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THE COLÔNIA CRATER, A PROBABLE IMPACT STRUCTURE IN SOUTHEASTERN BRAZIL.

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About 35 km from São Paulo, near Colônia, there is a conspicuous ring feature, 3.64 km in diameter, centered at 23°52'S, 46°42'20"W, within Precambrian crystalline basement rocks, and defined by a hilly circular outer rim up to 125m higher than an inner alluvial plain presently occupied by a swamp. The crater is filled with organic-rich clayey sediments of Quaternary age. Seismic survey indicated a maximum depth of 450m to the Precambrian crystalline substratum within the crater [1], in accordance with magneto-telluric data [2] and inferences based on morphological parameters [3,4]. A zone with low seismic velocity at the top of the basement may suggest the presence of brecciated and/or fractured rocks [1]. Paleogene sediments are tectonically imbricated within Precambrian gneisses of the basement in a low-angle fault zone one kilometer southward from the structure and this situation could represent a part of the overturned rim. The presence of higher altitudes in the southwestern part of the rim suggests a body trajectory from northeast before the presumable shock.

The hypothesis that this feature is a probable impact structure has long been postulated, ever since the first studies carried out in the area [5]. Further studies based on morphological parameters [3,4] and geophysical data [1, 2] have reinforced this idea. Alternative hypotheses to the origin of the Colônia crater, such as sinkhole, structural interference pattern, intrusion and phreatomagmatic structure related to a kimberlite, among others, may be rejected, respectively, by the absence of carbonate rocks in the region, the persistence of the ENE structural trend of the basement, the lack of structures and/or minor intrusive bodies (dikes, sills) that should be associated with such intrusions, and the excessively unusually large dimension for a kimberlite pipe. Despite the above arguments, no direct evidence of an impact, such as shock metamorphism, has yet been observed in the area, most likely due to the intense weathering. The peculiar circular shape and the typical depth/diameter ratio [3], as well as the semicircular outcrop patterns of the Paleogene sedimentary rocks along the southern and southeastern inner part of the rim, are the main indicators of a impact structure. The lack of convincing proof of endogenous process also reinforces this hypothesis.

Nowadays, the Colônia crater is a probable impact structure with ejecta removed, rim partly preserved, although deeply eroded, and crater-fill products preserved. Based on palynological data [6,7], the impact age is probably Neogene.

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METAL-SILICATE PARTITIONING OF VOLATILE, SIDEROPHILE ELEMENTS: NEW RESULTS FOR Sb AND As.

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Introduction: Antimony and As are siderophile elements that also exhibit volatile behavior. Their depletion in planetary mantles can thus be due to segregation of metal during core formation [1], or volatility-related depletion in the precursor materials [2]. This study builds on our previous work [3] and other studies [4] to understand the effect of temperature, pressure, oxygen fugacity and composition on the partitioning of Sb and As between metal and silicate melt. The results will be used to interpret depletions of Sb and As in the mantles of the Earth, Moon, Mars and the eucrite parent body (or 4 Vesta).

Experimental: Metal-silicate partition coefficients, D (wt% in metal / wt% in glass), were determined on two sets of experiments. One set was done at 1 bar, 1260 ˚C and 2.4 log fO_2 units above the iron-wüstite (IW) buffer, in evacuated silica tubes. Alumina crucibles containing Sb-doped basalt and mixtures of Fe-Ni-S metal were sealed into the silica tubes, held in the hotspot for up to 7 days, and then quenched. These runs were reported by [5], but Sb and As concentrations in the silicate were too low to detect by electron microprobe analysis. A second set of runs was done in a piston cylinder apparatus, at 10 kbar, 1500 ˚C, and just below IW, with variable silicate melt composition. Mixtures of Sb and silicate were contained in an iron capsule. Quenched run products from both series were mounted in epoxy, cut and polished.

Analytical: Metal was analyzed for Fe, Ni and Sb, and glass was analyzed for major elements at NASA-JSC using a Cameca SX-100 electron microprobe. Antimony and As were analyzed in glasses using a CETAC LSX-200 laser ablation peripheral with a magnetic sector ICP mass spectrometer, the Finnigan Element™, at the University of Chicago [6]. The NIST reference glass SRM 612 was used as a standard for measurements of ^{57}Fe, ^{69}Ga, ^{75}As, and ^{121}Sb. Locations to be analyzed were selected from polished sections of the experimental run products, using backscattered electron images to avoid interfering metal blebs or particles in the glass. Nevertheless, there was evidence in a few analyses (~10%) that small metal particles had been ablated in addition to the glass; these data were discarded. The dimensions of each laser ablation pit ranged from 100 to 150 m in diameter and ~15 to 25 m deep. The laser was operated at 10 Hz for 3 to 5 seconds for each analysis, and data collection from the mass spectrometer continued for ~20 sec as the signal reached a maximum and decayed away. During data collection the mass spectrometer was swept repeatedly over the mass range of interest with a period of about 0.5 sec.

Results: Concentrations of Sb in the experimental glasses ranged from 17 ppb to 1.35 ppm, corresponding to D(Sb) of 1700 to 240,000. Arsenic concentrations in three experiments range from 70 to 170 ppb, resulting in D(As) values of 32000 to 47000. These high D values indicate that Sb and As are strongly siderophile, at odds with the relatively moderate depletion of Sb and As observed in the terrestrial mantle [7,8]. However, the effects of pressure, silicate melt composition, and variable metal activity coefficients in the Fe-Ni-Sb system [5] will have to be evaluated before application of these results may be made to planetary differentiation.

(Research supported by NASA grants NAGW-12795 to MJD and NAG5-13133 to MH.)

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THE CRATER IN MESETA DE LA BARDA NEGRA, NEUQUEN, ARGENTINA: A NEW METEORITE IMPACT SITE?

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This work was funded by The Planetary Society, CA, USA.

Introduction: Recent efforts to indentify additional impact craters in Argentina, making use of LANDSAT imagery and aerial photographs, have identified a possible new example in this category in Neuquen Province, Patagonia: The Crater in Meseta de la Barda Negra (39º 10'S 69º53'W).
From the beginning of the search, Barda Negra's crater was evidently one of the most promising sites under study.
In the LANDSAT satellite images at the scale 1:250,000 and 1:100,000 it was visible as a 1.5 kilometers isolated crater in the middle of a large brown basaltic plateau. When aerial photographs of the area were obtained from the Instituto Geografico Militar (IGM) they proved this crater was in fact very similar to Barringer's meteor crater in Arizona, USA. The crater even resembles Barringer's in small details as the little squareness of it shape.
It has a 20- 50 meters raised rim. In the aerial photos there are also visible some 50-60 meters wide boulders resting on the crater's rims and all around it. Probably those blocks are parts of an ejecta blanket. The crater has been described as a "salitral" (= salitrous basin) containing blocks, conglomerates and sands in The Geologic Map of the Province and in the geological description by the SEGEMAR (=Geological Survey of Argentina)[1]. This is in no conflict with the hypothesis of a meteorite impact.
Probably this depression is not a doline. It has a raised rim and dolines never have raised rims.
Barda Negra's crater can not be a volcanic caldera. Its morphology is quite different, e.g. has a raised rim and there are no visible lava floods coming from the crater itself. The lava in the surrounding plateau was erupted from ground fissures during the Miocene (radiometric ages for the basalt : 14-10 Ma). The crater is located on those older lava floods. The Miocenic lavas came first, then the crater: this is a fact. The age of Barda Negra's crater is estimated in less than 10 Ma.
Barda Negra's crater could be a maar**.** Maars usually come in clusters[2]. However, Barda Negra's crater is an isolated feature alone in the basaltic plateau. No similar crater exists in the whole plateau. The hypothesis of Barda Negra as a maar can not be completely rejected at the present stage of investigation but so far it seems to be quite unlikely.
If this crater is in fact a new meteorite impact then it would be very important and interesting as the second simple-type impact crater in basaltic rocks on Earth. To date, Lonar Lake's crater in India, (1.8 km.), is the only terrestrial impact in basalt known in the World [3].
Further investigation of this interesting crater is in progress.

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POTENTIAL IMPACT SITES IN NORTHERN ARGENTINA.

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Introduction: The Northern part of Argentina is composed of 10 Provinces and has a total surface of 849,523 square kilometers.
A search for potential new impact sites in this area was performed by the author through the examination of 32 color LANDSAT satellite images (1:250,000 - resolution = 250 meters) at the Instituto Geografico Militar (IGM) of Buenos Aires city.
When a potential candidate was found, a more detailed study of images was done. LANDSAT color images at the scale of 1:100,000 and aerial photographs at the scale of 1: 60,000 (IGM) were then consulted.
Sites identified are described below. The co-ordinates given are those of the upper left and lower right corners of a rectangle enclosing the site. A review of the available published geologic information of each site was performed too.
Further evaluation of the proposed sites is in progress.
SALTA PROVINCE. 1) Salar del Hombre Muerto, Near Sierra de los Ratones, Puna. (67º 00' W 25º 10'S/ 66º 50' W 25º 15'S).
Possible 10 small (90 – 250 meters) fresh simple craters in Quaternary-Recent aluvional cone of sedimentary deposits.
These crateres were discovered by geologist Dr. Ricardo N. Alonso (Universidad Nacional de Salta, Salta).
Diameter of the largest: 250 meters. Craters are widespread in an oval area of 5 x 4.5 kilometers.
These craters are not located on a tectonic fault. They are not doline features. Most probably they are the result of a meteorite shower.
Their age is estimated in less than 0.5 Ma.
Curiously, none of them have been reported in the published geological reports of the area, [1,2].
CATAMARCA PROVINCE. 1) A site located 19 km. NE of Monte Piscis. (68º 44' W 27º 44'S / 68º 35'W 27º 45'S).
Possible eroded simple crater in fluvial pleistocene's sedimentary terrains. Diameter: 400 meters.
CHACO PROVINCE. 1)Presidencia de la Plaza-La Escondida. (59º 45' W 27º 08'S / 59º 30' W 27º 17'S). Possible 4 simple craters located in a Y shape configuration.
Diameters : 2.4 , 2.0 , 1.5 , 1.2 km.
Dense vegetation covers the area around.
The inside of each crater-like feature is free of vegetation.
The area is composed of loessoid Pleistocene's sediments,[3].
SANTA FE PROVINCE. 1) Arroyo Las Garzas. (59º 33' W 28º 42' S/ 59º 28' W 28º 45'S). Possible eroded simple crater.
Perfect semi circular structure. Possible raised rim.
Dense vegetation covers the area around this site but not its inside surface. Diameter: 1.5 km.. This area is covered by fluvial sandy-clay sediments of Pleistiocene age.The crater is probably younger than 0.1 Ma.[3].

