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Visible/near-infrared spectra of experimentally shocked plagioclase feldspars

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[1] High shock pressures cause structural changes in plagioclase feldspars such as mechanical fracturing and disaggregation of the crystal lattice at submicron scales, the formation of diaplectic glass (maskelynite), and genuine melting. Past studies of visible/near-infrared spectra of shocked feldspars demonstrated few spectral variations with pressure except for a decrease in the depth of the absorption feature near 1250–1300 nm and an overall decrease in reflectance. New visible/near–infrared spectra (400–2500 nm) of experimentally shocked (17–56 GPa) albite- and anorthite-rich rock powders demonstrate similar trends, including the loss of minor hydrated mineral bands near 1410, 1930, 2250, and 2350 nm. However, the most interesting new observations are increases in reflectance at intermediate pressures, followed by subsequent decreases in reflectance at higher pressures. The amount of internal scattering and overall sample reflectance is controlled by the relative proportions of micro-fractures, submicron grains, diaplectic glass, and melts formed during shock metamorphism. We interpret the observed reflectance increases at intermediate pressures to result from progressively larger proportions of submicron feldspar grains and diaplectic glass. The ensuing decreases in reflectance occur after diaplectic glass formation is complete and the proportion of genuine melt inclusions increases. The pressure regimes over which these reflectance variations occur differ between albite and anorthite, consistent with thermal infrared spectra of these samples and previous studies of shocked feldspars. These types of spectral variations associated with different peak shock pressures should be considered during interpretation and modeling of visible/near-infrared remotely sensed spectra of planetary and asteroidal surfaces. *INDEX TERMS:* 5410 Planetology: Solid Surface Planets: Composition; 5420 Planetology: Solid Surface Planets: Impact phenomena (includes cratering); 5460 Planetology: Solid Surface Planets: Physical properties of materials; 3924 Mineral Physics: High-pressure behavior; 3934 Mineral Physics: Optical, infrared, and Raman spectroscopy; *KEYWORDS:* feldspars, spectroscopy, visible/near-infrared, pressure, shock, maskelynite

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1. Introduction

[2] Feldspar minerals subjected to high shock pressures exhibit structural changes with increasing pressure (e.g., brittle fractures, plastic deformations, formation of diaplectic glass, and complete melting). Diaplectic glass is an amorphous phase of crystals (termed maskelynite for feldspars) formed from shock wave compression and pressure release, which retains the shape and internal features of the precursor crystal [e.g., *French and Short*, 1968, and references therein]. Petrologic and thermal infrared spectroscopic studies have shown that diaplectic glass formation in feldspars occurs between ~25 and 45 GPa, whereas significant melting occurs above ~45 GPa [*Stöffler*, 1971, 1972, 1974, 2001; *Stöffler and Hornemann*, 1972; *Gibbons and Ahrens*, 1977; *Ostertag*, 1983; *Heymann and Hörz*, 1990; *Bischoff and Stöffler*, 1992]. Past studies of visible/near-infrared spectra of plagioclase feldspars shocked to a small number of pressure levels (<3) demonstrated few variations in spectral features with pressure except for a decrease in the depth of the absorption feature near 1250–1300 nm and an overall decrease in reflectance [*Adams et al.*, 1979; *Lambert*, 1981; *Bruckenthal and Pieters*, 1984; *King*, 1986; *Langenhorst*, 1989]. Understanding the overall reflectance variations of shocked plagioclase feldspars has implications for analysis and modeling of visible/near-infrared remote sensing of planetary and asteroidal surfaces subjected to impact cratering events [e.g., *Lucey*, 2002]. New visible/near-infrared spectra (400–2500 nm) are reported here of albite- and anorthite-rich rocks

experimentally shocked over eleven peak pressures from 17–56 GPa. These spectra exhibit variations in reflectance with pressure indicative of (1) the degree of shock-induced disorder and melting and (2) the loss of spectral features associated with minor hydrated minerals present in the samples.

