Platinum Jubilee

Physical Research Laboratory

MetMeSS-2021

Symposium on *Meteoroids, Meteors and Meteorites: Messengers from Space*

Programme

29th November, Monday

Session-3: Journey to Differentiated Worlds

(Earth-Mars-Moon-Asteroids)

Session Chairs: Nachiketa Rai & Amit Basu

Abstract #	Time	Speaker	Title of talk
Invited	16:15-16:30	Ramananda Chakrabarti	Overview of differentiated planets.
S3-01	16:30-16:45	G. Srinivasan	Compositional Constraints on Late Veneer from Chalcogen Elements
S3-02	16:45- 16:55	Narendra Bhandari	Evidence and Consequence of presence of Niobium-94 in Gebel Kamil iron meteorite
S3-03	16:55-17:05	Amit Basu	Compositional Constraints on the Origin of Volcanism on Mars
S3-09	17:05-17:15	Gurpreet K. Bhatia	Early thermal evolution of Earth's embryos due to heat of ^{26}Al and impact-generated steam atmosphere
S3-04	17:15-17:23	Yash Srivastava *	Petrogenesis of A-881757: A non-KREEP Low Ti Lunar Meteorite Basalts
S3-05	17:23-17:31	Vishal Goyal*	Early Evolution of Mass-Averaged Temperature of the Moon
S3-06	17:31-17:39	P. Layak*	Constraining the composition of the parent planetisimal for the acapulcoite and Lodranite suite of meteorites- A trace element approach
S3-07	17:39-17:44	Rahul Das Gupta*	Formation of carbonate-sulfide association in the martian meteorite ALH84001 and implications for the nature of water-rock interactions on the martian surface in the Noachian Era
S3-08	17:44-17:49	Satvika Jaiswal*	Light noble gas study in Eucrites and diogenites

Compositional Constraints on Late Veneer from Chalcogen Elements.

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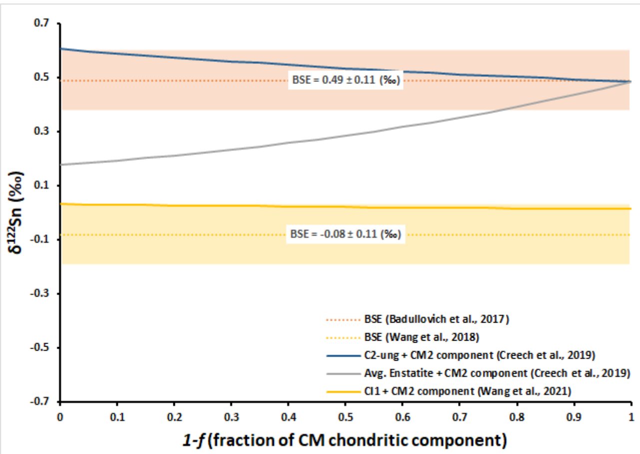
The composition of terrestrial planets is a function of their respective building blocks. The diversity of chemical and isotopic composition of Earth, Moon, Mars and meteorites is product of the varied physical and chemical conditions leading to their accretion. Dynamical modelling suggests that Earth accreted through collisional interactions of diverse material originating from a wide variety of heliocentric distances (Morbidelli et al. 2000). The composition of CI carbonaceous chondrites is a proxy for the primordial material from which the solar system formed. The composition of the Earth is very different from CI chondrites. One of the unresolved enigmas is that the Earth chemically resembles the carbonaceous chondrites (CC) while isotopically it is most similar to enstatite (NC) chondrites (Dauphas 2017). There is no exact equivalent meteorite composition which can be a source material for Earth. One wa.y to constrain the building blocks for the Earth is to compare and contrast the various elemental budgets based on volatility. There is no consensus on the sources of the volatiles or their mass fractions delivered towards the final stages of accretion. The obstacles in determining volatile inventory is that these elements have been redistributed due to core formation and or lost due to high temperatures generated by impact and accretion (Wang and Becker 2013). The elemental abundances of primitive meteorites and Earth decrease relative to CI chondrite composition as volatility increases. It was also observed that volatile element abundances may level off (Takahashi et al. 1978). More recent measurements by (Braukmüller et al. 2019) reveal that that volatile element abundances (e.g., S, Se, Te) do not fall off monotonically but level off into a plateau.

