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# Rock mineralogy and chemistry implications for spectral reflectance analysis

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**Abstract.** Our knowledge about the crustal composition of the Moon, Mars and Mercury are summarized, with particular regard to the models of crust structure, compositional profiles, and evolution, as a basis for the selection of suitable terrestrial analogues for the interpretation of reflectance spectra from orbit. The examples of analogues shown here are from genetically related rock sequences, and include a cumulate sequence from the Bjerkreim-Sokndal Layered Intrusion and basalts from the Mount Etna volcanic complex. The shift of the $Fe^{2+}$ absorption bands in pyroxene with the variations of either chemical and mineral composition of the rocks have opposite trends, and are representative of the specific initial composition of the magma and the evolution of the rocks. The range of wavelength variation with $Fe^{2+}$ content variation in rocks is larger than in pure minerals separated from the same rocks, and this discrepancy was tentatively attributed to bulk rock effects. These effects were particularly evident in basalts, were decomposition of spectra measured on bulk rock, groundmass and phenocrysts separated from the rocks was able to reproduce well developed absorptions in the phenocrysts spectrum, while retrieving extremely weak bands in groundmass and a wide, information-free band in bulk rock spectra.

**Key words.** Spectroscopy: Visible,NIR – Spectroscopy: mineral compositions

## 1. Introduction

The mineral assemblage of an igneous rock in a planet crust is determined by the evolution of a complex magma/rock system, where fractional crystallization from a melt with a given composition is dynamically controlled by processes in well defined pressure-temperature and oxygen fugacity conditions. Bedrocks therefore epitomise those systems, and recognizing their composition and mapping their distribution throughout the planet surface allow us to trace backward the history of the planet, providing some constraints to the physical and petrologic models of the planet evolution. Our levels of knowledge about the surface composition are different for planets such as the Earth, Moon, Mars and Mercury, and consequently different is the accuracy of the models developed for their starting conditions and evolution. In any case, the observed compositional differences, encompassing mineral composition and chemistry, imply that some of the parameters governing planetary processes can differ from one planet to the other, although others can be or have been similar in the past. The crust of Mars is mainly built up of volcanic rocks, emplaced as lava lakes, sheet lava and more recent flows from effusive centers (e.g., Pieters,

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1993). Part of these rocks has a so called primitive basalt composition, i.e., derived from the upper mantle without significant interaction with the crust. At the opposite extreme of the terrestrial planets row, Mercury has a more evolved crust, interpreted to primarily consist of anorthosites, mainly on the basis of spectroscopic analogy with the lunar highlands (e.g., Blewett et al., 2002). Anorthosites are cumulates, formed through complex, repeated interactions between melt and early crystallized minerals. Physical and petrologic models delineate a relatively simple internal structure for almost all of the terrestrial planets, considered as one-plate planets which experienced cooling through stagnant lid convection (e.g., Reese et al., 1999). Except for the Earth, where plate tectonics both sets areas where upper mantle material flows out on the ocean floor or on land, and areas where the magma is trapped within the crust, where it evolves developing suites of genetically related compositions and slowly cools producing complex textures. Some models of thermal evolution of the planets also infer that the two lithospheric structures can subsequently occur during a planet history (e.g., Sleep, 2000). Therefore, selected terrestrial contexts can represent natural laboratories to study the processes that have possibly occurred also on other planets, extending the data sets provided by meteorites inferred to come from those planets. Based on the background of knowledge summarized above, a critical selection of analogues for these planets can be made. Here we preliminarily present examples from (1) a suite of genetically related cumulates from the Late Proterozoic Bjerkreim-Sokndal Layered Intrusion (BKSK) belonging to the Rogaland igneous complex of South West Norway, and (2) a selection of a few basalt samples from the Mount Etna volcanic system, including an ancient, 100 ky B.P. old alkali basalt and a recent trachybasalt, erupted in 2002-2003 from the north-eastern flank.

## 2. Terrestrial analogues for crustal rocks

The examples presented in this paper were specifically chosen to illustrate two distinct aspects related to the spectroscopy of rocks as they are, or bulk rocks: (1) the relationship between spectroscopic parameters and those petrographic and chemistry rock parameters reflecting the rock compositional evolution and therefore the geologic context within which the rock formed; and (2) incongruities between bulk rock spectra and spectra measured on pure mineral mixtures, tentatively attributed to bulk rock effects.

