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An investigation of olivine crystal growth in a picrite dyke, using the fission track method

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ABSTRACT. A picrite dyke with an olivine-bearing chilled margin and an olivine-rich centre has been used to test for the presence of a boundary layer around rapidly grown olivine crystals and for any variations in the olivine/melt partition coefficient for uranium as a result of probably different crystal growth rates. The technique of fission-track mapping is shown to be suitable for this kind of study despite the very low uranium concentrations in the olivines. A boundary layer appears to be present around some olivine crystals but it is not a consistent feature. Uranium partition between olivine and melt was not affected by different crystal growth rates, as revealed by different crystal morphologies.

KEYWORDS: olivine, crystal growth, picrite, uranium, fission tracks.

THE kinetics of crystal growth in igneous rocks is an important topic, because knowledge of the rates of mineral crystallization are useful to petrogenetic studies and because element distribution can be dependent on crystal growth rates. Studies on the relationship between growth rate and element partition (crystal/melt) are still scarce for petrological systems and the results do not allow general conclusions to be made. For example, Lindstrom (1983) from a study using synthetic melts, found that the partitioning of 'excluded' elements between melt and olivine crystals was independent of the rate of crystal growth, and he did not find a boundary layer around the crystals, with a different composition from the bulk melt. However, Kouchi *et al.* (1983) showed that Ni distribution between olivine and its melt was dependent on crystal growth rate and that interface kinetics play a part in the growth rate.

Unfortunately the respective roles of diffusion and of interface kinetics are still not adequately understood. Shimizu (1981) showed that the differential partition of incompatible (excluded) elements in the slower and faster growing sectors of sector zoned clinopyroxenes could not be diffusion controlled, yet Henderson and Williams (1979) found that diffusion control provided a satisfactory explanation for the different uranium concentrations in olivines that probably grew at differing rates in the Rhum layered ultrabasic intrusion.

The purpose of this note is to report the findings of a pilot study on the effect that differences in mineral growth rate have on elemental distribution in a natural rock system. Our objectives were threefold:

1. To test a technique, the mapping of uranium distribution by the fission-track method, for its suitability in this kind of project.
2. To investigate the possible presence of a boundary layer around olivine crystals with morphologies indicative of rapid crystal growth.
3. To test for possible variations in uranium partition between crystals, of probably different growth rates, and co-existing melt.

A picrite dyke from the Isle of Skye, Scotland was selected. Uranium was considered to be a suitable element for this study because it is strongly incompatible in basaltic systems; it probably has a very slow rate of diffusion in silicate melts (based on the observations in Henderson *et al.*, 1985); and its distribution can be mapped.

Specimen description. One specimen from the centre and another from the chilled margin of a one metre thick picrite dyke were selected. The dyke is intrusive into lavas and eucrite and occurs on the SE flank of Gars-bheinn, Skye, Scotland (Grid Reference NG 478177). Analyses of the specimens are given in Table I, and they show similarities to analyses of picrite given by Drever and Johnston (1967).

The centre of the dyke contains abundant

TABLE I. Analyses of chilled-margin and centre of picrite dyke

	Margin	Centre
SiO_2	47.20	46.24
TiO_2	0.80	0.68
Al_2O_3	13.26	11.18
Fe_2O_3	2.60	2.89
FeO	7.77	8.19
MgO	14.50	20.68
MnO	0.19	0.19
CaO	11.16	9.34
Na_2O	1.39	1.19
K_2O	0.07	0.02
P_2O	0.06	0.04
CO_2	0.03	0.02
H_2O^+	1.22	0.84
Cr_2O_3	0.15	0.21
Total	100.40	101.71

Analyst: C.T. Williams

euhedral or rounded, olivine phenocrysts (Fo 85.6–90.6, by microprobe analysis), up to 3 mm in length with occasional olivine laths up to 4 mm long and 0.3 mm wide. There is no significant flow orientation of the crystals. Phenocrysts are set in a crystalline groundmass of pyroxene, olivine and abundant laths of plagioclase feldspar, the larger ones of which are patchily zoned. The margin of the dyke grades from a partly glassy junction (0.3 mm wide) of remelted basalt, through a chilled glass, but olivine phenocryst-bearing zone (about 1 mm thick) to a zone containing olivine and rare spinel crystals set in a cryptocrystalline to microcrystalline groundmass. The olivine crystals (Fo 87.2–91.2) in both zones have morphologies characteristic of rapid growth (fig. 1). Elongate crystals (up to 2.5 mm in length) tend to be orientated parallel to the dyke's margin.

