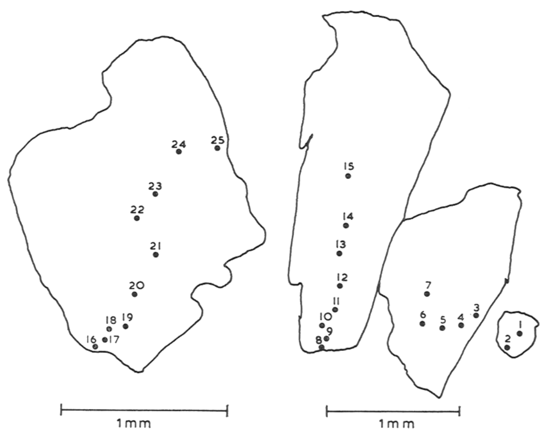


FIG. 1. Map of the minor intrusions immediately south of the Inaccessible Pinnacle, Sgurr Dearg.

Mineralogy and Petrography

The *lower chilled margin* extends upwards from the contact for approximately 30 mm. On a microscopic scale the contact is irregular and small fragments of 'gabbro' occur throughout the lower chilled margin. The contact rock is composed of olivine phenocrysts ($22\frac{1}{2}$ %) up to 2 mm long in a matrix of partially devitrified brown glass. The olivine crystals increase in size and amount away from the contact and 15 mm above the contact they may be as long as 5 mm. Approximately 20 mm above the base of the sheet the groundmass is microcrystalline and at the top of the lower chilled margin small variolitic intergrowths of clinopyroxene and plagioclase are discernible. Small plagioclase phenocrysts (less than 0·3 mm long) occur throughout the lower margin but are more abundant near the contact and are most probably xenocrysts.





FIGS. 2 and 3: FIG. 2 (left). Lamination on the weathered surface immediately above the lower contact. The area shown is 80 cm square. FIG. 3 (right). Tracings (from photomicrographs) of olivine crystals from the lower chilled margin showing the spatial relationships of the analyses presented in table I.

The compositions of a number of olivine crystals from the lower chilled margin have been determined by electron-probe microanalysis. Several spots within each crystal were analysed and the results for the four typical olivine crystals shown in fig. 3 are presented in table I. There is a slight but definite normal zoning throughout each of the crystals, which is most marked near the edges of the crystals, and it appears that the centres of smaller crystals are slightly more fayalitic than those of larger crystals (cf. analyses 1, 7, and 15, table I). No marginal zoning can be detected optically.

Stringers about 0·25 mm thick transgress the chilled margin, occasionally swelling to patches several mm in diameter. These stringers are composed of small plagioclase laths and granular crystals of clinopyroxene and magnetite. They are noticeably coarser-grained than the glassy or microcrystalline groundmass of the lower chilled margin and appear to have been formed by the injection of magma from slightly higher in the sheet subsequent to the initial chilling of the lower contact.

With the increase in the groundmass grain-size the lower chilled margin grades rapidly upward (fig. 5) into the olivine-rich zone.

TABLE I. *Electron probe analyses of olivine crystals from the lower chilled margin and the olivine-rich zone (numbers correspond to figs. 3 and 4)*

Lower chilled margin								Olivine-rich zone			
No.	% Fo	No.	% Fo	No.	% Fo	No.	% Fo	No.	% Fo	No.	% Fo
1	87·6	8	89·2	15	91·8	22	91·6	26	92·3	33	92·8
2	86·9	9	89·4	16	88·8	23	91·5	27	92·8	34	92·8
3	89·1	10	90·0	17	90·4	24	91·4	28	92·8	35	88·7
4	90·4	11	90·4	18	91·1	25	89·7	29	92·9	36	88·7
5	91·0	12	90·9	19	91·2			30	92·0	37	88·9
6	91·1	13	91·1	20	91·3			31	91·6	38	88·3
7	91·3	14	91·7	21	91·5			32	92·8		

