New petrographical data on the Shiant Isles picrite

By H. I. DREVER and R. JOHNSTON

Department of Geology, University of St. Andrews

Summary. A recent bore-hole through the Shiant Isles picrite established the existence of 45 feet more of the picritic facies, and also the lower margin of the sill, at a point almost vertically below the exposed 35 feet previously investigated. In the light of new field and laboratory information the picritic facies is briefly re-examined and its origin discussed.

THE Shiant Isles sill, from which the islands of Garbh Eilean and Eilean-an-Tighe are formed, is now so well known that no recapitulation of its main characteristics is necessary here. It is probably the finest sill of its kind in the world.

As a major part of a geological project, in the summer of 1963, attempts were made to explore some unexposed, critical sections of this sill by means of light hand-held drilling rigs. One of the drill-holes, driven vertically along a line about 10 yards south of the section through the exposed part of the sill previously subjected to a detailed examination (Drever, 1953; Johnston, 1953; Murray, 1954 *a* and *b*), reached the bottom of the sill at 49 feet (Hole No. 2). This means that a virtually continuous section of the sill has now been sampled through a thickness of over 500 feet.

The drilling equipment consisted of a Packsack Diamond Drill, capable of drilling to 100 feet (only 50 feet of drill rods were taken to the Shiant Isles) and a Dinky Diamond Drill, capable of drilling to 20 feet, the cores obtained by both being $\frac{7}{8}$ in. in diameter. These Canadian drills, purchased with the aid of a grant from the Royal Society of London, had not been previously used in the United Kingdom. Thanks to the skill and enthusiasm of the drilling technician, Seamus Young, and to the reliability of this equipment, the drilling programme resulted in a substantial amount of new petrographical information.

The best exposure of the discontinuity between coarse-grained picrite and the main part of the sill above it occurs in a 'trough' feature a short distance south of Hole No. 2. Some further observations on the relationships at this locality can be included in this short paper; but a full account of the discontinuity demands a much more detailed presentation. It is being thoroughly investigated by the present writers, and until the results of this and other work are completed the origin of the picritic rocks can only be discussed in general terms. The field and microscopic relations along the discontinuity, so far observed, are explicable without invoking any significant lateral movement of the main picritic facies relatively to the bulk of the sill. Even if further work were to reveal that the main picritic facies had moved independently, the writers believe that to publish new data now is a service to research involving problems of this kind.

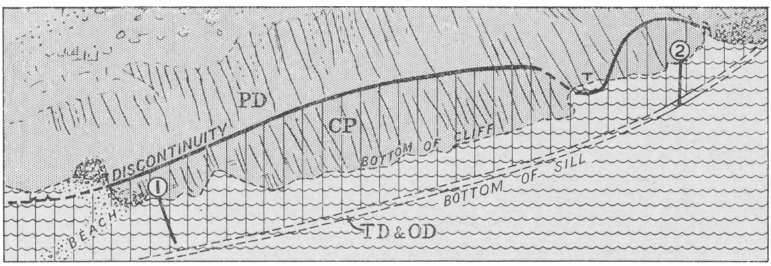

FIG. 1. The picritic facies forming the lower part of the south-eastern end of Garbh Eilean. Sketch based on a photograph taken from the north end of Eilean-an-Tighe. Distance between Drill Holes (1) and (2) is 150 yards. Immediately above Hole (2) the discontinuity is 44 feet above sea-level. The sea is at high-water mark. *PD*, fine-grained picrodolerite; *CP*, coarse-grained picrite; *TD* and *OD*, 4 feet of fine-grained teschenite and olivine-dolerite. (The thickness of this marginal facies is exaggerated, and marl occurs immediately below it.) *T*, 'trough'. Vertical lines indicate the picrite in vertical section.

The field relations of the picritic rocks on the Shiant Isles can only be adequately evaluated by very detailed examination, sometimes in precarious positions, by an application of both cragsman and driller techniques. This takes time, and more field work has yet to be undertaken, particularly on the north coast of Garbh Eilean and on Eilean-an-Tighe.