The building blocks for Earth perhaps had varying volatile element abundancs and redox state. The Earth building process could be subdivided into three primary simple steps a) accretion of 85% Earth mass material; b) followed by a Moon forming giant impact (~14 % of Earth Mass); c) late veneer with 1% Earth Mass. These steps could be further subdivided for compositional diversity and sequence vis-à-vis mile stone in Earth evolution (e.g., core-mantle formation). In this simplified scenario, in the first step matter could be dominated by enstatite like material while subsequent accretionary material may have been very different. The moon forming giant impact or material may have ranged in composition from a homogeneous (CC or NC) end member to a heterogeneous mixture of both. It could involve a primary event followed by a secondary event, or could be more exotic compositional equivalent of a reduced planet like Mercury (e.g., Wang et al.2021). This was followed by the impactor constituting the late veneer, 1% of total Earth mass, which is used to explain the abundance of highly siderophile elements (HSE) such as the platinum group elements and Re and Au. Similar to the HSEs, the abundance of volatile chalcogen elements, e.g., Se, Te, and Sn, with a 50% condensation temperature between 700K-500K are in depleted in BSE by core formation. If we assume that all the inventory of these elements in BSE is due to late veneer, we can use mass balance equation to calculate the composition of the impactor - a mixture of various CC type meteorite composition. Using mass balance equation it was shown (Varas-Reus et al 2019) e.g., that ~ 85% CI meteorite and ~ 15% CM meteorite material with nearly 1% Earth mass could contaminate the pre-late veneer silicate mantle to recreate suitable Se isotope composition. If we use this proportion of CI and CM material with measured $\delta^{122/118}$Sn isotope composition (Wang et al. 2021) one can generate



BSE like composition with suitable Sn isotope composition. This is a useful constraint in the chalcogen element budget as their values converge towards BSE composition (Figure).

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Evidence and Consequence of presence of Niobium-94 in Gebel Kamil iron meteorite

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We have measured spectrum of coincident gamma rays emitted by two large fragments of Gebel Kamil iron meteorite, found in 2009-10 near an impact crater, using a low background, highly specific gamma-gamma coincidence spectrometer in the underground laboratory of Monte dei Cappuccini in Torino, Italy. The results of ^{26}Al (mean life ~ 1million years), published earlier (Taricco et al, 2019), indicate a highly asymmetric ablation. The data also show a feeble but clear presence of ^{94}Nb (mean life ~ 30,000 years), identified by its characteriusctic coincident two decay gamma rays in the fragment exposed near the surface in the interplanetary space. The other fragment, located much deeper within the meteoroid, gives no such signal indicating that ^{94}Nb activity is steeply depth dependent, and this fragment can serve as an ideal background control, mimicking all the known and unknown processes. The results can be re-confirmed using radiochemical methods, and measurement in additional shallow fragments.

^{94}Nb, is known to be synthesised only in r-process in supernovae and giant stars and its presence in the meteorite demands a very special, multi step, scenario, in which, after being produced in the interstellar neighbourhood, ^{94}Nb is accelerated to very high (>GeV) energies while propagating through the interstellar medium, enter with galactic cosmic rays in the heliosphere by crossing the heliomagnetic field and then get implanted in the meteorite orbiting in the interplanetary space. The plausability of these steps, and their time scales considering the half life of the niobium radioisotope is discussed. No other mechanism appears probable. If confirmed, these results will provide new information about the supernovae events in solar neighbourhood in the recent past ($<10^5$ years). Plausibility of mechanisms and problems involved in these steps will be discussed.

We are indebted to S. Mohanty and K.K.Marhas for discussions.

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Compositional Constraints on the Origin of Volcanism on Mars

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Mars surface is thought of basaltic composition on an average. However, there are ample pieces of evidence of heterogeneous compositions. The martian surface displays a wide range from olivine-enriched basalt to felsic material material-rich dacite composition on a local scale. The olivine-enriched basalts, found from the eastern part of Valles Marineris, were interpreted as an eruptive event consisting of compositionally uniform flood lavas originating from a primitive mantle source region associated with the initiation of Tharsis volcanism. The presence of granitoid bodies at the central peaks of Syrtis Major might indicate mechanisms that produce highly differentiated /fractionated magmas.

Arabia Paterae is a unique and recently recognized Noachian volcanic province on Mars [1-4]. Relative abundances of different elements in Arabia Paterae relative to other volcanic regions on Mars can help to understand the mantle source composition and the petrogenesis during the oldest volcanic. The Hesperian volcanic domains on Mars are Syrtis Major, Tyrrhena Patera, Syria Planum, while the Amazonian volcanic domains are Olympus Mons, Alba Patera, Elysium Mons. If a gradational relation exists between compositional and spatial parameters, it will reflect the mantle heterogeneity and evolution of the mantle through geologic time. Being the Noachian age, Arabia Paterae volcanism was definitely influenced by more water activity and a better oxidation state than the later volcanic events.

