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The Suisnish layered dyke

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SUMMARY. A minor picritic body at Suisnish Point, Isle of Skye, is described. The mass has a dyke-like form, and is rhythmically layered. Cryptic layering, however, is absent. From a study of the field relations, contacts, metamorphic aureole, and other physical features, it is concluded that the mass crystallized *in situ* (i.e. it is a true dyke) and is not an upfaulted block of pre-existing igneous rock. The main physical and chemical features of the layered units and their mineralogy are described. The problems of generating horizontal rhythmic layers in a relatively small, essentially vertical, planar intrusion are discussed. It is concluded that the surrounding country rock was maintained at a moderate temperature during, and after, intrusion of the picritic magma and that this allowed a combination of gravity settling and magma flow currents to produce a cumulate rock with characters normally only observed in much larger intrusions.

SOME years ago, the author was shown a small picritic body at Suisnish Point (NG-585163), Isle of Skye, by M. J. Fleuty. The body is shown on the 1902 original 1 : 10560 manuscript field map with the annotation 'large multiple? dyke'. The presence of repeated, sub-horizontal, rhythmic layering (figs. 1 and 2) makes the use of the term dyke intriguing because rapid cooling would be expected to suppress the formation of extensive cumulate features. An alternative explanation is that the picrite was tectonically emplaced. The following text describes the field relations and petrology of the rocks and discusses the formation of what does seem to be a unique *in situ* layered dyke.

General relationships of the picrite and country rocks. The body is well exposed in the cliff and sea stack (Stac Suisnish), where it is 40 m wide with essentially vertical contacts against the enclosing Lower Lias siltstones, which dip locally 10° due west. Inland, exposures are limited but a well-defined, asymmetric ridge with a north-east facing scarp runs from the cliff south-eastwards about 600 m (fig. 3). This ridge has a stepped appearance transverse to its length, which may reflect minor faulting. In general, exposures of baked siltstone occur on top of the ridge with picrite exposed only on the scarp face, suggesting that the roof of the body lies some 90 m above the cliff exposures.

The picrite averages 50 % olivine, 35 % plagioclase, and 15 % pyroxene with a maximum grain size of 6 mm although aggregation gives the impression of a much larger grain size. Twenty obvious, and some less clear, sub-horizontal rhythmically layered units are exposed. These units are parallel to one another, dip 18° due west, vary in thickness from 15 to 120 cm, and comprise a lower olivine-rich portion and an upper feldspar-rich portion (figs. 1 and 2). Weathering has accentuated the leucocratic layers as a series of ridges. Microscopic study reveals transitional boundaries within, and sharper boundaries between the units and that the units with thick leucocratic zones have melanocratic zones richer in olivine than those with thin leucocratic zones.

In many cases the uppermost, and in some cases all portions of the felsic layers have a brecciated appearance with angular blocks of feldspar-rich material forming a discrete layer (figs. 1d and 2). Occasionally, isolated blocks of this type are found