Field Relations

Below the picrite cliffs on Garbh Eilean two drill holes, No. 1 inclined at 15° NE. and No. 2 vertical, were drilled with the Packsack Drill. In No. 2, fine-grained teschenite (*TD* and *OD*, fig. 1) was encountered at 45 feet below sea-level and metamorphosed marl appeared in the drill-core at 49 feet. This probe established at this point a total thickness of the coarse- to medium-grained picritic facies (*CP*, fig. 1), of 89 feet. In the lower drill-cores from both these holes there is a gradual decrease downward in the size of the felspar and the amount of olivine. At a depth of approximately 30 feet in Hole No. 1 the size of the felspar (An_{79-72}: due to peripheral zoning) can be matched with that of the felspar in the upper drill cores (1–10 ft.) from Hole No. 2. At a depth of 50–51 feet the size and composition of the zoned felspar (An_{78-61}) and the modal amount of olivine are very similar to those in the drill-core at 35–40 feet (5–10 ft. in fig. 3) in Hole No. 2. There is no change in the average size of the olivines. In the lowest picritic drill cores in Hole No. 2, between 39 and 45 feet (0–6 ft. in fig. 3), only the augite is unaltered, the olivine is partially or wholly serpentinized and there is an increase in the amount of analcite and zeolites. At approximately 45 feet, this picritic facies is succeeded downward by fine-grained teschenite which, with some variation in crystallinity and degree of late-magmatic alteration, persists for the next 4 feet, forming the bottom component of the sill. For 5 inches below the picritic facies the core recovery was insufficient to establish with certainty its relation with teschenite. But this teschenite is comparable with that in the banded zone and at the lower contact already investigated at the north end of Garbh Eilean (Drever and Johnston, 1959).

The abrupt plane of discontinuity is an undulating one, characterized by finely granular olivine crystals, very small stubby laths of felspar, and the absence of pyroxene (Drever, 1953). The zone in the picrite immediately below the discontinuity is a distinctive facies which can be referred to as the 'discontinuity zone'. It is variable in width and one of its narrowest developments is in the 'trough' on Garbh Eilean (fig. 1, *T*). At this locality, the width of this zone varies between 2 and 6 inches.

Although the thickness of the picritic facies below the discontinuity at the south-east end of Garbh Eilean is now known to be approximately 90 feet (cf. Turner and Verhoogen, 1960), half a mile to the north it has tapered to about 20 feet (Drever and Johnston, 1959). A distinctive characteristic of the relatively thick, coarse-grained picrite is the development of veins, mainly vertical, in which large calcic plagioclase, augite, and zeolites are the principal components. A few of these veins cut across the discontinuity.

Petrography

Classification of the Shiant Isles picritic rocks. In the writers' previous publications, dealing with alkaline picritic rocks, the terms picrite and picrodolerite were employed only loosely. It has now become necessary to find a more precise and serviceable classification based primarily on the modal amount of olivine. Rocks with more than 40 % olivine will be referred to as picrite and the prefix 'picro' will be employed in the case of percentages between 40 and 20. The adjective 'picritic' simply denotes a rock containing more olivine than a normal basalt or dolerite and more felspar than a peridotite. To include the name 'felspathic peridotite' in this context would be unhelpful.

