CATHODOLUMINESCENCE COLOR INDICES AS A PARAMETER FOR MEASURING PETROLOGIC CHANGES IN METEORITES.

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Introduction: Cathodoluminescence (CL) is the emission of light when a target material is placed in an electron beam. The wavelength of light emitted is a property of the composition and the crystallographic structure [1]. While the mechanism for the excitation/de-excitation with photon emission is well understood for free atoms, the mechanism for atoms in the solid state is less clear. Ions trapped in the crystal lattice can act as activators, and increase the luminescence of the sample. Other ions, notably Fe^{2+}, act as quenchers, and reduce or eliminate the luminescence. The presence of activator ions can radically alter the spectrum. For some ions, the position in the crystal lattice and abundance can affect whether they act as activators or quenchers. Cathodoluminescence was first applied in a systematic way to geological studies in the mid-1960's, and has since been used extensively in sedimentary petrography [2,3]. A recent application is the identification of shocked quartz in samples from potential terrestrial impact craters [4].

Meteorites are classified based on their composition and petrologic type. Determining mineralogical composition is accomplished using a variety of analytical techniques. Petrologic type is more difficult to determine. Our study attempts to define a way of measuring the petrologic types of meteorites. In our study, we obtained CL images of the major classes of meteorites and lunar samples. We found a trend in blue/red color index as petrologic type changed in carbonaceous, ordinary and EH chondrites that can be used as a guide to the thermal and metamorphic histories of the meteorites.

Experimental Section: Our CL images were produced using a MAAS Luminoscope©, attached to a standard petrographic microscope, with an electron gun operated at 15 ± 1 keV, 0.7 ± 0.1 mA and a beam focused to a 1 × 2 cm ellipse. The images were recorded using standard color film, typically 400 speed, and processed commercially using the C-40 process. A typical thin section required about 40 images; photomosaics were assembled from the prints, and then digitized using a large flatbed scanner. The exposure time for each image was adjusted to suit the luminescence intensity of the sample, but ranged from 15 seconds to 7 minutes. Thus apparent intensity of the images does not reflect true relative intensity.

The Adobe Photoshop 5.0 histogram function was used to measure the number of red and blue pixels in the photographs. The assumption is made that the number of pixels from each color was a function of the number of photons in that wavelength region emitted from the samples during the experiment.

Results and Discussion: *Carbonaceous chondrites.* CL images were produced for one CM and six CO carbonaceous chondrites. The blue/red color index increased as the meteorites increased in petrologic type. As petrologic type increases, the blue CL of feldspar continues to increase while olivine loses its red CL. It is thus possible to define a color index based on the relative proportions of blue and red CL in the section that increases with petrologic type (see Fig. 1).

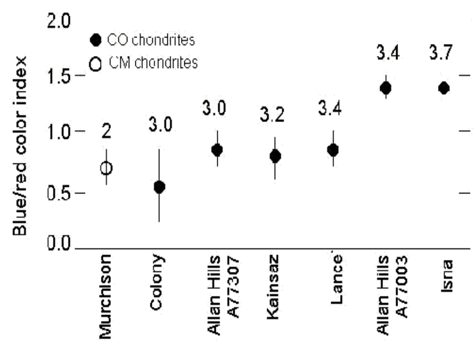

Fig. 1. Blue to red color index (ratio the number of blue pixels to the number of red pixels) for the CL images of C chondrites. The numbers above the symbols are the petrologic type [5]. The color index increases as a function of petrologic type. Detailed studies suggest that this trend reflects the destruction of forsterite with red CL and creation of crystalline feldspar with blue CL in response to metamorphism.

Ordinary chondrites. CL images were produced for 16 ordinary chondrites. As with the CO chondrites, the cathodoluminescence changes steadily with petrologic type, yellows and reds of calcium-rich glasses and olivines disappear, and the amount of blue due to feldspar increases. Again as with C chondrites, it is possible to define a color index for ordinary chondrites that increases with petrologic type (Fig. 2).

