THE SURVIVAL OF ANCIENT SOLAR WIND, GALACTIC COSMIC RAY PARTICLES AND SAMPLES OF THE EARLY EARTH IN LUNAR PALAEOREGOLITH DEPOSITS.

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Introduction: One of the principal scientific reasons for wanting to resume *in situ* exploration of the lunar surface is to access the record it contains of early Solar System history [1,2,3]. For example, studies of Apollo samples show that solar wind particles are efficiently implanted in the lunar regolith, which may therefore contain a record of the composition and evolution of the solar atmosphere [1,4]. Galactic cosmic ray particles may similarly be implanted, potentially leaving a record of high-energy galactic events such as nearby supernova explosions. It has also been suggested that samples of the Earth's early atmosphere may be preserved in the lunar regolith [5], as well as samples of its early crust blasted off in large meteorite impacts [6].

Clearly, this record provides a potentially very valuable window into the history of the early Solar System. However, as the present surficial regolith has been subject to comminution and overturning ("gardening") by meteorite impacts for the last three to four billion years, the record it contains will be an average over most of Solar System history, weighted towards relatively recent times. From the point of view of accessing ancient solar system history, it will be most desirable to find ancient regoliths (*palaeoregoliths*) that were formed, and buried, billions of years ago.

Palaeoregolith Formation: A regolith will form when a fresh surface is exposed to the flux of micrometeorites which constantly impinges on the lunar surface. The contemporary regolith formation rate is very low, of the order of 1mm per million years [7]. However, regolith is expected to have formed more quickly in the past, due to higher impact rates and the fact that a thickening regolith shields the underlying bedrock and thus slows its own formation. For example, the regolith at the Apollo 11 landing site is thought to have accumulated at the rate of 5 mm per million years when the underlying basalts were first emplaced at about 3.6 to 3.8 Ga [7]. Older lava flows are likely to have initially accumulated regolith at an even greater rate. As solar wind and galactic cosmic ray particles are implanted within the top few microns of exposed mineral grains, regoliths as thin as a few millimetres ought to be sufficient to retain a record of these, although thicker layers will be required to ensure survival (see below).

Most exposed mare basaltic surfaces date from between about 3.8 Ga (and perhaps earlier) to at least as recently as 3.1 Ga, with relatively small-scale, geographically restricted, volcanism continuing to perhaps as recently as 1 Ga [8,9]. The study by Hiesinger et al. [9] reveals a patchwork of discrete lava flows in northern Oceanus Procellarum with individual ages ranging from about 3.5 to 1.2 Ga. As younger lava flows are superimposed on older ones, we may expect to find layers of palaeoregoliths sandwiched between lava flows dating from within this age range. The archival value of such palaeoregoliths will be enhanced by the fact that both the under- and overlying basalt layers will lend themselves to radiometric dating, thereby precisely defining the age of the material and the geological record they contain.

Preserving a Record: A worthwhile geochemical record will only be preserved within a palaeoregolith layer if it survives the thermal consequences of burial by the initially molten overlying lava flow. In particular, solar wind-implanted ions are degassed from regolith grains if the latter are heated to a temperature of about 700°C [10,11]. The purpose of this paper is to determine the extent to which such preservation may be expected, by modelling the temperature profile within a palaeoregolith layer as it is covered by a fresh lava flow. Our principal aim is to determine the depth below which a palaeoregolith will not be heated above 700°C, and thus the minimum palaeoregolith thickness that will be required in order to preserve a useful record.

We have developed a numerical solution to the one-dimensional heat conduction equation to describe the heat transfer from a hot, initially molten lava flow to the underlying particulate regolith. We apply a radiative cooling boundary condition to the lava flow surface and account for the contrasting thermophysical properties of the lava and regolith. For the regolith, we adopt an initial temperature T_{0r} of 200 K, a density ρ_r = 1660 kg m^{-3} [12] and a heat capacity of c_r = 760 J kg $^{-1}$ K^{-1} [13] . Adopting the regolith thermal diffusivity measured during the Apollo 15 and 17 heat-flow experiments ($8.6\pm0.4 \times10^{-9}$ m^2 s^{-1} [14]), this yields a thermal conductivity k_r = 0.011 W m^{-1} K^{-1} (within the range of 0.010 – 0.013 W m^{-1} K^{-1} obtained by Langseth et al. [14], despite their slightly different assumed values for ρ_r and c_r). We adopt lava properties appropriate to a lunar basalt [15-17], assuming that the lava is emplaced at an initial temperature T_{0l} = 1500 K, has a density ρ_l = 2980 kg m^{-3} [13], and thermal conductivity k_l = 1.5 W m^{-1} K^{-1}, which represents an average of the variability expected over the temperature range of interest [16]. The lava heat capacity c_l also varies with temperature and with liquid vs. solid state. The latent heat released by the solidifying lava is accounted for by modifying its heat capacity, as proposed by [17]. We therefore adopted two end member values of c_l (1500 J kg^{-1} K^{-1} and 3200 J kg^{-1} K^{-1}) to account for the variability in heat capacity and latent heat release as the lava solidifies.

