Ferrodiorite from the Isle of Skye.

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Summary. As a preliminary to an account of the marscoite suite of the Western Redhills Tertiary igneous centre of Skye, a description is given here of one unit, the ferrodiorite. While accepting Harker's hypothesis of the hybrid origin of marscoite (1904, pp. 175–196) we consider that the ferrodiorite, with which marscoite on Marsco is associated, is not itself a hybrid, but one of the parents from which the hybrids were formed. Among Thulean igneous rocks the ferrodiorite has mineralogical and chemical affinities with Hebridean mugearites, on the one hand, and with the ferrogabbros of the Skaergaard intrusion on the other, but is probably significantly different from both.

FERRODIORITE forms the greater part of the patches indicated as modified gabbro on Harker's sketch-map of Marsco in the Skye Memoir (Harker, 1904, fig. 36). In the northerly outcrops of the marscoite suite of rocks from Sron a' Bhealain to Glamaig and on to the coast near Moll, no similar ferrodiorite is found although interesting xenoliths of a related material are present in small amounts. Ferrodiorite runs the whole length of Harker's Gully on Marsco, as a sheet between 50 and 70 yds wide and dipping at about 80° south (fig. 1); it is also found associated with marscoite on the east face of Marsco and, as shown by J. D. Bell (unpublished thesis, 1959), it extends to the southern ridge of Glas Bheinn Mhor, where it is cut off by a later granite. The ferrodiorite was intruded immediately after the marscoite proper, and in the field a gradual transition from marscoite to a porphyritic and then to a non-porphyritic ferrodiorite can be seen at many localities. Harker considered that the ferrodiorite in the NW. Gully on Marsco was a feeder-dyke for the Cuillin gabbro intrusion, preserved as a relic in, and acidified by, the later granophyre (1904, p. 180). There is no field evidence to suggest that the ferrodiorite was formed by hybridization in place, and petrological and chemical evidence, as will be shown below, suggests that it is to be regarded as a late-stage fractionation product of basic magma. The ferrodiorite, together with the rest of the marscoite suite, behaves as an integral part of the Western Redhills igneous complex, which came after the Cuillin complex and before the Eastern Redhills complex.

Petrology.

The very tough rock, H. 344, collected from a large overhanging rock or shelter stone at about 800 ft above sea level in Harker's Gully, has been analysed and is typical of the coarser, non-porphyritic type (fig. 2). The approximate volume mode is given in table I.

The plagioclase, average length 1·5 mm, has large cores of An_{49} with strong marginal zoning leading to about An_{30}. The alkali feldspar beyond this is untwinned and turbid. The central part of the plagioclase was no

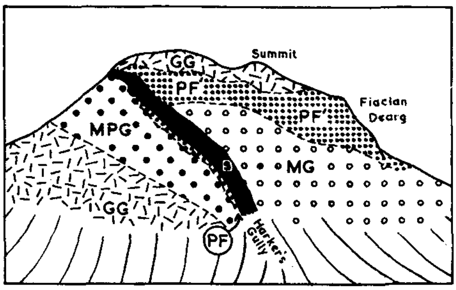

FIG. 1. Marsco from the NW. showing approximate position of the rock types. The black strip indicates the ferrodiorite with a thin zone of marscoite along the left-hand side adjacent to porphyritic felsite, PF; PF′, another type of porphyritic felsite; MPG, Marsco porphyritic granophyre related to PF; GG, Glamaig granite, earlier than the ferrodiorite; MG, Marsco granite, later than the ferrodiorite. S (shelter stone), the locality of the analysed ferrodiorite, H. 344.

doubt one of the earlier minerals to crystallize. Quartz occurs with interstitial habit. Apatite is strikingly abundant in small, well-shaped crystals.

Olivine, although in only small amounts (about 1 %), was an early mineral to crystallize. It is pale yellow in colour and its 2V is 59°, indicating a ferrohortonolite,[1] Fo_{22}. It alters readily to a dark-brown serpentine, and in specimens where no fresh olivine remains its former presence can often be inferred from this characteristic alteration product.

