THERMAL HISTORIES OF LUNAR METEORITES AND APOLLO SAMPLES: A THERMOLUMINESCENCE OVERVIEW.

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We have measured the induced thermoluminescence (TL) properties of seven lunar meteorites (three highland, four mare) in order to investigate their thermal and metamorphic histories. Most meteorites have TL sensitivities appropriate for their respective provenances, although shock has lowered the TL in two of the mare meteorites. The TL data indicate that all of our highland and mare meteorites contain a significant fraction of disordered feldspar, in contrast to Apollo highland soils, and more like Apollo highland impact melt rocks. The data suggest derivation of the lunar meteorites from a variety of depths in a melt sheet.

Introduction. The number of lunar meteorites now stands at 12, after pairing, and represent a variety of lunar rock types originating from environments of widely differing thermal history. About an equal number derive from mare and highland source regions, despite most of the lunar surface being highland. The highland meteorites studied here include mature (ALH A81005) to immature (MAC 88104/5) regolith breccias and a fragmental breccia (Y 82192). The mare meteorites include a mare basalt (Y 793169), a mare fragmental breccia (EET 87521), a mare cumulate (Asuka 881757), and the basalt-rich breccia QUE 94281. Because most of these rocks are brecciated and all of them have been ejected from the lunar surface, they provide the opportunity to study surface processes occurring on a large planetary body.

We have recently measured the induced thermoluminescence (TL) properties of various Apollo samples and found them uniquely suited to examining thermal and mixing historites [1]. Calcic feldspar is clearly the dominant phosphor in these samples (*e.g.* [2]). TL sensitivity reflects the composition, abundance, and crystallinity of the phosphors while TL peak temperature is related to feldspar structure with ordered feldspar displaying values lower than disordered feldpsars (roughly, <160°C and >160°C, respectively). Only a thermal history involving temperatures above the order-disorder transformation temperature and rapid cooling (for example, in an impact melt environment) can disorder originally ordered feldspar. We were able to disorder the feldspar in highland soil 61501 by heating to 900°C and cooling in air [1]. Highland soils are the only samples with primarily ordered feldspar and represent the most thermally primitive material [3]. Both mare basalts and highland impact melt rocks are dominated by disordered feldspar, but for different reasons. The mare basalts probably derive from cooling units <10 m thick [4], the rapid cooling resulting in feldspar in the disordered state. The impact melt rocks derive from high temperature surface processing and display a variety of textures indicating a variety of cooling histories and this is reflected in the spread of TL peak temperatures. In this study we measured the induced TL properties of eight samples of lunar meteorites and compare these results to those for Apollo samples.

Methods and Results. The TL sensitivities and peak temperatures of the lunar meteorites were measured using the techniques of [1] and are compared to Apollo samples in Fig. 1. Most of the meteorites have TL peak temperatures of ~170°C while 3 of the 8 samples show peaks ≥200°C. None of the meteorites have peak temperatures <160°C where the highland soils plot. The TL sensitivities vary over ~2 orders of magnitude, the highland meteorites having TL sensitivities similar to those of the Apollo highland samples and the mare meteorites having levels similar to those of Apollo mare samples.

Discussion. While all of our meteorites contain disordered feldspar, some approach the ordered field. Mare Meteorites. The TL properties of EET 87521 are consistent with it being a surface-cooled basalt similar to basalts from the mare dominated Apollo 11, 12, and 15 sites. The slightly higher TL sensitivity may indicate the presence of a small highland impact melt component. Asuka 881757 has a TL peak temperature similar to the Apollo mare basalts, but a lower TL sensitivity. This probably suggests a severe shock event followed by rapid cooling to keep recrystallization to a minimum, consistent with the plagioclase in Asuka 881757 being completely maskelynitized [5]. In contrast, while the TL sensitivity of Y 793169 is similar to that of Asuka, it's peak temperature is significantly lower suggesting a severe shock event followed by slow cooling, perhaps in a warm ejecta blanket, so that partially ordered feldspar formed. The feldspar in this meteorite also appears to have been maskelynitized, although feathery textures indicate small degrees of recrystallization [5]. QUE 94281 is a basalt-rich breccia [6] with a TL sensitivity appropriate for unshocked mare material, but substantial amounts of ordered feldspar relative to Apollo mare basalts. This meteorite may contain impact-melt clasts with relatively slow cooling histories similar to those of the highland meteorites.