Olivine-rich zone. At the bottom of the olivine-rich zone (fig. 5) the rock is composed of olivine phenocrysts ($35\frac{1}{2}$ %) in a variolitic groundmass of plagioclase laths, pale brown clinopyroxene, and small olivine crystals with accessory chrome spinel and magnetite. The olivine crystals may be as long as 5 mm. The variolitic intergrowths have a radius of approximately 0·5 mm. There is an upward increase in the olivine content (fig. 5), until approximately 43 cm above the base of the sheet the rock contains 48 % olivine and the average size of the crystals is at a maximum. Above this the olivine content gradually decreases. Around 20 cm above the base of the sheet the variolitic intergrowths often exceed 4 mm in diameter but above this the growths become less perfect and the texture gradually changes to sub-variolitic. The size of the plagioclase crystals, however, continues to increase until approximately 85 cm above the base they attain a maximum length of 3 mm. The modal composition of the mid point of the sheet is: olivine 42·1 %, altered olivine (mainly serpentine) 2·7 %, clinopyroxene 21·3 %, plagioclase 27·8 %, chrome spinel 1·7 %, chlorite 3·2 %, undifferentiated secondary minerals 1·3 %.

The composition of the olivine crystals in the most olivine-rich part of the zone has been determined optically by measurement of 2V and β and also by electron probe. The optically determined composition is Fo_{91} and the results of the electron-probe analyses for the four typical crystals shown in fig. 4 are given in table I. Like the olivine from the lower chilled margin, individual crystals are of slightly different compositions and are slightly zoned with the zoning most pronounced at the edges.

The plagioclase crystals, which are invariably lath-shaped, are continuously zoned throughout. Electron probe analyses of the centres of a number of crystals gave compositions ranging from An_{74} to An_{81} with a tendency for the larger crystals to have the more calcic centres. The compositions of the central parts of some of the largest laths were also determined optically and the most calcic composition obtained by this method was An_{83}. The range of values obtained may be attributable to the fact that the plane of the thin section does not intersect the most calcic zone of all the crystals but it seems equally probable that there exists a real compositional variation, with the crystals with the more calcic centres having nucleated earlier than those with the more sodic centres. Electron-probe analyses of the edges of some of the crystals indicate that the zoning extends to compositions more sodic than An_{60}.

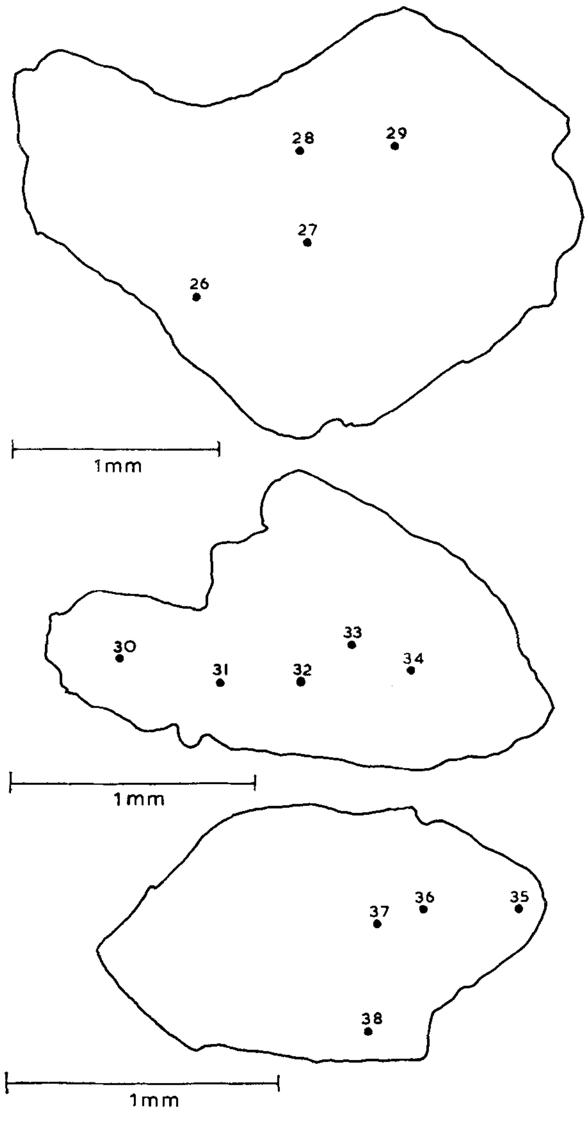


FIG. 4. Tracings of olivine crystals from the olivine-rich zone showing the spatial relationships of the analyses presented in table I.

The lamination observed on the weathered surface at the bottom of the olivine-rich zone is due to a preferred orientation of the short axes of the olivine crystals approximately perpendicular to the base of the sheet, i.e. a planar parallelism of tabular crystals.