Orthopyroxene is of two kinds: one contains exsolution lamellae indicative of formation by inversion of pigeonite, and the other, free from this type of exsolution, was presumably directly precipitated from the magma. Both have pink to pale green pleochroism while the 2V (−63°) and α refractive index ($>$ 1·725) indicate a composition close to En_{31}. Probably about half the orthopyroxene was formed by inversion

[1] Some of the mineralogical data for this rock are taken from J. D. Bell's unpublished Oxford D.Phil. thesis (1959).

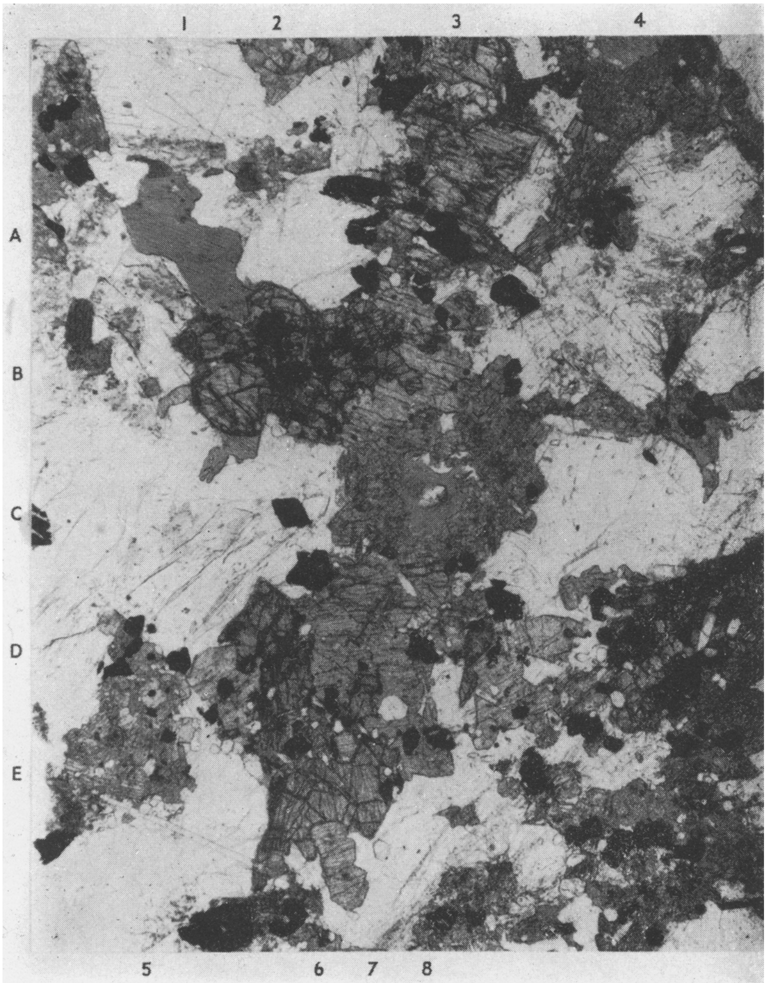

Fig. 2. Ferrodiorite, analysed specimen H. 344, from the shelter stone in Harker's Gully, Marsco. Olivines at 2B and 6E, orthopyroxene at 3 (crystal extends to the olivine 2B), 7D, etc.; clusters of small augites at 8C (with hornblende in centre), 5E, etc.; hornblende at 1A, 4, etc. Plagioclase, alkali feldspar, and quartz cannot be distinguished in the figure. Apatite is conspicuous and abundant. The particular part of the thin section photographed is more melanocratic than the average.

of pigeonite. The inverted pigeonite is often rimmed by directly precipitated orthopyroxene and is then evidently of earlier crystallization.