2. Methods

[3] Polycrystalline and essentially monomineralic feldspar-rich rocks were selected for the shock recovery experiments to avoid possible bias effects of crystal-lattice orientation relative to the propagating shock wave on the type and degree of shock deformation. This required target samples with millimeter-sized crystals of random orientations. Two samples that fulfilled these criteria were an anorthosite (~90% An_{70-80}; ~10% clays/clinozoisite) from the Stillwater Complex [*Haskin and Salpas*, 1992; *Therkelsen*, 2002], and an albitite (97–99% Ab_{98} with minor amounts of sericite, quartz, potassium feldspar, and amphibole) from Szklary (Lower Silesia), Poland [*Muszynski and Natkaniec-Nowak*, 1992].

[4] The experiments were performed at the Johnson Space Center using a powder propellant gun that provided peak pressures from 17–56 GPa for both samples. Experimental details can be found in *Gibbons et al.* [1975] and *Johnson et al.* [2002]. Briefly, a 12 mm diameter core was wafered into 1 mm thick discs from each rock sample; these discs were encapsulated into metal holders and placed into a vacuum chamber where they were impacted by a flat metal flyer plate to produce planar shock. The vacuum was needed to maintain an aerodynamically stable projectile flight and to keep the flyerplate from heating due to aerodynamic drag. Knowing the equations of state for both the holder and flyer plate metal [e.g., *Marsh*, 1980], the amplitude of the shock can be calculated from the measured impact speed [*Duvall*, 1962] with a peak shock pressure precision of ~2%. Following an experiment, a lathe was used to remove excess metal from the holder until the silicate target could be pried from its original target well. Careful prying allowed for the recovery of relatively large chips (2–10 mm) that were separated from the more fine-grained materials for use in separate experiments [*Johnson et al.*, 2002, 2003]. The latter were powdered to a homogeneous grain size (<20–30 μm) and residual metal blebs removed. Unshocked samples also were powdered similarly for better comparison to the shocked samples. Bidirectional reflectance spectra of the powders were acquired at a standard observing geometry (30° incidence angle, 0° emission angle) by the Reflectance Experiment Laboratory (RELAB) bidirectional spectrometer at Brown University (see details at http://www.planetary.brown.edu/relab/).

3. Results

[5] Figures 1 and 2 show the anorthosite and albitite spectra, plotted with and without offsets. The anorthosite spectra show differences in the strengths of the broad absorption band at ~1300 nm (Fe^{2+} in feldspars) and a broad, shallow absorption longward of 1000 nm (Fe^{3+} in clays or clinozoisite [*Therkelsen*, 2002]). A band near 2350 nm shallows with increasing pressure and is associated with Al-OH bonds in clinozoisite [*Cloutis et al.*, 2002] and/or Mg-OH bonds in clays [e.g., *Hunt*, 1977]. Overall, the ~1300 nm band is most apparent at pressures of 17.0, 21.5, and 22.6 GPa whereas the 1000 nm band is more prevalent at higher pressures. However, the ~1300 nm band is not present in the 0 GPa (unshocked) or 21.0 GPa samples, suggesting that subtle compositional differences among the anorthosite sample splits may contribute more to the observed spectral variations than the magnitude of peak shock pressures. Subsequent reanalyses of the 0 GPa, 17.0 GPA, and 56.3 GPa samples at RELAB verified that the features present in Figure 1 are repeatable.

[6] The albitite spectra show mainly water- and OH-related features near 1410, 1930, and 2250 nm related to minor amounts of fluid inclusions and/or mica [*Hunt and Salisbury*, 1970; *Delaney et al.*, 2003]. These bands first shallow and then disappear at the highest shock pressures. No bands near 1300 nm are observed, which is indicative of a low iron content in this sample. Electron microprobe measurements of these samples indeed show that the anorthosite contains <0.5 wt% FeO whereas the albitite contains <0.1 wt% FeO [*Therkelsen*, 2002; *Delaney et al.*, 2003].

