

**PROLONGED FLUID ACTIVITY IN THE EARLY SOLAR SYSTEM: EVIDENCE FROM SIMS U-PB DATING OF APATITE IN CARBONACEOUS CHONDRITE DAR AL GANI 978.** A. C. Zhang<sup>1,2</sup>, M. Y. Cheng<sup>1</sup>, Q. L. Li<sup>3</sup>, X. H. Li<sup>3</sup>, H. Yurimoto<sup>2</sup>, and R. C. Wang<sup>1</sup>, <sup>1</sup>School of Earth Sciences and Engineering, Nanjing University, China (aczhang@nju.edu.cn); <sup>2</sup>Department of Natural History Sciences, Hokkaido University, Japan; <sup>3</sup>Institute of Geology and Geophysics, Chinese Academy of Sciences, China.

**Introduction:** Abundant mineralogical evidence in carbonaceous chondrites indicates that aqueous fluid activity could have been very common in the Early Solar System (ESS) [1]. The Mn-Cr, I-Xe, and Al-Mg isotopic chronologies suggested that fluid activity in ESS could have lasted only up to ~15 Ma after CAI formation [2]. Whether alteration in ESS could have lasted more than 15 Ma remains unknown. Here, we report the occurrences and geochemical features of apatite in a type-3 carbonaceous chondrite Dar al Gani (DaG) 978 [3] and SIMS U-Pb dating results of apatite. This U-Pb age of apatite is not only the first absolute age of aqueous fluid activity in ESS, but also indicates that fluid activity in ESS could have lasted up to ~120 Ma after CAI formation.

**Analytical Methods:** Petrographic textures of apatite in DaG 978 were mainly observed with JEOL 7000F FE-SEM and JEOL 6490 SEM. Mineral chemistry of apatite was determined with JEOL 8100 EPMA. Oxygen isotope compositions of apatite and associated silicate minerals were determined with the Cameca IMS-1270 instrument at Hokkaido University. San Carlos olivine was used as a standard for the oxygen isotope analyses. The REE compositions of apatite and merrillite were determined with the Cameca IMS-6f instrument at Hokkaido University. A well-characterized Takashima augite was used as a standard for the REE analyses. The analytical procedures at Hokkaido University are similar to those reported in [4]. The U-Pb isotopic system of apatite was determined with the Cameca IMS-1280HR instrument at the Institute of Geology and Geophysics, Beijing, China. The analytical procedure is similar to that in [5-8].

**Results:** Apatite is common in DaG 978. Based on observations on eight polished sections of DaG 978, four major occurrences of apatite are observed. (1) A few apatite grains occur at the margins of large FeNi metal grains; however, apatite is rarely included in FeNi metal grains. Some apatite grains are up to 100  $\mu\text{m}$  in size. (2) The majority of apatite grains in DaG 978 are closely associated with altered Ca-Al-rich inclusions (Fig. 1). Most of them are larger than 20  $\mu\text{m}$  in size; roughly fifty percent of apatite grains associated with altered CAIs are larger than 50  $\mu\text{m}$  in size. Importantly, many apatite grains have well developed crystal forms. (3) A few anhedral to euhedral apatite grains are set in fine-grained matrix. Some of them

exhibit a moniliform distribution (Fig. 2). A few apatite grains set in matrix are very large, up to 280  $\mu\text{m}$  in size. Some apatite grains contain inclusions of diopside and olivine. However, olivine inclusions in apatite grains are relatively rare compared with diopside inclusions in apatite grains. (4) A few apatite grains occur at the margin of chondrules and are closely associated with FeNi metal [3].

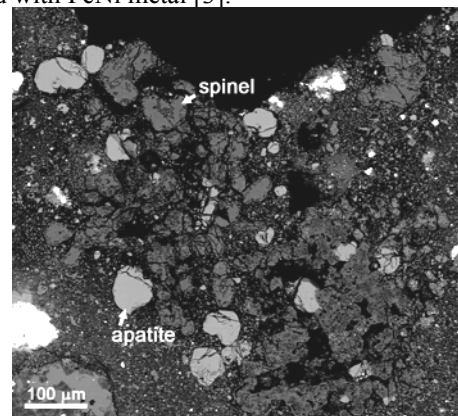


Fig. 1. BSE image of apatite grains closely associated with an altered CAI in DaG 978.

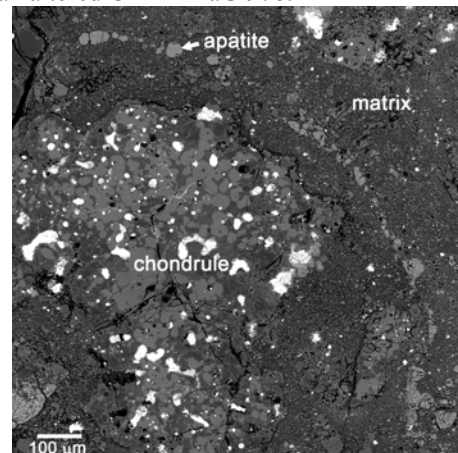


Fig. 2. BSE image of apatite grains with a moniliform distribution in DaG 978.