In the *non-porphyritic zone* olivine phenocrysts constitute less than 1 % of the rock. Throughout this zone, however, are small patches of brownish material, which may have been formed at the expense of small groundmass olivine crystals. If this is the case, it can be estimated that the rock may originally have contained as much as 5 % groundmass olivine.

Approximately coincident with the bottom of the non-porphyritic zone the texture changes from sub-variolitic to sub-ophitic. Throughout the non-porphyritic zone the grain-size of the rock gradually decreases upward until 40 mm below the top of the sheet the rock becomes microcrystalline.

The composition of the plagioclase in this zone has been determined by electron-probe analysis and found to be essentially the same as that in the olivine-rich zone.

Upper chilled margin. The change to microcrystalline groundmass and the reappearance of abundant olivine phenocrysts mark the bottom of the upper chilled margin. This margin is composed of approximately 17 % small phenocrysts of olivine and spinel in a groundmass of pyroxene, plagioclase, and olivine, which changes from microcrystalline to hyaline towards the upper contact of the sheet. The olivine phenocrysts are sometimes partly replaced by pyroxenes and are usually extensively altered to serpentine and the same brownish mineral as was observed in the non-porphyritic zone. The upper chilled margin differs from its lower counterpart mainly in the scarcity of small plagioclase phenocrysts (or xenocrysts), the smaller size of its olivine phenocrysts, which have a maximum length of 1·5 mm, and its slightly lower olivine content.

Chemical analyses

One specimen each of the olivine-rich zone, the non-porphyritic zone, and the upper chilled margin have been chemically analysed and the results are presented in table II.

TABLE II. *Analyses and norms of specimens from the ultrabasic sheet*

	1	2	3		1	2	3
SiO_2	42·86	44·43	44·89	Qtz.	—	—	—
Al_2O_3	9·20	11·95	11·72	Or	1·42	0·35	0·30
Fe_2O_3	2·57	3·87	6·53	Ab	6·26	10·06	7·87
FeO	7·78	7·20	4·74	An	21·07	27·09	27·66
MgO	24·53	16·63	15·25	Wo	7·08	9·64	7·45
CaO	7·74	10·20	9·29	En	5·38	7·20	6·16
Na_2O	0·74	1·19	0·93	Fs	0·98	1·49	0·36
K_2O	0·24	0·06	0·05	En	6·62	10·90	31·03
H_2O+	2·20	1·79	2·99	Fs	1·20	2·25	1·84
H_2O-	0·22	0·13	1·10	Fo	34·39	16·33	0·54
TiO_2	0·60	0·81	0·68	Fa	6·87	3·72	0·04
CO_2	0·88	0·61	1·05	Mt	3·73	5·61	9·47
P_2O_5	0·06	0·07	0·10	Il	1·14	1·54	1·29
Cr_2O_3	0·24	0·52	0·12	Crt	0·37	0·80	0·18
MnO	0·06	0·17	0·09	Ap	0·14	0·17	0·24
	99·92	99·63	99·53				

1. Olivine-rich zone, 34 cm above the base of the sheet.
2. Non-porphyritic zone, 132 cm above the base of the sheet.
3. Upper chilled margin.

Analyst: F. G. F. Gibb.

The normative amounts of the minerals bear little resemblance to the modal amounts, due mainly to the altered nature of the rocks, particularly specimen 3.

The analyses of specimen 2 from the non-porphyritic zone indicates that this zone is rich in Ca and relatively poor in alkalis

$$100\ (Na_2O+K_2O)/(Na_2O+K_2O+CaO) = 10{\cdot}9$$

and in this respect, therefore, it is similar to the non-porphyritic zones recorded from other ultrabasic minor intrusions by Drever (1956) and Drever and Johnston (1958, 1966, 1967). The differences between the analysis of the olivine-rich zone (1) and that of the non-porphyritic zone can be attributed entirely to the concentration of olivine crystals in the former and it is evident from the alkali/(alkali+lime) ratio of the olivine-rich zone (11·2) that the groundmass of this zone is ultrabasic in its own right (cf. Drever and Johnston 1966) and is essentially chemically identical to the non-porphyritic zone.

Petrogenesis

The nature of the olivine distribution within the sheet, the absence of a chilled contact between the olivine-rich and non-porphyritic zones, the correspondence between the alkali/(alkali+lime) ratios of these zones and the compositions of the olivine and plagioclase throughout the sheet appear to eliminate the possibility of multiple intrusion.

