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Aqueous Alteration in CM chondrites: Understanding planetary formation in the early solar system

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Abstract: The CM chondrites (Carbonaceous-Mighei type meteorite) are samples from the carbonaceous (C-type) asteroids, which were formed 4.56 billion years (Gyr) ago and thus, preserve signatures of the early solar system history. One of the important processes that happened after the accretion and formation of organic-rich asteroids is aqueous alteration, due to the interaction between an aqueous fluid and the anhydrous silicate minerals, metals, and sulphides. These reactions lead to the formation of secondary hydrated mineral phases, like serpentine, carbonates, sulfide (e.g., tochinilite), magnetite, and sulfates. Aqueous alteration changes the primitive nature of CM chondrites. It is therefore critical to study the process of this alteration in CM chondrites to better understand the formation and evolution of water-rich planetesimals and thereby the evolution of organics and water in the early solar system.
Keywords: Aqueous alteration, CM chondrites, Meteorites.

Introduction

CM chondrites are organic-rich meteorites that preserve early solar system history (Suttle et al., 2021) and could be a source of water and organics on Earth (Alexander et al., 2012). They are a distinct group of carbonaceous chondrites showing significant aqueous alteration and brecciation (Metzler et al., 1992). Spectra of CM chondrites are closely associated with several water-rich asteroids belonging to the C- type spectral class (Cloutis et al., 2011). Bennu is the target asteroid for a sample return mission: OSIRIS-REx and CM chondrites are the closest analogues to this asteroid (Hamilton et al., 2019). Understanding the formation history of CM chondrites and their alteration histories are important for answering questions related to the evolution of the early solar system and planetesimals, and the evolution of water in the solar system. The formation mechanism, the temporal order of formation and alteration, and the period of the metamorphic event for heated CM chondrites remain poorly understood. Mn-Cr dating of carbonates in CM chondrites indicates aqueous alteration started ~4.56 ± 0.5 Gyr ago (Fujiya et al., 2012). Supporting isotopic and chemical analysis suggest that the CM chondrites originated from one large planetesimal (Lindgren et al., 2017). But, material like CM is distributed all over the solar system (McCord et al., 2012), and from recent studies, it is very likely that the studied CM chondrites may have originated from several parent bodies (Takenouchi et al., 2014).

Asteroid meteorite link

Most of the meteorite samples come from the main belt asteroids that show different stages of evolution ranging from primitive (e.g. C-type, S-type, etc) to differentiated bodies (e.g.Vesta). The study of meteorites is extremely important for understanding the origin, formation mechanism, and evolution history of asteroids as well as the solar system. Asteroids of type C show spectral features pointing to the presence of hydrated minerals and low reflectivity due to the presence of organics. This and other studies have shown that they may be the parent bodies of carbonaceous chondrites. However, it is not clear if all the CM-chondrites in our collection are derived from a single-parent asteroid or if they belong to multiple-parent bodies. CM-like clasts are widely distributed in the different types of brecciated meteorites, indicating their number of parent bodies is more abundant in the asteroid belt (Bischoff et al., 2006). Some inclusions from different meteorites are also seen in CM chondrites (Zhang et al., 2010). In C-type asteroids (except the K-type) ice is generally present. The presence of ice in CM chondrites' parent bodies leads to aqueous alteration.

Aqueous alteration

CM chondrites are composed of chondrules, phyllosilicate-rich porous matrix, and minor calcium, aluminum-rich refractory inclusions (CAIs). Chondrules are silicates that are spherical in appearance and formed in higher-temperature environments (mainly in the protoplanetary disk). Chondrule size in CMs is up to 300 µm and abundance is up to 20 vol. % (Grimm and Mcsween 1989). Refractories like CAIs are first formed material in a nebular setting. After accretion of the CM chondrite parent body, the water ice melted and the reaction between water and silicates and metals resulted in the formation of dominant hydrated secondary minerals (Hazel et al., 2008). This process of conversion of primary minerals to secondary minerals in presence of water is known as aqueous alteration. The primary phases in the matrix of CM chondrites included amorphous material, metal particles and Fe-sulphides and the minerals present within chondrules and CAIs were olivine and pyroxene.

(a) (b) (c)

PLATE (**a**) Image of Near-Earth Asteroid Bennu, (**b**) a CM chondrite (Jbilet Winselwan) which most likely originated from a C- type asteroid (**c**) transmitted light image of a petrologic thin section prepared from Jbilet Winselwan.

After interaction with water, the matrix phases were converted to serpentine and minor carbonates, dolomite, magnetite, tochinilite, pyrrhotite, pentlandite and Fe, Ni-metal. As alteration gets advanced, silicates react with water, forming hydrous secondary minerals likes cronstedtite [$(Fe, Mg)_3 (Fe, Si)_2O_5) (OH)_4$] and Fe/Mg-serpentine [$(Fe, Mg)_3Si_2O_5(OH)_4$].