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RIO VICHADA: A POSSIBLE 50 KM WIDE IMPACT STRUCTURE IN COLOMBIA, SOUTH AMERICA.

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Introduction:
The Republic of Colombia in South America has a total surface of 1,138,914 square kilometers and as 2004 no meteorite impact sites have been reported in this Latin-American nation.
The geology of Colombia is dominated by the Tertiary-Quaternary mountains, volcanoes and ridges of the Andes in the West and by the tropical sedimentary basins in the East.
A possible new large impact structure in this country was discovered by the examination of color Landsat satellite images (NASA's John C. Stennis Space Center, USA, resolution = 200 meters).
Proposed name: **Rio Vichada Structure .**
Location: near Maleza city, Comisaria Vichada Norte**,** Colombia (4º30'N – 69º15'W); Diameter : 50 Km.
This area is part of the Llanos Basin and it is covered of tropical rainforest.
The structure has the typical multi-ring shape configuration of large impact structures: a central peak ring impact structure .
The central core consists of a ring about 30 Km. in diameter which surrounds a central depression of circular shape and 20 Km. in diameter. In this innermost region, there is a basin, the relief is quite smooth and it is the deepest part of the structure. The central basin is covered by jungle and it is surrounded by 2 concentric rings of low hills (no more than 200 meters high each). The outermost ring has 50 Km in diameter and in the South, the Vichada River flows around it in a perfect semi-circle following the external limits of this outer ring of hills. This flow around feature of the river is very interesting and anomalous.
The geology of the area is not known in very detail.
Rocks exposed in the Rio Vichada structure includes Precambrian metasedimentary and granitic rocks with an extensive sedimentary cover. The sedimentary cover is composed by an heterogeneous sequence of conglomerates, sandstones and clays. They are dated Oligocene to Pliocene and they cover the Precambric crystalline basement rocks. The structure is not a batolite.
This circular structure is probably older than 30 Ma.
Further investigation of this interesting site is in progress.
Acknowledgements: This work was funded by The Planetary Society, Pasadena, CA, USA. To Dr. Adriana C. Ocampo (ESA) for her valuable advice and help.
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A NEW MICROMETEORITE COLLECTION FROM ANTARCTICA AND ITS PRELIMINARY CHARACTERIZATION BY MAGNETIC METHODS.

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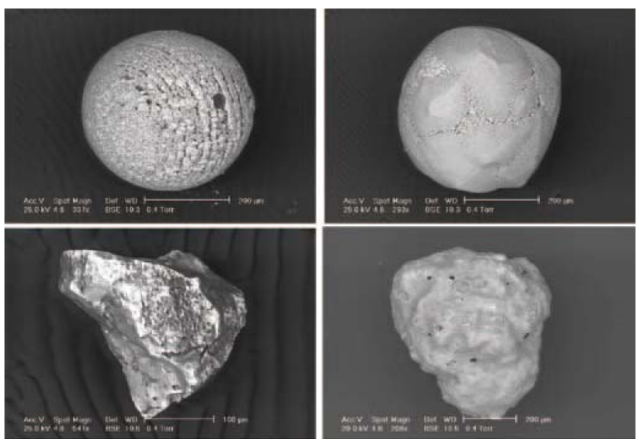
Introduction: In December 2003, the meteorite recovery party of the XIX PNRA expedition collected by magnetic extraction thousands of micrometeorites in the 100-800 µm size range in an aeolian deposit at the top of Frontier Mountain (northern Victoria Land, Antartica), a few Myr old glacially eroded surface. This discovery, located by the use of a magnetic gradiometer, offered a good opportunity to test and develop a magnetic classification procedure for these objects, in parallel to "classical" mineralogical and geochemical characterization.

After SEM imaging (see figure), magnetic measurements were performed on individual particles with diameter above 400 µm. EDAX detectable Ni and Cr contents of the particles confirm their extraterrestrial origin. Hysteresis loop parameters, magnetic susceptibility and demagnetization of isothermal remanence at saturation were obtained on single particles.



Backscattered SEM images of four micrometeorites collected at Frontier Mountain. Scale bar is 200 µm, 100 µm for lower left picture.

Preliminary results: The magnetic measurements allow the discrimination of at least four distinct populations of particles. The largest population contain about 10 wt. % magnetite. Another population contains around 2 w% magnetite in much smaller grains, likely concentrated in the external crust. The lower left particle in figure is dominantly made of Fe,Ni metal and a C-bearing phase.

Perspectives: Microprobe and noble gas analyses will be performed on these micrometeorites. The results will be compared to the magnetic classification in order to evaluate its accuracy and usefulness. If validated, the non-destructive and rapid magnetic classification will be applied to a large number of micrometeorites in order to compare the Frontier Mountain collection with other micrometeorite collections (e.g. the South Pole [1] or the Cap Prudhomme [2] collections).

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MÖSSBAUER INVESTIGATION OF 'BOUNCE ROCK' AT MERIDIANI PLANUM ON MARS – INDICATIONS FOR THE FIRST SHERGOTTITE ON MARS.

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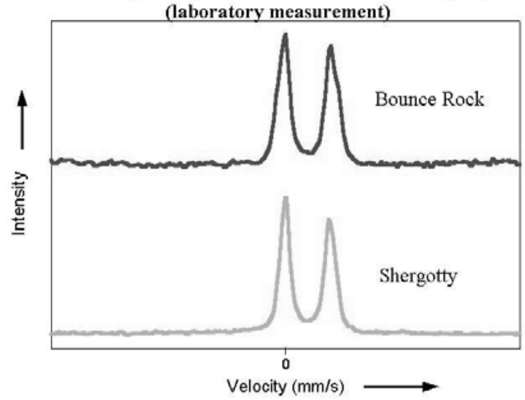
Introduction: During the Mars-Exploration-Rover (MER) 2003 Mission, an isolated rock lying on top of the plains at Meridiani Planum was analyzed by the Athena instrument suite. Remote sensing instruments [1] noticed its distinct appearance. Several areas on the untreated rock surface and one that was ground with the Rock Abrasion Tool (RAT) [1] were analyzed by the Mössbauer (MB) spectrometer Mimos II [2], the Microscopic Imager [1], and Alpha Particle X-ray Spectrometer (APXS) [3]. Results of all analyses revealed a close compositional relationship of this rock with known basaltic shergottites.

MIMOS II Mössbauer results: All seven MB spectra obtained on different places on Bounce Rock are nearly identical, indicating a rather homogeneous mineralogical composition. In the figure below the spectrum obtained at the Bounce Rock target named Fips-2 is shown, as well as one of our laboratory spectrum from Shergotty. Just by visual comparison it can be seen that they are very similar. The MB spectrum for EETA79001, lithology B, also is very similar in MB parameters to the Bounce Rock spectra. The mineralogy identified by Mössbauer spectroscopy is strongly pyroxene. This result is supported by the APXS data [4].

Mössbauer spectra of Bounce Rock (Meridiani Planum, sol 67) and the SNC meteorite Shergotty (laboratory measurement)



Conclusion: The Mössbauer mineralogy of Bounce Rock is very similar to basaltic shergottites, in particular to Shergotty, but also to EETA79001, lithology B. This finding as well as the results from APXS [4] support the evidence that Martian meteorites came from Mars.

Funded by the German Space Agency DLR and NASA, USA.

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THE JARAU STRUCTURE, SOUTHERN BRAZIL: AN ASTROBLEM?

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Introduction: In the late 60's an anomalous drainage with an eliptic pattern was identified in the Cerro do Jarau region, a circular feature with 10 km of diameter, located in the southwest part of Rio Grande do Sul State, Brazil. It was interpreted as a dome of tectonic origin formed after the deposition of Botucatu Formation (Latter Jurassic) and before the basaltic flows of Serra Geral Formation (Early Cretaceous) [1].

In the 80's an impact origin was sugested based on the analysis and interpretation of remote sensing products (aerial photographs 1:10.000, orbital images of medium spatial and spectral resolution of RADAR and LANDSAT-MSS) and field checking [2], [3], [4]. This hypothesis was based on four mapped morphological units: the isocline crests and hogbacks; the Nhanduvai Basin Depression; mesas and cuestas of Quaraí-Mirim Basin; and alluvial plains. The isocline crests and hogbacks, one of most important units, have a semi circular shape and correspond to fault lines with a drainage of a centrifugal radial pattern. Furthermore, the Nhanduvai Basin Depression (the central portion of the area) is surrounded by brecciated and silicified sandstones, showing a drainage with a centripetal radial pattern. However, until the present moment there is no cientific evidence that supports an impact origin.

Current Investigation: Recently, new studies have been reconducted in this area in order to find these evidences. The investigation has been carried out with the following approach: 1) analysis and interpretation of ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) remote sensing products with both high spacial and spectral resolution in 14 spectral bands from visible to thermal infrared region of eletromagnetic spectrum; 2) detailed geological mapping; 3) petrographic analysis to look for shock metamorphic features; 4) geophysical profiling (magnetics and gravity); and 5) thermocronology by apatite fission track analysis.