4. Discussion

[7] For both plagioclase samples reflectance values decrease from low to intermediate pressures, which was noted by *Adams et al.* [1979] but considered by *King* [1986] to be due in part to the microscopic contamination of Fe from the sample holders used in the shock experiments. However, little variation in Fe content with shock pressure is observed in these samples [*Therkelsen*, 2002; *Delaney et al.*, 2003], implying that no significant sample contamination occurred. Further, the high reflectance of stainless steel (~0.80 [*Zwinkels et al.*, 1994]) implies that any residual blebs of metal in the samples would not cause the observed effects. We interpret the initial decrease in reflectance to result from greater internal scattering as the proportion of fractured and disaggregated crystals increases with pressure [cf. *Hörz and Quaide*, 1973].

[8] Reflectance increases are observed between 22 and 28 GPa in the anorthosite and between 28 and 35 GPa in the albitite, followed by a continued decrease in reflectance in both samples at higher pressures. Figure 3 demonstrates this for a high-reflectance wavelength unaffected by absorption bands (1700 nm); similar trends are observed for the average spectral reflectance. Although other studies of shocked feldspars suggested the presence of higher reflectance values at intermediate pressures followed by decreased reflectance [*Adams et al.*, 1979; *Lambert*, 1981], none of those studies included the large number of shock pressure levels available here with which to more fully examine this effect.

[9] The different pressure regimes over which the reflectance increases occur between the two plagioclases coincide with the general onset of diaplectic glass formation in each feldspar, particularly for albite. Petrologic analyses of a subset of the shocked anorthosite chips done by *Therkelsen* [2002] demonstrated undulous extinction, planar deformation features, and the formation of maskelynite in small patches at pressures around 25–27 GPa, which gave way to

