A NEW PROXY FOR DOLERITE CRYSTALLISATION TIMES IN PLANETARY SAMPLES. M. B. Holness[1], C. Richardson[2], and M. Anand[3,4], [1]Dept. Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK marian@esc.cam.ac.uk. [2]BP Institute, University of Cambridge, Madingley Road, Cambridge CB3 0EZ, UK. [3]Planetary and Space Sciences, The Open University, Milton Keynes, MK7 6AA, UK. [4]Department of Mineralogy, The Natural History Museum, London, SW7 5BD, UK

Introduction: Cooling rates during solidification of magmas can be constrained from crystal shapes (e.g. whether equant or dendritic) [1] and from the distribution of crystal sizes (CSD) [2]. In this contribution we introduce a new parameter for constraining solidification times in mafic rocks: the median clinopyroxene-plagioclase-plagioclase dihedral angle, Θ_{cpp}.

The geometry of three-grain junctions: In textural equilibrium the sum of interfacial energies is minimized, with force balancing at all three-grain junctions. For two-phase junctions this results in a characteristic angle – the dihedral angle [3] – given by:

$$\gamma_{bb} = 2\gamma_{ab}\cos\left(\frac{\Theta}{2}\right)$$

Silicate minerals are generally anisotropic with respect to interfacial energies so texturally equilibrated rocks will display a range of dihedral angles. Equilibrated clinopyroxene-plagioclase-plagioclase (cpx-plag-plag) junctions have a median angle of 109˚ ± 2˚ and a standard deviation of ~10˚.

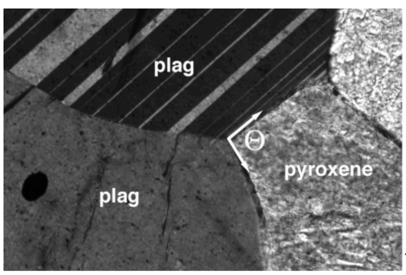

Fig 1. - A texturally equilibrated three-grain junction between two grains of plagioclase and one of pyroxene. The dihedral angle is controlled by the balance of interfacial energies at the junction.

Most mafic rocks are not in textural equilibrium: their microstructures were created during solidification. Plagioclase grains are commonly bounded by planar growth faces rather than the smoothly rounded boundaries expected for textural equilibrium (Fig. 2).

The ubiquity of plagioclase and Ca-rich pyroxene (usually augitic) in mafic igneous rocks, together with their robustness to chemical alteration (compared with olivine and Ca-poor pyroxene), provides the opportunity to explore systematic variations of Θ_{cpp}.

Measurement techniques: Dihedral angles in natural translucent samples are measured using a universal stage mounted on an optical microscope. The median value, Θ_{cpp}, is obtained from populations of 100 individual junctions, with the 95% confidence interval calculated according to Stickels & Hucke [4].

The average grain size was determined by measuring the apparent long axis of all plagioclase grains in photomicrographs. Resolution of the photographs was such that all grains could be seen. Between 150 and 300 individual grains were measured in each sample.

Dihedral angles in dolerites: Dolerite sills are generally unfractionated, with abundant evolved minerals, and have broadly constant compositions across their thickness. The major variable affecting microstructure of the fully solidified rock is cooling rate, with fast cooling at the margins compared to the centre.

In fast-cooled dolerites (such as on the margins of large bodies or within small shallow bodies such as dykes, sills and lava flows), in which plag and pyroxene are cotectic, pyroxene-plagioclase boundaries are planar and show no deflections at three-grain junctions (Fig. 2a): we interpret this as a consequence of fast growth of pyroxene into the pore space. Ca-rich pyroxene doesn't grow into the narrowest spaces: these are instead filled by glass or fine-grained Si-rich intergrowths of late-stage, low temperature mineral assemblages. Because the narrower pores are not infilled with pyroxene, Θ_{cpp} in these fast-cooled rocks is higher than the value of 60˚ expected if pyroxene were to fill all the spaces between plagioclase grains [5]. Θ_{cpp} in fast-cooled mafic rocks is ~78˚.

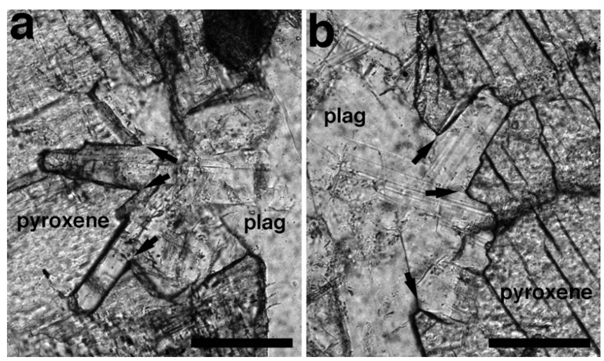

Fig. 2 – (a) dihedral angles in fast-cooled dolerites are low, while (b) those in slower-cooled parts of the same body are high. Scale bar is 200μm long.