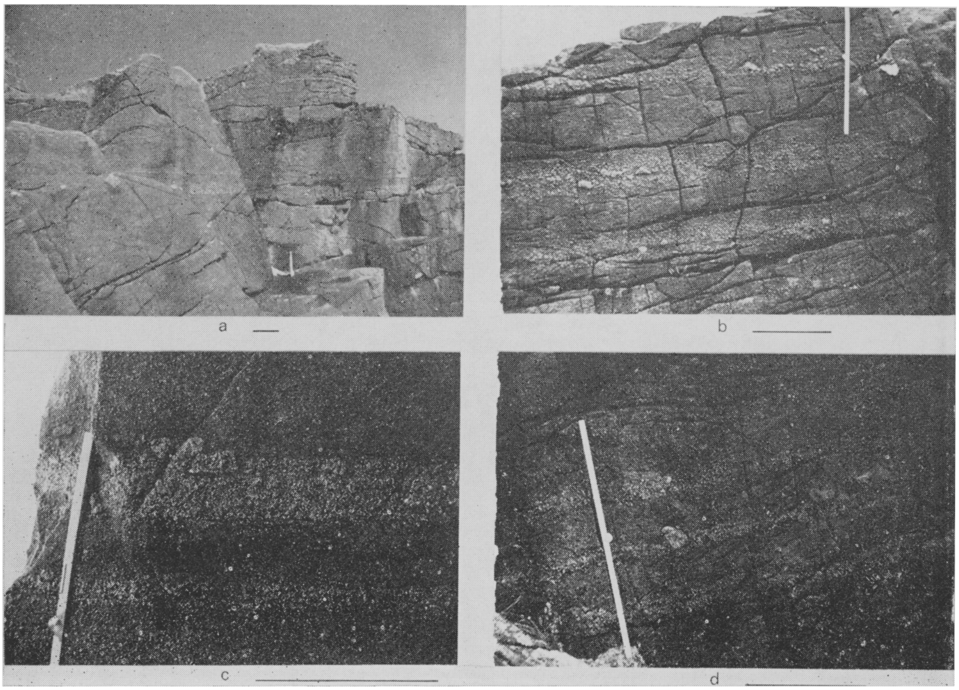

FIG. 1. Layering in Suisnish Picrite. a. General view of repeated, sub-horizontal, rhythmic layering. b, c, d. Close-ups of individual rhythmic layers. Bar represents 30 cm.

within the adjacent overlying mafic layers. The blocks are possibly akin to congnate xenoliths described by Gibb (1969) and may arise by autobrecciation (Weedon, 1965). The reverse feature, masses of mafic-rich material included within the feldspar-rich layers, is not observed. Rarely, clusters of olivine crystals, forming ellipsoidal masses, are found within the melanocratic layers; they attain a maximum dimension of 5 cm and resemble black 'pebbles'. One thick layered unit (120 cm) near the base of the outcrop has an autobrecciated feldspar-rich layer, which is distinctly saucer-shaped across the width of the dyke. The associated melanocratic layer is considerably altered, a feature that contrasts with the generally fresh mineralogy of the picrite. The layered units can be traced to within a few cm of the contacts without any sign of variation in thickness or attitude. Igneous lamination is absent in the main outcrop.

Some faults with displacements of up to 30 cm cross the dyke following the trends of the cooling joints. Occasionally, faults with displacements of up to 1 m are observed following the dyke/envelope contact. Since none of these faults control the general form of the dyke and often displace the numerous later minor dykes that crosscut the main picrite, they must represent minor post-consolidational movements and are not related to the emplacement of the picrite.