SNC martian meteorites are formed volcanically. The range of their composition also varies from most Fe-Mg rich ultramafic dunite-pyroxenite to permafic and mafic basaltic types to silicic clasts in brecciated rocks. The shergottites are of the late Amazonian age. Phase equilibria experiments indicate that these rock compositions represent multiply saturated magmas with olivine + orthopyroxene ± spinel at 1.0–1.2 GPa, corresponding to depths of 85–100 km [5-8]. This mineral assemblage is predicted as a partial melting residue for the Mars upper mantle. Noteworthy, martian surface rocks are higher in aluminum and alkali content than the martian meteorites, the bulk of which indicates late crystallization of plagioclase and abundant phosphates. The difference in rock compositions between old rocks on the martian surface and young martian meteorites is striking and suggests global magmatic evolution through time. Several explanations for this difference in composition have been offered, including melting and fractionation at different pressures, under different redox conditions, or with different water contents.

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Early thermal evolution of Earth's embryos due to heat of ^{26}Al and impact-generated steam atmosphere

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Earth and the Enstatite chondrite meteorites (dry) are known to have similar isotopic abundance [1]. Previous isotopic studies have suggested that the Earth initial accreted the reduced Enstatite material [2]. The volatile rich material was delivered from large heliocentric distances possibly through the moon forming giant impact [3]. However, recent studies have shown that the Enstatite chondrites are not depleted in volatiles [4]. These contain adequate hydrogen to deliver significant amount of water to Earth. It implies to the formation of an impact-generated steam atmosphere on the surface of Earth's embryos (building blocks) during their growth [5]. Further, the recent planet formation theories and isotopic measurements suggest that the embryos of Earth accreted very rapidly during the initial ~2 Ma of the formation of solar system [6-7]. The early accretion implies the role played by the short-lived radionuclide (SLR) ^{26}Al in the large-scale heating of embryo's interiors [8-9]. Based on these new finding, we performed numerical simulations to study the early thermal evolution and core-mantle separation of Earth's embryos ($0.2M_E$-$0.6M_E$) due to significant heating by short-lived radionuclide ^{26}Al and blanketing effect of the impact-generated steam atmosphere during accretion [10]. We also incorporated the heat energies of SLR ^{60}Fe along with long-lived radionuclides ^{40}K, ^{235}U, ^{238}U and ^{232}U. The bulk composition of the embryos was considered to be Enstatite type [5,9]. The initial water content (X_{wp}) of the accreting planetesimals was considered to be in the range of 0.1 – 0.54% H_2O by weight [4]. The results of numerical simulations show the formation of the magma ocean on the surface of embryos during accretion because of significant blanketing by the impact-generated steam atmosphere. Further, the core-mantle segregation in the interior was complete within the initial ~5 Ma of the formation of the solar system if the embryos accreted in the initial ~1.3-1.5 Ma after the formation of CAIs. The early segregation of massive embryos ($0.4M_E$-$0.6M_E$) at lower melt fraction of silicates was essential for complete core-mantle differentiation within the initial 5 Ma. These results seem to be consistent with the results of new finding for the rapid accretion and differentiation of main accretion phase of Earth within the initial ~5 Ma of the solar system [11]. The outcomes of the present works could be used to explain the anomalously high concentration of siderophile elements and Platinum group elements in the mantle of Earth.

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PETROGENESIS OF A-881757: A NON-KREEP LOW Ti LUNAR METEORITE BASALTS

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Low-Ti basalts spans over wider lunar volcanic history, with the oldest low Ti basalt age of ~ 4.39 Ga (Kalahari 009;[1]) to recently sampled Chang'E 5 low Ti basalt (~2.0 Ga;[2]). Asuka-881757 is a coarse, holocrystalline (grains more than 5 mm in length), low-Ti, high Fe (Mg# 38), unbrecciated mare basalt with pyroxene and plagioclase as the primary constituents. Similarity in textural, chemical and isotopic signature of A-881757 with lunar meteorites including Y-793169, MIL 05035 and MET 01210 led [3] collectively referred them as YAMM group of meteorites. Compared to the other lunar meteorites and returned VLT/Low-Ti samples, YAMM basalts with ~ 3.8-3.9 Ga age [4,5,6] are older and have fairly evolved (Mg# (32-41) bulk composition with low bulk concentration of REEs and other incompatible trace elements (e.g., 0.48 ppm Th). It is generally believed that the generation of mare basalts is assisted by the assimilation of KREEP components [7]. However, low Rb/Sr (Sr_i=0.69908 - 0.6991), high ε_{Nd}= 7.2-7.4 and unusually low U-Pb (μ = 11-20) suggest a non-KREEP (high Rb/Sr and low ε_{Nd}) related origin of these meteorite clan and also imply a distinct source than other lunar basalts [4]. Thus, it becomes important to understand as well as assess the role of KREEP and early impacts in ancient volcanism.