From the scarcity of skeletal olivines, especially near the chilled margins where the relatively rapid cooling would almost certainly have produced them (Drever and Johnston, 1957), and the abundance of translation lamellae in the olivine crystals, which are unlikely to have formed *in situ* (Gibb, 1968*a*), it appears probable that the sheet was emplaced as a suspension of olivine crystals in an ultrabasic liquid. The existence of such a high-lime ultrabasic liquid has been established by Drever and Johnston (1966) and need not be discussed further here.

The upper and lower chilled margins undoubtedly solidified relatively quickly after emplacement and consequently it seems probable that they correspond very closely to the material originally intruded along the top and bottom edges of the sheet. Since these zones contain 17 % and 22½ % olivine respectively and the average olivine content of the sheet is approximately 32 %, it seems reasonable to assume that the central part of the sheet must have contained more olivine than the edges at the time of intrusion. In addition, the average size of the olivine phenocrysts in the sheet is much greater than that of the phenocrysts in the margins. If the sheet was formed by a composite intrusion process with an initial olivine-poor magma being followed by one richer in olivine to form the margins and centre of the sheet respectively, the olivine-poor magma must have originally had a differential distribution of olivine within it to produce the difference in the olivine contents of the two chilled margins. To account for this and the fact that the olivine is concentrated in the lower part of the sheet gravitative settling during and after intrusion might be invoked but such a mechanism would cause the largest phenocrysts to be concentrated at the base of the olivine-rich zone and not the middle. Consequently, the sheet seems unlikely to have been formed by the intrusion of magma with an olivine content that increased during emplacement and was subsequently redistributed by gravitative settling.

Flow differentiation in a vertical or sub-vertical feeder of the sheet (Bhattacharji, 1967; Simkin, 1967), or possibly in the gently dipping sheet itself, could have produced a distribution of the type in which the olivine crystals increased gradually in size and amount from the edges of the sheet towards the centre. The maximum concentration would probably have been slightly below the centre of the sheet due to the effect of gravity (cf. Simkin, 1967) to which may also be attributed the slightly higher content of olivine phenocrysts in the lower chilled margin compared with the upper chilled margin. However, if such a distribution of olivine crystals was effected by flow differentiation, it appears that when flow slowed down and ceased the olivine crystals (other than those trapped in the chilled margins) must have settled under the influence of gravity. It has been pointed out by Bhattacharji (1965), Simkin (1967), and others that the settling rates of crystals decrease considerably with increases in their concentration. It is probable therefore, that the crystals above the level of maximum concentration established by flow differentiation would have settled out relatively rapidly to produce the non-porphyritic zone while those near the maximum may have undergone relatively little settling before the viscosity of the suspending liquid became so great due to crystallization that further sinking was prohibited. The sudden increase in the olivine content immediately above the lower chilled margin (fig. 5) suggests that the crystals at and below the concentration maximum did, in fact, undergo some degree of settling and it was almost certainly this settling that gave rise to the preferred orientation observed at the base of the olivine-rich zone (fig. 2).

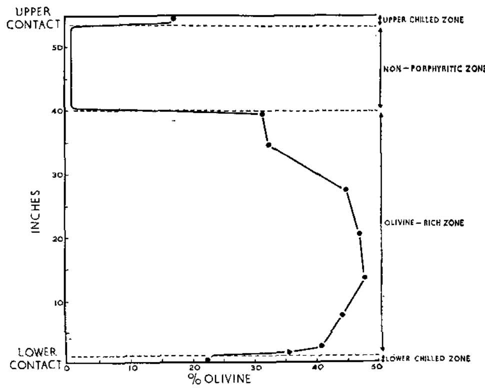


FIG. 5. Distribution of olivine in the Sgurr Dearg sheet.

Conclusions

The field relations, petrography, and chemistry of this ultrabasic sheet all indicate that it is one of the group of relatively small dykes, sills, and sheets that occur throughout southern Skye and the surrounding area (Drever and Johnston, 1967, pp. 70–1; Gibb, 1968*b*). Like several of the other sheets and sills in this group, it exhibits a differential distribution of olivine and it is concluded that the present distribution of olivine in the Sgurr Dearg sheet was caused by flow differentiation during intrusion followed by the formation of the non-porphyritic zone by gravitative sinking of olivine crystals *in situ*.

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