Thermal emission spectroscopy of shocked basalt from the Earth and Mars: A review plus new insights

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Introduction: Critical to the interpretation of remote thermal infrared (TIR) data is an understanding of the spectral characteristics of materials expected to exist on planetary surfaces. This includes a detailed study of the products of geologic processes such as impact shock to determine the spectral contributions of these processes to precursor minerals/lithologies.

Plagioclase-rich basalt has been identified from orbital TIR and Rover instruments [1-4]. As impact craters are abundant on the surface of Mars and are concentrated in the ancient southern highlands that exhibit the remote basalt signature, one would expect various degrees of shocked basalt to exist on these surfaces [1,5,6]. Determining the spectral properties of these impactites is the goal of this study. Here, previous work on the TIR spectra of experimentally shocked mafic minerals and shocked martian basalts (shergottites) are combined with recent spectroscopy and petrography of naturally-shocked terrestrial flood basalt for constraints on the effects of shock on the TIR spectrum of basalt.

Experimental shock: Constraints on the TIR spectrum of naturally-shocked basalt can be placed due to the previous work on quantifying the changes to the TIR spectra of experimentally-shocked plagioclase and orthopyroxene shocked to various pressures between 17 and 56 GPa [5,7]. Whereas orthopyroxene showed little changes in its TIR spectrum with increasing shock pressure, plagioclase has local effects as the crystal lattice is disordered in transformation to maskelynite. The Christiansen Feature (CF) shifts to lower wavenumbers and local absorption features disappear as the silica tetrahedra is depolymerized with increasing shock pressure [5,7]. The TIR spectrum of a shocked bytownite TIR end-member (49.2 GPa) is shown (Figure 1). These end-members are beneficial to the examination of TIR spectra of impactites because they are nearly monomineralic (90% An$_{75}$, 5% CPX, 5% OPX) and experimental shock pressures are known [5]. Their inclusion as end-members have resulted in near-exact deconvolution-derived abundances of Lonar impact melts [8] and the Los Angeles shergottite [9] (Figure 2).

Shergottites: All SNC meteorites have features attributed to shock. Because the nahklites and chassignites are composed predominately of augite and olivine, respectively, and the aforementioned effects of experimental shock on the TIR spectra of these inosilicates and orthosilicates, these are not discussed here. Rather, the focus of this paper involves the behavior of tectosilicate plagioclase in basalts that have been shocked or completely shock-melted. Isolated impact melt pockets and shock melt veins indicate localized regions of high pressure and temperature (most likely due to volatiles) in shergottites [10], but generally all plagioclase in shergottites have been shocked at specific pressures (30-45 GPa) to yield maskelynite. Compositionally, shergottites are dominated by pigeonite, with olivine-phyric shergottites and lherzolites containing more olivine, and varying amounts of maskelynite: generally 15-25%, but up to 45% in QUE94201 and Los Angeles [11-13]. Maskelynite is generally intermediate up to An$_{70}$.

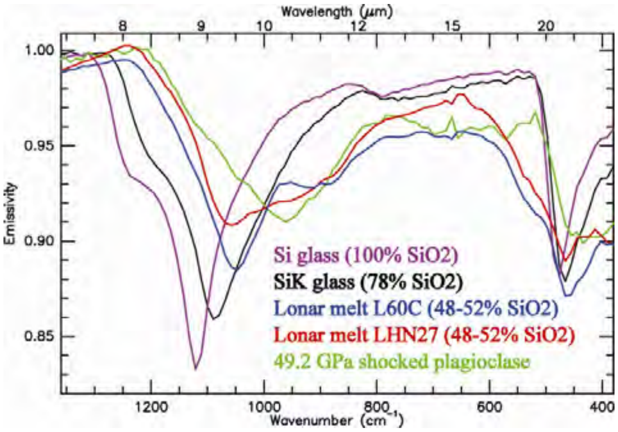

Figure 1. TIR spectra of glasses, impact melts, and shocked plagioclase end-member discussed in text.

Previous work has examined the laboratory TIR spectra of various shergottites [14] and their use as end-members in deconvolutions of global Thermal Emission Spectrometer (TES) data has shown that the shergottite spectra used are not abundant (<9%) in the upper 100 um of low-albedo regions [15]. The addition of shocked plagioclase feldspar [5] to the end-member library improved modeled fits and RMS errors for the Los Angeles shergottite [9] (Figure 2). As end-members, Los Angeles and olivine-phyric shergottite Dahr al Gani (DaG) 476/735 can be used to model Mini-TES data of Bounce Rock (Figure 3).

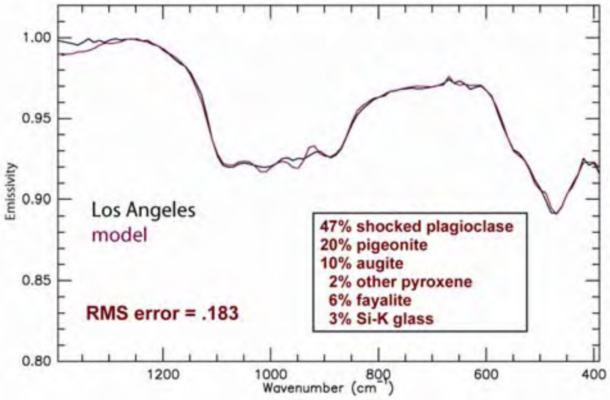

Figure 2. Deconvolution of the TIR spectrum of Los Angeles yields near-exact abundances [11-12] where shocked plagioclase end-members are included in the spectral library. Here, the end-member corresponding to 49.2 GPa (shown in Figure 1) is selected.

