THERMOLUMINESCENCE MEASUREMENTS AND THE THERMAL HISTORY OF MARTIAN METEORITES.

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Introduction: The number of martian meteorites recovered on the Earth's surface is now in the order of 66, excluding pairing [1]. An important aspect of these meteorites is their post ejection thermal history, which has relevance to the size of the ejecta and ejection mechanism, [e.g. 2], and the formation of features interpreted by some researchers as biogenic [3-8]. Post-ejection thermal histories of martian meteorites have been discussed in terms of optical and electron microscopy [9], magnetics [10-12], (U-Th)/He thermochronology [13,14], Ar-Ar data [15], XRD of pyroxene crystals [16], and feldspar [17,18]. Here we review the thermoluminescence data formartian meteorites and discuss some implications [19].

Thermoluminescence of Feldspar and Feldspar-bearing Materials: With very few exceptions (like micrometeorites, enstatite chondrites and chondrites of very low petrographic type, say <3.2), the mineral responsible for the TL of meteorites is feldspar. Mineral separations indicate that feldspar is the luminescent phase [20], cathodoluminescence imagery shows that feldspar is the most abundant or only mineral to produce luminescence in most meteorites [21,22], and studies on terrestrial natural and synthetic feldspars duplicate much of the behavior of feldspar-bearing meteorites [23,24].

Natural TL measurements provide information on radiation and recent low temperature (say <300^{o}C) thermal history of the meteorites, while induced TL – the signal induced by a standard test dose after removal of the natural TL – informs us on the amount and structure of the minerals or phases in the meteorite which, in turn, has implications for metamorphic history.

There are essentially two independent mearsurements possible with induced TL, (1) the normalized TL intensity (TL sensitivity) and (2) the shape of the apparent TL "peak" (actually a combination of several peaks). The peak shape is characterized by its "peak temperature" and "peak width".

TL sensitivity shows a huge dynamic range, with small relative uncertainties, reflecting the amount of crystalline feldspar present. The formation of feldspar by the crystallization of feldspathic glass during metamorphism causes a 10^5-fold increase in the TL sensitivity of chondrites. This is exploited in the subdivision of the type 3 ordinary, CV and CO chondrites into types 3.0-3.9 [25,26,27]. (Eucrites also show a 100-fold metamorphism-related range in TL sensitivity as metamorphism causes compositional changes to the feldspar [28]).

Trends in peak temperature and width with meteorites of various petrographic grades [29], and heating experiments on terrestrial feldspars [23], meteorites [30], and lunar samples [31], have shown these peak shape reflects the temperature at which the system crystallized and the rate of cooling during crystallization. This is because feldspars in the structly ordered state (which occurs when crystallization is <500 ^{o}C) have narrow peaks at low glow curve temperatures (~100 ^{o}C) and narrow widths, while feldspars in the disordered state (meaning crystallization >500 ^{o}C) have broader peaks with high glow curve temperatures (~200 ^{o}C). If crystallization started >500 ^{o}C, then the relative proportions of the high and low feldspars is a function of cooling rate [32].

Thermoluminescence of Martian Meteorites: Four shergottites measured to date have TL sensitivities of 0.15 to 1.8 (where Dhajala = 1000), suggesting that like type 3.0 to 3.3 ordinary chondrites most of their feldspar is in amorphous forms (glass in the chondrite case, maskelynite in the shegottite case). Maskelynite is extraordinarily unstable, [33], and after only an 100 hour at 800^{o}C, for instance, the TL sensitivity of the shergottites increased by a factor of 5-10 [34]. This suggests that the systems have been undisturbed since maskelynization and that incipient crystallization is detectable by TL measurement.

Thermal History of Martian Meteorites: All four shergottites examined to date, Shergotty, EETA79001, Zagami and ALHA77005, have TL glow curves that when into high and low components have a boad peak at ~200^{o}C (Shergotty and EETA79001 are shown in Fig. 1) characteristic of feldspar in the high temperature (disordered) form and suggesting some level of crystallization above 500 ^{o}C [33]. However, in addition to the high peak, Shergotty has the a peak ~100^{o}C characteristic of feldspar in the low temperature (ordered) form. Zagami and ALH77005 show intermediate behavior. Therefore, all four shergottites started to crystallize trace amounts of feldspar above the order-disorder transition temperature (~500^{o}C) but while EETA79001 cooled too fast to produce low-feldspar, Shergotty cooled slowly enough to produce relatively large amounts of low feldspar. In fact, the relative cooling rates of these four shergottites increased along the series Shergotty, ALHA77005, Zagami, and EETA79001 [33]. In the pressure experiments of Hartmetz et al. [24], the order-disorder transformation known to occur at ~500 ^{o}C, occurs at 25 GPa.

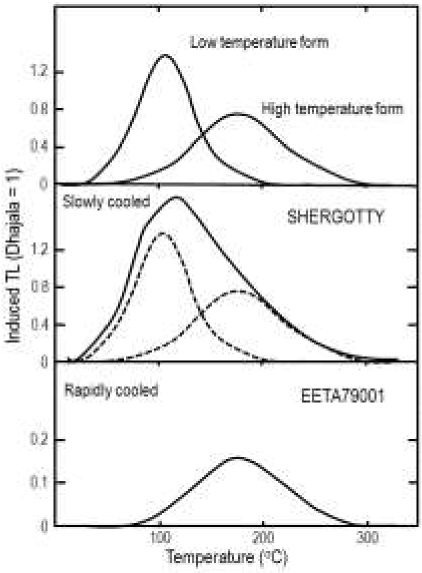

Fig. 1. The glow curves of Shergotty and EETA79001 with curves representing high and low (disordered and ordered) feldspar indicated. From [33].

