LLNL-CONF-479981

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April 11, 2011

42nd Lunar and Planetary Science COnference (2011)
The Woodlands, TX, United States
March 7, 2011 through March 11, 2011

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EXTREMELY NA AND CL RICH CHONDRULE AL3509 FROM THE ALLENDE METEORITE. G. J. Wasserburg[1], I. D. Hutcheon[2], J. Aléon[3], E. C. Ramon[2], A. N. Krot[4], K. Nagashima[4], and A. J. Brearley[5]. [1]CalTech, MC 170-25, Pasadena CA 91125, gjw@gps.caltech.edu, [2]Glenn Seaborg Institute, LLNL, Livermore, CA 94511, USA, [3]CSNSM IN2P3-CNRS, Batiment 104, 91405 Orsay Campus, France, [4]HIGP/SOEST, University of Hawai'i at Manoa, Honolulu, HI 96822, USA, [5]University of New Mexico, Albuquerque, NM 87131, USA.

Introduction: *This work is dedicated to the memory of Brian Mason.* We report on the mineralogy, petrology, chemistry, oxygen isotopes, ^{26}Al–^{26}Mg and ^{36}Cl–^{36}S isotope systematics of the Allende chondrule *Al3509* discovered and described by [1] and [2]. This spherical object (~1cm ϕ) contains ~10% Na and 1% Cl, and nearly pure ^{129}Xe [(^{129}Xe/^{127}I) = 1.1×10^{-4} [3)]. This high enrichment in halogens makes it of interest in searching for radiogenic ^{36}S from ^{36}Cl ($t_{1/2}$ ~ 0.3 Ma) decay. While there is strong evidence for the presence of ^{36}Cl in sodalite and wadalite in CV CAIs [4,5], some sodalites show no evidence for excesses of ^{36}S (^{36}S*). In contrast, high inferred initial ^{36}Cl/^{35}Cl = 2×10^{-5} has been found in wadalite from the Allende CAI *AJEF* [5]. The observed ^{36}S excesses in sodalite are not correlated with radiogenic ^{26}Mg, decay product of ^{26}Al ($t_{1/2}$ ~ 0.72 Ma) [4]. From the inferred initial ^{36}Cl/^{35}Cl ratios and consideration of both *AGB* and *SNe* stellar sources, ^{36}Cl must be the product of charged particle irradiation within the early solar system. However, neither the specific nuclear production mechanism nor the irradiation site have been identified. Both sodalite and wadalite are found as late stage alteration products of CAIs together with grossular, monticellite, Al-rich pyroxene, wollastonite, nepheline, ferroan olivine, and ferroan pyroxenes. This late-stage alteration has been found to extensively change some CAIs in Allende, but clear residues of spinel, hibonite and Wark-Lovering rims are recognizable remnants of the original CAIs. The nature of the widespread volatile alteration process as well as that of the fluid phase remain controversial.

Results and Discussion: Our studies were carried out on two new polished sections of *Al3509*, Mann#1 and #2. Figures 1a, b show the combined elemental K_α x-ray maps in Mg/Cl (red), Ca/Na (green) and Al/Fe (blue). The chondrule is radially zoned in Na, Cl, Ca, Fe, Mg, and Al (Figs. 1a,b); the zones are numbered from 1 to 9 and illustrated in Figures 1c, d. The chondrule consists of fine-grained ferroan olivine, ferroan high-Ca pyroxene, nepheline, sodalite, and andradite, and is crosscut by numerous veins of nepheline, sodalite, and ferroan high-Ca pyroxene. The mineralogy and mineral chemistry of *Al3509* are close to those found as the alteration products of Allende CAIs and chondrules, which are attributed to late-stage iron-alkali-halogen metasomatic alteration of primary high-temperature minerals.

The ^{26}Al–^{26}Mg isotopic data for sodalite and ferroan pyroxene in *Al3509* (Fig. 2) show no resolvable excess of ^{26}Mg (^{26}Al/^{27}Al < 3×10^{-6}). All sodalite grains measured for ^{36}Cl–^{36}S isotope systematics show large but variable ^{36}S*; however, there is no correlation of ^{36}S/^{34}S with ^{35}Cl/^{34}S (Fig. 3). We infer that (*i*) ^{36}S* is due to decay of ^{36}Cl originally present in *Al3509*, and (*ii*) the radiogenic ^{36}S was redistributed during subsequent thermal metamorphism. An analogous process (post formational heating to ~800K for ~1 Ma) has been proposed by [6] to explain the general absence of ^{36}Ar, the principal decay product of ^{36}Cl, which has not yet found in sodalite grains (but with the preservation of ^{129}Xe*).