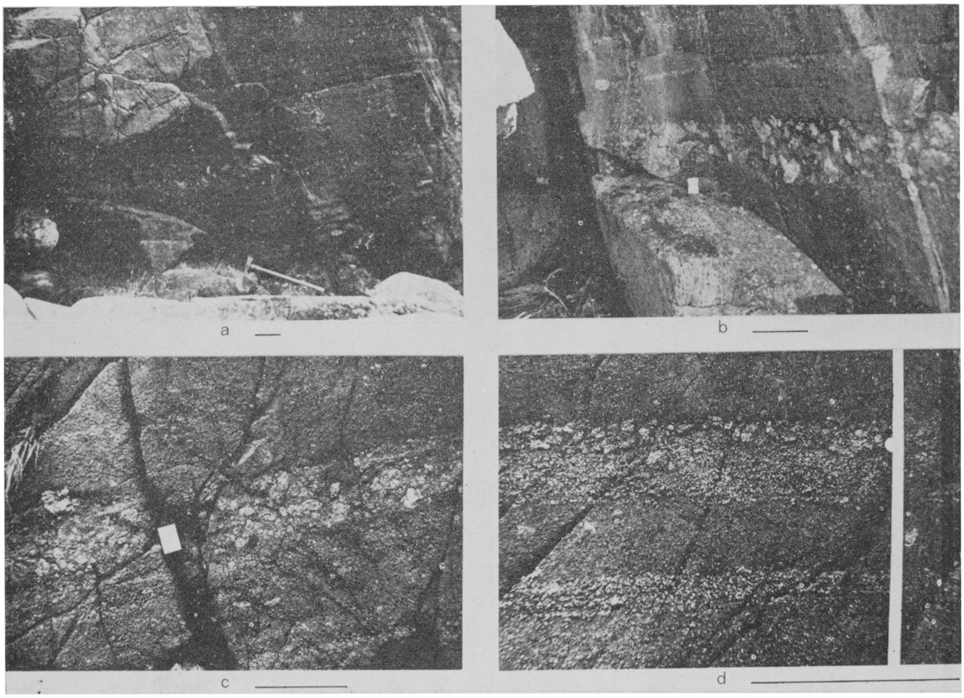

FIG. 2. Layering in Suisnish Picrite. a, b. Large saucer-shaped felsic layer near base of outcrop, exhibiting scour features. c, d. Close-ups of scour features in individual layers. Bar represents 30 cm.

The actual dyke/siltstone contact is poorly exposed and thus sampling is difficult. However, the actual contact is phaneritic with an average grain size of 0·2 mm and occasional plagioclase megacrysts (about 2 mm long). This contact facies only extends inwards some 30 cm before the grain size has increased to that of the normal picrite. This seems to represent a true chilled margin. It cannot represent later minor dyke rock intruded along the picrite/siltstone contact, for these rocks when observed elsewhere in the area have aphanitic margins.

In an attempt to further delineate the picrite inland, diamond drilling and a proton magnetometer survey were undertaken. Positions of the holes, which averaged 7 m in depth, and the magnetometer traverse lines, with readings every 3 m, are shown on fig. 3. The latter survey was unsuccessful because of the reversely magnetized nature of the picrite relative to the sedimentary and minor dyke rocks. Recovery of sedimentary rock from the drill holes was generally poor because of its weathered and jointed nature; however, DDH 4 substantiated the presence of a roof to the picrite. General