THERMAL HISTORIES OF LUNAR METEORITES. Symes S. J. *et al.*

Highland Meteorites. Most of the TL of the highland meteorites is probably being produced by the clasts. Macroscopically, our lunar meteorites are similar in texture; polymict breccias with abundant clasts and comminuted mineral fragments set in a glass welded matrix (*e.g.* [7]). The clasts are often impact-melt lithologies dominate d by plagioclase, and the high TL sensitivity is consistent with the clasts being derived from highland precursors. They often show granulitic or recrystallized textures and are the dominant rock types in Y 82192 (~50%) and ALH A81005 (~56%) [8], while several granulites in MAC 88104/5 have uniform mineral compostions suspected to be the result of equilibration during metamorphism [9]. The low TL peak temperatures of these meteorites relative to mare basalts and rapidly cooled impact melts like 14310, suggest that the clasts experienced relatively slow cooling.

It is generally believed that the precursors to regolith breccias are lunar soils [10]. It is therefore of interest that the lunar highland meteorites differ markedly from highland soils in terms of their TL peak temperatures. The highland soils found in core 60009/10, 60013/14, and 70001-9 (a mare/highland mix) all show predominantly ordered feldspar, despite covering a wide range in maturity. Purely maturity-driven processes can at most account for a difference in peak temperature of ~20°C [11], yet the highland meteorites plot >20°C away from the soils. This must result from either mixing with highland impact melt rocks or conversion of originally ordered feldspar to the disordered state during the brecciation event itself (or both). Since the order-disorder transformation temperature for lunar feldspar is ~900°C, the brecciation event(s) must involve temperatures this high and rapid cooling. If pre-existing impact melt rocks were admixed, the majority must be of highland origin to retain the high TL sensitivity displayed by the whole-rock. In the case of MAC 88105, the wide degree of shock experienced by the clasts [6] suggests formation through multiple impacts so the likelihood of mixing pre-existing impact melt rocks is high. Furthermore, the clasts in MAC 88104 must have experienced cooling after the melting event fast enough to preserve totally disordered feldspar.

Conclusions. The similarity in TL properties (TL sensitivity and, especially, peak temperature) between the three highland meteorites indicates similar thermal histories. They were clearly derived from a highlands region, probably the ancient ferroan anorthosite lunar crust [5]. It is likely that these ancient crustal materials developed ordered feldspar during their initial slow cooling, similar to the ordered feldspar found in immature highland soils [3], but their relatively high peak temperatures suggest a thermal event(s) above 900°C. Most of the clasts in Y 82192, ALH A81005, and MAC 88105 are of impact-melt origin but must have cooled slow enough for the feldspar to approach the ordered field. This could be achieved, for example, near the bottom of a thick melt sheet, implying that the clasts in these breccias were formed in relatively large scale impacts. Our sample of MAC 88104 is dominated by disordered feldspar suggesting that it is composed mainly of lithic casts which cooled much faster (perhaps near the top of a melt sheet) than the majority of clasts found in other highland meteorites.

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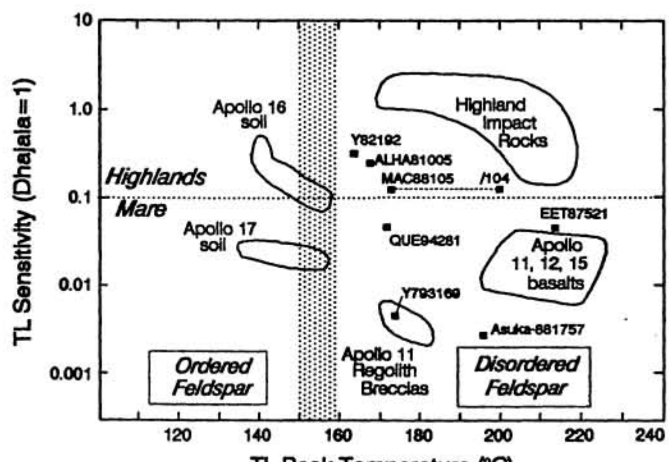

Fig. 1. TL properties of highland and mare lunar meteorites compared with various Apollo samples.