THE AMERICAN MINERALOGIST, VOL. 50, SEPTEMBER, 1965

A NEW TYPE OF BANDING IN ULTRABASIC ROCKS FROM CENTRAL RHUM, INVERNESS-SHIRE, SCOTLAND[1]

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ABSTRACT

Three tongues of peridotite project northwards from the main layered ultrabasic complex of Rhum. From their field relations it is concluded that they form part of a complex formed earlier than the emplacement of the main layered series. The peridotites of the tongues show considerable variation in olivine composition (Fa_{6-31}), and banding which is parallel to the margins of the dikes is due to changes in the relative proportion of the interstitial minerals plagioclase and clinopyroxene. The banding is ascribed to periodic undercooling of an eutectic pore fluid. The name "matrix banding" is proposed for banding of this character.

INTRODUCTION

During the course of a reinvestigation of the eastern part of the northern margin of the Tertiary igneous complex of the Isle of Rhum, Western Scotland, three dike-like masses of peridotite were mapped, which extend northwards from the main layered ultrabasic complex. These masses of peridotite, referred to hereafter as tongues, are vertically banded in contrast to the nearly horizontal layering of the adjacent peridotites of the main layered complex. The purpose of this paper is to describe the field relations and petrography of the tongue rocks, which were found to exhibit a new type of banding, and to suggest an explanation of this type of banding. A brief summary of the nature and origin of the main group of layered rocks will be given first, so that a comparison can be drawn with the peridotites of the tongues.

Rhum is divided into northeastern and southwestern portions by a ring-fault convex to the northeast, which uplifts the southwestern region around 3000 feet. Whereas the northeastern portion is dominantly Precambrian Torridonian arkose, the southwestern portion is composed largely of Tertiary igneous rocks. An area of approximately thirteen square miles is covered by ultrabasic and associated basic rocks out of the twenty-two square miles within the ring fault. The bulk of the remainder is granophyre, with subordinate felsite, explosion breccia, tuffisite, and Lewisian and Torridonian Precambrian country rocks. The course of the main ring-fault was first traced by Harker (1908) but he believed it was a thrust associated with the Caledonian front. Bailey (1945) reinterpreted Harker's data, and suggested that the dislocation was a steeply inclined ring-fault. This has been confirmed by all subse-

[1] Published under the auspices of the Committee on Experimental Geology and Geophysics, Harvard University.

quent investigations (Black, 1954; Brown, 1956; Hughes, 1960; Wadsworth, 1961; Dunham, 1962). The main ring-fault was formed after the intrusion of the granophyres but before the emplacement of the ultrabasic complex.

The layered ultrabasic rocks of the Hallival-Askival area, eastern Rhum, have been meticulously investigated by Brown (1956). He showed that a total thickness of 2600 feet was formed by fifteen units, each one grading from peridotite at the base to allivalite at the top. In a few cases a thin chromite band forms the base of the unit. Brown found no cryptic variation; the variation in rock type is due solely to different mineral proportions. The abundant small scale layering he attributed to the effects of gravity separation of crystals of different density during descent through the magma, combined with the winnowing effects of currents. Each unit was believed by Harker (1908) and Geikie (1897) to be the result of a single intrusion of already differentiated magma, with further differentiation in situ. Bailey (1945) agreed with this interpretation but Tomkeieff (1945) concluded that the entire ultrabasic mass was injected at one time in a differentiated state. Further streaking out of the component parts formed the small scale layering. Brown (1956), however, concluded that the major units were formed by crystal accumulation on the floor of the magma chamber. Each new unit was initiated by the outpouring of lavas and the replenishment of the magma chamber with new magma, to bring the composition of the magma back to its original state. Brown (1956) and Brothers (1964) found that the layering dipped at low angles (10°–20°) towards a centre in Glen Harris.