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THE DISTRIBUTION OF MINOR AND TRACE ELEMENTS WITHIN PRETERRESTRIAL ALTERATION ASSEMBLAGES IN THE LAFAYETTE MARTIAN METEORITE.

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Introduction: While the Martian origin of carbonate and silicate alterations found in the nakhlite Lafayette is well established [1,2], the details of their mechanism of formation are still poorly constrained. However, it seems certain that both the silicate assemblage and carbonates result from low temperature secondary mineralization [2-4]. We have examined olivine-hosted alteration veinlets comprised of amorphous silicates, poorly crystalline clay minerals, and Fe-rich ankerite by Time of Flight-Secondary Ion Mass Spectrometry (ToF-SIMS). In doing so, we hope to constrain the nature and number of fluids involved in near-surface alteration of the Martian crust.

Method: A submicron (~300 nm) primary beam of Ga^+ ions was used for the ToF-SIMS analyses. All ions of positive polarity were collected virtually simultaneously. Particular interest was paid to the following 3 groups of elements: alkali metals (Li, Na, K, Rb), alkaline earth metals (Sr, Ba), and 1st row transition metals (Sc, Ti, V, Mn, Co, Ni, Cu).

Results: To date, two veinlets containing a silicate assemblage (+carbonate) have been analyzed. Secondary ion images reveal distinct compositional zonation between alteration minerals as well as within secondary phases. From the central most portion of the veinlets outwards the veinlets typically contain: 1) Si-rich amorphous silicate, 2) Fe-rich amorphous silicate, 3) poorly crystalline clays, and, 4) +/- carbonate [5]. Our preliminary SIMS data (expressed as ppm by weight) for the silicate-bearing phases reveal the following:

Alkali metals. Na, K, and Rb all covary and are most abundant in clays (e.g., Rb: 25-40), followed by the Fe-rich$_{amp}$ phase (Rb: 20), and the Si-rich$_{amp}$ phase (Rb: 3). Li, however, is lower in the Fe-rich$_{amp}$ phase (~8) relative to the Si-rich$_{amp}$ phase (15) and the clays (10-18).

1st row transition metals. Sc, Ti, V, Cr, Mn, and Cr are enriched in clays relative to both amorphous phases. Conversely, Ni, and to a lesser extent Co and Cu, are more abundant in the amorphous phases compared to the clays.

Alkaline earth metals. Overall, Sr in the veinlets is concentrated in carbonate, and otherwise, is nearly evenly distributed among silicate phases. The concentration of Ba in clay exhibits a rather limited range (190-300), while the carbonate appears to differ greatly in Ba concentration as indicated by the secondary ion images.

Discussion: These results represent the first spatially-resolved trace element data for such a complex low-temperature alteration assemblage formed beneath the surface of Mars. The available data are consistent with the notion of multiple pulses of fluid alteration, however, we are still searching for unambiguous chemical signatures that can identify specific fluid alteration mechanisms (e.g., low-T mobilization of surface evaporites or hydrothermal processes).

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LIMITED MELTING AND CRYSTALLIZATION FOLLOWING FINAL CHONDRULE HEATING: EVIDENCE FROM RELICT GRAINS. Alan E. Rubin, Inst. of Geophysics, UCLA, Los Angeles, CA 90095-1567, USA. (aerubin@ucla.edu)

Although some workers have modeled porphyritic chondrules as having experienced high degrees of melting during a single heating episode, studies of narrow overgrowths on relict grains in porphyritic chondrules have shown that this model is untenable.

Type-I chondrules – High-FeO foreign relicts with low-FeO overgrowths: Relict "dusty olivine" grains in type-I chondrules consist of olivine cores with numerous metallic Fe grains formed by solid-state reduction of FeO. Most dusty cores are rimmed by metal-free ~5-µm-thick olivine overgrowths similar in composition to non-dusty grains in the host chondrule. The calculated, pre-reduction compositions of the dusty olivines are Fa~8, consistent with derivation from foreign ferroan material, i.e., type-II chondrules. The nature of these overgrowths implies that final chondrule heating involved limited melting and crystallization.

Type-II chondrules – Low-FeO foreign relicts with high-FeO overgrowths: Ferroan olivine overgrowths on relict low-FeO olivine grains in type-II chondrules are generally ~5 µm thick. The mineral and O-isotopic compositions of the relict grains indicate that they were derived from foreign magnesian material, i.e., disrupted type-I chondrules. By analogy with the history inferred above for type-I chondrules, melting and crystallization were limited during the final chondrule melting event.

Semarkona chondrule D8n – High-FeO relicts with foreign low-FeO overgrowths: Olivine phenocrysts in this 1300×1900 µm PO chondrule contain curvilinear trails of numerous aligned 1-2-µm-diameter blebs of low-Ni metallic Fe. The trails trace partially healed fractures. A 2-8-µm-thick band of Fa3-5 olivine flanks individual trails of metal grains; outside the bands, the olivine core has a composition of Fa7-10. Each core is rimmed by a 3-5-µm-thick overgrowth of Fa1-2 olivine. The perimeter of chondrule D8n consists of a 45-140-µm-wide remelted zone containing low-FeO olivine (Fa1), low-FeO low-Ca pyroxene, minor Ca pyroxene, and abundant kamacite, sulfide and magnetite. A 260-540-µm-thick lump consisting of kamacite and troilite rimmed by magnetite occurs at the chondrule margin.

It seems likely that the precursor of D8n was a type-II chondrule that was coated with foreign material consisting of low-FeO mafic silicates, metallic Fe-Ni, sulfide, and, possibly, reduced carbon. The conjoined object was heated; the metal-sulfide and low-FeO mafics at the chondrule margin melted. The melt wetted the primary chondrule and penetrated the interior; pyroxene and anorthitic mesostasis also melted and the Fa7-10 olivine phenocrysts were partly resorbed. During this event, a reducing fluid penetrated fractures in the olivine and caused solid-state reduction via a reaction such as Fe_2SiO_4 + C $FeSiO_3$ + Fe + CO. The $FeSiO_3$ was transported to nearby crystallizing low-Ca pyroxene. During the heating event, much more low-FeO olivine was melted than ferroan olivine resorbed; this resulted in low-FeO olivine crystallizing as overgrowths on ferroan olivine cores.

This study confirms that both low-FeO and high-FeO varieties of relict-grain-bearing porphyritic chondrules experienced only limited melting during final heating. If final chondrule heating events were not atypical, porphyritic chondrules must have formed by multiple melting events, each event involving only limited melting and crystallization. We can infer that coarse phenocrysts in type-II chondrules did not form during a single episode of crystallization; they reflect a more complex history.

MAGNESIUM ISOTOPE MASS FRACTIONATION OF FINE-GRAINED INCLUSIONS FROM CV3 METEORITES

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Introduction: Although excesses of ^{26}Mg from the decay of ^{26}Al have been well-documented in CAIs, there has been less focus on the mass fractionation of Mg in refractory inclusions. Clayton et al. (1988) showed that the degree of Mg isotope fractionation in CAIs varies by >10 per mil/amu [1]. While a subset of CAIs are isotopically light with respect to magnesium isotopes, most CAIs measured are isotopically heavy compared to terrestrial values, with FUN CAIs and hibonite-bearing CAIs showing the highest degrees of fractionation [1,2]. Recent high precision MC- ICP-MS data have confirmed that Mg in igneous CAIs is typically isotopically heavy, and often show heterogeneities of a few ‰/amu between the cores and rims [3,4,5,6].

The majority of work to date including the recent ICP-MS studies have focused on igneous, coarse grained, CAIs. We have expanded this study to include three fluffy, fine-grained CAIs, that have never experienced extensive melting, from the CV3 meteorites Allende and Vigarano, in order to clarify the relationship between these inclusion types. Measurements were made at UCLA by LA-MC- ICP-MS with a precision of ~0.2‰.

Samples and results: Vigarano V9 is a fluffy Type A CAI, 3mm in maximum dimension, that is very irregular in shape. It is composed of spinel nodules surrounded by gehlenitic melilite and each nodule has a thick (up to 10 m) forsterite rim. The magnesium isotope composition varies from ^{25}Mg = -0.1 to -1.0 ‰, with a mean value of –0.6 ‰. The olivine rims appear to be isotopically lighter than the cores.

Vigarano V10 is a rounded CAI 1.5mm across composed of spinel intergrown with melilite and surrounded by a diopside rim. Part of the inclusion is highly fragmented and porous. The ^{25}Mg varied between –2.2 to +0.1‰, with a mean value of –1.1‰. The non-porous part of the inclusion is isotopically heavier than the porous part.

Allende MRS5 is an unzoned, fine-grained, irregularly shaped melilite rich inclusion composed of melilite and spinel nodules surrounded by a thin diopside rim, with minor secondary nepheline and andradite. The ^{25}Mg varied between –1.2 to 0.0‰, with a mean of –0.6‰.

The 3 CAIs all contained ^{26}Mg* consistent with ^{26}Al decay.

Discussion: Each of the fine-grained inclusions analysed to date exhibited some isotopic heterogeneity, of the order of 1-2 ‰/amu, and all are isotopically lighter than bulk chondrites. In the latter respect the inclusions differ from most previously analysed, isotopically heavy coarse-grained CAIs. The isotopic difference is unlikely to have been caused by evaporative loss of Mg during melting of fine-grained CAIs to form compact CAIs, since the bulk Mg abundance is not systematically lower in igneous CAIs. Instead, some fine-grained CAIs may have formed by recondensation of previously evaporated material, as also implied by their typically Group II REE patterns [e.g. 7].