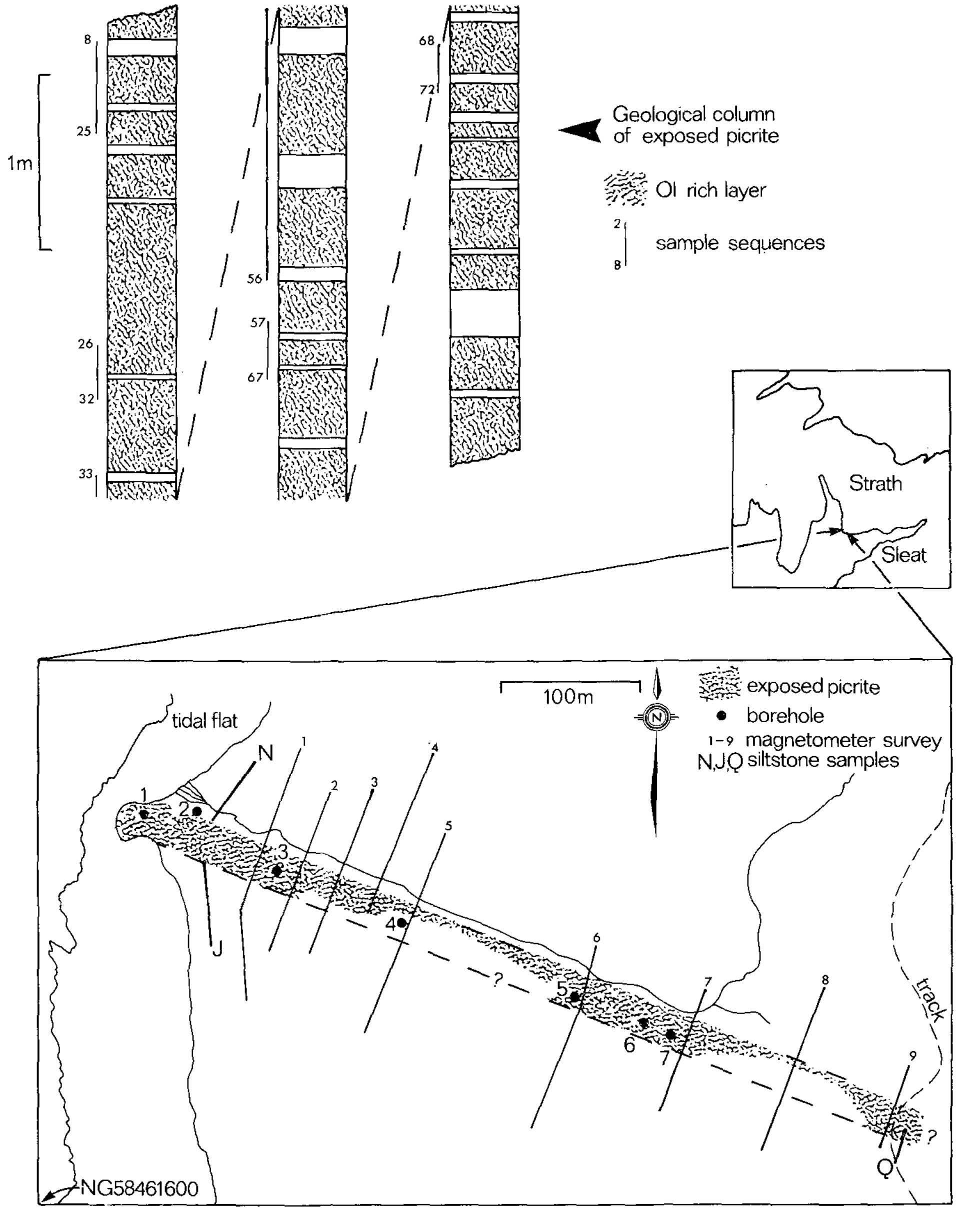

FIG. 3. Geological map of the Suisnish picrite.

recovery of the picrite was good and typical layered material was found in all holes as far inland as DDH 6. DDH 7 encountered later minor dyke material only.

In the field, metamorphism due to the dyke is visible as a hardening and darkening of the siltstones within 1 m of the contact. Also, a tendency for fossils in the vicinity to be moulds filled with iron oxide powder was noted. Samples were collected from one stratigraphic horizon at varying distances from the dyke in three areas (sample sets N, J, and Q on fig. 3). Microscopically, the siltstones consist of quartz grains with minor alkali feldspar and biotite in a mud matrix with rare composite grains of quartz and mud pellets. The rocks are generally well layered. In all samples the mud matrix has recrystallized and is micaceous. The subangular quartz grains are typically clastic but the presence of irregular interlocking grain boundaries indicates an unusually high degree of packing for a clastic sedimentary rock. Although minor changes, these features suggest that metamorphic effects, such as baking, are present as far as 65 m from the contact. The only obvious metamorphic changes are observed in samples taken within 5 to 10 cm of the contact. One such change is an overprinting of the bent and damaged detrital biotites by metamorphic biotites, which cut across the bedding and mud lenses. Within 5 cm of the contact there is fusion of the siltstone, and quartz in stellate forms with irregular and diffuse boundaries is observed. Patches of fused quartz are also found in the outer 5 cm of the picrite. These fusion effects have been noted around other picrite bodies (Wyllie, 1959 and 1961). Densities and porosities of the samples were determined and the results indicated a slight increase in bulk density, and a sympathetic decrease in porosity, as the picrite is approached. It has been shown that reflectivity values are sensitive indicators of thermal metamorphism and consequently reflectivity measurements of the included carbonaceous material in the siltstones were undertaken by the University of Newcastle Organic Geochemistry Unit. All the samples fell in the anthracite range.

The features thus far described all support the idea that the picrite is an *in situ* dyke. The conclusion is that a picritic magma was intruded into a fracture, during subsequent cooling the dyke-like body developed its rhythmically layered appearance, at some later time was cut by a swarm of minor dykes, and finally was subjected to minor faulting.