Results: The model was run for lava flow thicknesses of 1 and 10 m. The lower value is appropriate for the thinnest individual flows exposed in the wall of Hadley Rille (see, e.g. Fig. 1.22 in [18]), while many individual lava flows identified from orbit have thicknesses of the order of higher value [18].

Figure 1 shows the temporal evolution of the temperature profile through a 1 m thick lava and the underlying regolith. It is clear that baking of the regolith to temperatures in excess of 700˚C (973 K) is restricted to very shallow depths; the 973 K isotherm never propagates further than ~3.5 cm (for c_l = 1500 J kg^{-1} K^{-1}) to 7 cm (for c_l = 3200 J kg^{-1} K^{-1}; Fig. 1) into the regolith. The depth of baked zone scales approximately with lava flow thickness. Figure 2 shows the propagation rate of the 973 K isotherm for a regolith heated by 10 m thick lava. The maximum extent of the baked zone is 37 cm. A similar plot for a 10 m flow with c_l = 3200 yields a thickness of ~80 cm. Despite this variation in lava properties, the regolith properties exert the strongest control over heating depths [19]. Future work will employ temperature-dependent thermophysical properties as well as a more sophisticated treatment of latent heat release.

Conclusions: Our results show that the low thermal conductivity of the particulate regolith restricts the depth of penetration of the 973 K isotherm into the substrate. For lava flows ranging from 1 to 10 m thickness, our first-order model predicts that solar wind and galactic cosmic ray particles should be preserved in palaeoregoliths at depths of <0.1 to 1.0 m beneath an overlying lava flow, depending on the thickness of the latter. Palaeoregoliths of this thickness may also be sufficient to preserve ancient terrestrial meteorites [6], which will therefore also be protected from thermal alteration by the overlying lava. Given the regolith accumulation rates estimated for early lunar history [7], individual lava flows would have to remain exposed for between 20 and 200 Myr to accumulate regoliths in this thickness range. The ages of individual basalt flows mapped by Hiesinger et al. [9] indicate that this is likely to have been a common occurrence, and we recommend that a search for such palaeoregolith deposits, and the geochemical record from the early Solar System that they contain, should be a major element of future lunar exploration.

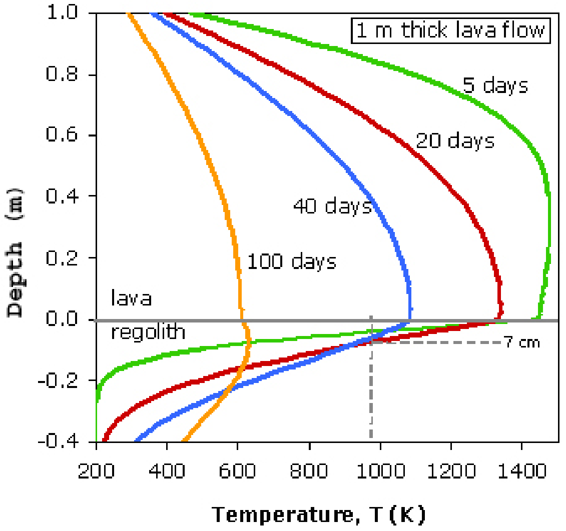

Fig. 1. Temperature profiles through lava and regolith at four times after flow emplacement (5, 20, 40, and 100 days) for a 1 m flow thickness. The 973 K (700 °C) isotherm is represented by a vertical dashed line. The maximum penetration of this isotherm into the regolith is ~7 cm for the case shown here (c_l=3200 J kg^{-1} K^{-1}).

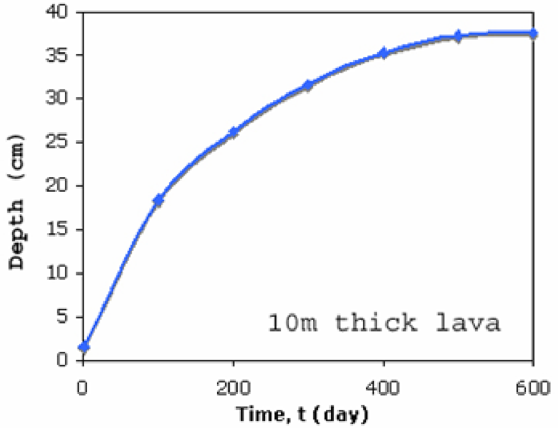

Fig 2. Penetration depth of 973 K isotherm as a function of time for a regolith heated by 10 m thick lava with c_l = 1500 J kg^{-1} K^{-1}. Maximum extent of zone heat to >973 K is 37 cm.

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