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PRODUCTION OF SHORT-LIVED NUCLIDES BY MAGNETIC FLARING IN THE EARLY SOLAR SYSTEM.

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Introduction: Presence of ^{7}Be in the early solar system [1] indicates intense magnetic flaring activity associated with the proto-sun or its accretion disc. Continuing our attempts to numerically simulate evolution of proto-CAIs and their irradiation in the reconnection ring [2], we have included ^{7}Be production.

Methodology: Simulations were extended for 2 decades and were refined by incorporating constant mass accretion rates (M_t; monitored @ 100 days) by the reconnection ring. In addition to the flares with Lx~$10^{29\text{-}32}$ ergs/s [2], we irradiated grains throughout the reconnection ring by flares with Lx~$10^{27\text{-}28}$ ergs/s for timescales comparable to $10^{29\text{-}32}$ ergs/s flares. Finally all the grains were thermally processed, *homogenized* and irradiated at the end of simulations by 'superflares' [3] with Lx~10^{33} ergs/s for couple of hours (~1 hour for Lx~10^{34} ergs/s flare). In addition to previous grain coagulation models [2], we tried models '*var'*, where small sized grains are preferentially 'accreted' by larger.

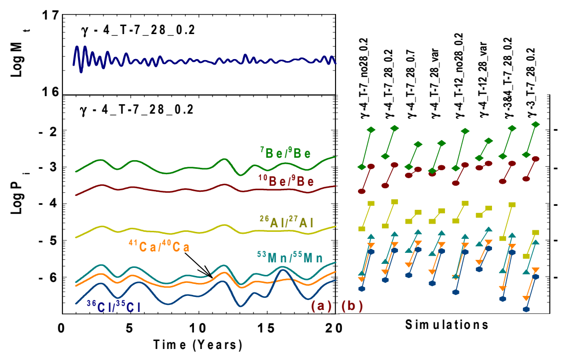

Fig.1. a) Evolution of the average production rates 'P_i' of radioisotopes & M_t for the model [-4*(dE/dN~E⁻)*_T-7*(Flare timescales: 1-7 hours/day)*_28(*Lx~$10^{27\text{-}28}$ ergs/s. flares included*)_0.2*(Coagulation %)*]. b) Results for the various models. Lower and the upper ends of the lines represent average production rates without and with 'superflare' contributions, respectively, at the end of simulations. ^{3}He/H~0.3.

Results and Discussions: Average production rates remain constant over time except for small deviations essentially due to variations in M_t (fig. 1). The inferred spread in the production rates among the various processed grains are at least two orders of magnitude and can yield canonical values for the radioisotopes only if we anticipate 'superflares' that can thermally re-process and homogenize their compositions at the end of their processing in the reconnection ring. Superflares may also be essential for the required production of ^{7}Be. In fact these intense flares could alone produce all the radioisotopes without significant contribution from the x-wind scenario thereby avoiding close encounters of CAIs and chondrules with the proto-sun. These intense flaring events, generally associated with accretion disc [3], could be responsible for all the irradiation effects observed in meteorites and the thermal processing of CAIs and chondrules in accretion disc. ^{41}Ca production is high in impulsive flare simulations and its observed abundances would require late-stage secondary alterations of CAIs. In general, all the gradual/impulsive flare simulations produce ^{9,10}Be, ^{53}Mn, ^{36}Cl. Other than stellar nucleosynthesis (essential for ^{60}Fe), ^{26}Al & ^{41}Ca production require impulsive flares.

***Acknowledgements**:* This work is supported by ISRO (PLANEX) grant.

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PROTOPLANETARY PYROTECHNICS: LIGHTING UP THE CONUNDRUM OF CHONDRULE CHRONOLOGY.
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Introduction: If chondrules and CAIs were formed in the solar nebula, as is widely supposed, then why do they differ in age? Why are chondrules generally between 1.5 and 2.5 Myr younger than CAIs [1]? The age difference is a conundrum that frustrates efforts to reconstruct the first few 'dark years' of the circum-solar disk [1,2]. Here I explore the idea that during these early years planetesimals suffered rapid meltdown, and periodically burst on collision into cascades of molten droplets (chondrules) that were lofted into the nebula.

Meltdown: An excellent correlation exists between the Al-Mg ages and the Pb-Pb ages of CAIs, chondrules, mineral grains in Ste Marguerite, and mineral grains in Forest Vale [3]. The correlation not only shows that the Al-Mg system works as a chronometer but also confirms that $^{26}Al/^{27}Al$ was equal to 5 x10^{-5} widely throughout the primitive dust of the solar nebula when CAIs were formed. At this time each gram of dry primitive dust contained about 9 kJ of radioactive energy due to its ^{26}Al. ^{60}Fe possibly contributed a further 1.5 kJ per gram of dust [4]. With over 10 kJ/g available, and with only 1.6 kJ/g needed to heat cold (250K) dust to melting, it follows that the insulated interiors of planetesimals that formed from dry dust during the first 1.5 to 2 Myr after CAIs had no choice but to melt. 'Melting' is taken here as the change from a rigid to cohesionless partial melt at about 1725K. The interior of a planetesimal that accreted at the time of CAI formation would have melted by 0.3 Myr and the molten centre would probably have expanded outwards due to excess radiogenic heat as a turbulently convecting slurry of molten silicate, metal and olivine crystals for a further 2 Myr. Planetesimals that accreted at about 2 Myr after CAIs would eventually have melted at about 5 Myr. The inevitable collisions between molten planetesimals during the first 2 or 3 Myr must have yielded chondrules in abundance!

Chondrules and CAIs: Where are the chondrules that formed before 1.5 Myr? They presumably accreted to new generations of planetesimals and, with ^{26}Al still very active, were destroyed by meltdown. Why were chondrules produced only rarely after 3 Myr? Perhaps by this time, with radioactivity now very weak, planetesimals were becoming thickly coated by chondritic debris which could no longer melt: it merely became reworked by impact. In this light chondritic parent bodies are not first generation planetesimals; they must have accreted after 2 Myr, i.e. after magmatic parent bodies accreted.

How did CAIs survive? According to [5] CAIs with excess ^{26}Mg never got hotter than about 650°C, yet they were resident in planetesimals from the outset. Perhaps their host planetesimals were over endowed with grains of water ice. A massive 3.2 kJ/g is consumed in changing ice at 250K to water vapour at 400K. A planetesimal with 5 parts ice to 2 parts dry dust could never melt. On this basis, chondrules as old as 0.3 Myr should survive too. Perhaps they do, but have not yet been identified. Two 0.7 Myr chondrules have been found so far [1]. Who knows, CAIs may also be a product of overheated planetesimals [6], particularly if lunar sized runaways existed 200 kyr. *before* CAI formation?

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EXTRAPOLATING LABORATORY EXPERIMENTS TO THE 'REAL WORLD'

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Laboratory impact experiments provide the only way to witness the complexities of the impact process through all temporal and spatial scales. As informative and compelling as such experiments might seem, they cannot be used to simulate directly the terrestrial and planetary record. Rather, laboratory-scale experiments can be used to isolate processes and control independent variables. Theory or full-scale examples then allow assessing and testing extrapolations. For example, loose particulate targets (e.g., sand) to simulate the post-shock conditions and the role of gravity in limiting growth. But the early-time transfer of energy and momentum will be very different from impacts at much higher velocities and larger scales.

Oblique impacts, however, map time into space by exposing successive stages of the cratering process that are preserved in the planetary impact record. Such stages are successively overprinted during near-vertical impacts. This strategy reveals that the impactor trajectory may not be lost in the geologic record. It is expressed by: (1) multiple stages of ejection (jetting, downrange-moving vapor, uprange plume, excavation flow); (2) shock asymmetries (crater shape, structural elements, and ejecta distributions); and (3) even impactor size and direction (central uplift, offset, and shape of central peak complex). With increasing crater size and decreasing impact angle, the impactor becomes more evident as the coupling stage comprises an increasing fraction of the crater excavation. The "basin-scaling paradox" for oblique impacts underscores this point: the impactor diameter may be only 1/3 to 1/5 of the transient basin diameter if current scaling relations are applied. This contrasts with laboratory-scale impacts into sand where the impactor is only 1/20 to 1/50 the size of the final crater. Since peak pressures are also reduced during oblique impacts, expressions of early-stage processes (e.g., impactor failure and structural asymmetries) may be preserved.

New experimental strategies and diagnostic techniques using the NASA Ames Vertical Gun Range now allow probing time-resolved details in the transfer of energy and momentum. These techniques include high-speed spectroscopy, direct shock measurements, nanosecond photometry, and 3-Dimensional Particle Imaging Velocimetry, and mega-frame imaging. The challenge is not just calibrating computational codes but also to recognize key signatures in the geologic record. But in 2005, the first "live" collision experiment will allow probing below a comet (NASA's Deep Impact Mission) and exploring the consequences of increasing velocities by 40%, increasing mass by three-orders-of-magnitude, and decreasing gravity by four-orders-of-magnitude.

LATE CENOZOIC IMPACT RECORD IN THE ARGENTINE PAMPAS SEDIMENTS

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The vast loess-like sediments of Argentina provide a unique depositional and lithologic environment for generating and preserving impact-generated glasses (1,2,3). Such glasses are commonly called "escorias" and can easily be misinterpreted as anthropogenic slag or even volcanic glass. Their stratigraphic setting, age (radiometric and magnetostratigraphic), and petrographic indicators of transient high temperatures, however, all indicate their origin by impact. At least 7 different layers of impact glass are now recognized including Holocene (6 ± 2 ka), Pleistocene (114 ± 26 ka, 230 ± 30 ka, and 445 ± 21 ka), Pliocene (3.27 ± 0.08 Ma), and late Miocene (5.33 ± 0.05 and 9.23 ± 0.09 Ma) in age based on $^{40}Ar/^{39}Ar$ dating (3). The glass fraction ranges from clast free (< 109 vol.) to clast rich (80% vol.) with unmelted clasts are predominantly quartz grains and feldspars. Although they could be classified as impact-melt breccias, their unique appearance may warrant a new term "pampasites" reflecting distinctive glasses created by melting of porous loess substrates. In this case, embedded clasts are simply minerals undergoing various degrees of melting from the loessoid sediments.