This inferred autochthonous origin raises problems as to the development of repeated layering and coarse grain size in what is assumed to be a rapidly cooled mass. Assuming a settling rate of 10 cm/year (Wager and Brown, 1968) then 500 years are required for the exposed portion of the picrite to accumulate. On the other hand, assuming an initial temperature of 1100 °C (Wyllie, 1961) and solving various of Jaeger's formulae (1967) for sheet-like bodies figures of 5 to 10 years for total solidification are obtained, if the country rock is assumed to be at 100° or less. Thus, if the body is a dyke then it is necessary to propose a slower cooling rate and this is most simply achieved by raising the ambient temperature of the country rocks, such as by increasing the depth of burial or the geothermal gradient. Since the Hebridean igneous province involved extensive volcanic activity and associated intrusions are thought to be high-level crustal phenomena (Thompson *et al.*, 1972; Carmichael *et al.*, 1974), the latter suggestion is preferred. Evidence for an elevated local geothermal gradient is to be had from Almond (1964) who refers to changes due to the Cuillin gabbros and this is supported by the oxygen work of Tan (1969) and Tan and Hudson (1974). Arkell's (1933) account of widespread alteration implies a regionally enhanced temperature and Tan and Hudson (1971) note that the lavas may have significantly heated the underlying rocks. Tuttle and Bowen (1958) and Turner (1968) have commented on the high-temperature characters of the Skye granitic rocks and D. F. Paterson (personal communication) has noted widespread wollastonite. The presence of basic igneous material about 15 km thick and probably less than 3 km below Suisnish Point (Bott and Tuson, 1972) also encourages belief in the slow cooling hypothesis, allowing ample time for the production of the rhythmic layering.

Petrography of the picrite. Table I lists modal analyses of samples indicated on the geological column of fig. 1. The average coarse-grained picrite agrees with modes of similar rocks referred to as picrite by Drever and Johnston (1967). Average grain sizes (smallest and largest dimensions) are: olivine, 0·5–1·7 mm; plagioclase, 0·2–0·9 mm; pyroxene, 0·5–0·7 mm; opaques, 0·1–0·1 mm; 'ocelli', 0·1–0·1 mm.

In the melanocratic portions of layers, hand specimens of picrite display equidimensional olivine crystals, whose distribution gives a net-like appearance to cut surfaces. This texture is typical of that which results from settling of olivine crystals in a liquid with little or no later adcumulus growth. Between the olivine crystals are subhedral plagioclase and anhedral clinopyroxene in a sub-ophitic relationship. Clinopyroxene crystals occasionally reach dimensions where they become poikilitic to the plagioclase. In the felsic portions of the layers this ophitic relationship is maintained. A well-defined microscopic fracturing of the rock (oriented 127°/80 NE., approximately parallel to the weaker joint set) is visible in most layers; its effect is to make the optical determination of specific minerals difficult.

The chilled margin is typically phaneritic with 8 % of total olivine and 10 % of total plagioclase present as phenocrysts. Modal differences between the coarse- and fine-grained material are essentially a marked decrease in olivine, and a much larger pyroxene/plagioclase ratio. No border group of cryptic layering, similar to those found in larger intrusions, is apparent.

Olivine. Generally, the olivines are somewhat altered and cracked, this alteration amounts to 8 % of total olivine content. The modes indicate that the rhythmic layering is essentially a melanocratic zone of olivine concentration grading to a feldspar-rich upper part. The average Fo content of the olivines of selected units is 83 % (σ: 2·8), obtained from chemical and optical studies, and this high forsterite content of the olivines is in agreement with values obtained for other picritic bodies (Drever and Johnston, 1957; Simkin, 1964).

Small spherical structures are common in the centres of many olivines. When the crystals within these structures are large enough to be identified under the microscope, they are normally clinopyroxene or less commonly plagioclase. Drever and Johnston (1957), in a study of olivines in picritic rocks, have described similar structures, which they attribute to liquid inclusions. This explanation is feasible and if accepted substantiates the late development of the clinopyroxene and plagioclase in the picrite while the olivine was early and probably present in large amounts prior to intrusion of the magma. There is no indication of adcumulus growth of the olivines.