Some compositional, modal, and textural variations in the lower part of the sill. In the picritic facies the main rock-type is a fresh and homogeneous picrite in which large unzoned felspars weather differentially in relief to display their criss-cross, random orientation. Their size is not so readily seen in thin section and has indeed been underestimated in earlier publications (e.g. Johnston, 1953). The habit of the plagioclase is tabular parallel to (010), the unusual features being the thinness of the tablets, their occasional tendency toward arborescent branching, and their frequent development to a large size, with a maximum longitudinal dimension of 2 inches. They all enclose large numbers of olivines poikilitically, they are characteristically unzoned and their composition is (or is very close to) An_{80}. The olivines throughout the picritic facies show no measurable zoning and no significant compositional variation. Olivine from the main picrite is Fa_{17} according to Johnston (1953) and Fa_{19} according to Yoder and Sahama (1957) who used the X-ray method. Recently Smith and Stenstrom (1965), by electron microprobe, have determined the same olivine as $Fa_{18\cdot8}$. Optical determination of olivine compositions in the drill cores further substantiated this very restricted composition (Fa_{16} to Fa_{20}) in the picritic facies below the discontinuity (Fig. 3). The composition of the olivine at 50 feet in Hole No. 1 is Fa_{19}. Characteristically, the augite has grown as large, sporadically distributed, anhedral crystals which, like plagioclase, poikilitically enclose many olivines. It moulds itself on the plagioclase (fig. 2) and is clearly the last of the principal minerals to crystallize. Contrasts between the fine-grained picrodolerite above the discontinuity and the relatively coarse-grained picrite have been described by Johnston (1953). Table I summarizes some salient data.

Apart from the size reduction in the minerals of the picrite near the discontinuity, there is some horizontal variation in mineral size at one point on the cliffs when compared with another at 10–20 yards away. At one place a size variation has been observed within 1 foot. Such horizontal variations are unaccompanied by any change in the amounts and textural relations of the minerals. In general, the coarse-grained

TABLE I

No.	Locality	Rock	Mode and chem. comp. of minerals		Wt. % SiO_2, MgO, Na_2O, K_2O	
1*	Sea-level (H.W.M.) (45 ft. above bottom of picritic facies)	Coarse-grained picrite	Ol. ($Fa_{21\cdot4}$,† Fa_{19},‡ $Fa_{18\cdot8}$)	66	SiO_2	40·55
			Pyr ($Ca_{47}Mg_{42}Fe_{11}$)	8·5	MgO	28·31
			Plag. (An_{80})	23	Na_2O	1·23
					K_2O	0·21
2*	Below discontinuity (76 ft. above bottom of picritic facies)	Coarse-grained picrite	Ol. (Fa_{20})	62	SiO_2	40·79
			Pyr. (n.d.)	4	MgO	27·26
			Plag. (An_{80})	28·5	Na_2O	1·06
					K_2O	0·13
3*	Localities at vertical intervals from sea-level to locality 2 (above)	Coarse-grained picrite	Average of 6 *complete* modes		Average of 4 complete analyses	
			Ol.	62		
			Pyr.	9	Figures almost identical with those above (2)	
			Plag.	23		
4*	Above discontinuity (83 ft. above bottom of picritic facies and 36 ft. above sea-level). (Specimen collected by Drever in 1949)	Fine-grained doleritic picrite	Ol. ($Fa_{23\cdot1}$,† $Fa_{25\cdot1}$,‡ $Fa_{23\cdot2}$§)	44	SiO_2	41·63
			Pyr. ($Ca_{44\cdot5}Mg_{43\cdot5}Fe_{12}$)	19	MgO	21·98
			Zoned plag. (An_{80-55})	33·5	Na_2O	1·32
					K_2O	0·16
5	1 ft. above discontinuity and 3 ft. above sea-level (H.W.M.) in the trough *T*, fig. 1.	Fine-grained doleritic picrite	Ol. (Fa_{20})	40		
			Pyr. (n.d.)	12	n.d.	
			Zoned plag. (An_{77-59})	34		

* Data from Murray (1954 *a* and *b*) and/or Johnston (1953).
† Murray's chemical analyses. Optical determinations indicated: (1) Fa_{17}, (4) $Fa_{22\cdot5}$, Johnston (1953).
‡ Data from Yoder (1957).
§ Data from Smith (1964).
n.d.: no determinations available.

picrite is a remarkably uniform rock with no preferred mineral orientation. New information on its marginal relations are summarized in fig. 3. Size variation in the felspar is plotted with reference to approximate estimates only and the graph indicates, in the picritic facies, the length of the larger felspars. Where possible, felspar compositions were determined by measurement of Köhler angles and elsewhere by the Rittmann method. Olivine compositions were determined by measurement of $2V(\pm\frac{1}{2}°)$.