In addition to evidence for rapid extreme heating and quenching (e.g. baddeleyite, diaplectic glass, and ß cristobalite), these glasses contain geochemical signatures of materials from depth. Such signatures include elevated relative abundances of MgO, CaO, Na_2O, and P_2O_5 most likely representing incorporation of Miocene marine sequences at depth. This inference is reinforced by systematic changes in key trace and rare-earth element ratios (Th/Sc, Rb/V, La_n/Yb_n, and Zr/HF). Glasses from Rio Cuarto, however, indicate a near-surface provenance (4,5).

The source craters for these impact glasses have not been identified, with the possible exception of Rio Cuarto (1). While the loessoid sediments provide an ideal archival setting, craters would have been rapidly destroyed. Major landscape changes appear to be correlated with at least two events and could signify a nearby crater. Almost 20 craters larger than 1 km in diameter should have formed in these sediments over the last 10 Ma. Consequently, more pampasites should be found at other levels but careful radiometric dating will be necessary in order to establish if they represent a new occurrence or distal materials from a known event. As described elsewhere (5), dated impact glasses provide critical benchmarks for refining (and revising) the stratigraphic record in the important fossil-bearing sediments of Argentina.

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HELIUM LOSS AND SHOCK PRESSURE IN MARTIAN METEORITES – A RELATIONSHIP

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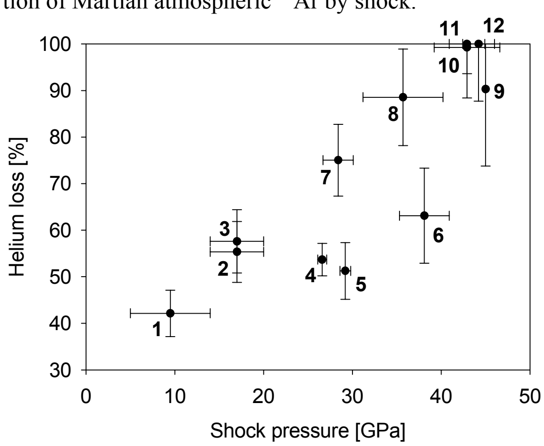
Introduction: Impact on a parent body causes shock effects, which have been shown to influence the inventory of noble gases and easily volatilized elements in the affected rocks [1, 2]. A well-known example is the resetting of the Ar-"clock" by a major degassing event and therefore a pronounced clustering of Ar-ages around ~0.5 Ga for the L-chondrites [2]. The influence of shock on the nobel gas content in chondrites has been demonstrated for ^{40}Ar [3] and ^{4}He [4], with a complete loss resulting from shock pressures in excess of ~35 GPa.

Methods: Here we investigate the effects on the radiogenic ^{4}He inventory of Martian meteorites. We combine data from three studies: Radiogenic ^{4}He from noble gas mass spectrometry, U and Th contents measured by SSMS [5], and peak shock pressures based on the shock induced reduction of the refractive index of plagioclase [6]. The loss of ^{4}He is inferred from the difference between the amount of ^{4}He produced by radioactive decay of U and Th since closure of the magmatic system (as deduced from ages obtained by Rb/Sr and/or Sm/Nd dating [7, 8]) and the measured ^{4}He amount.

Results: Our data show a correlation between the ^{4}He loss and the shock pressure as determined with the method of [6] in the range of ~10–45 GPa, indicating that the amount of energy deposited by shock is correlated with the loss of ^{4}He. In addition to our data it is known [9] that the heavily shocked LEW88516 (~44 GPa [6]) also suffered complete loss of ^{4}He. For ^{40}Ar the situation is more complicated, as there is both, loss and implantation of Martian atmospheric ^{40}Ar by shock.



Helium loss vs. shock pressure. 1: Lafayette, 2: Nakhla, 3: Gov. Valadares, 4: Chassigny, 5: Zagami, 6: EETA79001, 7: Shergotty, 8: ALHA84001, 9: QUE94201, 10: SaU005, 11: DaG476, 12: ALHA77005.

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DRUSE PYROXENES IN D´ORBIGNY: A MÖSSBAUER SPECTROSCOPY STUDY.

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Introduction: D'Orbigny is the sixth and by far the largest angrite known. It is peculiar with respect to three features: the abundance of hollow shells, the abundant presence of glasses and the open druses with perfectly crystallized augites of prismatic habit [1-2]. Here we report on the distribution of Fe^{2+} among the non-equivalent sites in the druse pyroxenes of the D'Orbigny meteorite as determined by Mössbauer spectroscopy.

Sample: Our specimen consists of 200 mg of euhedral augites, ranging in size from 70 to 400 m. Electron microprobe analyses showed that augites are chemically homogeneous with a slight compositional change at the outermost ~ 5 µm (rim) – in wt%: SiO_2 - 46.4 (45), TiO_2 - 1.53 (1.91), Al_2O_3 - 8.1 (9.4), FeO - 12.7 (13), MgO - 9.1 (8.3), CaO - 22.7 (22.9).

Results and Discussion: The study of cation distributions over non-equivalent lattice sites in minerals can provide valuable information on its pT history. In pyroxene crystals that have been cooled slowly to temperatures lower that 500 ºC, the Fe^{2+} ions populate primarily the M_2 position whereas the Mg^{2+} ions occupy predominantly the M_1 position. In crystals that have been rapidly cooled, a more disordered Mg, Fe distribution over the M_1 sites is observed.

The Mössbauer spectra of D'Orbigny druse augites obtained at room temperature consist of an intense inner doublet due to Fe^{2+} at the M_2 sites and a less intense outer doublet due to Fe^{2+} at the M_1 sites, whose relative areas are A_2=70% and A_1=27% respectively. Most Fe is present as Fe^{2+} but traces of Fe^{3+} (3%) have also been observed and can be due to the presence of superparamagnetic particles of Fe oxide. By means of the relative areas A_1 and A_2 we determine the population of the Fe^{2+} in M_1 and M_2 crystallographic sites of the augite. The Fe^{2+} occupancies at M_1 and M_2 in these two nonequivalent sites are given by $X_{Fe}(M_1)=2yA_1/(A_1+A_2)$ and $X_{Fe}(M_2)=2yA_2/(A_1+A_2)$, being A_1 and A_2 the Mössbauer relative areas and y=Fe/(Fe+Mg+Ca+Al).

Considering the disordering reaction due to intracrystalline Mg^{2+} and Fe^{2+} exchange among the non equivalent M_1 and M_2 sites, the site populations of Fe^{2+} and Mg^{2+} can be related to the disordering coefficient , defined by $=X_1(1-X_2)/X_2(1-X_1)$ where $X_1=X_{Fe}(M_1)$ and $X_2=X_{Fe}(M_2)$. Taking into account the chemical composition data, our results yield a disordering parameter = 0.31. Comparing this result with values obtained from heating experiments with orthopyroxenes under controlled conditions [3], we can suggest that D'Orbigny augite exhibits a cation distribution corresponding to equilibrium temperatures of at least 1000 °C to 1200 °C. This is in good agreement with late phases equilibrium which indicates formation of kirschsteinite and ferro-augite at similar temperatures [1]. Further variable temperature Mössbauer experiments are in progress in order to acquire more details on the thermal history of these pyroxene crystals.

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CLUES TO THE INTERNAL STRUCTURES OF SMALL ASTEROIDS FROM METEORITE BRECCIAS

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Introduction: Spacecraft images and geophysical data from the small S-type S asteroids, Eros, Gaspra, and Ida, show that they are fractured, coherent bodies [1], not the classic "rubble pile" asteroids that are predicted from models of catastrophic asteroidal impacts, family and satellite formation, and studies of asteroid spin rates, and other diverse properties of asteroids and planetary craters [2]. Reconciling these conflicting views is crucial for asteroid science and hazard mitigation.

Impact histories of Eros, Gaspra, and Ida: Three possible impact histories can be envisaged for small asteroids. They may have formed as impact shards from much larger bodies, as rubble piles from catastrophic collisions, or they may be largely intact bodies that accreted 4.6 Gyr ago. Ida and Gaspra, like many asteroids, are members of families [3] and formed from impact debris in catastrophic impacts. Other small asteroids, like Eros, are probably derived from families. Hydrocode and N-body models used to simulate catastrophic impacts suggest that asteroid family members >1 km are all rubble piles [4]. Modeling of Vesta's family [5] and an extrapolation from the sizes of the largest ejected boulders around impact craters [6] suggest that the largest single blocks in family-forming impacts are kilometer in size. We conclude that most 1-100 km asteroids formed as rubble and that S asteroids like Eros, Gaspra, and Ida were later consolidated.

Consolidation of breccias and asteroidal rubble: Brecciated ordinary chondrites and many other meteorite breccias testify to a long history of impact fragmentation and consolidation by alteration, metamorphism, melting and impact processes. Some breccias were lithified in regoliths but many appear to have formed after disruption and reaccretion events as asteroid impact models would predict. Some L and LL chondrite breccias were lithified by metamorphic processes, and a few breccias were lithified by injected impact melt, but most are regolith and fragmental breccias that were lithified by mild or moderate shock, like most lunar breccias. We suggest that the impact processes that converted impact debris into meteorite and lunar breccias may have consolidated asteroidal rubble in the same way. Small asteroids that formed as gravitational aggregates developed regoliths that partly filled internal voids during impact-induced seismic shaking. Consolidation of regolith-filled voids beneath large craters may have helped to lithify asteroidal rubble to form a more coherent body. Impacts consolidate porous chondritic powders by forming bridges of silicate shock melt that glue grains together during mild shock [7], and by friction and pressure welding of silicate and metallic Fe,Ni grains. Fractures on Ida created by antipodal impacts [8] are concentrated in and near large craters consistent with this model.