Augite, pinkish-brown in colour, occurs in clusters of zoned crystals. Very thin exsolution lamellae give faint Newton's interference colours in ordinary light, as in the ferroaugites of the Skaergaard ferrogabbros.

In polished section, the principal opaque constituent is seen to be ilmenite, generally in idiomorphic to euhedral crystals. Perhaps a quarter of the opaque ore is a titaniferous magnetite in less well-formed crystals, showing very fine-scale exsolution networks of ulvöspinel and occasional lamellae of ilmenite. Pyrrhotine, in globular form, is a noteworthy accessory; it is frequently partly or completely altered to marcasite.

The second analysed ferrodiorite, H. 870, collected 30 yds north of the shelter stone, is similar to H. 344 but is more easily weathered and has scattered porphyritic plagioclase crystals, while the rest of the rock is slightly finer-grained. It occurs in Harker's Gully as a persistent variant lying to the north of the non-porphyritic type, that is nearer the marscoite. The chemical analysis of this rock shows that it has essentially the same composition as the non-porphyritic ferrodiorite H. 344, except that the iron is slightly more oxidized (table I). The opaque oxide mineral assemblage in H. 870 is, however, identical with that in H. 344, but the proportion of titaniferous magnetite is apparently higher. Noteworthy accessory pyrrhotine and marcasite occur in this rock also. The analysed porphyritic ferrodiorite is slightly more altered than the non-porphyritic. all the olivine being altered to serpentine.

In the porphyritic ferrodiorite, raft-like masses of coarse andesinite occur. measuring a few inches to a few feet in length. Rather similar small masses also occur in the neighbouring marscoite. The andesinite has the appearance of being the result of an accumulation of plagioclases similar to the larger crystals of the porphyritic ferrodiorite. The andesinites occur as blocks with definite margins towards the enclosing ferrodiorite and they must be regarded as cognate xenoliths rather than aggregations of crystals accumulated in the position in which they now occur.

The compositions of the plagioclases and olivines that are found together in the Skye ferrodiorite are compared in fig. 3 with the compositions of these minerals in the Beaver Bay diabase (Muir, 1954), the upper part of the Bushveld (unpublished data from a thesis by J. C. Boshoff, kindly supplied by Dr. B. V. Lombaard), and the Skaergaard intrusion. It is apparent that the coexisting plagioclases and olivines of the ferrodiorite of Skye are not in step with any stage of the cryptically varying layered series of the Skaergaard, but that the discordance is less in the case of the Beaver Bay and the Upper Bushveld rocks.

