POWDER X-RAY DIFFRACTOMETRY OF CM1/2 AND CM2 CARBONACEOUS CHONDRITE FALLS

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Introduction: Powder x-ray diffraction (XRD) provides unparalleled "bulk" mineralogical information from meteorites. The XRD reflections are a direct probe of the crystal structure of the individual components in a material. A first-order interpretation of an XRD pattern provides a qualitative assessment of the major minerals in a sample and their relative concentrations. A host of more sophisticated analyses are possible with powder XRD, e.g., [1-3]. In addition, powder XRD is widely available, relatively affordable, and easy to operate. The most commonly used diffractometers have the Bragg-Brentano para-focusing geometry where a flat sample is positioned on the tangent plane of the focusing circle. For many applications, the bulk sample consists of a powder supported on a flat sample holder. "Bulk" is a vague term as desktop diffractometers acquire high signal-to-noise ratio data from samples on the order of 10 mg, and suitable data can be acquired from samples in the 0.1 mg range. While the sample analysis is nondestructive, the common form is a powder, requiring the sample to be crushed and placed onto the flat sample holder.

Here we demonstrate the utility of powder XRD by comparing the patterns for 16 of the recorded CM1/2 and CM2 falls (Fig. 1). The CM group underwent significant aqueous alteration and brecciation on their parent body(s) [4,5]. They contain 56 to 89 vol% phyllosilicates dominated by serpentines [2,3]. These CCs are also of interest because similar materials are thought to be present on asteroid 101955 Bennu, which is the focus of the NASA led OSIRIS-REx sample return mission, and asteroid Ryugu, which was visited by the Hayabusa2 mission operated by the Japanese space agency JAXA. Thus, the detailed study of the CCs provides the framework and basic knowledge with which to study the samples returned from hydrous, clay-rich asteroids.

Method and sample: Powder XRD patterns were acquired with a Rigaku MiniFlex 600 diffractometer. This diffractometer is operated with Cu *K*α radiation and is equipped with a post-diffraction graphite monochromator and automatic divergence slit system. Data were acquired from 2 to 65 °2θ at 0.02° steps, and 30 to 60 s/step. Samples were prepared from an ~2-mm-sized fragment, which weighs ~10 mg, or aggregates of fragments with this approximate mass. Fragments were selected that appeared as "average" lithology. The chips were lightly powdered and mixed with a few milliliters of dry methanol. The resulting slurry was pipetted and spread into a thin, smooth film on a low-background, single-crystal, quartz plate, and dried rapidly (~5 s) under flowing warm air.

Results and discussion: The powder XRD data from the meteorites show the same overall pattern shapes (**Fig. 1**). Each pattern is dominated by reflections for serpentine group minerals, on which are superimposed reflections for ferrotochilinite, 1:1 regularly interstratified ferrotochilinite/cronstedtite, anhydrous silicates, ±calcite, ±dolomite, Fe-Ni sulfides, and minor phases. Below we focus on the bulk matrix hydrous phases.

Characteristic of the XRD data is a relatively featureless pattern from the data acquisition onset of ~2 °2θ (~4.4 nm) up to the serpentine 001 reflection (peak S1) [6]. Above ~10 °2θ (~0.88 nm) and up to ~32 °2θ (~0.28 nm) the patterns exhibit two sharp 00*l* reflections and a well-defined 02*l*-prism characteristic of disordered phyllosilicate stacking (**Fig. 1**) [6]. Most prominent at low-2θ is the intense serpentine 001 reflection (peak S1) with a maximum between 0.732 and 0.722 nm. The 001 reflection is relatively broad in Boriskino and Nawapali. The better-resolved 002 reflection (peaks S2 and S3) show that Boriskino and Nawapali are dominated by two structurally distinct serpentines with 001 of 0.7176 and 0.7284 nm. Similarly, Cold Bokkeveld, Kolang, Mighei, Mukundpura, Murchison, Murray, Nogoya, and Winchcombe show a low-angle shoulder to the 0.358 nm 002 reflection. A peak at 0.605 nm (**Fig. 1**, peak FC) is present in many of the patterns, corresponding to the 003 reflection from 1:1 regularly interstratified ferrotochilinite/cronstedtite [6,7]. A 0.54 nm reflection (peak FT2) corresponding to the 002 reflection of ferrotochilinite is present in many of the patterns, most prominently in Maribo, Mighei, and Murchison. The absence of reflections on the low-2θ side of the serpentine 001 also makes it possible to resolve the weak ferrotochilinite 001 reflection (peak FT1) near 0.108 nm in Maribo, Mighei, and Murchison.