Fig. 2. Typical, coarse-grained picrite with large crystals of bytownite (toward left) and augite poikilitically enclosing olivines, the augite being moulded on the plagioclase. Interstitial analcite is not indicated. Sketched from a photograph. Scale: ×18.

The size change in the felspars is a very rapid decrease toward the discontinuity—in marked contrast to their gradual decrease in size toward the teschenite at the bottom. Correlated with this variation is the appearance of peripheral zoning followed by the full-scale zoning that characterizes the smaller felspars. The size of the augite below the discontinuity tends to vary in accordance with that of the felspar. Very close to the discontinuity and in the picritic facies the textural relations of the augite to felspar is simply ophitic. Only along the actual discontinuity is there any change in the average size of the olivine. At 10 feet down in Hole No. 2 its modal percentage is 57 ; at 20 feet, 53 ; at 30 feet, 46 ; at 40 feet, 35 ; and at 45 feet, 28. Correlated with this downward decrease in olivine the felspar and augite increase in amount without any significant change in their relative proportions.

Discussion

With reference to the picritic facies in the sill as a whole, the abrupt relations that occur at the bottom, and across the discontinuity, must be regarded as phenomena of crucial significance. The relations with the

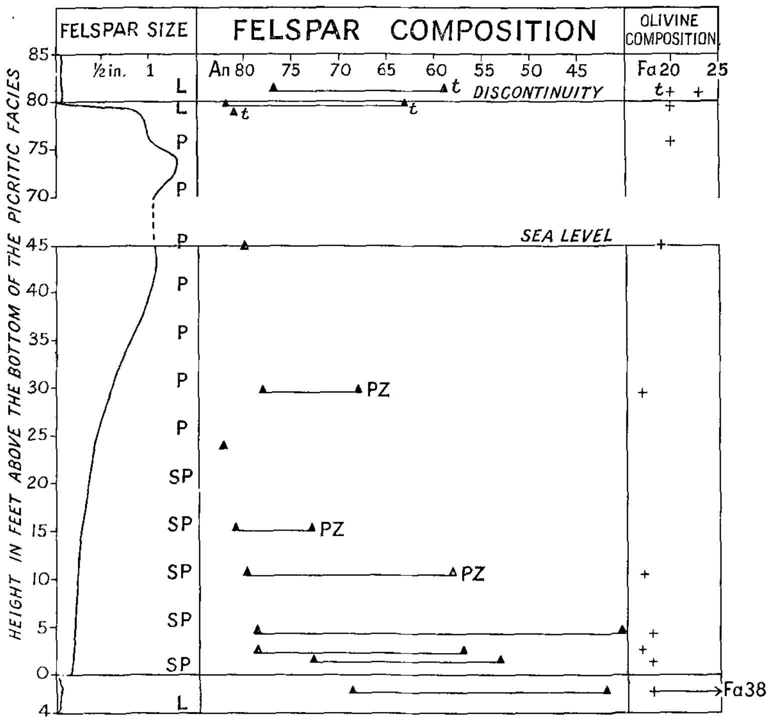

FIG. 3. Plagioclase and olivine variation in drill-cores from Hole No. 2 and in the vicinity of this drill site. *L*, small laths of felspar ophitically enclosed in augite; *P*, large poikilitic felspar enclosing olivine; *SP*, sub-poikilitic to sub-ophitic felspar enclosing olivine; *PZ*, peripheral zoning only; *t*, determinations made on specimens from the 'trough'. Sea-level corresponds with high-water mark. Height of the discontinuity on the cliff immediately above the top of Hole No. 2 is 46 feet (measured accurately by T. E. Simkin in 1963).

bottom teschenite are probably similar to those already described (Drever and Johnston, 1959), which were believed to be due to independent movement of the picritic and teschenitic material. On the other hand, there is no unambiguous evidence of any independent movement of the two picritic facies above and below the discontinuity. There is no significant reduction in the amount of olivine toward this discontinuity either from above or from below it. A marked reduction in the amount of olivine is a characteristic feature of chilled margins of alkaline picritic rocks. There is a sharp reduction in the amount of olivine across the discontinuity, in an upward direction, but the rock is still very rich in olivine.

