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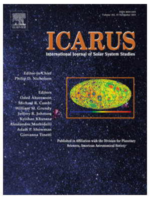

Deconvolution of mixtures with high plagioclase content for the remote interpretation of lunar plagioclase-rich regions

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ABSTRACT

Anorthositic rocks are widespread on the lunar surface and have probably been formed by flotation of PL over a magma ocean. A large portion of pristine rocks are characterized by a low Mg/(Mg+Fe) ratio, and have been classified as ferroan anorthosite, and recently, after observation from SELENE Spectral Profiler,pure anorthosites regions with more than 98% PL have been recognized.

In this paper, we analyze a set of mixtures with PL content similar to the ferroan anorthosites and to the pure anorthosite regions, using the Origin Software and the Modified Gaussian Model. We consider three plagioclases with varying FeOwt% contents (PL1, PL2 and PL3)andthree mafic end-members (1) 100% orthopyroxene, (2) 56% orthopyroxene and 44% clinopyroxene, and (3) 100% olivine (OL). The spectral parameters considered here are: band depth, band center, band width, c0 (the continuum intercept) and c1 (the continuum offset).

Here we have shown that in pyroxene (PX)-bearing mixtures, the PX is distinguishable even in mixtures with only 1% PX and that PX band at ca. 900 nm is always deeper than PL1 band while PL2 and PL3 are deeperthan OPX 900 nm band from 95, 96% PL. In OL-bearing mixtures, OL detection limit is 2% when mixed with PL1, and 3% and 4% if mixed with PL2 and PL3.

We also demonstrated how spectral parameters vary with PL%, and, generally, increasing the PL content: (1) 1250 nm band depth decreases when mixed with OL, while it deepens in mixtures with PX; (2) 1250 nm band centers generally move towards longer wavelength for PL1-bearing mixtures, while do not show significant variations considering PL2/PL3-mixtures; (3) 1250 nm band width of PL1 in E1 and E5-mixtures substantially widens while in other mixtures it only slightly varies.

Here we also proposed an application to a real case, from Proclus crater, revealing how studying terrestrial analogues is fundamental to infer hypothesis on the mineralogical composition of a planetary surface, but also how the spectral convergence of spectra characterized by different compositions can led to misleading interpretations.

1. Introduction

The Moon is one of the most studied planetary bodies across the Solar System. Its crust is composed with a very large anorthositic complex (Warren, 1895) and the plagioclase (PL) is widespread on the surface, both in Maria and in Highland regions (Hiesenger and Head, 2006 and references therein). Lunar meteorites, returned samples and remote sensed data, both Earth-based and from orbit, permitted the analysis of the lunar surface mineralogical composition. In particular, several missions spectroscopically measured the lunar surface, e.g. Clementine (McEwen and Pieters, 1997), Kaguya/SELENE (Kato et al., 2008; Ohtake et al., 2008) and Chandrayaan-1 (Pieters et al., 2009; Boardman et al., 2011; Green et al., 2011).

Studying the Apollo samples, it has been observed that a large portion of pristine rocks were characterized by a low Mg/ (Mg+Fe) ratio (Warren, 1985), thus differing from the Mg-rich rocks, and so classified as ferroan anorthosite (FAN). The authors also stated that the mean PL content in FAN is 90–92%, with low content of ferroan mafic minerals (see also McGee, 1993), e.g., orthopyroxene (OPX), clinopyroxene (CPX) and olivine (OL). FAN rocks have probably been formed by flotation of PL over a magma ocean, and Mg-rich magmas intruded the anorthositic crust thus forming the Mg-suite (Smith et al., 1970; Wood et al., 1970; Warren, 1985; Brown and Elkins-Tanton, 2009).

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Tompkins and Pieters (1999) show the spectral data acquired by the UVVIS camera (0.4–1.0 μm), onboard Clementine mission, from 109 impact craters with central peaks or peak rings. It is widely acknowledged that original material, not affected by the space weathering, have been uplifted to the surface in central peaks and in peak rings: so, their composition and mineralogy are expected to reflect deeper crustal compositions. The presence of PL has been inferred from the presence of weak or absent mafic absorption bands (calculated from the 1000 nm band depth) and from the spectral curvature of the 1000 nm band (i.e., the angle formed between 750, 900 and 950 nm). In general, Tompkins and Pieters (1999) concluded that the lunar crust is extremely anorthositic, with a PL content ~82%.

In some cases, featureless spectra, such as full-resolution telescopic data from the Orientale Basin, were related to shocked PL (Spudis et al., 1984), because high shock pressure weakens the PL absorption band (Adams et al., 1979).

Early investigations based on Earth-based telescopic data (Spudis et al., 1984; Bussey and Spudis, 2000; Hawke et al., 2003) revealed featureless high albedo material inferred to be associated with shocked anorthosites.

In 2007, the Japanese SELENE spacecraft has been launched, carrying onboard the Spectral Profiler (SP), a visible near-infrared (VNIR, 0.5–2.6 μm) spectrometer with a high spectral resolution of 6–8 nm. The spectrometer detected the presence of an absorption band at ca. 1250–1300 nm, consistent with Fe^{2+} transition in crystalline PL, in central peaks of impact craters (Matsunaga et al., 2008). Matsunaga et al. (2008) proposed a new interpretation of Tsiolkovsky central peak, previously classified as OL-rich, as composed with PL and Pyroxene (PX). Ohtake et al. (2009) defined the pure anorthosites (PAN) as regions with more than 98% PL: PAN regions are characterized by a lower limit of PL higher than FAN, thus leading to new constraints on models of the lunar magma ocean evolution. PAN regions have been identified in Tycho, Tsiolkovsky, Orientale, and Jackson craters (Ohtake et al., 2009). Furthermore, Ogawa et al. (2011) detected spectra of high-Ca PX and PL widely distributed in and around the bright-rayed craters, and Yamamoto et al. (2010) showed the presence of both PL and OL in the Copernicus crater.