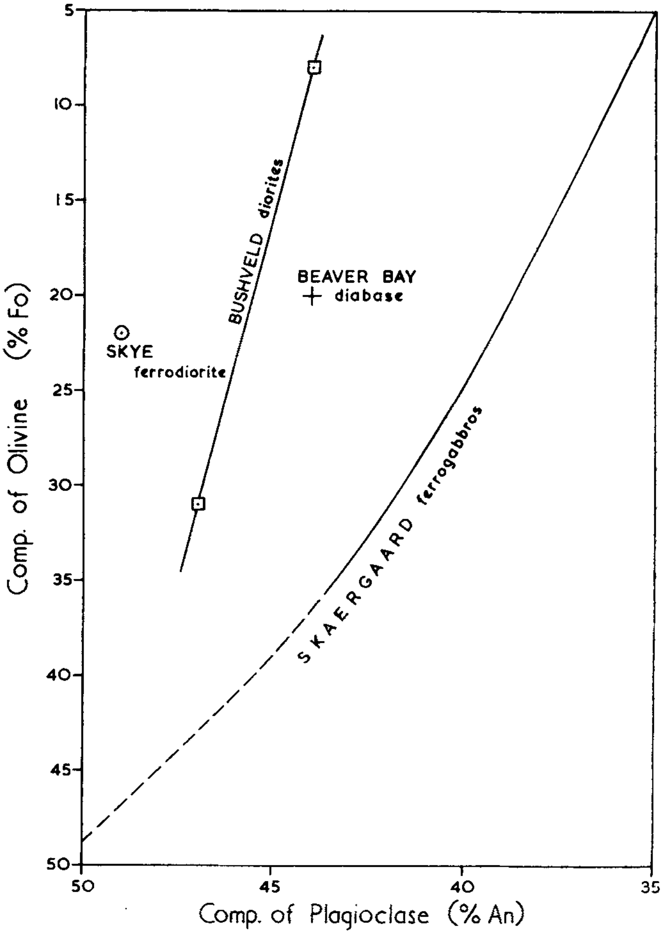

FIG. 3. Contrasted compositions of coexisting plagioclases and olivines in certain late fractions of basic magma. The broken line for the Skaergaard liquid indicates the range within which olivine is unstable.

In describing the Skaergaard intrusion, the term ferrogabbro was used for rocks with andesine feldspar associated with iron-rich ferromagnesian minerals (Wager and Deer, 1939, pp. 98–99). It was suggested that to belong to the ferrogabbros a rock should have olivine richer in iron than

Fo_{50}. In this sense the Skye rocks are ferrogabbros. It has, however, often seemed to the authors of the original Skaergaard paper that it would have been better if the ferrogabbros of the Skaergaard intrusion had been termed ferrodiorites, because of the andesine composition of the plagioclases. This possibility was considered when the name ferrogabbro was adopted, but the overall gabbroic appearance of rocks having 50 % or so of olivine and augite, and a low silica percentage, as well as the gradational nature of the layered series from gabbros into these rocks, made the authors decide to use the term ferrogabbro rather than ferrodiorite. This was probably an unwise decision, because plagioclase is the most significant mineral for any natural classification of igneous rocks and the general name diorite is being increasingly used for rocks with andesine feldspar. It is no doubt desirable to give up the name ferrogabbro for the Skaergaard rocks and to substitute ferrodiorite. Some of the upper Bushveld rocks occurring between the magnetite horizon and the overlying granophyre and granite show many similarities with the Skye rocks described here and are called by Lombaard (personal communication) diorites, fayalite diorites, and syeno-diorites. In the present paper the iron-rich Skye rocks that resemble, without being identical with, the Skaergaard ferrogabbros, will be called ferrodiorites. It is suggested that the name be used for rocks in which the actual plagioclase is not more calcic than about An_{50}, while the ferromagnesian minerals are iron-rich. If olivine is present it should be more iron-rich than about Fo_{40} (see fig. 3) and any other ferromagnesian minerals should be correspondingly iron-rich.

The chemistry of the Skye ferrodiorite.

The chemical compositions of the two analysed ferrodiorites from Harker's Gully on Marsco (table I) are very similar. The main difference is in the state of oxidation of the iron. The C.I.P.W. norm and also the approximate modes are given in table I, along with certain ratios. The An_{49} composition of the extensive plagioclase cores is sufficiently different from the plagioclase molecular ratio of the norm, An_{35}, to indicate that the rims and outer alkali feldspar must be rich in soda. The iron-rich nature of the ferromagnesian minerals is reflected in the high value of 100 $Fe''/(Fe''+Mg)$, 72. The reduced state of the rock is indicated by the high ratio 100 $Fe''/(Fe''+Fe''')$, which is 86. If the rock is the result of fractionation of basic magma, as seems probable, it must be regarded as a late-stage fractionation product because of its high albite and iron ratios, using these terms as defined by Wager (1956, p. 219).

In the late stages of fractionation, the changes in amounts of many of the elements are rapid, and comparisons are difficult unless made between rocks at approximately the same stage of fractionation. To help in making significant comparisons with other rocks or rock series, the albite- and iron-ratio plot (see Wager, 1956) for the two analysed Skye ferrodiorites and for some other Thulean igneous rocks is given in fig. 4. The ferrodiorite is seen to belong to the late stage β fractionation stage and it falls midway between the alkali-basalt–mugearite–trachyte series and the Skaergaard liquid differentiation series.