In slower-cooled dolerites, pyroxene-plagioclase grain boundaries curve into three-grain junctions (Fig. 2b), most likely reflecting simultaneous growth of plagioclase and pyroxene during the filling of the melt-filled pore spaces, and resulting in higher Θ_{cpp}.

Θ_{cpp} was measured across 4 dolerite sills ranging in thickness from 3.5 m to 266 m. In the 3.5 m thick Traigh Bhan na Sgurra sill, Θ_{cpp} is 78˚ throughout. In the 38 m thick Whin Sill and the 130 m thick Portal

Peak sill, Θ_{cpp} is 78° at the margins but increases towards the centre. The 266 m Basement Sill shows strong asymmetry of Θ_{cpp}, with higher than expected values in the top half and significant increases in Θ_{cpp} at both margins. These higher angles are associated with significant rounding of grains and loss of the original igneous microstructure, attesting to sub-solidus textural equilibration most likely facilitated by the fine grain size and the relatively long times at elevated temperatures experienced by the early-forming chilled margins.

Relationship between Θ_{cpp} and cooling rate: We modeled the thermal history of the sills using a 1D conductive heat transfer model assuming:

$$(1 + L_T)\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2}$$

where L_T is a latent heat function, T is temperature, and κ is the thermal diffusivity. The initial condition is a boxcar function, of width w and amplitude T_0, representing the width and initial temperature of the intrusion. The far-field temperature is set at 0°C, with $\kappa = 10^{-6}$ m^2/s, and L_T is calculated using a typical basaltic composition [6].

We calculated the time, τ, taken to cool and crystallise from an assumed intrusion temperature of 1200°C to the solidus (taken as 1000°C) as a function of distance from the centre of each sill. The variation of Θ_{cpp}, with τ (Fig. 3) is well fit by the empirical relationship:

$$\Theta_{cpp} = \Theta_{max} - (\Theta_{max} - \Theta_{min})\exp\left(-\left(\frac{\tau}{\tau_o}\right)^n\right)$$

where Θ_{max} = 109° is the equilibrium value, and Θ_{min} = 78° the value observed in rapidly cooled bodies. The time constant τ_o is best fit by a value of 275 years, and $n = 0.42$.

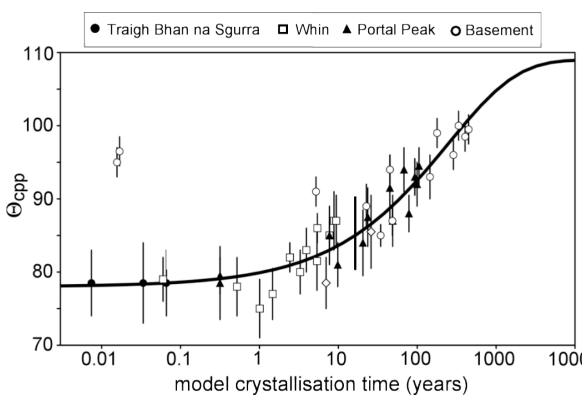

Fig. 3 – variation of Θ_{cpp} with model cooling time for four dolerite sills. The best fit line is empirical. The fast-cooled data points falling off the trend are from the chilled margin of the Basement Sill.

Microstructures of lunar rocks: We determined the values of Θ_{cpp} and the average plagioclase grain size for a suite of lunar rocks, chosen for their relatively coarse grain size (to facilitate optical measurement of Θ_{cpp}) and large sample area.

Sample	Θ_{cpp}	st. dev.	τ (years)	Grain Size (mm)
12051,59	79 ± 4	20.7	< 10	0.12
10050, 11	85 ± 5.5	21.5	< 50	0.10
75055,49	90 ± 3.5	21.6	23 - 110	0.27
12047,9	91 ± 6	21.1	10 - 250	0.13
14053,19	93 ± 3	17.0	50 - 200	0.12

Discussion: The controls on Θ_{cpp} are not yet understood but it is almost certain that important parameters are the rates of mass transport and crystal growth in a gradually occluding pore network, together with the constraints placed by very small pore size on crystal growth kinetics [7]. It is likely that these processes operate at the same rates regardless of the size of the body in which they occur: if so then the cooling rate proxy obtained from terrestrial intrusions can be applied directly to the extra-terrestrial samples. These suggest timescales for solidification ranging from < 10 years for 12051 to 200 years for 14053, consistent with all samples other than 12051 being derived from small shallow intrusions rather than lava flows.

The average grain size bears no relationship to Θ_{cpp}. Four of the five samples have similar grain size, despite a range of Θ_{cpp} from 79 – 93°, suggesting that grain size is not a robust indicator of crystallization times. While CSDs are commonly used to place constraints on timescales of crystallization [2], this requires independent knowledge of crystal growth rates. Growth rates are themselves a function of cooling rate [8] so many authors use estimates of the growth rate, ranging over two order of magnitude. In contrast, the dihedral angle method is purely empirical, based on direct observation of a single parameter, with no requirement for estimating unknown parameters. It also shows more variation than grain size and may be a more robust parameter for determining cooling rates of intrusive rocks solidifying over time periods < 1000 years.

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