In this study, we have revisited the petrogenesis of YAMM basalts with special emphasis on A-881757 to understand the ancient lunar volcanism. We show that detailed petrology of A- 881757 provides insight into the generation of VLT/low Ti basalts and their source chemistry, as well as highlight the importance of trapped residual components in generating trace element variations in lunar basaltic magmas.

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Early Evolution of Mass-Averaged Temperature of the Moon

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The Moon is considered to have formed as a result of the giant collision of proto-planetary body 'Theia' with proto-Earth [1]. The event happened after the exhaustion of short-lived radionuclides ^{26}Al and ^{60}Fe [2-3]. In the absence of short-lived radionuclides, the thermal energy comes from only the initial energy of accreting moonlets and impact-induced heating. In this study, we have analyzed the evolution of mass-average of lunar thermal profile based on numerical simulations.

We have run several models with the initial temperature of accreting moonlets, T_{ini} in the range of 1700-2100 K, and efficiency of impact-induced heating (h-parameter) in the range of 0.01-0.5. After capturing the thermal profile at several time points, mass-average was computed thereafter.

Fig. 1 shows the evolution of mass-averaged lunar temperature for our 14 models. The general trend among the models show that temperature increase for the initial 200 years on account of impact-induced heating due to dependence on surface gravity. After that, a sharp decline for about 10000-20000 years on account of liquid-state convection followed by slow cooling by remnant convection and conduction. Fig. 1 starts at time t = 1.0 years when the Moon was already formed 1280 km in radius by then, making temperature different for the same T_{ini} at that time-point. For all the models, the averaged temperature rises to different levels at t = 200 years, i.e., at the end of accretion. Except in T_{ini} = 2000 K and h = 0.5, sharp decline due to rapid convection completes in nearly same time interval whereas it is double for the former. Furthermore, the final temperature at the end of 2 Myr is in a narrow band 1650-1700 K except for T_{ini} = 1700 K

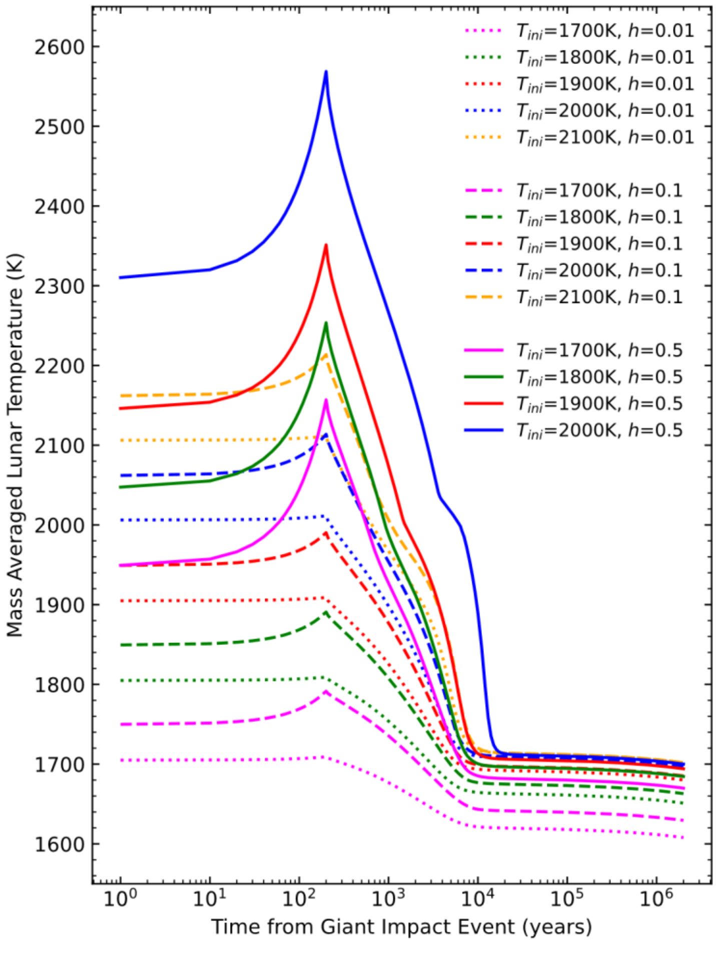

Figure 1: ***Mass-Averaged Lunar Temperature***. Different colours show the different values for initial temperature of accreting moonlets, T_{ini}. Different linestyles epresents distinct values for h-parameter. The figure startes at t=1.0 year, when the Moon was accreted to 1280 km.

