LOW-CALCIUM AND CALCIUM-FREE CLINOPYROXENE SPECTRA AND THE IMPLICATIONS FOR UOC MATERIAL ON ASTEROIDS.

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Introduction: While some authors suggest that S asteroids have a similar mineral assemblage to ordinary chondrites, altered by space weathering and with small amounts of unknown admixtures [e.g. 1], others have argued that – based on comparison with terrestrial minerals – most of the S asteroids are a wide variety of materials, many of which are igneous assemblages unknown on Earth [e.g. 2]. In a recent study of eleven S asteroids we have observed by NASA's IRTF all but one contained evidence for clinopyroxene when analyzed by the MGM method [3-5]. Since Ca-free clinopyroxene is a major component in the unequilibrated ordinary chondrites (UOC, also referred to as type 3 ordinary chondrites), and is absent in more populous equilibrated ordinary chondrites (EOC, type 4-6) where the pyroxene is in the orthorhombic form, we have argued that many or perhaps even most of the S asteroids have UOC material on their surfaces.

An issue in this proposal is that the MGM method is calibrated on the clinopyroxenes commonly encountered on Earth which are Ca-rich and normally have igneous associations [6,7]. The clinopyroxene in UOC is an unusual Ca-free variety, and it is not clear that this would have the same spectral properties as the Ca-rich forms. Most critical is the presence of an absorption band at ~2.3 µm, which is present in the Ca-rich clinopyroxenes but absent in the orthorhombic forms characteristic of most ordinary chondrites. We have therefore obtained near-IR spectra for calcium-free or calcium-poor clinopyroxenes. Here we report the results.

Experimental: Five low calcium or calcium-free terrestrial clinopyroxene samples were identified from their descriptions in ref. [8] and obtained from the Smithsonian Institution (Table 1). The samples were crushed and ground using a pestle and mortor and infrared spectra obtained over the range 0.8 – 2.5 µm, the range best suited to mineral identification and the range of our IRTF observations. The spectra were then analysed using the Modified Gaussian Model (MGM) [6].

Table 1. Low-Ca and Ca-free clinopyroxenes used in the present work*.

Sample and Number	Location	Formula
Aegerine C2431	Quincy, Massachusetts	$NaFe^{3+}(Si_2O_6)$
Clinoenstatite 163346	Napoui, New Caledonia.	$MgSiO_3$
Clino-ferrosilite 145787	Ravensworth, New South Wales, Australia	$FeSiO_3$
Jadeite 113778	Clear Creek, California	$NaAl(Si_2O_6)$
Spodumene R3068	Etta mine, South Dakota	$LiAl(Si_2O_6)$

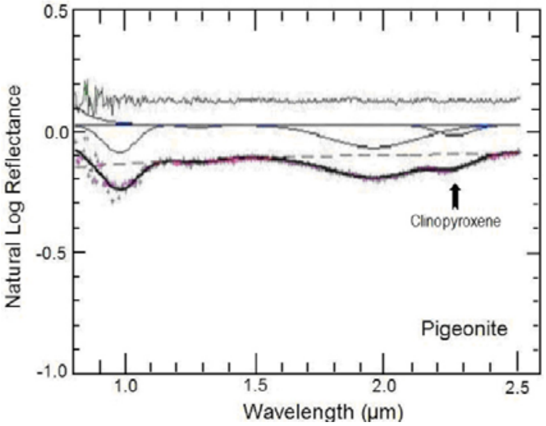

Fig. 1. Spectrum for a low-Ca clinopyroxene (purple dots) analyzed by the MGM method. The clinopyroxene absorption is indicated. Like Ca-rich clinopyroxenes, low-Ca clinopyroxenes have an absorption band at ~2.3 µm.

Results: While the whole spectrum is considered in mineral identification, the absorption band for Ca-rich clinopyroxene is located at ~2.3 µm, the exact position depending slightly on grain size, Fe content, and other factors. All five of our terrestrial low-Ca clinopyroxenes showed an absorption feature at ~2.3 µm. As an example, we show one of the spectra and the results of MGM analysis in Fig. 1. We plot the locations of the ~2.3 µm absorption bands in Fig. 2.

Discussion: The majority of ordinary chondrites, are the highly metamorphosed EOCs. Relatively rare are the UOC some which are thought to be close in physical form to the material that accreted from the primordial solar nebula and of special importance in deciphering early solar system history. While rare on

Earth, low-Ca clinopyroxene is abundant in the UOC, maybe 25 vol% of the meteorite [9]. Thermal metamorphism to temperatures of greater than ~700°C produces a wide variety of mineralogical, chemical, and physical changes in the meteorites including the conversion of clinopyroxene to orthopyroxene. Thus the great majority of ordinary chondrites contain orthopyroxene and this goes some way in explaining the mismatch between ordinary chondrites and S asteroids since orthopyroxene does not display the ~2.3 μm absorption (Fig. 3). Thus it is possible that many, perhaps most, of the S asteroids have surfaces consisting of UOC or UOC-like materials.