Methods and Results. The uranium concentrations in the two specimens of the dyke were determined by the fission track method using an external recorder, as outlined by Storzer and Sélo (1974). Two irradiations were used; the first with an integrated thermal neutron flux of 8.6×10^{16} n cm^{-2}, and the second of 6.8×10^{18} n cm^{-2}. These high integrated fluxes were necessary because of the low U concentration in the specimens. The first irradiation enabled the determination of the overall U concentrations; the second was performed to study the U distribution around the olivine crystals

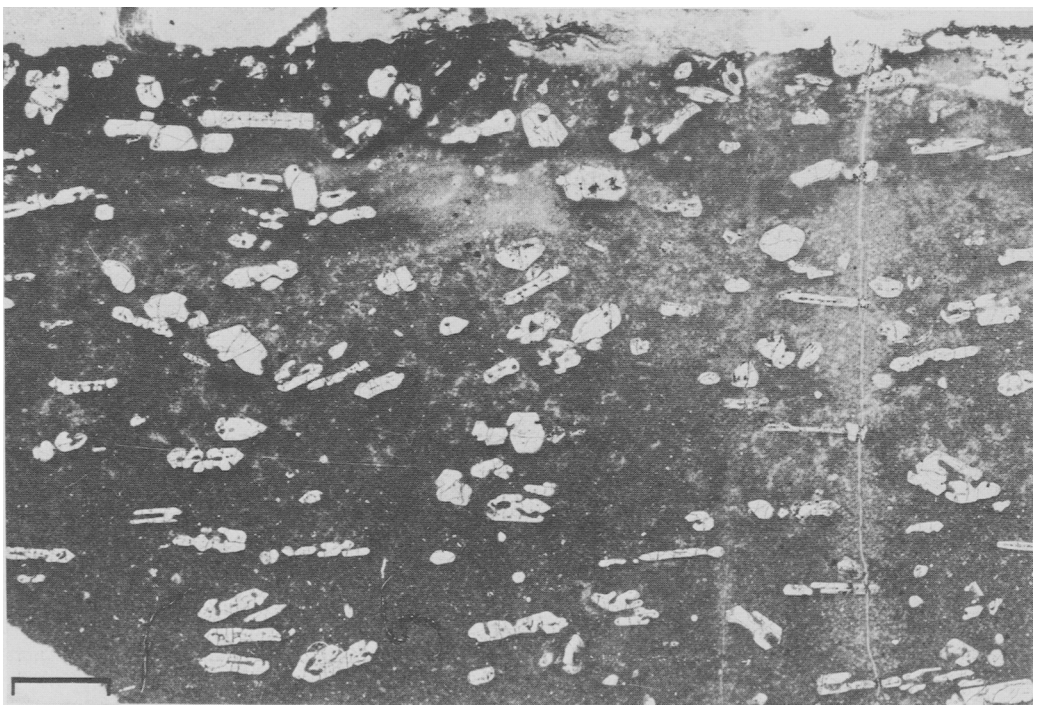

FIG. 1. Photograph of thin section of picrite dyke. The contact of the dyke is along the top of the photograph. The scale bar at the bottom left-hand corner represents 1 mm.