The presented patterns are typical profiles that display the "bulk" mineralogy. However, CM meteorites are breccias, with clasts that show various degrees of aqueous alteration, e.g., [8]. For example, separate mm-sized fragments of Aguas Zarcas and Murchison [6] show significant variations in the intensities of the ferrotochilinite and 1:1 regularly interstratified ferrotochilinite/cronstedtite reflections relative to the serpentine 001 reflection. Similarly, the ratio of hydrous phases to anhydrous silicates can vary widely from one mm-sized fragment to another. However, despite these variations, most profiles display a consistent bulk mineralogy characteristic of CM1/2 and CM2 meteorites.

Bulk powder XRD is a non-destructive, efficient, and rapid method that can provide fundamental mineralogical information from meteoritic and asteroidal returned materials.

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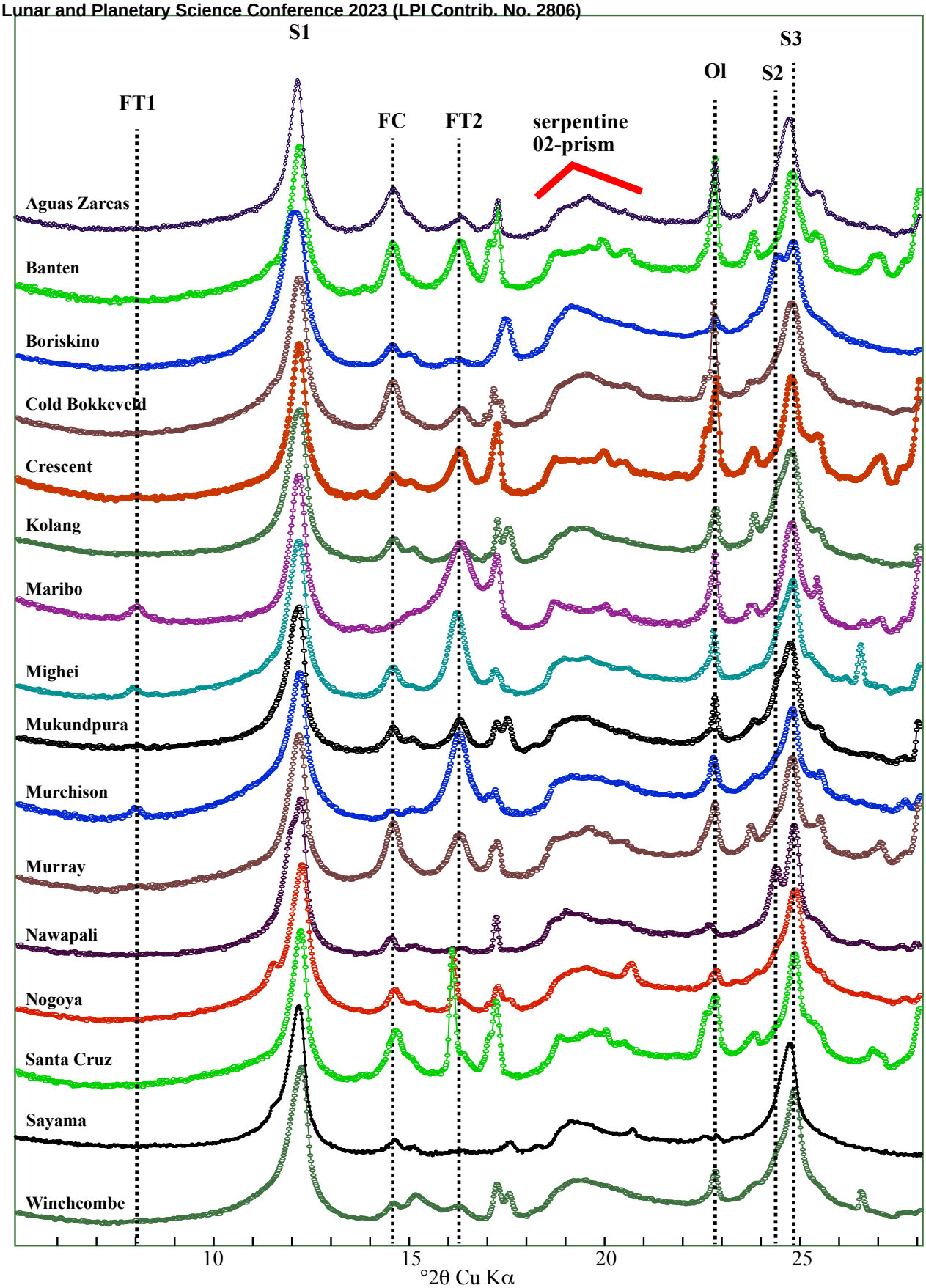

Figure 1. Bulk powder XRD patterns for 16 CM1/2 and CM2 falls. All are CM2 except Kolang which is a CM1/2. Patterns have been shifted along the y-axis for clarity, plotted on a log intensity scale, and scaled with respect to the serpentine 001 reflection. FT1 and FT2 - reflections for ferrotochilinite. S1, S2, S3 - 00l reflections for serpentine. FC - 1:1 interstratified ferrotochilinite/ cronstedtite. Ol - forsterite.