Table I. Analyses of Skye ferrodiorites.

	1. H. 344.	2. H. 870.
SiO_2	54·18	53·43
Al_2O_3	13·74	13·88
Fe_2O_3	1·88	3·27
FeO	10·79	10·32
MgO	2·42	2·56
CaO	6·34	6·45
Na_2O	3·46	3·69
K_2O	1·85	1·84
H_2O^+	1·40	0·93
H_2O^-	0·26	0·38
TiO_2	1·97	2·25
P_2O_5	1·30	1·10
MnO	0·30	0·32
Total	99·89	100·42

C.I.P.W. norms.

		H. 344.		H. 870.	
Q			7·77		6·37
Or		10·91	56·69	10·85	57·96
Ab		29·26		31·20	
An		16·52		15·91	
Di	Wo	2·73	5·58	3·74	7·60
	En	0·79		1·21	
	Fs	2·06		2·65	
Hy	En	5·23	18·72	5·16	15·63
	Fs	13·49		10·47	
Mt			2·73		4·75
Ilm			3·74		4·26
Ap			3·02		2·53
Water			1·66		1·31

Molecular and atomic ratios.

	H. 344.	H. 870.
Albite ratio $= \frac{100\,Ab}{Ab+An}$	65·3	67·4
$\frac{100\,(Ab+Or)}{Ab+Or+An}$	71·7	73·5
Iron ratio $= \frac{100\,(Fe''+Mn)}{Fe''+Mn+Mg}$	72·3	70·0
$\frac{100\,Fe''}{Fe''+Fe'''}$	86·2	77·7

Modes (vol. per cent).

	H. 344.	H. 870.
Quartz	8	8
Feldspar	53	51
Clinopyroxene	8	9
Orthopyroxene	11	12
Olivine	1	—
Hornblende, biotite, and chlorite	12	14
Iron ore	4·5	6
Apatite	2·5	—

1. Ferrodiorite (H. 344), Shelter stone in Harker's Gully, Marsco, Isle of Skye. (Anal. E. A. Vincent.)
2. Ferrodiorite (H. 870) with sporadic andesine phenocrysts from middle of Harker's Gully, Marsco and 30 yds N. of H. 344. (Anal. E. A. Vincent.)

For comparison, the analysis of a Skye mugearite of this fractionation stage is given in table II, along with an estimate of average Hebridean mugearites corresponding to the middle of the late stage β, taken from a previous graph (Wager, 1956, fig. 7). The mugearites are considerably poorer in silica, but richer in alumina and soda. They are similar in their richness in P_2O_5. Chemically the Skye ferrodiorites cannot be regarded as belonging to the alkali-basalt–mugearite–trachyte series.

Similar comparisons can be made with the Skaergaard differentiation

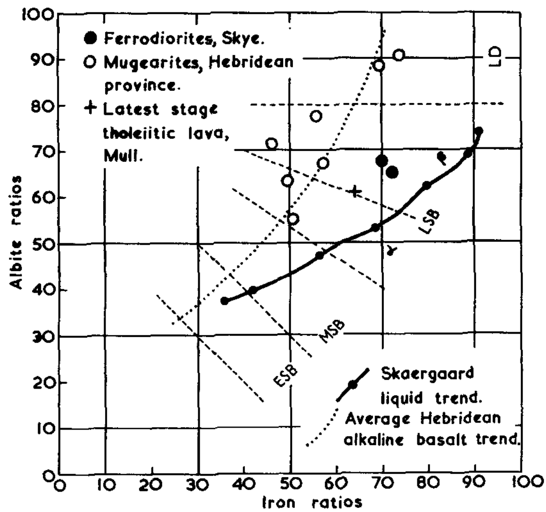

FIG. 4. Plot of albite and iron ratios for the Skye ferrodiorite and other late-stage rocks.