The distribution in the amount of olivine appears to bear some relation to the size and composition of the plagioclase, the maximum concentration coinciding with the crystallization, throughout a thickness of up to 50 feet, of the large unzoned bytownite. Probably, a considerable amount of this olivine was precipitated and concentrated before and during emplacement. After emplacement there would be further concentration by gravitative settling (cf. Walker, 1930). On the other hand, the random orientation, and the poikilitic relations to olivine, of the tabular felspar imply that it crystallized principally *in situ*. The soda, represented in the 5–10 % interstitial analcite, has been stored up in a water-rich pore liquid some of which may have migrated, mainly upward.

As a generalized working hypothesis, the writers are agreed that the main sequence of events could have been as follows. A liquid (presumably basaltic) rich in water and soda, in which some marl was probably assimilated, preceded the main intrusive influx of alkaline olivine-basalt magma. This magma carried olivine in suspension which settled downward during and after emplacement of the sill. While olivine crystallized, to augment the crystals already settled and settling, calcic plagioclase began to crystallize.

Variations within the picritic facies in the size of the felspar, in its composition, and in the degree of zoning developed are regarded as the most profitable evidence on which to interpret the development of this facies. The location of the large unzoned bytownite in the thickest part of this facies suggests a relatively slow adcumulus (Wager, 1963) type of growth at a slightly higher temperature level than in the picritic rocks nearer the bottom. The writers would like to emphasize, however, that while admitting the possible validity of this concept in explaining the crystallization of this bytownite, they are unable to invoke it to explain the crystallization of an identical bytownite in relatively small picritic intrusions, including dykes. Moreover, the lack of determinable zoning in the felspar, together with the textural evidence (fig. 2) that its precipitation was largely completed before the augite began to crystallize, warrants the inference that its precipitation can be referred to relatively steep liquidus and solidus slopes. If, at the same time, the degree of supersaturation was relatively slight (Wyllie, 1963), the crystallization of the bytownite below the discontinuity zone would seem to be adequately explained, without invoking adcumulus growth.

A tectonic disturbance, involving release of pressure, may then have shifted the course of crystallization to one where felspar and augite were precipitated simultaneously and rapidly. As Wyllie (1963) has also indicated, such a change to co-precipitation is likely to imply a change to a sharp flattening of liquidus and solidus slopes. And this change in conditions would also give rise to a much higher degree of supersaturation and to the zoning in the felspar of the finer-grained picritic rocks at (and near) the discontinuity. The chemical change effected in the case of the augite in these rocks appears to have been relatively slight (Table I, cf. Nos. 1 and 4). The interpretation of the disappearance of augite along the discontinuity plane must await further investigation.

Settling of olivine now became impeded and differentiation became dominated by reactions between crystals and liquid. Sagging of the almost wholly crystalline picritic facies at this stage may be the explanation of the undulations along the plane of discontinuity. There is no convincing evidence of any slumping or brecciation (cf. Wadsworth, 1961), although unambiguous evidence of granulation along this plane has occasionally been discerned, and at one locality there is some interpenetration of the two picritic facies.

During late-magmatic consolidation of the sill, liquid trapped within the picritic facies migrated into rifts, very few of which extended across the discontinuity. A uniform development of massive columnar jointing finally demonstrated and defined the ultimate unity of the sill.

This hypothesis will now be tested in the light of the further, more detailed, inquiry which the writers and their colleagues are actively pursuing.

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