Drever and Johnston (1957) note that skeletal olivine growth is possibly a function of more rapid cooling than is the growth of inclusion-free equant olivines. The equant olivines of the Suisnish dyke are essentially inclusion-free (ignoring the spherules) and

TABLE I. *Modes of Suisnish picrite*

Sample	Ol	Pl	CPx	Op	'Ocelli'
1*	11·7	50·9	33·8	3·0	—
2	6·8	49·6	39·6	4·0	—
3†	8·5	51·8	36·3	3·1	—
4	9·4	51·0	36·7	2·9	—
5	8·8	49·0	37·3	4·9	—
6	6·3	49·3	39·3	5·1	—
Average (Fine)‡	8·6	50·3	37·1	3·8	—
7	44·8	87·3	13·9	1·1	2·9
8	48·1	35·5	13·9	0·7	1·8
9	52·1	32·4	13·9	0·4	1·2
10	53·0	31·7	12·9	1·1	1·3
11	62·7	25·0	10·3	0·9	1·1
12	61·6	25·1	11·1	1·3	0·9
13	56·8	27·4	13·9	0·8	1·1
14	62·7	23·7	11·1	0·9	1·6
15	64·3	18·8	14·9	0·9	1·1
16	62·8	25·6	9·1	0·7	1·8
17	57·8	25·5	14·2	0·9	1·6
18	61·7	22·8	13·2	0·7	1·6
19	47·4	37·0	14·1	0·3	1·2
20	37·2	46·1	13·7	0·8	2·2
21	55·6	26·1	17·3	1·0	—
22	57·6	25·6	15·0	1·7	0·1
23	57·1	25·3	15·1	1·3	1·2
24	63·9	24·0	10·2	1·0	0·9
25	56·1	25·9	15·2	0·9	1·9
26	63·5	24·3	10·9	0·9	0·4
27	56·5	31·2	11·2	0·7	0·4
28	60·3	24·8	13·1	1·0	0·8
29	43·1	39·4	16·2	0·6	0·7
30	58·9	25·7	13·7	0·9	0·8
31	58·5	25·6	14·9	0·9	0·1
32	58·1	26·1	13·3	1·7	0·8
33	43·2	39·8	14·1	1·0	0·9
34	26·0	55·6	14·6	2·1	1·7
35	55·5	26·7	15·5	1·4	0·9
36	60·3	22·1	14·6	1·5	1·5
37	59·5	25·8	12·6	1·0	1·1
38	63·2	19·3	14·2	1·6	1·7
39	60·6	23·9	14·2	0·3	1·0
40	59·4	19·6	17·0	1·3	2·7
41	62·7	16·8	13·9	1·0	5·6
42	49·9	35·6	10·1	1·0	3·4
43	40·6	43·9	13·4	0·6	1·5
44	41·6	43·0	13·1	0·6	1·7
45	50·0	37·8	10·6	0·8	0·8
46	17·9	63·9	17·0	1·0	0·2
47	43·3	42·5	13·1	0·6	0·5
48	62·3	26·5	9·9	0·6	0·7
49	63·0	25·8	10·3	0·5	0·4
50	52·2	29·9	15·5	1·0	1·4
51	55·1	30·9	11·4	0·9	1·7
52	55·3	28·9	12·6	1·7	1·5
53	62·0	24·1	11·5	1·0	1·4
54	20·5	65·9	12·7	0·6	0·3
55	42·0	45·0	10·3	1·2	1·5
56	40·3	42·2	14·9	1·1	1·5
57	67·1	20·9	10·6	0·7	0·7
58	60·9	23·7	14·1	0·7	0·6
59	45·8	43·7	8·7	0·6	1·2
60	54·6	19·4	13·5	1·4	1·1
61	54·9	33·5	9·9	0·5	1·2
62	58·9	27·8	11·6	0·8	0·9
63	54·5	30·7	13·4	0·8	0·6
64	53·8	34·4	9·1	1·3	1·4
65	46·6	40·7	10·4	0·8	1·5
66	49·0	36·2	12·5	0·9	1·4
67	53·2	32·3	12·5	0·4	1·6
68	57·9	25·6	13·9	0·6	2·0
69	53·9	27·7	15·1	1·0	2·3
70	56·6	26·6	11·8	1·0	4·0
71	36·2	50·0	9·5	0·9	3·4
Average (Coarse)	53·5	31·1	13·0	0·9	1·5

* Also Qz 0·6. † Also Qz 0·3. ‡ Also Qz 0·2.

a slow-cooling origin seems most likely. Also, the packing texture indicates the olivines apparently crystallized slowly before intrusion of the picrite into its present position.