series. Since the composition of the Skye ferrodiorite probably represents the composition of the liquid from which it was produced, the comparison is made with the estimated compositions of Skaergaard liquids. No one liquid is close to the Skye ferrodiorites for the major elements. Thus to cover both the albite and iron ratios of the Skye ferrodiorite, it is necessary to consider the liquid over the range LZc, MZ, UZa, and UZb (Wager, 1960, p. 386). The Skye ferrodiorite is considerably richer in SiO_2, poorer in iron and lime, and rather richer in potash than the nearest Skaergaard liquids. The Skaergaard differentiation series, which may be fairly characteristic of the differentiation trend of high-alumina type basalts (cf. Kuno, 1960), apparently does not closely correspond at any stage with the Skye ferrodiorites.

It seems probable that the Skye ferrodiorite belongs to a late stage in the fractionation of the non-porphyritic central, i.e. the tholeiitic

TABLE II. Analysis of Skye ferrodiorite and comparisons.

	1	A	B	C L, MZ	D L, UZa	E L, UZb	F	G	H	I	J	K
SiO_2	54·18	49·24	48·9	46·9	47·5	49·8	53·78	52·36	46·05	51·25	45·87	52·41
Al_2O_3	13·74	15·84	15·2	14·1	12·5	11·8	12·69	12·34	14·49	13·20	10·66	12·23
Fe_2O_3	1·88	6·09	5·5	3·6	3·8	4·3	3·44	2·81	4·95	2·84	4·11	3·53
FeO	10·79	7·18	8·0	15·0	17·3	17·8	8·94	13·59	15·13	15·48	15·59	12·86
MgO	2·42	3·02	3·7	4·0	2·5	1·3	2·58	2·87	3·74	1·43	3·50	2·62
CaO	6·34	5·26	6·3	9·5	9·5	8·0	6·36	7·54	9·26	7·04	8·28	8·48
Na_2O	3·46	5·21	4·7	3·0	3·2	3·4	2·74	2·99	3·19	3·13	2·84	2·01
K_2O	1·85	2·10	1·5	0·4	0·7	1·0	2·27	0·80	0·33	1·77	0·96	0·85
H_2O^+	1·40	1·61	1·3	—	—	—	2·19	0·77	0·74	1·48	1·42	0·92
H_2O^-	0·26	1·08	1·7	—	—	—	1·19	0·12	0·03	0·03	0·47	0·14
TiO_2	1·97	1·84	2·2	2·7	2·2	1·8	2·28	2·95	2·10	1·86	4·65	3·14
P_2O_5	1·30	1·47	0·8	0·5	1·3	1·4	0·55	0·76	trace	0·31	1·70	0·23
MnO	0·30	0·29	0·3	0·2	0·3	0·4	0·53	0·22	0·35	0·28	0·29	0·26
F	—	0·18	—	—	—	—	—	—	—	—	—	—
S	n.d.	0·03	—	—	—	—	0·42*	—	—	—	—	—
BaO	—	0·09	—	—	—	—	0·09	—	—	—	—	—
CO_2	—	—	—	—	—	—	0·08	—	—	—	—	0·12
Total	99·89	100·53	100·1	—	—	—	100·13	100·12	100·36	100·10	100·34	99·80