Lonar Crater shocked basalt and impact melts: TES data and deconvolution-derived mineral abundances of equatorial low-albedo regions on Mars is similar to the TIR spectrum and modal mineralogy of Deccan Trap flood basalt from west central India [1-3,8,9]. Lonar Crater, India is emplaced in Deccan basalt and represents the only known terrestrial impact site emplaced in flood basalt [16,17,refs within]. Whereas Kieffer *et al*. located and categorized 5 petrographic classes of shocked Lonar basalt with specific shock pressure intervals of 20 GPa [16], limited petrography performed for this study has located only 2 of these categories to date (Figure 4). A recent study identified four morphological groups of impact melt rocks and glasses at Lonar [17] with no significant compositional differences; petrography of these 4 groups is identical to Classes 4/5 of Kieffer *et al.* [16] and here (Figure 4B). Consistent with the finding of near-identical compositions [17], TIR spectra of Class 4/5 impact melts from Lonar Crater fall into two near-identical spectral classes distinctive from other TIR spectral end-members used to model glass content (Figure 1). Whereas Class 1 (fractured plagioclase grains) and Class 4/5 (plagioclase completely melted, pyroxenes highly fractured or melted) have been located (Figure 4), petrography has not revealed Classes 2 (maskelynite) or 3 (glass of plagioclase composition) described earlier [16]. However, recent field work has yielded the finding of probable Classes 2/3 that will be compared to spectra and petrography of shergottites (which are all Class 2).

Discussion: Whereas shergottites and shocked lunar mare basalts have unique TIR spectral shapes attributed to pigeonite and maskelynite [9,14,15,18], TIR spectra of impact melts from Lonar Crater are more similar to "volcanic" glasses [19]. This is a key point to consider where examining the TIR spectra of impactites. At higher pressures where shock-induced heating occurs, feldspar (>50 GPa) and pyroxene (>80 GPa) will melt into a amorphous mixture.

The amount of SiO_2 in glass has effects on the absorption feature of its TIR spectrum [19-21] (Figure 1). This has implications for the position of the CF, which decreases as plagioclase is shocked to maskelynite [5], but then increases to reflect glass content as all minerals are shock-melted to impact glass (Figure 1).

Removing the shock? … effects on remote end-member selection: Whereas the effects of shock on the TIR spectrum of every mineral contained in the Los Angeles shergottite are not known, the previous experimental work on shocked plagioclase [5,7] has allowed an estimated reconstruction of the TIR spectrum of the original, unshocked basalt prior to shock and ejection/spallation from Mars [9]. Further, where the effects of shock are accounted for [5-7], using shergottite end-members provides an excellent fit to Mini-TES spectrum of pyroxene-rich Bounce Rock found in Meridiani. This unique "ground-truthing" provides clues on mineralogy and suggests Bounce Rock is an unshocked shergottite (Figure 3). Thus, it is suggested that the spectrum of Bounce Rock and/or shock-removed Los Angeles be used as an end-member in deconvolutions of global TES data for constraints on the source craters/regions of Bounce Rock and/or Los Angeles [9]. As multiple shergottites share recent ejection events [22,23], this has implications for locating the source crater of these shergottites.

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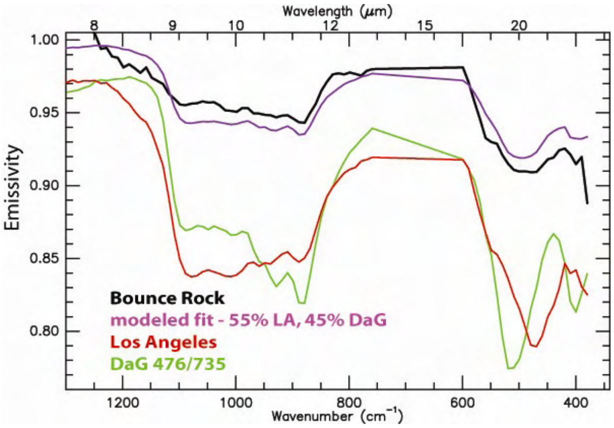

Figure 3. Deconvolution of Bounce Rock TIR spectrum with shergottite end-members. The shergottite spectra are offset for clarity and are convolved to Mini-TES spectral resolutions for deconvolution purposes. The two end-members are a good fit except for the 1230 to 1140 cm-1 region. This shift in the CF is likely due to the shergottites containing maskelynite whereas Bounce Rock contains plagioclase [3-5,7].

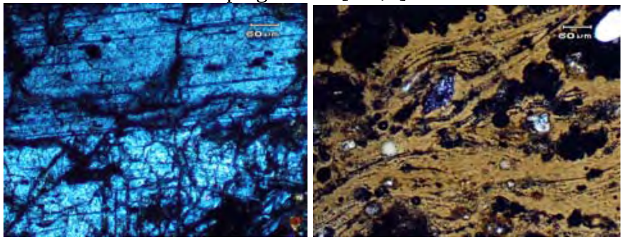

Figure 4. Petrography of Lonar shocked basalt

On left - fractured labradorite phenocryst from Lonar sample LC05-QC-032, shown in cross polarized light (cpl). Local PDF's can be seen. This sample corresponds to Class 1 shock [16] and its TIR spectrum (not shown here) is unchanged from unshocked Deccan basalt [1,2] (as expected [5-7]). On right - sample LHN27 in plain polarized light showing schlieren and flow features. Fractured relict pyroxene grains can be seen and are the only anisotropic materials in cpl (not shown here). The TIR spectrum of LHN27 is shown along with a similar melt (Figure 1). LHN27 correlates to Class 4/5 [16].

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