Oxygen isotopic data of ferroan olivine, ferroan pyroxene, sodalite, nepheline, and olivine+chlorite(?) in *Al3509* plot along a mass-dependent fractionation line at Δ^{17}O ~ –2.5‰ (Fig. 4). This pattern is the same as found in secondary minerals resulting from iron-alkali-halogen metasomatic alteration of Allende CAIs and chondrules and in melilite and anorthite of most CAIs in Allende [e.g., 7,8]. The oxygen-isotope data suggest that the *Al3509* minerals precipitated from or equilibrated with a fluid of similar oxygen isotopic composition. These observations suggest that the formation of *Al3509* and alteration products in CAIs and chondrules in Allende requires a very similar fluid phase, greatly enriched in volatiles (e.g., Na and Cl). We argue that internal heating of even small planetesimals by ^{26}Al would efficiently transfer volatiles to their outer portions and enhance the formation of minerals highly enriched in volatiles. We conclude that this volatile rich outer zone was the site for production of the Na- and Cl-rich fluids responsible for the formation of *Al3509* and the alteration of Allende CAIs and chondrules transported into this zone. This event must have occurred on a protoplanetary body prior to incorporation into the Allende meteorite.

A difficult problem exists with regard to the production of ^{36}Cl by solar energetic particle irradiation. Irradiation of dust would produce other short-lived nuclei such as ^{26}Al, which is not observed to co-exist with ^{36}Cl in any systematic pattern. A possible solution would be irradiation of ice (with little dust) that is highly enriched in Cl. This scenario would co-produce B and Li isotopes and we suggest these effects should be looked for in *Al3509* and other sodalite- and/or wadalite-rich rich samples.

References: [1] Clarke R. S. et al. (1970) *Smithsonian Contrib. Earth Sci.*, **5**, 1–53. [2] Mason B. & Martin P. M. (1977) *Smithson. Contrib. Earth Sci.*, **19**, 84–95. [3] Wasserburg G. J. and Huneke J. C. (1979) *LPS* **10**, 1307–1309. [4] Lin Y. et al. (2005) *Proc. Nat. Acad. Sci.*, **102**, 1306–1311. [5] Jacobsen B. et al. (2009) *LPS* **40**, #2553. [6] Turner G. et al. (2009) *MAPS* **44**, #5255. [7] Cosarinsky M. et al. (2008) *GCA* **72**, 1887–1913. [8] Krot A. N. et al. (2000) *LPS* **31**, #1463. [9] Work performed under the auspices of the DOE by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. G. J. Wasserburg acknowledges support by a NASA Cosmochemistry RTOP to J. Nuth, at GSFC, & by the Epsilon Foundation.