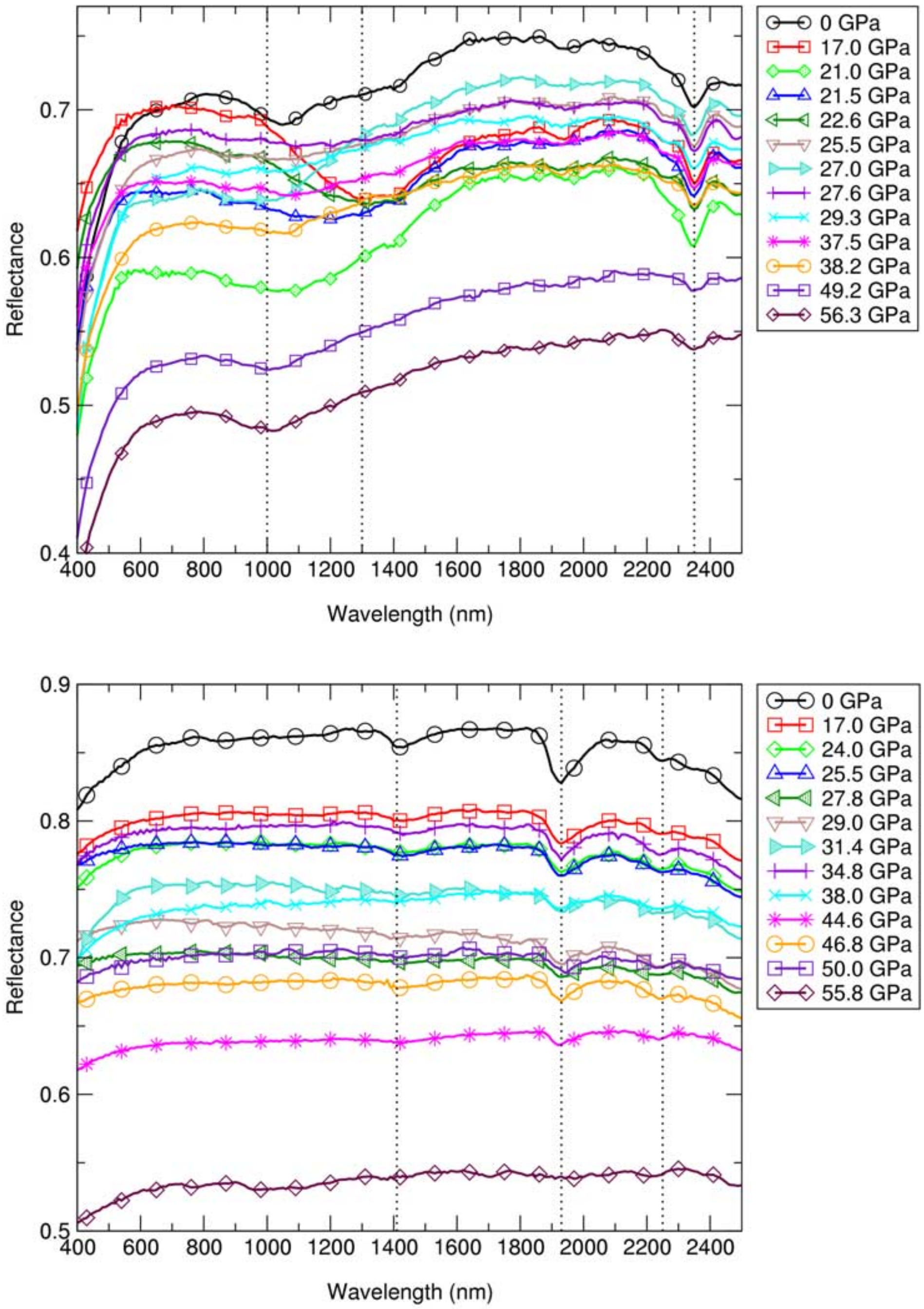

Figure 1. RELAB spectra of anorthosite (top) and albitite (bottom) shown from unshocked to a peak shock level of 56 GPa. Symbols shown every tenth wavelength channel. Dotted lines shown at 1000, 1300, 2350 nm (anorthosite) and 1410, 1930, and 2250 nm (albitite).

nearly complete formation of diaplectic glass at pressures greater than ~30 GPa. This is consistent with previous studies of shocked Ca-rich plagioclase [e.g., *Ostertag*, 1983; *Bischoff and Stöffler*, 1992; *Schmitt*, 2000]. Similar progressions of shock features are observed in Na-rich plagioclase, although at higher pressures (e.g., diaplectic glass formation begins around 30 GPa and is mostly completed by 32–35 GPa) [*Ostertag*, 1983; *Schmitt*, 2000]. Thermal infrared spectra of these samples [*Johnson et al.*, 2002, 2003] as well as other feldspars [*Ostertag*, 1983; *Williams*, 1998] combined with petrologic, Raman spectroscopy, and X-ray analyses of naturally and experimentally shocked feldspars [e.g., *Stöffler et al.*, 1986, 1991; *Velde et al.*, 1989; *Heymann and Hörz*, 1990], also demonstrate that this onset occurs at lower peak shock pressures in anorthite than albite, consistent with Figure 3.

[10] Generally, feldspars shocked to low pressures often appear in thin section to be heavily fractured and exhibit pronounced mosaicism and patchy extinctions [e.g., *Bunch et al.*, 1967, 1968]. *Hörz and Quaide* [1973] demonstrated