Cathodoluminescence is particularly well-suited to observing the textural and compositional diversity of chondrules and tracking changes during metamorphism. CL properties have led to the identification of 8 classes of chondrules in type 3 ordinary chondrites defined in terms of the composition of the olivine grains and mesostasis [6]. Four of the chondrule classes are primary (*i.e.* existed prior to the final aggregation of the meteorite and thus are abundant in the low petrologic types), four are formed as a result of metamorphic alteration and are seen at various petrologic levels throughout the sequence. The final fate of all chondrules is to be compositionally uniform and of a single class (so-called class A5).

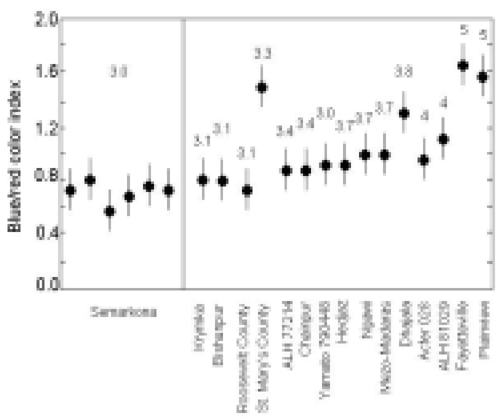

Fig. 2. The blue to red color index for ordinary chondrites. The numbers above the symbols are an indication of the petrologic type [7]. As with C chondrites, the color index increases as a function of petrologic type as forsterite is destroyed and feldspar crystallizes in response to metamorphism.

Enstatite chondrites. Cathodoluminescence of the enstatite chondrites is dominated by enstatite that produces high levels of luminescence. In the low petrologic types, the chondrules and individual grains stand out fairly well, but as petrologic type increases, textures become less easily delineated. In the high types, chondrules are difficult or impossible to locate, but the high EH types contain enstatite whose CL is blue, with only an occasional magenta grain, while the high EL types have enstatite with a uniform magenta CL. A color index of the blue to red ratio for the EL chondrites is thus independent of petrologic type, while for EH chondrites it decreases with petrologic type (Fig. 3).

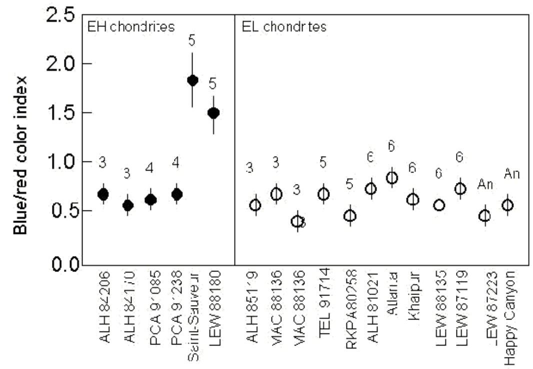

Fig. 3. Blue to red color index for enstatite chondrites. The numbers above the symbols indicate the petrologic type [8]. For EH chondrites, the index increases with petrologic type, but this is not true of EL chondrites. This difference in CL trends between the EH and EL chondrites does not appear to reflect difference in mineral chemistry but seems to be related to difference in thermal history and pyroxene structure.

Achondrites. CL images were produced for Pasamonte, Juvinas and Kapoeta, all of which were thought to originate on the large asteroid Vesta [9]. The Pasamonte meteorite shows the yellow CL characteristic of feldspars containing appreciable amounts of calcium, but the intensity is relatively weak and uneven, often almost brown. The non-luminescent gains are pyroxene. In contrast, the feldspar in Juvinas has relatively bright yellow CL, the metamorphic equilibration having driven trace amounts of quencher iron out of the feldspar crystals [10]. In this instance a color index can be defined by the green -to-blue, integrated over the sections, that increases with petrologic type.

Conclusion: We have identified a series of color indices that can be used to quantitatively assess the level of thermal processes in a variety of extraterrestrial samples. Rock samples that show too little CL for meaningful study are very few; in fact we are not aware of any (although SNC meteorites come close). Thus by taking a single low resolution image of a centimeter-sized thin section in a CL microscope it is possible to quickly and quantitatively determine the thermal alteration of a large number of samples from a given field site.

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