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STONY METEORITE CHARACTERIZATION BY NON-DESTRUCTIVE MEASUREMENT OF PETROPHYSICAL PROPERTIES.

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Introduction: The National Meteorite Collection of Canada comprises over 700 different stony meteorites. There are statistically large numbers of different meteorites in many classes. Work on these meteorite samples complements previous studies [1]; see also ref. in [2]. Non-destructive measurement of their petrophysical properties is being systematically undertaken to: (1) define a range of properties for each chondritic and achondritic class; (2) develop simple techniques to discriminate among classes, and within classes, i.e. to rapidly and non-destructively classify meteorites, or to check their classification; and (3) gain insights into their conditions of formation, and the nature and history of parent bodies.

Techniques: We have modified previously published bulk magnetic susceptibility measurement techniques by varying frequencies; so far 304 specimens have been measured for bulk susceptibility at two frequencies (825 and 19000 Hz). In addition, 67 specimens have been measured for anisotropy of magnetic susceptibility at a frequency of 19000 Hz [2]. We also plan natural remanent magnetization (NRM) and bulk density measurements.

Classification Parameters: Currently we recognize four parameters which show promise as classification tools and discriminants: frequency dependence, bulk susceptibility, degree of anisotropy, and shape of anisotropy. The achondrites appear to have a larger frequency dependence than the chondrites with acapulcoites (ACA), aubrites (AUB) and SNC (Martian meteorites) showing the highest dependence. Plots of susceptibility vs. degree of anisotropy show a clear distinction between chondrites and most achondrites. Acapulcoites (ACA) and Ureilites (URE) are exceptions. They plot at higher susceptibilities than expected for their metal contents. Aubrites (AUB) are particularly distinct, with low average susceptibility (3.41 ± 0.51)[log χ in units $10^{-9}m^3/kg$, $\pm 2\sigma$ error] but a remarkably high degree of anisotropy (30-50%). They also have a prolate anisotropy fabric in contrast to most other meteorite types. These characteristics may indicate a distinctive origin and/or provenance. The eucrites (EUC) have the lowest susceptibilities (2.97 ± 0.62). The highest susceptibilities belong to the E-chondrites (5.29 ± 0.37), and there is a general trend, on bulk susceptibility vs. degree of anisotropy plots, from C-chondrites through LL, L, and H to E, probably largely controlled by metal content.

The shape of anisotropy of the classes measured is dominantly oblate ellipsoidal. The degree spread of ellipsoid shape varies among classes. The L, H and E chondrites display the largest spread with E-chondrites showing no preferred oblate or prolate shape. The C-chondrites display the tightest ellipsoid groupings ranging from 1 to -10% as well as the tightest groupings for degrees of anisotropy (1 to 10%).

Sub-classes: There are some within-class differences that may be significant and related to provenance and parent body history. Camel Donga has a bulk magnetic susceptibility of 4.31 -- distinct from other EUC, e.g. Millbillillie, 2.66. CM2's have a distinctively lower susceptibility range then the other measured classes (CO, CV, CR, CK and C3.x). The ability of bulk magnetic susceptibility alone to help distinguish among the various C-chondrite sub-classes makes it a potentially valuable parameter for their classification, given their complexities, and sample fragility.

Summary: By continuing to measure different petrophysical properties, and identifying more parameters for discriminating among stony meteorites, we expect to contribute to a worldwide database that allows rapid systematic and non-destructive classification [1], and also to gain new knowledge of their provenance.

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Os ISOTOPIC EVOLUTION AND FRACTIONATION OF HIGHLY SIDEROPHILE ELEMENTS IN THE EARLY SOLAR SYSTEM

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Re-Os analysis of mineral fractions and chondrules from Allegan (H5) yield a precise isochron (4568±11 Ma, initial $^{187}Os/^{188}Os$ = 0.09542±6). The Allegan isochron comprises handpicked metal, olivine, and several types of chondrules. FIG. 1 shows this result (filled diamond) along with previous Re-Os results for magmatic [1] and non-magmatic [2] irons, and Ochansk (H4). The Re-Os age of Allegan coincides within uncertainties with that of IIIA iron meteorites, and is resolvably older than the ages of the other magmatic groups. Both studied H-chondrites, along with non-magmatic IAB irons, plot within error limits on the evolution line defined by magmatic iron meteorites. This fact implies isotopic homogeneity of primordial Os in differentiated and chondritic parental bodies.

HSE distribution patterns determined for mineral fractions of Allegan, Ochansk, and Tieschitz show that surprisingly high levels (~10% of bulk CI) of Os, Ir, and Ru reside in non-metal components (e.g., troilite, olivine). All analyzed olivine samples are strongly enriched in Pt (up to 10 x CI in terms of Pt/Ir ratio). Conversely, these fractions display prominent depletions in Pd (from 10 to 100 times relative to bulk CI). Rhenium and Os are significantly fractionated among chondritic components: from supra-chondritic Re/Os ratios in coarse metal and troilite (up to 1.3 x CI) to strongly sub-chondritic in olivine and plagioclase, as well as in some types of chondrules. Duplicate analyses of two excentroradial chondrules from Allegan have extremely low Re/Os ratios (~0.2 x CI) implying that strong HSE fractionation occurred during chondrule formation.

Conclusions: High-precision Re-Os isochrons for Allegan and Ochansk may permit a direct reconciliation of Re and U decay constants. These results also demonstrate the capabilities of the Re-Os system for studies of early Solar System processes; from chondrule formation to thermal metamorphism.

Acknowledgments: This work is funded by NRC Research Associateship through NASA NAI and CIW/DTM. Some aspects of this work were supported by NASA grant NAG510425 (to RJW).

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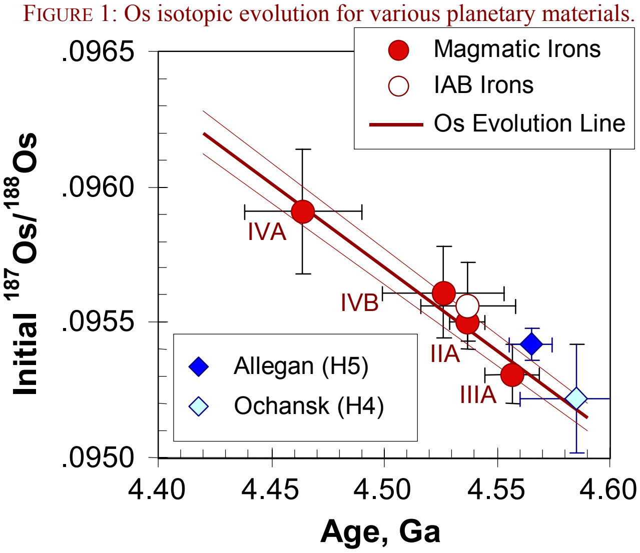
FIGURE 1: Os isotopic evolution for various planetary materials.



DEVELOPING PROTOTYPE CROSS-SECTIONS OF THE UPPERMOST MARTIAN CRUST

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We have attempted to establish prototype cross-sections through the uppermost 100 m of the Martian crust for several different Martian terrains: (a) generic northern hemisphere; (b) generic southern hemisphere; (c) generic older cratered terrain; (d) generic younger cratered terrain, and (e) polar regions. The cross-sections are built from four main materials: (1) uncemented sediment (i.e., dust and aeolian deposits, unconsolidated fluvial and mass wasting products); (2) cemented sediment (i.e., evaporites, sediment consolidated by diagenesis); (3) igneous rock (e.g., basaltic lavas and related intrusions, impact melt) and (4) megaregolith (i.e., impact-bombarded and impact-mixed materials from 1-3 above). Megaregolith constitutes the foundation component. We also consider H2O-CO2 ice in the cross-sections, which are dependent on latitude, as well as other factors. The cross-sections have been constructed primarily in order to help optimize the design of a potential orbital ground-penetrating Synthetic Aperture Radar (SAR) system for Mars, but they have applications in other planetary exploration technologies (e.g., site selection for multi-metre drilling programs).

Understanding the composition of the uppermost 100 m of the Martian crust is important for future missions. We need to estimate the likely substructure for landing sites so that we can optimize mission design. This is particularly important for rover-based drilling, ground-penetrating radar technology, sampling for evidence of life, and accessing H2O. Constructing cross-sections is an iterative process, largely based on remote sensing data (Mariner, Viking, MGS, Odyssey, Mars Express), combined with analogies with other terrestrial planets, especially Earth and the Moon. In this respect, Mars shows similarities with both the Moon (e.g., in megaregolith development and its preservation) and Earth (e.g., relatively recent volcanism, presence of sedimentary deposits). Establishing Martian crustal structure helps to address a number of Mars Exploration Program Assessment Group (MEPAG) objectives, including Goal C: Determine the evolution of the surface and interior of Mars (“Geology”), including establishing the large-scale vertical structure of the crust and its regional variation, assessing sedimentary processes and their evolution through time, and indicating favourable sites for seeking evidence of life.

KYANITE: A NEW SHOCK-INDUCED HIGH-PRESSURE SILICATE PHASE FROM THE RIES CRATER.