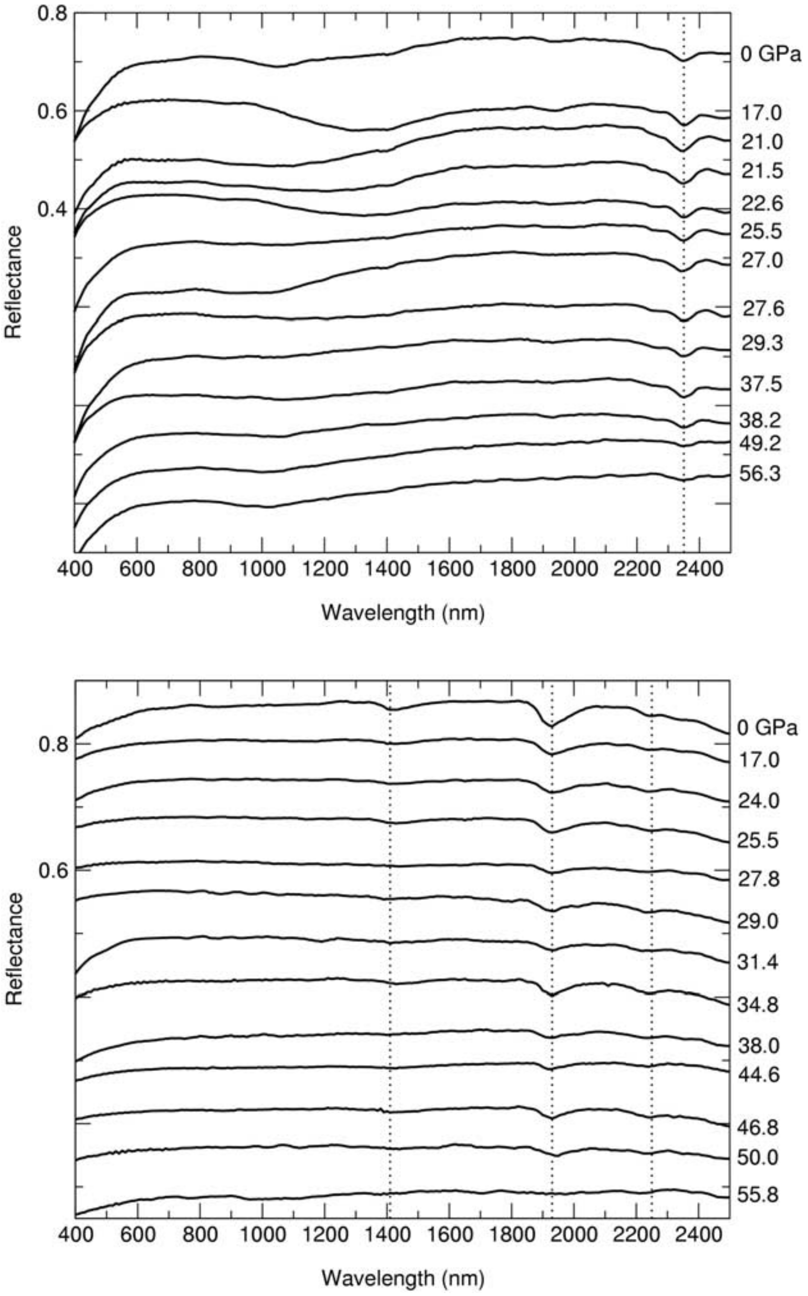

Figure 2. RELAB spectra of anorthosite (top) and albitite (bottom) offset and ordered by shock pressure to emphasize the shallowing of the 2350 nm band in the anorthosite (dotted line) and 1410 nm, 1930 nm, and 2250 nm bands in the albitite (dotted lines) with increasing pressure.

at 10–30 GPa a systematic disaggregation of the feldspar lattice into decreasing domain sizes that ultimately are beyond coherent X-ray diffraction, rendering the material X-ray amorphous and optically isotropic. The fraction of submicron grains is relatively high in this pressure regime, and the volume scattering associated with particle sizes near the visible/near-infrared wavelength of light contributes to increased reflectance [e.g., *Hapke*, 1993]. The subsequently formed diaplectic glasses are not heavily fractured at optical scales, exhibit only weak birefringence, and are texturally much more homogeneous than their modestly shocked equivalents. The lack of internal scatterers in these homogeneous glasses further enhances the high reflectance values.

[11] Given those observations, it is proposed that the reflectance increases in these shocked feldspars (Figure 3) occur at intermediate pressures as the amount of submicron feldspar grains and diaplectic glass increases relative to the less shocked components. As the proportion of maskelynite increases, the reflectances peak at pressures of ~27 GPa in anorthosite and ~35 GPa in albitite, coincident with the greatest abundances of maskelynite. Subsequent decreases in reflectance at higher pressures are caused by intimate mixtures of small amounts of localized real melts (with