In addition to the fifteen units in the Hallival-Askival area, Wadsworth (1961) has described four thicker units from the Harris area, southwest Rhum. Three of these grade from peridotite upwards to allivalite, but in contrast to the eastern area slight cryptic variation is present with reversals at the base of each unit. In addition to the small scale layering Harrisitic layering forms an important part of the southwestern area. Harrisite, consisting of elongate vertical branching olivines with interstitial plagioclase, is believed to have formed by upward growth from the floor of the magma chamber during periods of quiescence in gravity accumulation of crystals.

Both Brown (1956) and Wadsworth (1961) present evidence that the layered ultrabasic rocks of the Hallival-Askival and Harris areas were emplaced as a solid mass, lubricated by a "marginal gabbro." However, recent work on the northeastern margin of the layered complex has shown that only the "fine-grained olivine gabbro" of Brown (1956) is present and it dies out before it reaches the tongues of peridotite (Dunham, 1964).

Bailey (1945) believed that the tongues and the knolls of gabbro and peridotite which occur to the north of the main layered complex traced out part of a large ring complex, but it is now suggested that these masses may form part of a radial system from the Glen Harris centre.

Field Relations

Three tongues of ultrabasic rock extend northwards from the main layered ultrabasic complex, to the east of Long Loch (Figure 1). The eastern tongue forms a prominent ridge almost half a mile long and up to 200 yards wide, which cuts the ring-fault at its northern end. The other two tongues are not so extensive and do not form areas of positive relief. No trace has been found of any gabbro surrounding the tongues but the contacts are not well exposed.

Banding is excellently displayed on the horizontal slabs on the top of the eastern tongue. On the eastern side weathering has produced vertical slabs of peridotite whose shape is probably controlled by the banding. The banding is parallel to the margins of the tongue over most of its length, and is steeply inclined which suggests that the mass as a whole is dike-like in form. At the northern end of the eastern tongue, however, the banding is vertical at the margins but changes to horizontal in the centre of the tongue. This bowl form in the banding occurs where the tongue has cut through the main ring-fault. Similar banding can be observed in the other two tongues, but they are not so well exposed as the eastern tongue.

The vertical banding in the tongues contrasts strongly in attitude with the gentle inclination of the banding in the main layered ultrabasic complex to the south of the tongues. Unfortunately it is not possible to observe the junction between the tongues and the main mass as this critical region is covered with drift, which lies along a stream valley. It is believed that this valley lies near the course of a fault which separates the tongues from the main mass (Fig. 1).

Petrography

The tongues are composed entirely of slightly feldspathic peridotite in which light and dark bands can be distinguished on weathered surfaces. The darker bands are rusty brown in color and discontinuous, being up to two feet in length and an inch across. These bands are set generally two or three inches apart in a direction perpendicular to their strike. The intervening peridotite weathers to a grey-brown color. The darker bands form hollows within the lighter peridotite.

In thin section almost all the rocks examined are very similar. They consist of approximately 90 per cent by volume of olivine, the remainder being basic plagioclase, clinopyroxene with a little chromite and altera-