Following is the different alteration postulated in CM chondrite (Howard et al., 2009):

1. Generally, the reaction between kamacite and S-rich fluid results in the formation of tochilinite:

$$\underset{\text{(Kamacite)}}{Fe, Ni} + H_2O\,(l) + S\,(aq) \rightarrow \underset{\text{(Tochilinite)}}{Fe(OH)_2 . (Fe, Ni)\,S}$$

2. Iron (Fe) rich cronstedtite formed by alteration of Fe-rich matrix olivine in an oxidizing condition.

$$\underset{\text{(Olivine)}}{(Fe, Mg)_2SiO_4} + H_2O\,(l) \rightarrow \underset{\text{(Fe-rich cronstedtite)}}{(Fe, Mg)_3(Fe,Si)_2O_5(OH)_4}$$

3. Si and Mg are released from olivine and Mg-rich pyroxene and they react with tochilinite to form Mg-rich cronstedtite

$MgSiO_4 + 2Fe(OH)_2.(Fe,Ni)S + H_2O(l) \rightarrow (Mg, Fe)_3(Fe, Si)_2O_5(OH)_4 + Fe(OH)_2.(Fe, Ni)S$

(Olivine) (Tochilinite) (Mg-rich cronstedtite) (Tochilinite)

4. Mg-rich cronstedites and Mg, Fe-serpentine are produced by the consumption of tochilinite. S is released from tochilinite and redeposited as Fe–Ni sulphides

$(Fe, Mg)_3(Fe, Si)_2O_5(OH)_4 + Fe(OH)_2(Fe, Ni)S \rightarrow (Mg, Fe)_3Si_2O_5(OH)_4 + (Fe, Ni)_9S_8$

(Fe-rich cronstedtite) (Tochilinite) (Mg-rich cronstedtite)

Sample and Techniques

Several techniques are used to understand the physical, chemical, mineralogical, structural, and geochemical properties of a meteorite. In a preliminary study, we used the Jbilet Winselwan CM chondrite found on May 24, 2013, near Smara in Western Sahara and the fourth largest CM chondrite. Fusion crust from a sample was removed, a petrologic thin section was prepared from a freshly cut sample and powder is prepared for optical and geochemical studies respectively. To know the abundance of mineral phases, powder XRD is used, and to know the highest temperature (peak metamorphic temperature) achieved in a meteorite, Raman spectroscopy is used. To know the parent bodies, we need to perform spectroscopy over meteorite samples. Then we need to match the reflectance spectra of the meteorite to the remotely studied spectra of the asteroid.

Discussion and Conclusions

The mineral phases present in Jbilet Winselwan from powder-XRD are olivine, enstatite, magnetite, sulfides, and sulfates (gypsum and anhydrite). We did not find any diffraction peaks of phyllosilicate which are generally at ~12° (2θ) and ~25° (2θ) (Fe-rich phyllosilicate) and ~19° and ~61° (2θ) (Mg-rich phyllosilicate). From Raman spectroscopy of matrix organics, the peak temperature obtained both on the powder sample and thin section is below 2200 C. It indicates that after aqueous alteration, Jbilet Winselwan was subjected to high metamorphic temperatures during which phyllosilicates got converted to olivine. CM chondrites are the most primitive meteorites which preserve early solar history. A detailed study of more CM chondrites can resolve some questions regarding the early solar system such as formation conditions and timing of formation. As aqueous alteration changed the initial mineralogy of CM chondrite, which hampers the primitive nature of CM chondrites. So, it is very important to know more in detail about the factor for aqueous alteration, where these aqueous alterations are occurring, and the parent bodies of most primitive materials present in our solar system.

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Glossary

CAI- In chondritic meteorites, calcium-aluminum-rich inclusions (CAIs) are sub-millimeter to centimetre sized clasts that are almost totally made up of CaO-Al2O3-MgO-SiO2-TiO2. They are believed to have originated from a high temperature (>1300 K) gas that was present in the protoplanetary disc at the beginning of the Solar System's.

CM chondrites- A series of carbonaceous chondritic meteorites known as "CM chondrites" are similar to its typespecimen, the Mighei meteorite.

C-type asteroids- Around 75% of known asteroids are made up of this most prevalent kind. They are rich in volatilesand have a very low albedo because to the greater carbon content.

K-type asteroids - Low-albedo K-type asteroids are a very uncommon class of asteroids. Their spectra are comparable to some carbonaceous chondrite meteorites, such as CV and CO.

S-type asteroids - A siliceous mineralogical composition with a greater density is indicated by the spectra of S-typeasteroids. These are the second most common asteroid after C-type.

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