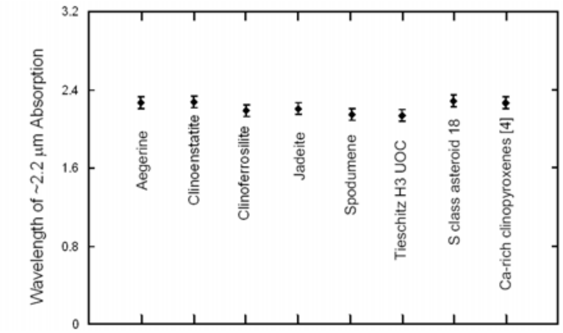

Fig. 2. All low-Ca clinopyroxenes studied here display an absorption at ~2.3 μm which is similar to that of UOC, S asteroids, and calcic clinopyroxenes, and which distinquishes them from the common ordinary chondrites (the EOC).

If we are correct, then there are major ramifications for meteorite genesis and asteroid structure. UOC are rare on Earth, yet would seem abundant on asteroids, consistent with several lines of data that suggest stochastic events dominate in determining the nature of the ordinary chondrite flux to Earth. The ordinary chondrites came from very large objects (~100km) whose fragmentation is documented by clusterings in the cosmic ray exposure ages (8 Ma for the H chondrites, 17 Ma for the LL condrites) and K-Ar ages (500 Ma for the L chondrites). These were huge events that must have largely exposed interior and highly metamorphosed materials [10].

Several authors have published thermal models for the interior of asteroids, and assuming modest levels of internal heating by ^{26}Al, much of the asteroid is expected to be highly metamorphosed. In fact, only the outer 5% or so of a typical asteroid experienced UOC levels of alteration according to such models [e.g. 11]. Thus an onion skin (concentrically zoned) structure would be inferred and much of the surface would be UOC and most of the interior would be EOC material. Alternatively, if the bodies formed late and did not aquire the rapidly decaying ^{26}Al, then the entire body would be UOC and these asteroids could be rubble piles.

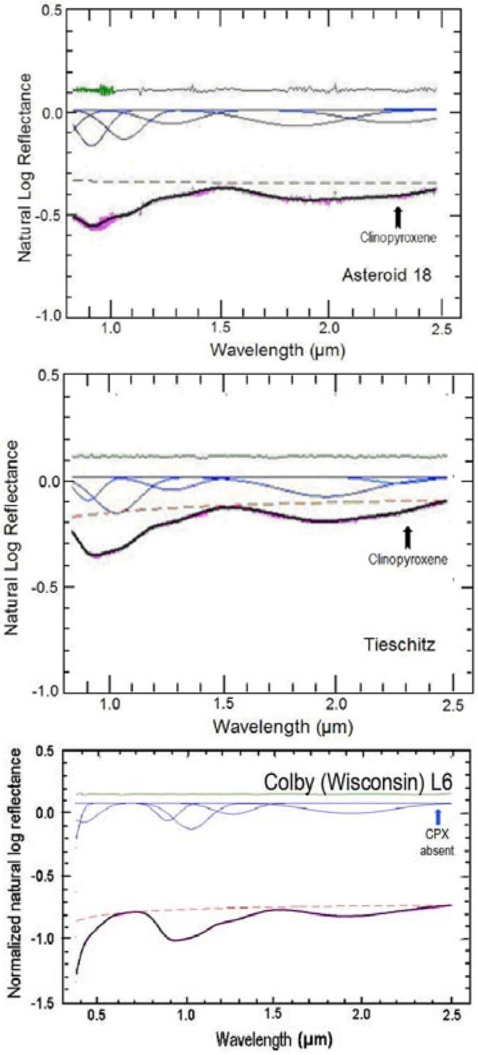

Fig. 3. Spectra for an (a) S asteroid 18, (b) UOC Tieschitz, (c) EOC Colby. The asteroid and the UOC contains spectroscopic evidence for clinopyroxene, the EOC does not. This is consistent with the S asteroids have UOC or UOC-like material on their surfaces.

References: [1] Binzel *et al.* (1993) *Icarus* **170**, 259. [2] Gaffey *et al.* (1993) *Icarus* **106**, 573. [3] Gietzen *et al.* (2007) *AAS/DPS, #39*, 33.11 [4] Gietzen *et al.* (2008) *LPSC XXXIX*, #1125. [5] Sears *et al.* (2008) *MAPS* 43, A142. [6] Schade *et al.* (2004) *Icarus* **168**, 80. [7] Sunshine & Pieters (1993) *JGR* **98**, 9075. [8] Deer *et al.* (1978) *Rock Forming Minerals.* [9] Sears (1978) *Nature and Origin of Meteorites.* [10] Eugster *et al.* (2006) In *Meteorites and the Early Solar System,* 829. [11] Akridge *et al.* (1996) *Icarus* **132**, 18.