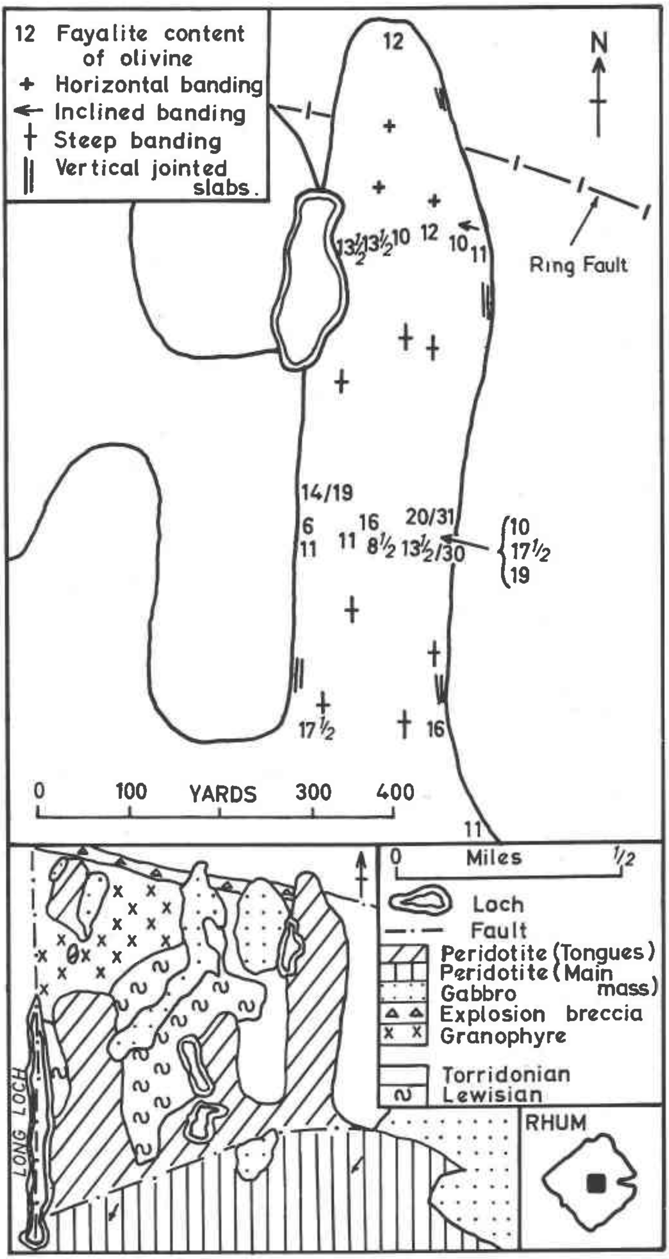

FIG. 1. Sketch map of the ultrabasic tongues. The lower map shows the general setting of the tongues. Two unmarked arrows show the direction of dip of the layered rocks of the main complex. The upper map is an enlarged portion of the eastern tongue.

tion products after olivine. Modal analyses of three typical rocks are given in Table 1. The olivine crystals vary in size from 0.5 mm to 5.0 mm, and are generally euhedral in shape. The forms (100), (010) and (021) are the most common, with (001) occurring occasionally. The crystals are commonly platy, with $Z > X \gg Y$. Most rocks show a platy lamination parallel to the banding. Some of the larger grains are bent and may be fractured, whereas the smaller olivines, entirely enclosed within clinopyroxene are commonly rounded.

TABLE 1. MODAL ANALYSES OF ULTRABASIC ROCKS FROM THE TONGUES AND THE MAIN LAYERED COMPLEX OF RHUM

Rock	Olivine	Pyroxene	Plagioclase	Chromite	Alteration products
197	90.0	2.5	3.7	0.5	3.3
200	85.7	3.9	4.4	2.3	3.7
204	90.1	2.1	3.5	1.2	3.1
562	68.5	0.2	25.5	0.8	5.0
586	69.4	5.4	12.9	1.4	10.9
589	62.8	6.0	26.7	3.0	1.5
5575	79.4	5.3	23.0	1.3	—
5583	14.1	4.9	80.9	—	0.1
Ard Meall average	83.5	1.8	11.2	1.6	1.9
9720	95.8	1.3	1.9	1.0	—

197, 200, 204 and 562 from the eastern ultrabasic tongue.

586 and 589 from the first outcrop of the main layered series to the south of the eastern tongue.

5575 and 5583 peridotite and allivalite respectively from the base and top of unit 7, Hallival-Askival area. Brown, 1956, Table 5, p. 33.

Ard Meall average is the average of six. Wadsworth, 1961, Table 3, p. 38.

9720 is an olivine rich cumulate from the base of the Ruinsval series, Harris area. Wadsworth, 1961, Table 6, p. 44.

The composition of the olivine has been determined by the x-ray method of Yoder and Sahama (1957) on whole rock powders from twenty-one rocks. The results, shown in Table 2 and Fig. 1 represent bulk compositions, although in one or two cases two separate peaks were obtained indicating olivines of two compositions in the rock. The overall composition varies from Fa_{6-31}, which is in sharp contrast with the small variation (Fa_{14-18}) reported from other parts of the layered ultrabasic mass (Brown, 1956; Wadsworth, 1961).