Plagioclase. The feldspar laths are normally zoned with a decrease in the An content from the centres to the limits of the crystals of about 20 %. The average An content (determined optically) of the phenocrysts is 90 % (σ : 4) and the 'normal' laths 80 % (σ : 4). The change in An content outwards in crystals suggests adcumulus growth from the original phenocryst.

Pyroxene. The pyroxene is an augite with an average composition of $Ca_{40}Mg_{40}Fe_{20}$.

There is little variation in its textural relationships with the plagioclase or its modal amount. The only noticeable decrease in the clinopyroxene occurs in the plagioclase-poor layers.

Minor minerals. Magnetite and chrome spinels are ubiquitous, the former occurring both as primary granular aggregates and secondary strings of fine particles within the cracked and altered olivine.

Ocelli are characteristic features of most thin sections. They are subspherical to typically interstitial and appear to be later in origin than the major minerals. The ocelli are filled with fibrous radiating growths of zeolites. The origins of such structures are obscure; however, Carmichael *et al.* (1974) suggest an origin related to a vapour phase, rather than a second (immiscible) silicate liquid.

Cumulus character of the picrite. The individual units, as the tabulated modes indicate (Table I) vary from an olivine-rich base to a feldspar-rich top. The shape and packing of the olivine crystals, and the interstitial nature of the plagioclase and pyroxene, are typical textures of cumulus rocks elsewhere, such as Skaergaard, Rhum, and Stillwater. It is apparent that the olivine is dominantly cumulus and the other two minerals are essentially intercumulus in nature.

Wager and Brown (1968, p. 267) state that packing experiments indicate olivine will pack to the extent of about 60 % crystals to 40 % void. Since the olivine-rich modes of the Suisnish picrite rarely reach 60 % olivine and the olivines tend to have point contacts with each other, rather than interlocking grain boundaries, it is considered that adcumulus growth has been minimal.

The plagioclase is normally zoned but the cores have an essentially unchanged An content and suggest that adcumulus growth occurred around original plagioclase phenocrysts that represented as much as 20 % of the original melt.

Most examples of pure gravity settling are minor intrusions (e.g. Palisades Sill) and in such intrusions there is a marked accompanying differentiation, or put another way, a marked cryptic layering from the base (or near base) to the top. Thus, the Suisnish rhythmic layering and lack of cryptic layering cannot be adequately described by gravity alone.

Igneous lamination, exhibited by plagioclase, is common in many layered igneous rocks of cumulate origin (e.g. Skaergaard, Stillwater) but is absent in the Suisnish picrite. Such linear fabrics are thought to be a direct result of magma movement due to convection or flow. The lack of igneous lamination in the picrite may be due to the fact that much of the plagioclase is adcumulus and developed in 'pore' areas between the olivines, and hence was protected from overlying currents. Another possibility is that the plagioclase and pyroxene settled out as clots (Hawkes, 1966) and the sub-ophitic texture precluded the formation of any obvious plagioclase orientation. The fracturing noted in thin sections could be a result of the post-consolidation stresses that produced the joint and fault movements parallel to the length of the dyke. An alternative suggestion is that the fracturing represents the shearing stress generated as an allochthonous body was faulted into its present position. The latter suggestion is not favoured in view of the accumulated evidence for the Suisnish dyke being an *in situ* intrusion.

Origin of the cumulate features. Most recent syntheses of work on layered rocks (Wyllie, 1967; Wager and Brown, 1968; Carmichael *et al.*, 1974) indicate that rhythmic layering without cryptic layering involves gravity plus either convection currents, flowage of magma, or temperature fluctuation.

