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The origin of spinifex texture in komatiites

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Komatiites are high-temperature, fluid, magnesium-rich lavas typically of archaean age. A striking characteristic feature of such lavas is 'spinifex' texture—plate-like crystals of olivine ($(Mg,Fe)_2SiO_4$), millimetres to decimetres long, in a fine-grained matrix of spherulitic clinopyroxene ($Ca(Mg,Fe,Al)(Si,Al)_2O_6$), dendritic chromite ($(Mg,Fe)(Cr,Al,Fe)_2O_4$) and altered glass[1–4]. Sheaves of olivine crystals can reach lengths exceeding one metre, even in komatiite flows less than 10 metres thick, in sharp contrast to the millimetre-scale post-eruption growth of crystals in more common volcanic rocks. Crystal growth of this magnitude might be a consequence of the high content of the constituent elements of olivine in komatiitic liquid, combined with the low viscosity and high chemical diffusivity of the lavas. But flows lacking spinifex texture are not uncommon, and those with such texture often contain substantial amounts of submillimetre olivine crystals of unremarkable appearance, so chemical considerations alone do not appear to provide a sufficient explanation. Here we present evidence that spinifex texture develops as a result of large thermal gradients, coupled with conductive and radiative heat transfer within olivine crystals fixed in the cool upper layers of the lava flows. This mode of growth has features in common with the high-temperature techniques used to grow large synthetic single crystals, but is rarely considered in geological contexts.

Many komatiites, including the exceptionally fresh and well exposed flows at Pyke hill in Munro township, northeastern Ontario, erupted as subaqueous lava flows[1,4]. The thermal effect of seawater infiltration. into the fractured upper crust of the flows has not previously been considered in komatiite cooling models[5,6]. Thermal contraction of the solidified sheet-like lava flows (below ~1,000 °C) caused extensive fracturing on a centimetre to decimetre scale (Fig. 1). The permeability of a rock body can be estimated from the number and mean width of its fractures[7]; that of the illustrated Pyke hill lava tube is $\sim 10^{-11}\,m^{-2}$. This is close to the calculated bulk permeability of young oceanic crust ($\sim 10^{-12}\,m^{-2}$)[8]; by contrast, unfractured igneous rocks have typical *in situ* permeabilities of the order of 10^{-16} to $10^{-18}\,m^{-2}$. Thus we expect a substantial heat flux to have been transported by water circulation through cracks. Semiquantitative measurements of hydrothermal heat fluxes from basalt flows include $\sim 40\,kW\,m^{-2}$ at Heimaey[9], $100\,kW\,m^{-2}$ (with transient fluxes approaching $1\,MW\,m^{-2}$) at Kilauea[10], and $\sim 1\,MW\,m^{-2}$ at Vatnajökull[11] (estimated from data in that reference). Such heat transfer rates cannot be achieved by conduction through more than a few centimetres of solid rock. Because fracturing leads to further ingress of sea water, hydrothermal cooling/cracking fronts are probably self-propagating (at least in thin flows) and would migrate rapidly downwards. Observations[9–11] and modelling[12] of subaqueous basalt flows have demonstrated that cooling fronts could move at rates as high as several decimetres per hour, resulting in thermal gradients $>10^4\,K\,m^{-1}$ and much faster cooling of flow interiors than would occur via purely conductive cooling.

Rapid cooling, coupled with the absence of pre-existing nuclei of clinopyroxene and plagioclase (komatiite lavas were commonly superheated with respect to these minerals[3]), can explain the spherulitic habit and aluminium-rich composition of clinopyroxene (high pressure, high temperature, and rapid growth are some factors promoting coupled substitution of 2 Al for Mg + Si in clinopyroxene[13,14]), as well as the delayed crystallization of plagioclase in many komatiites. However, rapid cooling and high thermal gradients offer only a partial explanation for spinifex texture, as komatiite flows typically contain a substantial proportion of millimetre-sized olivine crystals of similar morphology to those of basalt and other common rock types.

Textural evidence, including the preferred orientation of the olivine sheaves perpendicular to cooling contacts and their thickening away from the flow surface (Fig. 2), indicates that downward growth of olivine was a competitive process[2,3]. At the microscopic scale, we observe (Fig. 3) that the growth of plate-like olivine crystals was commonly blocked by earlier-formed crystals. Growth of the later crystals proceeded only on faces away from the blocking crystal due to a lack of available space and material (primarily Mg).

The nucleation and growth of olivine occurs readily in ultramafic liquids[15,16], to the point that it is difficult to quench even strongly superheated liquids to crystal-free glasses. Chilled margins of Pyke hill flows, originally glassy, now contain sparse millimetre-sized euhedral olivine crystals as well as hundreds to thousands of micrometre-sized olivine crystallites per cubic centimetre (ref. 4) (Author: is this what you mean?). Thus, even minor differences in olivine growth rates, due to favourable orientation with respect to thermal gradients, gravity or crystallographic axes, could produce a strongly anisotropic fabric over the hours to days required to solidify a thin komatiite flow.

An important factor is the large difference in the thermal properties of olivine and molten komatiite at the temperatures of interest (~1,300–1,550 °C). The mean lattice (or photon) thermal conductivity k_L of olivine is estimated to be $2–3\,W\,m^{-1}\,K^{-1}$, as extrapolated from lower-temperature measurements ($T = 20$–1,200 °C)[17–20] assuming $k_L = 1/(a + bT)$, where a and b are constants. This relationship is not exact, but is reasonably accurate at ambient to high temperatures for olivine and other ionic crystals with moderately complex structures[19]. Inconsistencies between different data sets are largely due to the variable effects of crystallographic orientation in single-crystal studies, grain boundaries in polycrystalline material, geometrically dependent radiative heat transfer, oxidation/reduction of samples at high temperature, and overall experimental difficulties of measurements at high pressures.

Because of the high temperature of molten komatiites, we must also consider radiative heat transfer in olivine, which has previously been studied as a mechanism of heat flow within the Earth's mantle. The radiative thermal conductivity (k_R) within an optically thick body (such that heat transfer can be considered a diffusive process) at thermal equilibrium, with temperature varying in one direction, is described by the expression[21]:

$$k_R = \frac{20\sigma T^3}{\pi^4}\int_0^\infty l_x \frac{e^x x^4 n_x^2}{(e^x - 1)^2}\,dx \qquad (1)$$

where $x = h\nu/(kT)$, l_x and n_x are the photon mean free path and refractive index at frequency ν and mean temperature T, h is Plank's constant (6.626×10^{-34} J s), k is Boltzmann's constant ($1.38 \times 10^{-23}\,J\,K^{-1}$), and σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8}\,W\,m^{-2}\,K^{-4}$). Where scattering is minimal, as in a single crystal, the mean free path approximately equals the reciprocal of the absorption coefficient. Calculations[21] using equation (1) and the measured visible to mid-infrared absorption spectra of magnesian olivine (($Fe/(Mg + Fe) = 0.08$, similar to komatiitic olivines) show that the effective radiative thermal conductivity within single crystals is $2.0–2.2\,W\,m^{-1}\,K^{-1}$ at 1,400 °C. Although blackbody emissivity increases by 40% from 1,400 to 1,550 °C,