The variation of olivine composition throughout the tongue seems to

TABLE 2. *X*-RAY DETERMINATIONS OF OLIVINES FROM THE EASTERN PERIDOTITE TONGUE

Sample	d	Molecular % fayalite
22	2.7740	12
25	2.7750	13½
26	2.7750	13½
27	2.7725	10
28	2.7740	12
29	2.7725	10
30	2.7731	11
32	2.7731	11
33	2.7731	11
34	2.7715	8½
35	2.7750	13½
	2.7860	30
36	2.7725	10
37	2.7775	17½
38	2.7782	19
40	2.7765	16
41	2.7731	11
42	2.7775	17½
197[1]	2.7700	6
200[1]	2.7765	16
204[1]	2.7790	20
	2.7865	31
562_a[1]	2.7785	19
562_b[1]	2.7750	14

[1] Specimens in the Accession Series of rocks in the Department of Geology and Mineralogy, Oxford University. The remainder are in the writer's possession.

562a is a plagioclase rich band, and 562b is a pyroxene rich band. For location see text.

be random except that none of the higher fayalite values occur in the northern part of the tongue. For example the variation in a traverse 200 yards from the southern end of the tongue seems completely haphazard.

Thin section examination indicates that the banding depends on the dominance of clinopyroxene or plagioclase in the interstitial areas, giving rise to dark and light colored bands respectively. The olivine content remains roughly constant. Plagioclase has cores of An_{80} but is usually heavily zoned. The grains are poikilitic and vary up to 1.5 mm in size. No phenocrysts have been observed. The clinopyroxene is variable in size with poikilitic grains up to 4 mm across. It has a composition similar to that in the normal peridotites of Rhum ($Ca_{44}Mg_{49}Fe_7$, Wadsworth, 1961), but the small quantities preclude accurate optical or *x*-ray determination ($b=8.91$ Å). Two generations of chromite are present, one enclosed within the olivines and the other moulded on the olivines.

Two small areas within the eastern tongue contain less olivine and more plagioclase. Samples 562 (100 yards south of the small loch on the west side of the tongue) and R 36–38 (150 yards east of sample 562) illustrate this type. Banding is very well developed in 562 and a modal analysis of a feldspar-rich band from this specimen is shown in Table 1. The plagioclase in this rock reaches 2.6 mm in diameter. Modal analyses of a typical peridotite and allivalite from Hallival are given in Table 1 for comparison, together with modal analyses of rocks from the first outcrop of normal layered rocks to the south of the eastern tongue. The marked contrast in olivine content between the normal layered rocks and the rocks of the tongues must be emphasized.

The olivine-rich peridotites of the Ard Meall series and the Ruinsival series of the Harris area (Wadsworth, 1961) are modally very like the tongue rocks. However, dendritic iron ore inclusions occur in the larger olivines of the Ard Meall series, though none have been observed in the tongues and Wadsworth does not report any in the Ruinsival series.

Discussion

Three major problems are posed by these rocks. The first is their relationship to the main layered complex. The second is the origin of the banding, and the third and related problem is the cause of the variation in the olivine composition.

Brown (1956) suggested that the layered ultrabasic rocks were emplaced in their present position by a ring fault, the uprise being lubricated by a peripheral contemporaneous gabbro intrusion. However, no trace of such a gabbro has been found around the tongues, and this absence and the shape of the tongues suggest that they were not emplaced by faulting of a solid mass. Bailey (1945) believed that the tongues and gabbros of the northern margin of the igneous complex traced out part of a ring complex of large radius. If this is the case, or if the tongues and knolls form part of a radial system, then there must be a faulted relation between the tongues and the main layered complex, the main layered complex being the later. Unfortunately it has not been possible to confirm this hypothesis in the field because of poor exposure in the critical region, but the fact that there is a drift filled valley on the proposed line of such a fault is at least suggestive. The distribution of ultrabasic rocks at the southern end of the tongues suggests that either one fault may be present with the joining of the parallel tongues at this point, or two or more faults may be present. The nature of the rocks suggests that one fault is the more likely hypothesis.