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CONSTRAINING THE COMPOSITION OF THE PARENT PLANETESIMAL FOR THE ACAPULCOITE AND LODRANITE SUITE OF METEORITES - A TRACE ELEMENT APPROACH.

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In spite of the detailed petrogenetic history of the Acapulcoite-Lodranite (A-L) suite of meteorites, its original parent body composition still remains an unsettled question. In this study, we have compared the source composition of the A-L suite of meteorites to a host of chondritic compositions [1-6, 8-9] viz. ordinary (H) chondrites, Carbonaceous Bencubbinites (CB), Carbonaceous Renazzo (CR) and Kakangari (K) chondrites, as possible representatives of the source materials of the A-Lsuite using the trace element systematics for lithophile and siderophile elements to shortlist the most plausible parent body composition for the A-L suite of meteorites.

The A-L source material has undergone 1-4% partial melting without the loss of a metallic melt to give rise to the acapulcoites (A). Thus, a compositional homogeneity in terms of their bulk trace element concentration is expected between A and H, CB, CR and K chondrites. It is observed that the CI normalized values for refractory lithophiles (Al, Ca, V, La, Sm, Mg, Cr, Na and K) and siderophiles (Ru, Os, Ir, Fe, Co, Ni, Ga, As and Au) for K chondrites, H chondrites and CR chondrites lie within ±1σ of A. But, the CB chondrites show depletion in lithophiles (0.4±0.1×A) and enrichment in siderophiles (3.4±0.2×A) (Figure 1) as compared to acapulcoites, owing to which it is ruled out from the list of possible source materials for the A-L suite of meteorites. Despite the mineralogical and geochemical similarities of the H chondrites with ALs, isotopic signatures rule out the H-chondrites. On the other hand, the K chondrites satisfy both the trace element criterion with matching isotope signatures to the A-L suite. From the analysis of all chondritic compositions (H, CB, CR and K chondrites), the K chondrites offer best correlations with the A-Ls.

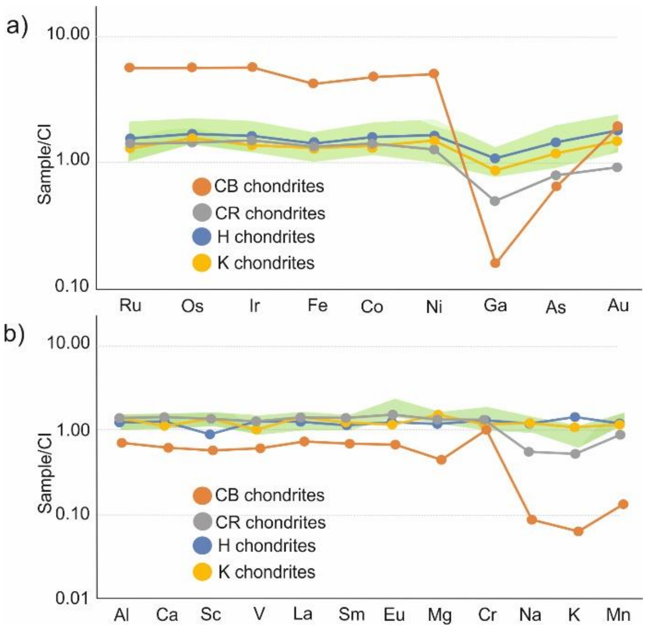

Figure 1: CI normalized plots showing element depletion patterns for H, CB, CR and K chondrites. The CI normalized values for ±1σ for acapulcoites is calculated, which marks the upper and lower limit, demarcated by green zone.