The more or less doleritic chilled margin also suggests slow cooling when compared to the aphanitic chilled margins of the associated small secondary dykes. However, the olivine-free nature of the chilled margin still requires explanation.

One method of removing the olivine from the chilled zone is to invoke the process of flow differentiation during intrusion (Bhattacharji, 1967*a*, *b*) to concentrate the olivine towards the centre of the dyke and allow the remaining, still liquid, magma to crystallize as plagioclase and clinopyroxene. This process of flow differentiation has been cited in many cases of minor intrusions on Skye to explain chilled margins of dykes and sills that do *not* have the same chemical and mineralogical composition as the interior portions (e.g. Gibb, 1972). Since phenocrysts are not obvious in the main coarse-grained picrite, it is apparent that as much as 80 % of the olivine was crystalline prior to intrusion and the marked decrease in this mineral in the chilled zone and its concentration towards the centre of the dyke was produced by some process such as axial flow differentiation. Alternatively, olivine reaction with silica derived from the wall rocks could have increased the pyroxene content at the expense of olivine. Although the olivine is extensively altered, no reaction effects or typical orthopyroxene byproducts are visible, thus a physical means of altering the mineral distribution is favoured, rather than a chemical means of changing the mineralogy.

Since the picrite contains scour features (feldspar-rich blocks included in overlying melanocratic units) and lacks a border group it is obvious that some current action was present during intrusion. Gibb (1969) describes 'cognate xenoliths' that are very similar to the scour features of the Suisnish intrusion. His mechanism for production of these features is flow differentiation rather than convection currents. This process has been investigated experimentally by Bhattacharji (1967*a*, *b*) who has shown that a common end-result is an axial concentration of included phenocrysts relative to the walls of the intrusion, especially phenocrysts of olivine, and, to a lesser extent, plagioclase. The Suisnish picrite does have an olivine-free chilled margin but contains a few plagioclase phenocrysts and so it is possible to invoke flow differentiation for the axial distribution of the olivines across the dyke, to explain the scour features and to explain the rhythmic layering. With regard to the layers, each layer is thought to represent the cycle of a pulse of magma, inducing flow with associated axial concentration of included phenocrysts and the scouring of underlying units. As this pulse waned gravity settling became dominant to produce the next layer and so on.

The use of flow differentiation as a process resulting in rhythmic layering is attractive in thin planar bodies where convection cells are not easily generated. An advantage of flow differentiation is that the system can be open rather than the closed system envisaged for convection.

If indeed the system was open, this implies that the crystallizing magma was using the fracture, now filled with picrite, as a conduit. The conduit may have been linked with the Cuillin massif or the postulated buried mafics and ultramafics of Bott and

Tuson (1972) or even a fissure opening to the surface where the volcanics were being extruded (Thompson *et al.*, 1972).

Conclusions. The minor intrusion of picrite at Suisnish Point on the Isle of Skye has two apparently mutually antithetic features: a dyke-like form and numerous sub-horizontal rhythmic layers. The origin of the dyke can be argued as autochthonous or allochthonous; the following points indicate that the former, the *in situ* origin, is the more feasible of the two:

The intrusion has a typical dyke-like form with associated thermal aureole and chilled margin.

Joints, faults, secondary dykes, and evidence of a roof to the picrite all provide information vindicating the theory of an *in situ* origin.

The coarse grain of the picrite is indicative of slow cooling and a regional heating of the area prior to and during intrusion or development of the mass is invoked to decrease the cooling rate sufficiently to allow cumulate features to develop.

The picrite textures are typically cumulate but repeated rhythmic layering without cryptic layering indicates that these features were not produced by gravity alone.

The lack of olivine in the chilled margin, the absence of cryptic layering, and the very noticeable scour features suggest that rather violent magma movements such as flow, producing flow differentiation, rather than convection producing fractionation, were operative.

Flow differentiation adequately explains the observed features but infers an open system or conduit gradually filling with cumulus material. Such a conduit could only have remained 'open' if a regional heating of the country rocks is envisaged.

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