To the west of the Long Loch fault (see map in Black and Welsh, 1962) lies another northward prolongation of the ultrabasic complex. While this mass does not exhibit banding similar to that in the tongues under consideration it seems possible, if the relations deduced above are correct, that the much broader mass adjoining the ground mapped by Wadsworth (1961) may also be a tongue.

The banding shown particularly well in the eastern tongue is believed to be a new type, for the banding is caused by the relative abundances of the interstitial minerals plagioclase and pyroxene, instead of the more normal variation in cumulus minerals (Wager *et al.*, 1939, 1960; Brown, 1956; Wadsworth, 1961). It is suggested that the tongues formed by the intrusion of a crystal mush, similar to that described by Bowen (1928) for the ultrabasic dikes of Skye. The proportion of olivine crystals in this mush is believed to have been high, possibly as high as 70 per cent, though it is not possible to give any exact figure. The crystal mush is believed to have formed in the main magma chamber by the processes which formed the main layered series (Brown, 1956; Wadsworth, 1961) Wadsworth (1961) describes two zones of igneous breccias, from Lag Sleitir and Ruinsival in the Harris area, which he believes to be the result of faulting taking place during the accumulation of the Ard Meall-Dornabac series and Ruinsival series of layered rocks respectively. These tectonic disturbances may have been associated with faulting in the country rocks, into which the crystal mush was swept. It is not possible to link either of the breccia zones with the rocks in the tongues with certainty, but their petrographic similarity has already been noted.

The variation in the composition of the olivines is believed to be due to different degrees of overgrowth on the original olivine grains from the trapped pore liquid. It is hoped to clarify this point by work with an electron probe microanalyser on the zoning within individual grains. While the feldspar is obviously zoned, variations in the pyroxene are difficult to detect optically.

The banding is considered to be the result of super-cooling the pore liquid which had a composition lying near the triple point in the system diopside-forsterite-anorthite (Osborn and Tait, 1952). Presumably the original pore liquid lay well within the olivine field, hence overgrowths on the olivine would take place first. Plagioclase may have begun to crystallize with the olivine but the liquid must soon have reached the triple point. Wager (1959) has suggested that olivine nucleates more easily than the structurally more complex plagioclase and pyroxene, so olivine may have crystallized together with either or both of the other two minerals. Olivine crystallization seems to have been restricted to crystal growth on the pre-existing olivine grains. The important feature is the nature of the plagioclase-pyroxene crystallization sequence, and this can be regarded as an approximation to a binary system with an eutectic. It is interesting to note that the most fayalite-rich olivine compositions measured are near to that at which olivine ceased to crystallize in the Skaergaard intrusion (Wager *et al.*, 1939).

Crystallization was then controlled by the effects of supercooling the eutectic liquid (Harker, 1909; Taubeneck and Poldervaart, 1960). The important feature of such a system is that nucleation will not take place until a certain degree of supercooling has taken place, which varies for different minerals. Unfortunately there is little experimental data on this topic. A possible course of crystallization is shown in Fig. 2. In this diagram plagioclase is assumed to nucleate more easily because it has a