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Introduction: Clasts of shocked garnet-cordierite-sillimanite gneisses from the fallout suevite of the Ries crater were studied in transmitted and reflected light. These rare graphite-bearing rocks in the suevite breccia show various shock phenomena and may contain high-pressure phases [1,2]. Among the garnetiferous rocks, a dense, very strongly shocked garnet-sillimanite restite (= 3.34 g/cm^3) contains sillimanite grains with high-refractive mineral aggregates at the edges or along internal fractures. Modally, the rock fragment is composed of about 40% sillimanite, 30% garnet, 10% biotite, 16% pinite, 0.5% ilmenite and 0.5% rutile. Calculated from breakdown temperatures of selective minerals the equilibrium shock pressure and temperature of the dense clast is estimated according to customary shock scales to ~60.0±3.1 GPa and ~850±100 ^{o}C. Although natural shock behavior of sillimanite from the Ries and the Canadian Haughton crater has been described in detail [3,4,5], the micron-sized, high refractive aggregates within the host sillimanite remained undiscovered. High-resolution scanning electron microscopy and Raman spectroscopy were used to determine the composition and structure of the tiny aggregates.

Results: Electron-microprobe analyses reveal that the high refractive aggregates and host sillimanite grains are identical in chemical composition. The Raman spectrum of the aggregates correspond to spectra of kyanite minerals with highest wavenumber mode at 949 cm^{-1} [6]. The thin kyanite borders around the sillimanite host show typical lattice-controlled shrinkage cracks because the shock-produced formations are approximately 10.5% denser than sillimanite [7]. Small-striped kyanite aggregates along the rims of adjacent, touching sillimanite grains are usually 0.5-2.0 m wide, whereas some roundish-shaped kyanite particles attain sizes of up to 10 m.

Sillimanite grains in the garnetiferous rock with wider interstices in the range of 2-10 m contain vesicular melt glasses and lathy microcrystals. Intense shock wave interactions in porous spaces resulted in partial melting of sillimanite at high temperatures in the range of 1300-1690 ^{o}C [8]. Adjacent kyanite aggregates along sillimanite rims are very likely back-transformed due to the influence of high post-shock temperatures.

Conclusions: Compared to kyanite in regional metamorphic rocks, the shock-produced kyanite shows unique textures due to the occurrence along grain boundaries and internal fractures of host sillimanite. Contrary to shock experiments on andalusite [9], high-pressure kyanite minerals can be formed in long-lasting natural impact events. After coesite and stishovite, kyanite is the third high-pressure silicate phase found in the Ries crater.

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ADSORPTION AS A MECHANISM TO DELIVER WATER TO THE EARTH.

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Introduction: The origin of water in the terrestrial planets has been long debated. The two most popular theories envision supply of water from outside of the local feeding zone after most of the Earth had accreted, either by means of comets or of asteroids of composition similar to carbonaceous chondrites. However, these theories have some severe limitations. Both mechanisms would produce isotopic and geochemical signatures inconsistent with observations for the Earth's water and mantle, which rules out a substantial water contribution from these sources.

The amount of water vapor present in the accretion disk within 3 A.U. equals about three times the Earth's mass [1]. Therefore, the inner solar system should have had sufficient water to allow for adsorption of vapor to the surfaces and pore spaces of grains that subsequently accreted to form the inner planets.

Methods: We modeled the adsorption of water from 1500K to 1000K using a Monte Carlo simulation with a grid of 10000 adsorption sites, and an iterative process allowing the surface to reach a steady state saturation at each temperature. Water molecules not only interact with the substrate by means of weak bonds (~5kJ/mole) but also establish hydrogen bonds with other water molecules present in a monolayer [2]. We took this cooperative behavior into account by increasing the bond energy proportionally to the number of nearest neighbors (max allowed = 4). Incoming molecules stuck to the surface if their kinetic energy was lower than 5kJ/mole. If a particle collided on an occupied site, the resident molecule was dislodged only if the incoming particle had an energy exceeding the total bond energy of the adsorbed molecule. The energy of the incoming molecules was computed using the Maxwell-Boltzmann probability distribution. We allowed only for the adsorption of one monolayer, neglected porosity and surface roughness, considered water an infinite reservoir, and assumed that all the particles interacting with the surface were water molecules.

Preliminary results: This simple model allows for a coverage up to ~ 50% of the available adsorption sites. To scale this into moles of water, we pulverized the Earth into homogenous spheres of 0.1 m in radius, with total volume equal to the Earth's volume. We then computed the total surface area available for adsorption. Given that each adsorbed water molecule occupies about $10Å^2$ [2], we obtained the number of available adsorption sites (3.6E47). Since half of these sites can be occupied, then the adsorbed water potentially stored in the dust corresponds to ~ three times the Earth's oceanic + atmospheric + crustal water (OAC) [3] and ~ 1.5 times the Earth's OAC + mantle water [3]. If the grain size increases, however, the amount of water adsorbed on the surface decreases; in this model the biggest grain size that allows for 1 Earth's OAC water to be adsorbed is ~ 0.3 m. On the other hand, porosity and surface roughness would increase the number of adsorption sites as well as sheltering adsorbed molecules from bombardment.

Even though this is a simple model, it indicates that adsorption may play an important role in delivering water to the Earth.

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EXCESS ^{235}U IN CHONDRITES: IMPLICATIONS FOR THE ^{247}Cm-^{235}U COSMOCHRONOMETER.

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The *r*-process only nuclide ^{247}Cm decays to ^{235}U with a characteristic half-life of ~16 million years. ^{247}Cm is presently extinct, but offers considerable potential as a short-lived *r*-process chronometer, providing constraints on the time interval between the last *r*-process nucleosynthetic event and the formation of the solar system. The existence of "live" ^{247}Cm in the early solar system should be manifested today as variations in ^{238}U/^{235}U, provided Cm was chemically fractionated from U when solids formed in the early solar system.

Using a Nu Instruments NuPlasma multiple-collector ICPMS and a high-purity mixed ^{233}U-^{236}U spike to monitor and correct for mass fractionation during chemical separation and isotopic analysis, we are able to resolve variations in ^{238}U/^{235}U at the two epsilon level ($2\sigma_M$; 1 epsilon = 1 part in 10,000) on sample sizes comprising <3 ng of total uranium, corresponding to <20 pg of ^{235}U.

Previous uranium isotopic measurements acquired on bulk samples of a suite of carbonaceous chondrite, ordinary chondrite and eucrite meteorites, for which conflicting results had previously been obtained, show no well-resolved excursions in ^{235}U/^{238}U from the terrestrial value at the ~2 epsilon level. These data constrain the amount of ^{247}Cm-produced excess ^{235}U atoms to less than ~1 x 10^8 atoms per gram of chondritic meteorite, with respect to terrestrial ^{235}U/^{238}U [1].

We have extended the search for "live" ^{247}Cm in the early solar system to small samples from mineral phases in primitive objects that are likely to display strong Cm-U fractionations. In particular, uranium isotopic measurements acquired on acid-etched leachates for a suite of chondritic meteorites show positive anomalies in ^{235}U/^{238}U with respect to the compositions of the bulk samples and the terrestrial standard. These excursions are consistent with a model in which excess ^{235}U was produced from the decay of live ^{247}Cm in the early solar system. As such, these data have important implications for the ^{247}Cm-^{235}U cosmochronometer and the timing of *r*-process nucleosynthesis relative to the formation of the solar system materials.

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VARIATIONS IN MICROCRACK POROSITY ACROSS METEORITE TYPES.

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Introduction: We have been studying microcrack porosity in meteorites [1] using a computerized point-counting system [2] to learn about the formation and evolution of meteorites and their parent bodies. Previous studies evaluated various stages of weathering (using ordinary chondrites for consistency) to see if observations were consistent with models [3] and concluded that the porosity tends to be constrained to a relatively narrow field, whether the samples are relatively fresh and unweathered, or have been extensively weathered (as can be determined from the bright phase materials filling in microcracks). We also looked at a suite of samples centered around a common mineralogy [4] using basalts as representative of most types of bodies, to evaluate if microcrack porosity varies with planet of origin. In this work we extend the types of meteorites examined to ask: Can one see a different kind of porosity in unequilibrated versus equilibrated chondrites? Do non-chondritic meteorites look less or more cracked than ordinary chondrites? What do non-chondritic breccias like mesosiderites or howardites look like?

Results: Ordinary chondrites range from porosities of 2% to 20% [1]; carbonaceous chondrites and enstatite chondrites fall in this same range (Orgueil 6.7%, Nogoya 1.8% and Abee 4.9%); and similarly achondrites, lunar meteorites and martian meteorites exhibit porosities from 3 to 11%. By contrast, terrestrial samples all fall at the low end of the range (0.7% to 3.9%). As we continue to expand the number and variety of samples we examine, the range does not change significantly.

There does not seem to be any consistent pattern to the values of the porosities and the type of meteorite. Values at the low end cross types (McKinney L4: 2.6%, Nogoya CM2: 1.8%, Dar al Gani Lunite: 2.9%), as do those at the high end (Durala L6: 9.8%, Bishopville Aubrite: 8.2%, Chassigny Chassignite: 10.9%).

Conclusions: Microcrack porosity in meteorites, though greater than that seen in terrestrial samples, does not appear to be correlated with meteorite type, and thus it may have its origin in a process common to all meteoritic material. One such process is the impact environment that has shaped the bodies on which they formed, and from which they were ejected. The subsequent decompression following passing of a shock wave through the material [5] is a very likely source of this porosity.

A further test of this hypothesis would be to examine Apollo samples that have been exposed to an impact environment on their parent body without having been ejected from that body or decelerated upon impact with the Earth.

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MICROSTRUCTURES AND ISOTOPIC COMPOSITIONS OF TWO SiC X GRAINS

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Introduction: Approximately 1% of presolar SiC grains belong to the class known as X grains. These grains have isotope signatures that are consistent with an origin in the ejecta of type II supernovae, in contrast with mainstream presolar SiC grains, which formed in C-rich AGB stars. Daulton et al. used transmission electron microscopy (TEM) to measure over 500 grains to determine the polytype distribution of presolar SiC [1]. However, it is not known which of those grains were X grains. Here we present results from coupled TEM and isotope studies of SiC X grains.