## 3. Spectroscopy and rock petrography and chemistry

The BKSK cumulitic sequence includes genetically related rocks belonging to the anorthosite kindred, i.e., andesine anorthosite, troctolite, leuconorite, norite, gabbronorite, jotunite, mangerite, quartz-mangerite and charnockite. The sequence crystallized in a continuously fractionating, periodically replenished magma chamber, with assimilation of pre-existing rocks during its evolution (e.g., Wilson et al., 1996). Although stratigraphically characterized by a cyclic repetition of similar compositions, the rocks generally display more evolved compositions upwards. Mineral composition includes plagioclase as the most abundant phase, Ca-poor orthopyroxene, minor Ca-rich clinopyroxene, and opaque. The samples used consisted of slightly polished rock slabs, pure minerals separated from individual rocks, and mineral mixtures of the separates, with relative abundance of the phases chosen to reproduce the modal composition of the rocks from which they were separated (Pompilio, 2005). The reflectance spectra of the bulk rocks were subdivided into three groups, two of which are dominated by the crystal field (CF) electronic absorption bands in $Fe^{2+}$ in octahedral M2 sites in Ca-poor pyroxene, which occur near 900 and 2000 nm (Pompilio, 2005; Pompilio et al., in press). Mineral chemistry is strongly homogeneous for all rock samples, where $Fe^{2+}$ almost represents the total iron content, and systematically occupies the M2 sites. The relationship between position of the CF $Fe^{2+}$ absorption bands and $Fe^{2+}$ abundance is well known from the literature (e.g., Cloutis and Gaffey, 1991). According to this relationship, the 900 and 2000 nm absorption band positions were observed to shift to longer wavelength with increasing $Fe^{2+}$ atoms per formula unit (a.p.f.u) in the spectra of both the bulk rocks and the pyroxenes separated from the rocks. When the $Fe^{2+}$ content was considered in its distribution within the total pyroxene modal abundance, the relationship between the $Fe^{2+}$ absorption bands and this petrographic parameter was inverted. The opposite variation trends of the iron band position for two distinct compositional parameters (either $Fe^{2+}$ a.p.f.u. in pyroxene, or $Fe^{2+}$ in pyroxene volume distribution within individual rocks) are related to the inverse relationship between these parameters throughout the rock sequence. This is the result of the specific evolution of the rocks in the sequence, controlled by the composition of the initial magma and the melt composition evolving through the time. Consequently, the correlation curves between spectroscopic parameter and two distinct compositional variables also describe the evolution of the magma/rock system, reflecting the petrologic processes and deep-seated geologic environment within which the rock sequence formed. Moreover, this description appears to be highly accurate, in that two distinct rock populations (leuconorites-norites and melanorites) can be delineated, each characterized by its own regression function (Pompilio et al., in press).

## 4. Spectral incongruities and bulk rock effects

Magmatic rocks are characterized by extremely variable textures, resulting from different grain size, arrangement, and degree of crystallization. The effects of these textural characteristics on reflectance spectra are still unknown. In intrusive rocks, texture is characterized by large-grained, closely-packed assemblages of minerals. Overgrowths on cumulus grains produce anhedral to subhedral crystal habits and triple junctions between crystals (e.g., Best, 1982). In the BKSK cumulate sequence, the linear relationships between $Fe^{2+}$ /M2 absorption band positions and $Fe^{2+}$ (a.p.f.u.) in rocks and separate pyroxenes showed however a larger range of wavelength variation for the rocks than the separate minerals. This difference can be related to the overall shape, or continuum, of the spectra for the two types of samples. The significance and the physical factors controlling the continuum of the spectral curves of minerals and rocks still are not fully understood. Tentatively, we suggest the texture of the sample as one among these factors in rocks and separate pyroxene spectra. In effusive rocks, the rapid cooling produces a texture characterized by pheno- and micro-phenocrysts enclosed within a micro- and submicro-crystalline groundmass, with variable content of amorphous phases, and variously oxidized during syn-effusive degassing. The spectra of these rocks presented a high variability of shapes, including spectra with relatively well developed absorption features as well as spectra with extremely weak or absent absorption bands (Sgavetti et al., 2006). In the Mount Etna volcanic complex, lava compositions varied through time (Cristofolini and Romano, 1982) as a response to the depth and extent of the mantle source regions and degree of mixing in the deep reservoir (**?**)(Clocchiatti et al., 2004). The samples discussed here included an about 100000 BP alkali basalt and a 2002 BP trachybasalt. The rocks were separated into the component phenocrysts (including plagioclase, pyroxene and olivine) and groundmass, and the reflectance spectra were measured for the two components and the bulk rock. The spectral decomposition using Gaussian distribution showed well defined bands in the spectrum of separate phenocrysts, due to the combined contribution of CF electronic absorptions in $Fe^{2+}$ in M3 in clinopyroxene and olivine, and a minor absorption attributed to $Fe^{2+}$ in seven-coordinated sites in plagioclase. In the spectrum of groundmass the intensity of the bands of clinopyroxene-olivine were extremely reduced, and in the spectrum of the bulk rock a unique, wide Gaussian was obtained, within which the contributions of individual mineral phases could not be resolved. Such a spectral diversity was clearly independent from the mineral composition, comparable for the three types of samples, while it can be tentatively attributed to the dramatically different textures. Amorphous phase content has certainly important effects on rock spectra. To analyze these effects, we planned to generate synthetic phases with different crystallization degree, starting from a melt obtained from basaltic powders with well defined compositions, cooled under controlled temperature and pressure conditions.

## 5. Conclusions

The spectral properties of magmatic rocks depend on a complex interaction of factors including rock chemistry, modal composition, texture, and crystallinity. The correlation of rock spectroscopic parameters with different compositional variables can give insights into the magma-rock dynamic system evolution, not only providing information on the rock composition, but also on the geologic context of the rock formation, with important implications for the knowledge of composition and structure of a planet crust. Future work is planned to extend the spectroscopic studies to a significant number of rocks belonging to different genetic sequences. Texture affects the spectral properties of both intrusive and effusive rocks in a still not fully understood way. Beyond the effects due to mineral grain size, arrangement and close packing, the study of the spectral behavior of the intergranular materials in rocks, with particular regard to amorphous phases in effusive rocks is planned. For this analysis, the synthesis of specific phases will be accomplished, involving laboratories of experimental petrology.

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