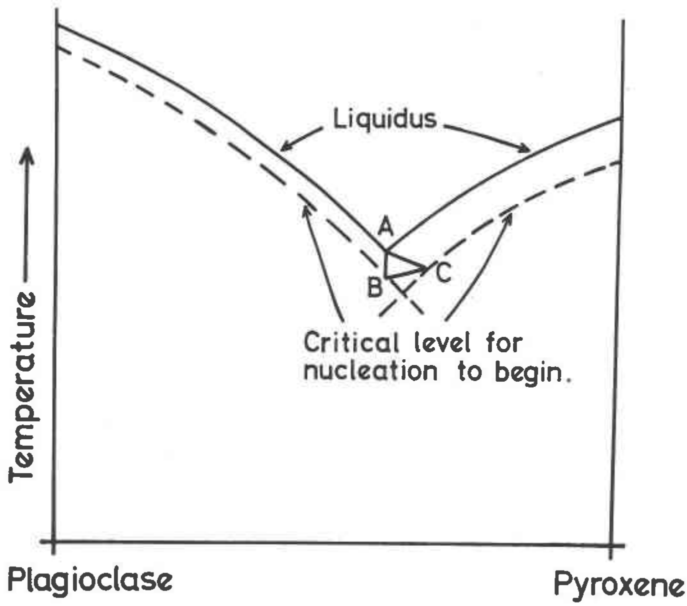

FIG. 2. The effect of different levels for the onset of nucleation in a simple binary system. See text for details.

higher melting temperature, and the critical level at which nucleation begins, corresponding to the early labile region (Wager, 1961, Fig. 1) is shown as a dashed line. The liquid of composition A, an eutectic mixture, would cool to B at a temperature below the liquidus with no crystallization. At B nucleation and crystal growth of the plagioclase would begin, but because the temperature has not fallen far enough to reach the critical level for pyroxene none of the latter forms. However, the removal of plagioclase out of solution will cause a shift of liquid composition towards pyroxene. This line BC is shown moving towards pyroxene at approximately constant temperature because the heat of crystallization will maintain the temperature or at least not let it fall far. From B to C crystal growth of plagioclase continues, as the maximum rate of crystal growth is achieved with less supercooling than the maximum rate of nucleation (Mullin, 1961; Dunham, 1965) but probably no nucleii are formed; hence large but few grains of plagioclase are formed. At C nucleation and growth of pyroxene begins. Crystallization of this phase causes the liquid to move back towards its original composition possibly with a rise in temperature. Crystallization then ceases until further cooling initiates a new cycle. Thus, one pair of bands is believed to represent one cycle which operated of the order of 2000 times during the crystallization history of the dike.

Taubeneck and Poldervaart (1950) have described layered rocks from the Willow Lake intrusion, Oregon, which they believe to be the result of supercooling from an eutectic melt. However, in layered rocks of the Willow Lake type the minerals grow elongated at high angles to the banding, and the banding is continuous, in contrast to these Rhum rocks. They believe the undercooling is maintained by convection currents sweeping past the site of crystal growth, a quite different situation from that envisaged for the tongues on Rhum, where supercooling was essentially cyclic in character and operating in trapped pore liquid.

In order to highlight the nature of the layering in the peridotite tongues from Rhum, and to contrast them with cumulus or Willow Lake type layering, it is suggested that this new type of layering be known as "matrix banding."

It is concluded from this preliminary study of some of the ultrabasic rocks of central Rhum that a new type of layering called "matrix banding" has formed in dikes which belong to a phase of emplacement earlier than the main layered series of Rhum. The dikes are believed to have been filled with a crystal mush very rich in olivine, with a pore liquid near in composition to the triple point in the system diopside-forsterite-anorthite. The olivines were then enlarged by overgrowth, and the banding formed by the subsequent alternate crystallization of plagioclase or pyroxene from the supercooled pore liquid, which had an eutectic composition.

Acknowledgements

This work was begun in Oxford, and the writer wishes to thank Professor L. R. Wager and Dr. G. M. Brown for their help and encouragement, and the Nature Conservancy both for assistance in Rhum and for financial support. The work was completed in Durham, where the advice of Professor K. C. Dunham, Dr. W. G. Hancock and Dr. D. M. Hirst was most freely given. The writer also wishes to thank Dr. C. H. Emeleus for many stimulating discussions on Rhum Geology. Dr.

T. P. Thayer read the manuscript and made many helpful suggestions which are most gratefully acknowledged.

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Manuscript received, December 2, 1964; accepted for publication, June 8, 1965.