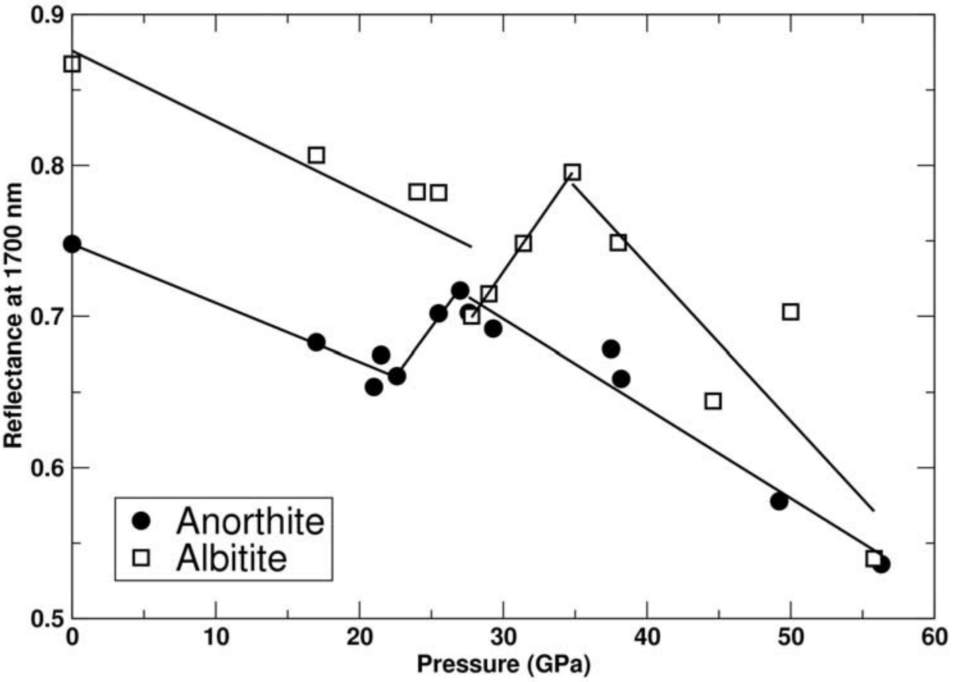

Figure 3. Comparison of 1700 nm reflectance values as a function of pressure for albitite and anorthosite spectra. Linear fits to different portions of the data are used to emphasize the increase in reflectance at different pressures for the two feldspars, near where the onset of diaplectic glass formation occurs.

vesicles and flow features) and diaplectic glasses, which result in additional internal scatterers or discontinuities [*Stöffler et al.*, 1986; *Yamaguchi and Sekine*, 2000].

5. Conclusions

[12] Changes in reflectance with increasing peak shock pressures in experimentally shocked plagioclase feldspar-rich rocks are non-linear, with overall decreases in reflectance interrupted by increases coinciding with the onset of diaplectic glass formation. The prevalent fracturing and mosaicism observed in feldspars shocked to pressures below that required for maskelynite formation likely provide the internal scattering necessary to cause the observed decrease in reflectance at low pressures. Conversely, the reflectance increases at intermediate pressures could be explained by a combination of volume scattering caused by mechanically broken, submicron feldspar grains and diaplectic glasses with homogeneous textures. Finally, as true melts are generated at higher pressures, the presence of mixed phases of crystals and glass combined with the presence of vesicles may provide internal scatterers capable of resuming decreases in reflectance [cf. *Yamaguchi and Sekine*, 2000]. Detailed radiative transfer modeling of these effects is needed to constrain these interpretations more fully, but is beyond the scope of this report.

[13] The absorption band strengths related to water and OH-bonds in trace minerals in these samples decrease with increasing with pressure. Observed variations in band depths at 1000 nm (Fe^{3+}) and ~1300 nm (Fe^{2+}) in anorthosites may be related more to minor compositional differences among sample splits. Future analyses of visible/near-infrared spectra of experimentally shocked basalt and basaltic andesite will provide additional context for how the effects of dynamic shock pressures are distributed through multimineralic samples.

[14] Finally, these observations have implications for analysis and modeling of remotely sensed visible/near-infrared observations of planetary bodies. For example, the effect of high shock pressures on reflectance values will be an additional contributor to albedo variations on silicate planetary surfaces. Further, the degradation or loss of water and OH-bands associated with impact ejecta on Mars also could be explained in part by shock effects. This could influence interpretations of data acquired from both Earth-based telescopes and spacecraft observing feldspar-rich surfaces such as the Moon, Mars, Mercury, and the asteroids.

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