Recently, the Indian Chandrayaan-1 mission, with the M^3 (Moon Mineralogy Mapper) imaging spectrometer onboard, analyzed the lunar surface with a very high spectral resolution (spectral range: 405–3000 nm; spectral resolution: 10 nm). Basing on M^3 results, Cheek at al. (2012; 2013) confirmed the presence of PAN in the Orientale Basin and in Tsiolkovsky crater, and Kramer et al. (2013) recognized PAN, OPX and OL in Schrödinger Basin.

FAN and PAN rocks, composed with PL content >90% and minor amounts of mafic minerals, were probably formed by the crystallization and segregation of PL inside a magma ocean of the Moon, and the remaining liquid may have produced mafic-rich anorthosite.

2. State of the art

PL, OPX, CPX, and OL have been clearly recognized on the lunar surface (see Papike et al., 1991).

PX are characterized by two absorption bands at ca. 900 nm and ca. 1800 nm (Burns, 1993; Sunshine and Pieters, 1993), due to the Fe^{2+} transition in the M2 site, that shift towards longer wavelengths with increasing Fe^{2+} and Ca^{2+} in the PX crystal structure. Fe^{2+} can enter in the M1 site thus producing an absorption band at ca. 1200 nm (Klima et al., 2008).

OL shows a broad absorption band resolvable with three absorptions at ca. 900, 1050 and 1200 nm, due to Fe^{2+} transition in M1 and M2 sites (Burns, 1993; Sunshine and Pieters, 1998).

PL contains only low amount of Fe^{2+} but an absorption band can be easily recognized at ca. 1250 nm, attributed to Fe^{2+} transition in the large 8–12 fold Ca^{2+} site (Bell and Mao, 1972; Adams and Goulland, 1978; Cheek et al., 2011; 2014; Serventi et al., 2013; 2015).

Although in the literature many works characterizing reflectance spectra of PX, OL and their mixtures can be found (e.g., Cloutis and Gaffey, 1991; Sunshine and Pieters, 1993, 1998; Clenet et al., 2011), PL and mixtures with mafic materials have been poorly analyzed, probably because PL has always been considered a spectroscopically transparent mineral, being, from a stoichiometric point of view, an iron free mineral. The recent identification of a well-defined absorption band at 1250 nm on the lunar surface, interpreted as indicative of the presence of crystalline PL, makes it fundamental to analyze in detail the spectral behavior of very high PL concentrations in the soils. As previously stated, PL absorption band has been interpreted as the transition of Fe^{2+} in PL crystal structure (Adams and McCord, 1971; Bell and Mao, 1972; Adams and Goulland, 1978). In particular, Adams and Goulland (1978) tried to relate the PL band center to the anorthite (An) content (Ca content). Recently, Cheek et al. (2011) investigated PLs with different iron content, focusing on their spectral behavior. Furthermore, Cheek and Pieters (2014) analyzed PL-rich mixtures with varying content and composition of OL, PX and very high-Mg spinels and demonstrated that PL can significantly contribute to reflectance spectra if strongly absorbing minerals are present in low abundances, particularly in mixtures with PX. In their paper, a PL and six non-PL end-members (one forsteritic OL, one intermediate OL, a OPX, a diopside and two Mg-spinels) have been selected at the 45–75 μm particle size. Non-PL minerals have been mixed with PL in different proportion: in PL dominated mixtures, non-PL minerals vary from 2%, 5%, 7% to 10%, while in non-PL dominated mixtures, non-PL minerals vary from 15%, 20% to 50%. The authors conclude that: (1) 2% OPX is distinguishable from PL, while diopside minimum content is 5%; (2) OL is distinguishable from 5%; (3) mixtures with OL<5% and diopside<5% may be indistinguishable; (4) in mixtures with spinels, the detection of PL depends on the iron content in spinel: iron-rich spinel significantly subdue PL absorption; and (5) PL is recognized in mixtures with spinels more than 15%, while PL results in only a spectrum flattening in mixtures with OPX>10% and in a broadening of the 1000 nm band in mixtures with OL>10%.

Serventi et al. (2013; 2015) analyzed a set of mixtures composed of PL and mafic minerals (a mixture of OPX and CPX, an OPX, an OL and two mixtures with different relative content of OPX and OL), with PL ranging between 20–90%, at two particle sizes, 63–125 and 125–250 μm. The authors shown that, generally, adding PL produces spectra with higher reflectance and reduced spectral contrast. The Modified Gaussian Model (MGM, Sunshine et al., 1990) results also shown that increasing the vol. FeO% in PL, the 1250 nm band deepens in PX-bearing mixtures while it decreases in OL-bearing mixtures, and that the 1250 nm band center always shifts toward longer wavelengths. The authors also demonstrated how high content of iron-rich PL can play an important role and spectrally dominate when mixed with mafic minerals.

For this reason, it is fundamental to analyze mixtures with PL content >90%, not analyzed in the cited papers, because these concentrations seem to form the lunar highlands.

In this paper, we report analyses of mixtures with PL content similar to FAN and PAN rocks, in order to show the effects of PL on reflectance spectra when >90% of PL, with increasing Fe^{2+}, are mixed with <10% of different mafic minerals. The purposes of our study are to show if it is possible to (1) recognize the PL 98% concentration, stated as the limit for PAN by Ohtake et al. (2009), for different mafic mineral content, thus also involving the mafic