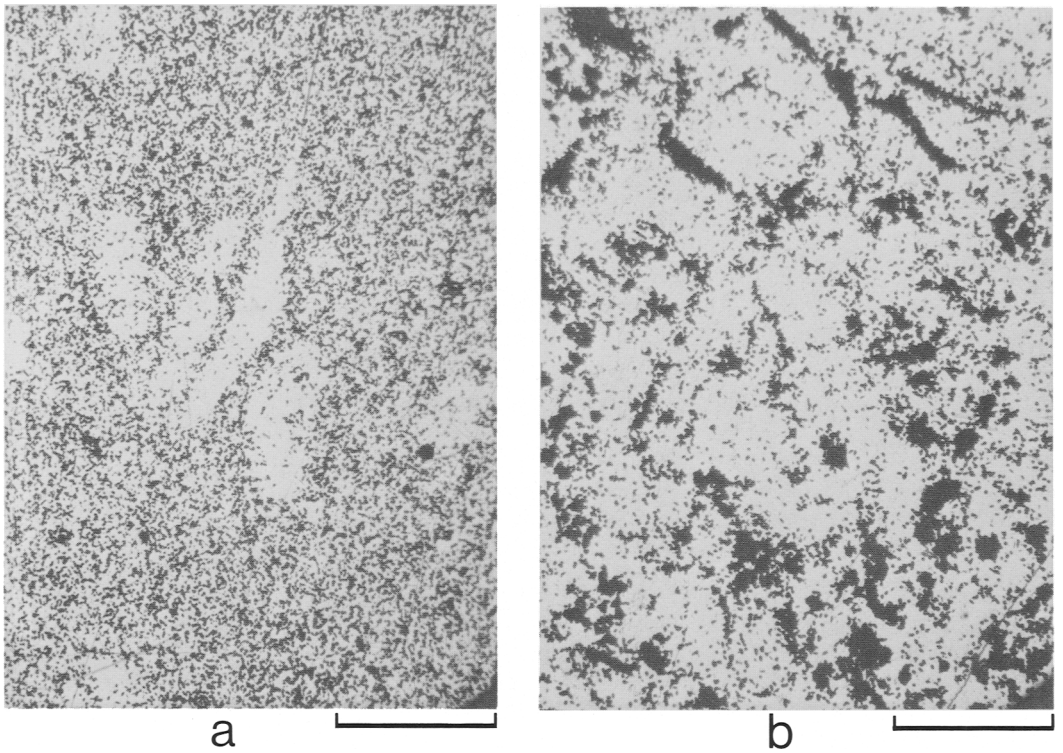

FIG. 2. Fission-track map of the distribution of uranium in (*a*) the chilled margin and (*b*) the centre of the picrite dyke. The scale bar at the bottom right-hand side represents 500 μm.

and to allow a better assessment of the U concentration in the olivine crystals.

The etching of the track recorder resulted in a track resolution of approximately 2 μm. Tracks were counted optically at a magnification of 1000. Fig. 2 shows photographs of the track distribution for two samples.

The bulk uranium concentrations, after correction for background, are virtually identical in the chill and the centre of the dyke (Table II). Approximate concentrations of U in the olivine crystals, based on the low track count are also given in Table II. The results allow for background and do not include the relatively high uranium levels along the centre of some crystals where there was evidence of included melt (see also fig. 1). The matrix, or mesostasis, at the centre of the dyke contains 54 ppb U, while that at the dyke's edge, but not immediately adjacent to olivine crystals contains an average of 23 ppb (Table II). The partition coefficient of uranium (concentration in olivine/concentration in bulk melt) is 0.015 for olivine crystals at the dyke centre, and virtually the same value for crystals at the dyke margin (mean 0.016).

The higher concentration in the mesostasis adjacent to olivine crystals at the dyke's margin (Table II) occupy a band approximately 14 μm wide but such a band is not present around all the olivine crystals, nor where present, is it always continuous around a crystal. It is clear that the U distribution in the band is variable but the real extent of the variations is too small to allow a determination of the concentration range around a given crystal; the results in Table II are, therefore, the concentration range among different bands and their mean. The Table includes an estimate of accuracy (one standard deviation).

Discussion. Under conditions of rapid crystal growth from a melt, a boundary layer of a composition different from that of the bulk of the melt can develop. It could arise because the diffusion rates of some elements in the melt are insufficiently fast in relation to the crystal growth rate, to maintain equilibrium concentrations. The width of a diffusion-controlled boundary layer will be dependent on the diffusion rates, the crystal growth rate and also on the degree of turbulence in the melt (Carruthers, 1975). One theoretical analysis