The EPMA analyses reveal that apatite in DaG 978 is highly Cl-rich with a Cl concentration of 4.94-5.61 wt%. Based on the stoichiometry of apatite, the hydrogen contents vary from 233 to 451 ppm, if assuming that the X-site of apatite crystal structure is only occupied by F, Cl, and OH. Apatite grains and their diopside inclusions show similar oxygen isotope compositions with an average  $\Delta^{17}\text{O}$  value of  $-1.5 \pm 3.2\%$  ( $2\sigma$ ).

Two merrillite grains and nine apatite grains were measured for REE compositions (Fig. 3). The two merrillite grains show different REE patterns with one grain having a weak and positive Eu anomaly and the other having a negative Eu anomaly. However, the apatite grains show LREE-enriched REE patterns with consistently positive Eu anomalies although different apatite grains have variations in the REE concentrations (e.g., La  $\sim 26\text{--}62 \times \text{CI}$ ).

The 16 SIMS U-Th-Pb isotope analyses on 13 apatite grains reveal that apatite in DaG 978 contains very low U ( $<0.178$  ppm) and Th ( $<0.096$  ppm). The 16 analyses show a well-defined linear correlation between  $^{204}\text{Pb}/^{206}\text{Pb}$  and  $^{207}\text{Pb}/^{206}\text{Pb}$ , giving a  $^{207}\text{Pb}/^{206}\text{Pb}$  isochron age of  $4450 \pm 50$  Ma ( $2\sigma$ ; Fig. 4). Meanwhile, the 3-D least-square fit gives a total Pb/U isochron age of  $4448 \pm 110$  Ma ( $2\sigma$ ), well consistent with the  $^{207}\text{Pb}/^{206}\text{Pb}$  isochron age.

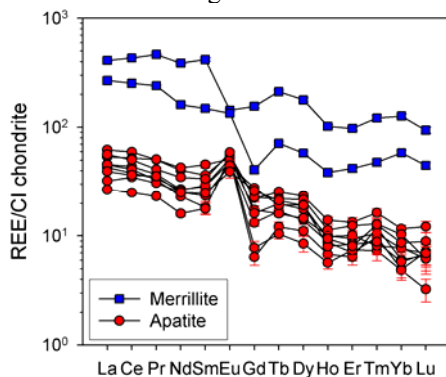


Fig. 3. REE patterns of merrillite and apatite in DaG 978.

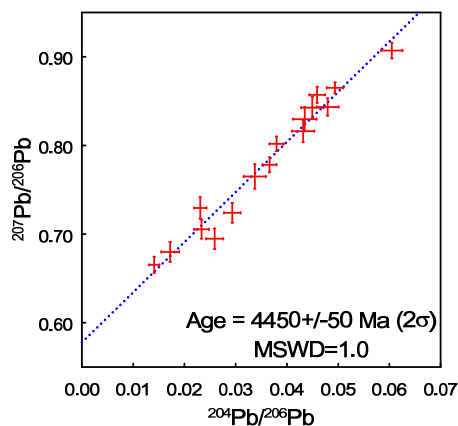


Fig. 4. Inverse  $^{204}\text{Pb}/^{206}\text{Pb}$ - $^{207}\text{Pb}/^{206}\text{Pb}$  isochron diagram for apatite in DaG 978.

**Discussion:** (1) Aqueous alteration origin of apatite. Apatite has been reported in both ordinary and carbonaceous chondrites [9-12]. However, apatite in equilibrated ordinary chondrites has different petrographic textures and REE patterns from that in carbonaceous chondrites. Most apatite grains in ordinary chondrites show recrystallized textures with olivine and pyroxene

and their REE patterns usually show negative Eu anomalies [10-11]. Therefore, apatite in equilibrated ordinary chondrites was mainly attributed to thermal metamorphism on the parent bodies [9-11]. However, phosphate minerals (merrillite and apatite) in carbonaceous chondrite are closely associated with magnetite [13] and have positive Eu anomalies [12]. Their origins were attributed to aqueous alteration [12-13]. In this study, all the petrographic textures, oxygen isotope compositions, and REE patterns also support that apatite in DaG 978 has an aqueous alteration origin.

(2) Timescale of aqueous fluid activity on the carbonaceous chondrite parent bodies. The consistence between the  $^{207}\text{Pb}/^{206}\text{Pb}$  isochron age and the total Pb/U isochron age indicates that the crystallization age of apatite in DaG 978 is  $4450 \pm 50$  Ma. Since apatite in DaG 978 has an aqueous alteration origin, this age has two important implications. First, this age indicates that the alteration event could have taken place on the parent body rather than in the solar nebula. Second, this age indicates that aqueous fluid activities in ESS could have lasted much longer than previously thought based on short-lived radionuclides chronology [2]. Since the crystallization of apatite in DaG 978 post-dates CAI formation by  $\sim 120$  Ma, it is difficult to explain the formation of fluid by melting of water ice due to decay-induced heating of short-lived radionuclides. Instead, it is very likely that an impact event at 4450 Ma resulted in melting of water ice that could have been buried in the parent body of DaG 978 or a comet impacted at 4450 Ma and brought fluids into the parent body of DaG 978. Recently, two investigations on shocked ordinary chondrites suggested that ordinary chondrite parent bodies could also have been impacted at  $\sim 4450$  Ma [7-8]. It is very likely that there were widespread collision events at  $\sim 4450$  Ma in ESS.

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**Acknowledgements:** This study was financially supported by NSFC (No. 41373065), the Fundamental Research Funds for the Central Universities in China, and the JSPS Fellowship to ACZ.