1. Ferrodiorite H. 344. Shelter stone in Harker's Gully, Marsco, Skye. (Anal. E. A. Vincent.)
A. Mugearite S. 8932. Lower member of composite double sill (or lava). Tertiary. Druim na Criche, 5 miles SSW. of Portree, Skye. (Anal. W. Pollard.) Harker, 1904, p. 263.
B. Average of three late-stage Hebridean mugearites. Wager, 1956, p. 231, table 2.
C, D, E. Skaergaard liquids of the MZ, UZa, and UZb stages (approx. percentages estimated graphically). Wager, 1960, p. 386, table 4.
F. Tholeiite S. 14824. Tertiary lava. 1 mile NE. of Loch Bà and 2 miles E. of Gruline House, Mull. (Anal. E. G. Radley.) Bailey *et al.*, 1924, p. 17, no. V.
G. Segregation vein in augite olivine basalt (HK 51092202 a), a prehistoric lava in western wall of the caldera, Kilauea Volcano, Hawaii. (Anal. Katsura.) Kuno *et al.*, 1957, p. 188, table 5.
H. Average diorite, Bushveld Intrusion. Average of 2 analyses (nos. 72 and 74). *Boshoff, 1942*, table 13.
I. Average syeno-diorite, Bushveld Intrusion. Average of 2 analyses (nos. 85 and 10). Boshoff, 1942, table 13.
J. Iron-rich diabase M. 3174, Highway 61, $\frac{3}{8}$ mile SW. of settlement, Beaver Bay, Minnesota. (Anal. J. Scoon.) Muir, 1954, p. 377, table 1.
K. Fayalite quartz dolerite, New Amalfi Sheet, South Africa. Poldervaart, 1944, p. 116, table vi.

* FeS_2.

magma-type of Mull. Unfortunately the results of fractionation of tholeiitic basalt in Mull, in the authors' opinion, are not yet well established, because some of the rocks that have been considered the products of its fractionation may also have suffered some degree of hybridization with acid materials. However, one analysed Hebridean tholeiitic basalt falls just within the late stage β as defined in the paper on fractionation stages, and the analysis is rather close to the Skye ferrodiorites (table II, column F). A segregation vein from a prehistoric Kilauea basalt described by Kuno (1957, pp. 187–189) is also given for comparison. This is undoubtedly a direct fractionation product of a tholeiitic basalt and again bears considerable resemblance to the ferrodiorite. Comparison is also made with certain late-stage Bushveld rocks (Boshoff, 1942), the Beaver Bay iron-rich diabase (Muir, 1954), and the fayalite quartz dolerite of the New Amalfi Sheet (Poldervaart, 1944), all of which have some degree of resemblance to the Skye ferrodiorite.

The relationship of the intrusion of the ferrodiorite to other Tertiary igneous events in Skye.

Judging by the evidence from the Skaergaard intrusion about 95 % of a basic magma has to be crystallized with strong fractionation to produce late stage β differentiates such as the Skye ferrodiorite or mugearite (Wager, 1960) and it is worth noting that only relatively small amounts of these presumed late-stage differentiates are found in Skye.

The Cuillin complex, at least in part, is a layered intrusion with cryptic variation, the rocks changing in composition from ultrabasic to gabbroic. The latest layered rocks that have been preserved are found on Druim Hain but they have not reached the ferrogabbro stage (Carr, unpublished thesis, and cf. Weedon, 1961, p. 191). It is possible that fractionation in the Cuillin centre produced rocks of a later stage than this, but even so, it is impossible for this centre to be the source of the ferrodiorite magma of Marsco because of the observed time sequence of events. Thus after the Cuillin gabbro layered intrusion was solidified it was injected by a series of cone sheets and these are not known to cut the Redhills granites. Richey (1933, pp. 74–76) therefore suggested that the emplacement of the granites was subsequent to all the events at the Cuillin centre and this has been abundantly confirmed by J. D. Bell (unpublished thesis 1959), who has mapped the area north of the Blaven range. Since the Marsco ferrodiorites are intruded into certain of the Western Redhills granites, the time sequence makes it impossible for the ferrodiorite to have originated from differentiation in the Cuillin gabbro complex.

It seems necessary to postulate that the ferrodiorite magma is the result of the deep-seated events that produced the Western Redhills complex. The simplest hypothesis seems to be that a differentiating basic magma, perhaps another layered intrusion, exists below the Western Redhills complex, and that a late fraction of this was injected to give the Marsco ferrodiorites. Geophysical evidence that dense basic rock occurs at no great depth beneath the Western Redhills supports this hypothesis (personal communication from Dr. M. H. P. Bott and Dr. J. Tuson).

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