TABLE II. Uranium distribution

		U, ppb	Partition coefficient (olivine/matrix)	
Bulk rocks:	dyke margin.	13.6 ± 1.0		
	dyke centre.	13.6 ± 1.0		
Dyke margin:	olivine.	0.38 ± 0.08		
	mesostasis.	16-32	0.012 - 0.024	(range)**
	mean.	23.3 ± 0.6	0.016 ± 0.004	(mean)
	mesostasis at olivine boundary*	25-40	0.010 - 0.015	(range)**
	mean.	32.0 ± 1.9	0.012 ± 0.003	(mean)
Dyke centre:	olivine.	0.83 ± 0.08		
	mesostasis.	48-62	0.013 - 0.017	(range)**
	mean.	54.5 ± 2.4	0.015 ± 0.002	(mean)
	mesostasis at olivine boundary*	51-57	0.015 - 0.016	(range)**
	mean.	53.3 ± 2.9	0.016 ± 0.003	(mean)
	mesostasis trapped in olivine.	42.6 ± 4.8	$0.019^{+0.005}_{-0.003}$	(mean)

* see text

** analytical errors are not included in the range

Analysts: M. Sélo and D. Storzer

of its form (Burton *et al.*, 1953) has been applied to several problems of crystal growth in mineralogy (e.g. Shimizu, 1978; Henderson and Williams, 1979). There are few data on the nature of the boundary layer in silicate systems. Crystallization of silicates in experimental charges has sometimes produced compositional gradients in zones around the minerals (e.g. Seitz, 1974; Lindstrom, 1983) similar to those observed in natural quenched melts (Bottinga *et al.*, 1966; Donaldson, 1975; Evans and Nash, 1979).

The present investigation has not given a convincing demonstration of the occurrence of a boundary layer during rapid mineral growth in magmatic systems, because the U concentrations are not consistently higher around the rapidly grown olivine crystals than in the bulk of the mesostasis. Where there is a boundary layer its width is of the order of 14 μm, similar to those recorded in other cases (Seitz, 1974; Bottinga *et al.*, 1966; Donaldson, 1975). Absence of a boundary layer, even if it was initially present, can be caused by an insufficiently fast quench rate or subsolidus diffusion. The investigation has shown, however, that the fission-track method is suitable for studies of this kind even when uranium concentrations are very low (see Table II). The resolution of the method is more than adequate to reveal boundary layers of thickness measured here (14 μm) and recorded elsewhere (Bottinga *et al.*, 1966; Donaldson, 1975; Evans and Nash, 1979). The technique is thus more suitable for indicating the presence of a boundary layer than is electron probe microanalysis.

Our results on the concentration of U in the olivines and groundmasses of the specimens are particularly interesting with respect to the third aim of the project for, despite the occurrence of rapidly grown olivine crystals in the quenched margin, the U partition coefficients are similar for crystals at the centre and margin of the dyke (Table II) even though the absolute concentrations are different. This finding is contary to what might have been expected but does conform to the observations by Lindstrom (1983) on the distribution of excluded elements (Al, Ca, Lu) between melt and olivine grown at differing rates (see first paragraph of introduction). An alternative explanation for the similarity in the U partition coefficients for olivine crystals at the centre and at the margin of the Skye dyke is that the olivine crystals at the centre grew at about the same rate as those at the margin but the former continued to grow to a larger and more equant morphology.

The findings presented here and by Lindstrom (1983) concerning the absence of variations in U partition coefficients raise the problem of the causes of the U variation in olivines from the Rhum intrusion as described by Henderson and Williams (1979), especially since the Rhum olivines were estimated to have grown at rates (maximum ~ 6 μm s^{-1}) slower than some of those studied by Lindstrom (> 10 μm s^{-1}). Entrapment of melt within some of the rapidly grown olivine crystals is

observable in the Skye dyke and could have occurred during the growth of the Rhum olivines. However, inclusions containing relatively high U concentration were not recorded in the Rhum examples; the uranium appears to be homogeneously distributed within the limits imposed by the analytical method. Much more research is needed into the effects of differing crystal growth rates on elemental distribution in *natural* rock systems.

Although the purposes of this work were not to investigate the origin of the different textures in the dyke, it is noteworthy that since the bulk rocks from the centre and margin of the dyke have the same U concentrations, and since the U concentration in the mesostasis at the centre is much higher than that in the margin, flow differentiation cannot have been the principal cause of the much higher modal proportion of olivine in the centre compared with the margin. If flow differentiation had been the principal cause then the concentration of incompatible elements, such as U, would be significantly lower at the dyke's centre than at the margin if the liquid component of the intrusion was of uniform composition throughout.

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