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Formation of carbonate-sulfide association in the martian meteorite ALH84001 and implications for the nature of water-rock interactions on the martian surface in the Noachian Era

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Introduction: The geologic evolution of Mars is characterized by a shift from wet to dry surface conditions due to the loss of the martian atmosphere, resulting from the loss of its magnetic field before 4 Ga [1]. In addition, the transition from neutral-pH fluids during Noachian to acidic fluids during Hesperian led to the formation of distinctive mineral assemblages in martian meteorites [2]. The martian meteorite, ALH 84001 is an orthopyroxenite cumulate rock, which represents the oldest igneous rock among the martian meteorites [3-5]. The crystallization age of this rock is estimated to be 4.091 ± 0.03 Ga based on Lu-Hf isotopic ratios, whereas the other martian meteorites formed later than 2.5 Ga [3]. Hence the secondary minerals formed in ALH 84001 records the conditions of aqueous alteration on Mars in the Noachian Era.

Research gap and significance of this study: The presence of phyllosilicates, sulfates in the SNC meteorites indicate oxidizing conditions on Mars, particularly during the Hesperian era following the loss of the martian atmosphere [6-7]. In contrast, the presence of Mg-Fe carbonates, sulfides, magnetites in ALH 84001 suggest reducing conditions on Mars before 4 Ga [2, 8]. The carbonates and sulfides are likely to have formed during hydrothermal alteration on Mars [9]. The enriched sulfur isotopic compositions of the pyrites in ALH 84001 have been explained by mixing of sulfur from the martian mantle with the isotopically heavy sulfur from the martian atmosphere [9-10]. This implies that the formation of these sulfides is likely to be related to impact driven hydrothermal alteration. The formation of the carbonates has also been attributed to hydrothermal alteration based on their oxygen isotopic compositions [11]. Hence, the isotopic compositions of the carbonates and sulfides along with their textural association suggests a possible genetic relationship.

Preliminary results and future work: Polished and gold-coated epoxy mounts of several pieces of ALH 84001 were studied using the JEOL JSM-IT300 SEM at Physical Research Laboratory. In addition to the orthopyroxenes, formed by igneous processes, this meteorite shows presence of veins of Na, Al-rich maskelynite, grains of chromites, Ca-phosphate, carbonates and sulfides. The concentrations of Mg, Fe and Ca in the carbonates show significant heterogeneity, suggesting these have been modified after their precipitation. The relationship of these zoned carbonates with the formation of the sulfides will be investigated in this study based on their elemental and isotopic compositions. The measurement of oxygen isotopes in the carbonates and sulfur isotopes in the coexisting sulfides would help us to better understand their possible formation from hydrothermal fluids.

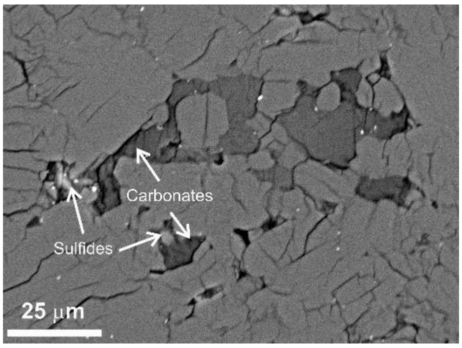

Fig. 1: Representative image of the association of carbonates and sulfides in ALH 84001

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Light noble gas study in Eucrites and diogenites

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HED is a group of differentiated meteorites believed to be derived from asteroid Vesta. Eucrites, howardites and diogenites represent different parts of Vesta and hence we can learn the geology and the processes that occurred deep within and on the surface of this asteroid. Eucrites and diogenites are achondrite meteorites and are the products of igneous processes. Eucrites are mafic igneous rocks of pyroxene plagioclase rich. They are likely derived from subsurface. Diogenites are coarse-grained monomict orthopyroxene-rich cumulates that likely formed from a fractionally crystallizing magma. Noble gas study is a tool to understand the history of volatile degassing from the interior and to constrain the types of precursor materials.

Neon shows widely differing isotopic compositions in different reservoirs. The isotopes of neon are used widely to understand the trapped component, cosmic ray exposure age and many other scientific aspects. The present study, which has been carried out to assess the abundance and isotopic composition of light noble gas neon in the Eucrites and diogenites based on bulk samples compiled from literature. The bulk dataset is used to identify the major trapped component in the HED parent body.

The three-isotope plot of ^{20}Ne/ ^{22}Ne vs. ^{21}Ne/^{22}Ne ratios of eucrites and diogenites indicates that all the samples are lie in the spallation component line and there is no evidence of solar wind gases. We than compare the concentrations of trapped noble gases with Chassigny, a representative of interior of Mars, carbonaceous chondrites, the accreting material of the parent bodies and MORB, the representative of interior of Earth.There is variation in abundances of neon gas, which is imprint of the different geological evolution of objects.