Optical properties of the maskelynite, in particular refractive index measurements, are frequently used to determine shock pressures and post-shock temperatures [35,36]. A recent study of eighteen martian meteorites was recently published by Fritz et al [18]. Their results for twelve shergottites are shown in Table 1.

The data in Table 1 suggest that just over half the shergottites were heated to above 500 °C during the shock event that produced the maskelynite. However, five of the meteorites, including three in the TL study, have ΔT less than 500 °C which is inconsistent with the presence of high temperature TL peaks. The data in Table 1 refer to ΔT and not peak T, but it is difficult to appeal to differences in ambient temperature on Mars to explain this, since surface temperatures are essentially <0 °C. Kubo et al [37] have shown that amorphization pressure decreases with the temperature at which the shock occurs, so the ΔT estimates in Table 1 will need to be increased. Whether this enough to remove the inconsistency is unclear at the moment.

Other authors have argued that maskelynite was not formed by solid state transformations and the estimates in Table 1 are flawed [38]. Instead, they suggest that highly localized excursions to high temperatures and pressure caused melting and decomposition to produce the glass in shergottites commonly called maskelynite. El Goresy et al [39] suggest peak pressures and temperatures were <22 GPa and <500 °C. From a consideration of high pressure phase relationships in the Ca-Na feldspar system, Akaogi et al [40] suggest that Zagami had post-shock crystalization conditions of ~22 GPa and 2000-2200 °C.

Conclusions: The TL data indicate high temperature feldspar is present in all four shergottites measured, but it is not clear that this is consistent with previous suggestions for Shergottite thermal history. However, the inconsistencies are such that further TL data may resolve the issue.

Table 1. Shergottite shock pressures and post-shock ΔT according to ref. [18]

Name	Pressure (GPa)	ΔT (K)
Y-980459	20-25	50 ± 5
Dhofar 019	26-29	60 ± 10
Zagami	29.5 ± 0.5	70 ± 5
Shergotty	30.5 ± 2.5	100 ± 50
EET 79001	36 ± 5	240 ± 160
DaG 476	40-45	470 ± 100
Y-793605	40-45	470 ± 100
SaU 005	40-45	470 ± 100
QUE 94201	45 ± 3	560 ± 120
Los Angeles	45 ± 3	560 ± 120
LEW 88516	45 ± 3	560 ± 120
ALH 77005	45-55	800 ± 200

[1] MetSoc Database (http://www.lpi.usra.edu/meteor/) as of 6 Jan 2012. [2] Head et al 2002 Science 298, 1752. [3] McKay et al 1996 Science 273, 924. [4] Treiman 1998 MAPS 33, 753. [5] Scott et al 1998 MAPS 33, 709. [6] Golden et al 2001 Amer. Min. 86, 370. [7] Brearley 2003 MAPS 38, 849. [8] Gibson et al 2004 Proc. IAU SYmp 213, 203. [9] Barber and Scott 2006 MAPS 41, 643. [10] Kirschvink et al 1997 Science 275, 1629. [11] Collinson 1997 MAPS 32, 803. [12] Weiss et al 1999 5th Int Conf Mars #6204. [13] Min and Reiners 2005 36th LPSC #2214. [14] Min et al 2004 Geology 32, 677. [15] Weiss et al 2002 EPSL 201, 465. [16] Domeneghetti et al 2007 5th Int Conf Mars #3024. [17] Michouchi et al 1998 Ant Met XXIII, 77. [18] Fritz et al 2005 MAPS 40, 1393. [19] Hasan et al 1986 GCA 50, 1031. [20] Valladas and Lalou 1973 EPSL 18, 168. [21] DeHart et al 1992 GCA 56, 3791. [22] Akridge et al 2002 JGR 109, CiteID E07S03. [23] Pasternak 1974 PhD Thesis, Penn State U. [24] Hartmetz et al 1986 JGR 91, E263. [25] Sears et al 1980 Nature, 287, 791. [26] Sears et al 1995 Meteoritics 30, 707. [27] Keck and Sears 1987 GCA 51, 3013. [28] Sears et al 1997 MAPS 32, 917. [29] Guimon et al 1985 GCA 19, 1515. [30] Guimon et al 1984 Nature 311, 363. [31] Batchelor and Sears 1991 GCA 55, 3831. [32] Benoit and Sears 1992 Icarus 101, 188. [33] Duke (1968) in Shock Metamorphism, pp 613. [34] Hasan et al 1986 GCA 50, 1031. [35] Ostertag 1983 JGR 88, B384. [36] Stoeffler et al 1986 GCA 50, 889. [37] Kubo et al 2010 Nature Geoscience 3, 41. [38] Chen and El Goresy 2000 EPSL 179, 489. [39] El Goresy et al 2010 Amer. Min. 95, 892. [40] Akaogi et al 2010 EPSL 289, 503.

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