Experimental: The SiC grains were prepared as an acid-resistant residue of the Murchison meteorite. Carbon and Si isotopes were automatically measured in over 1100 SiC grains [2] using the Carnegie ims-6f ion probe, allowing members of rare sub-groups to be identified. Ultra-thin sections of two isotopically-characterized X grains were prepared by focused ion beam lift-out, and subsequently analyzed using a JEOL 2010-F TEM.

Results: The properties of the two identified grains, hereafter M11B-371-2 and M11B-180-7 are compared below.

	371-2	180-7	X grain range [3,4]
$^{12}C/^{13}C$	178	17.1	13 – 6800
$^{29}Si/^{28}Si$ (‰)	-222	-447	-750 – 120
$^{30}Si/^{28}Si$ (‰)	-357	-301	-770 – -10
Polytype	3C	2H	N/A
Al/Si	0.01	0.02	0.02 – 0.20

Discussion: The isotope ratios of the grains are well within the reported ranges for X grains, with the exception of the $^{12}C/^{13}C$ ratio of M11B-180-7, which is at the ^{13}C-rich end of the distribution. The two different crystal structures of the two X grains are also consistent with the earlier TEM results for presolar SiC [1]. In addition to different crystal structures, the grains display different morphologies. One (M11B-371-2) is a porous aggregate of ~ 100-nm crystallites, whereas the other (M11B-180-7) is a dense packing of ~ 10-nm crystallites. The crystallite size of these grains is much smaller than that of the majority presolar SiC, for which the entire grain (~ 1 m) is typically a single, twinned or otherwise defect-laden crystal. The aluminum present in both grains appears to be distributed uniformly as a solid solution, and not as distinct subgrains, in agreement with earlier models [5]. A trace amount of Mg was also detected in M11B-180-7, presumably resulting from decay of ^{26}Al. NanoSIMS measurements of the ultra-thin sections are planned.

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A Cathodoluminescence Study of Amoeboid Olivine Aggregates in Yamato 81020.

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Introduction: Two types of forsterite were reported in amoeboid olivine aggregates (AOAs) in CR chondrites [1,2]. One type has blue cathodoluminescence (CL) and the other red. The red olivine has higher MnO and Cr_2O_3 concentrations than the blue olivine. Mainly based on the high Mn concentrations, nebula origin of the red olivine was suggested. Here we report similar observations of AOAs in the Yamato 81020, CO3.0 chondrite.

Instrumental: CL was observed using MiniCL (Gatan Inc.) attached to a scanning electron microscope. CL images were taken with RGB filters, and color images were synthesized using the photoshop software. Trace element analyses were made either with an electron microprobe (WDS) or with a SEM-EDS.

Results and discussion: Red CL is seen, 1) over the entire AOAs that are severely fractured and/or very porous, 2) on the rim of unfractured AOAs and 3) near fractured area of partly fractured AOAs. In all cases Mn and Cr concentrations are high in red CL areas compared with blue CL areas. Thus, it is likely that Mn and Cr are red CL emitters in the AOA olivine. The association of red CL with fractures and/or periphery of AOAs suggests that Mn and Cr were introduced into olivine during secondary events after the formation of AOAs.

CaO and V_2O_3 concentrations are generally higher in blue olivine. On the V_2O_3 vs. CaO diagram red-dominant AOA and blue-dominant AOA are plotted in separated regions. In contrast, on the MnO vs. CaO diagram, red and blue olivines show a continuous trend, although the trend diverges at low CaO concentrations. The MnO/FeO ratios are not more than 0.6 and are not as high as those reported for CR chondrites [2].

Two disparate interpretations of the formation of Mn-Cr-rich olivine seem possible: formation in the nebula or formation in the parentbody. In the former case, Mn-rich olivine is formed by reactions of nearly pure forsterite with the nebula gas around ~1100K where Mn-olivine becomes stable [2]. In this case, concentrations of various trace elements in olivine are established in the nebula and hence different environment is necessary for the presence two types of olivine. MnO/FeO ratios are well explained in this model.

In the latter case, all AOAs were initially identical to the blue olivine, containing large amounts of refractory elements and small amounts of more volatile elements (Mn and Cr). A significant part of the refractory elements was lost from olivine during the alteration in the parentbody and replaced by Mn, Cr, Fe etc. There are yet unsolved problems against this model. First, Mn/Cr ratios in various Mn-rich olivines are not identical. If all AOAs experienced similar alteration in the parent body, this is not easily explained. Second, Mn/Fe ratios in the Mn-rich olivines are much higher than that of CI composition or that in the matrix in the Yamato 81020. Partitions of Mn and Fe under the metamorphic conditions of the parentbody has to be investigated to see if Mn can be preferentially partitioned to olivine to produce the observed high Mn/Fe ratios.

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EXPLORING A POSSIBLE SHERGOTTITE SOURCE CRATER AND CALIBRATING THE MARTIAN CRATERING CHRONOLOGY.

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Although we have > 20 meteorites from Mars, we do not know where on Mars they originated. Similarly, although we have a good relative chronology of many Martian geologic units, we do not understand the absolute chronology with much confidence. Here, we show how it would be possible, using a potential source crater for Martian meteorites, to answer several key questions about the recent geological history of Mars and the source of the meteorites with a single well-designed spacecraft mission.

The shergottites have the youngest crystallization ages of the Martian meteorites, 165 Ma to ~500 Ma [1]. They probably come from at least three, perhaps seven or more, different craters [1]. Most estimates of the absolute chronology suggest that most of Mars is older than this [2], so the shergottite source crater must be on very young terrain. One of the youngest areas is the Cerberus Plains, suggested as a potential source for the shergottites [3]. The most prominent crater on the Cerberus Plains is Zunil, a young 10.2 km crater. Zunil has prominent rays extending 1600 km from the crater, and produced as 10^7 to 10^8 secondary craters >10 m [4]. Given the characteristics of Zunil and the target material, it seems likely to have sent material to Earth [4, 5].

A mission to the Cerberus Plains to calibrate the Martian cratering record and investigate the timing of Zunil would be scientifically valuable, regardless of whether Zunil is a shergottite source crater. The landing target would be not Zunil itself, but an area where a rover could access one or more secondary craters as well as undisturbed and unmantled Cerberus surface lavas. The K-Ar ages of rocks, both those disturbed by the formation of the secondary crater and those untouched on the surface, would provide an age for the original lava flow. Since the crater(s) involved is only secondary, less energy is involved in formation, so there is less chance of either thermal resetting or atmospheric implantation than in a primary crater. Determination of the cosmic ray exposure age of ejecta from the craters would determine the age of those craters, and hence of Zunil itself. Cosmic ray exposure ages of undisturbed surface rocks could confirm the age for the original lava flow, or, if the lava has been eroded by water floods, could date the last floods. Determination of the chemistry and mineralogy of the rocks in the area would provide ground truth for remote sensing data, advance our understanding of recent volcanic and/or fluvial activity, and address the possible link with the shergottites. Finally, comparison of the chemistry, K-Ar ages and morphology of undisturbed surface rocks with those in the crater(s) could be used to address the thickness of the most recent lava flow, at least to the depth of the secondary crater.

All of this could be accomplished with a simple in-situ geochronology instrument [6], along with a careful selection of other instruments, on the next Scout-class mission.

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THERMOBAROMETRY OF MARTIAN NAKHLITES AND A LHERZOLITE - A COMPARISON

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Introduction:. Based on mineralogy and texture, Martian clinopyroxenites (nakhlites) and the lherzolitic ALH77005 are plutonic rocks from the interior of Mars. We have studied the thermal history, geothermobarometry and oxygen fugacity indicators of the nakhlites Nakhla, Lafayette, Y000593, NWA998 and the lherzolite ALH77005.

Thermometry: Minimum temperatures range from 1000 to 1150 °C for the cores of the large augites of all nakhlites studied, using the phase diagram of Lindsley [1]. Pyroxene thermometry for ALH77005 give significantly higher temperatures of up to as 1200 to 1300 °C. Both, the pyroxene cores in nakhlites and in ALH77005 are chemically homogeneous and must have cooled rapidly, as indicated by the lack of exsolution lamellae.

Oxygen fugacity: A new determination of the fO_2 of Lafayette, based on Fe-Ti-oxides, is with QFM 0.1 ± 0.6 in good agreement with earlier results on other nakhlites [2]. Estimates for ALH77005, based on Fe^{3+} in chromite [3], give a much lower fO_2 of QFM –3.3 ± 0.7 in agreement with results of Goodrich [4].

Barometry: Application of the single clinopyroxene barometer of Nimis [5] give a crystallization pressure of 1.2 – 2.4 ± 1.0 kbar for ALH77005 corresponding to a depth of ~ 18 km in Mars. The method is not applicable to nakhlites.

Discussion: The significantly higher fO_2 recorded by nakhlites when compared to ALH77005 is surprising. A possible explanation is extensive reaction of nakhlites with an oxidized crustal reservoir, a model suggested by Herd [6] to explain the large fO_2 variations among shergottites. The untypical high enrichment of light REE in nakhlites supports this model, at least qualitatively. In addition, evidence for reaction of nakhlite augites with an oxidized environment is provided by the microstructure of these meteorites. The FeO-rich rims in Nakhlite augites show extensive exsolutions [7], and with increasing FeO-content the width of the exsolution lamellae increase which is opposite to the trend expected from experimental data [8]. We concluded earlier that the nakhlites experienced a two stage evolution [7]. After formation and thermal equilibration of the augites above 1150 °C, the pyroxene crystals were rapidly transported to a location close to the surface of planet Mars, where they reacted with a highly oxidized melt or fluid enriched in light REE. Cooling of FeO-rich pyroxenes under these conditions may lead to the observed extensive exsolution phenomena.

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