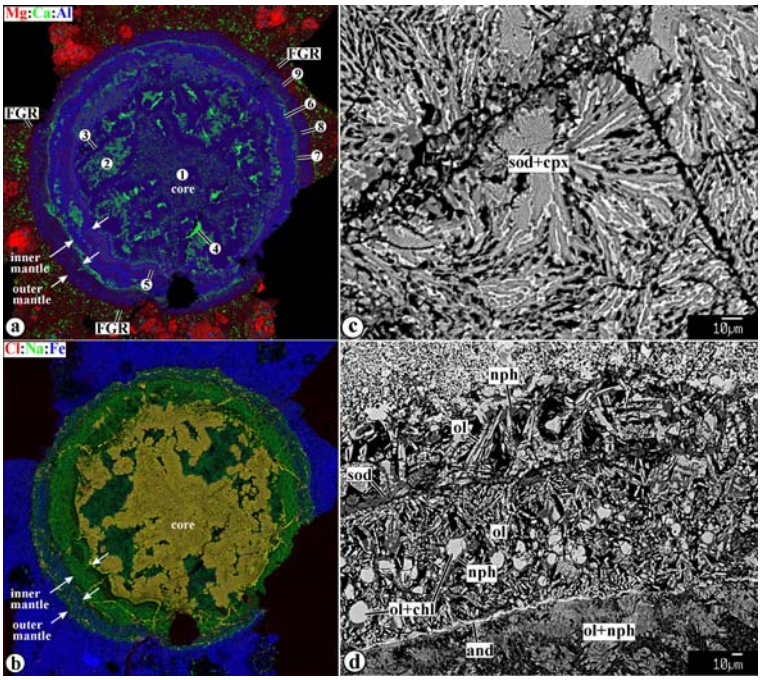

Fig. 1. Combined elemental maps in Mg (red), Ca (green), and Al (blue) and Cl (red), Na (green), and Fe (blue) ((a) and (b), respectively) and backscattered electron images ((c) and (d)) of the Allende chondrule *Al3509*, Mann#1. The chondrule is rich in Al and Ca, but contains no identifiable Mg-rich phases, typically observed in Ca,Al-rich chondrules and CAIs. It shows radial chemical and mineralogical zoning (1–9) and is surrounded by a thin fine-grained rim (FGR). The yellow and green colors in Fig. 1b correspond to sodalite- and nepheline-rich portions of the chondrule that is depleted in Fe and highly enriched in Cl and Na compared to the adjacent Allende matrix. Fig. 1c and 1d show the core and the mantle portions of *Al3509*. The chondrule has a quenched texture and consists of sodalite (sod), nepheline (nph), ferroan olivine (ol), ferroan high-Ca pyroxene (cpx), andradite (and), and possibly chlorite (chl).

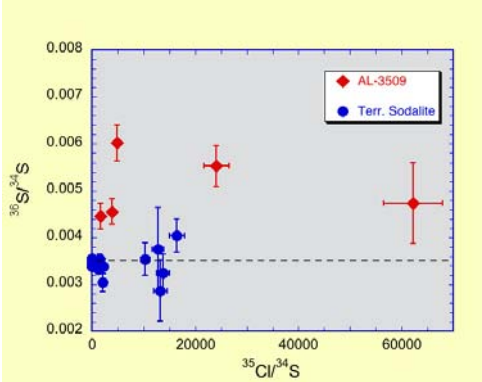

Fig. 3. Chlorine-sulphur isotope diagram of sodalite in *Al3509* and analyses of terrestrial sodalite.

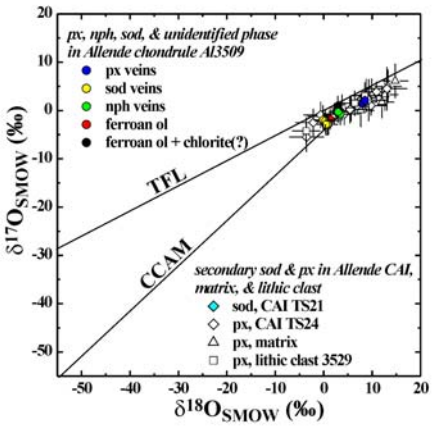

Fig. 4. Three-isotope oxygen diagram of ferroan Al-diopside (px), nepheline (nph), sodalite (sod), ferroan olivine (ol) and a mixture of ferroan olivine and chlorite (ol+chl(?)) in *Al3509* (this study) and of secondary Ca,Fe-rich pyroxenes (px) and sodalite in the Allende matrix, rim around Allende CAI *TS24* (data from [7]), and Allende dark inclusion *3529* (data from [8]); error bars are 2σ. Oxygen isotopic compositions of all these phases plot along mass-dependent fractionation line with $\Delta^{17}O$ value of ~ –2.5‰ suggesting precipitation from or equilibration with a fluid of similar O-isotope composition.

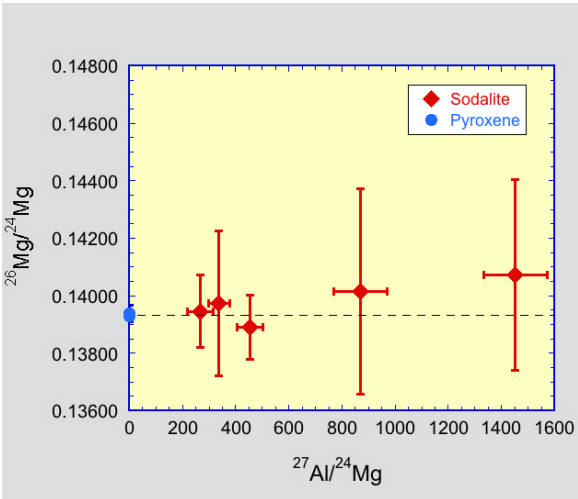

Fig. 2. Aluminum-magnesium isotope diagram of sodalite and ferroan Al-diopside in *Al3509*.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.