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MAGNETIC PALEOINTENSITIES OF METEORITES: A NEW METHOD AND PRELIMINARY RESULTS

J. Gattacceca[1] and P. Rochette[1]. [1]CEREGE, Aix-en-Provence, France. E-mail: gattacceca@cerege.fr.

Introduction: We propose a new relative magnetic paleointensity method that does not involve heating of the sample and can resolve multicomponent magnetizations. This non-destructive method is particularly well adapted to meteorites that have magnetic mineral assemblages that are often metastable under heating and are characterized by complex magnetic remanence.

REM' method: It is based on normalization of natural remanent magnetization derivative vs. alternating field by isothermal remanent magnetization derivative vs. alternating field (REM' ratio). This method has been calibrated using available data [1, 2, 3] and acquiring new ones on pyrrhotite. It is well calibrated for magnetite, titanomagnetite, and pyrrhotite. A remarkable feature is that the trend of REM' ratio vs. magnetizing field is the same for these minerals. The few pieces of data for Fe-Ni alloys [4] follow the same trend. The REM' method can thus be applied regardless of the magnetic mineralogy of the studied meteorite.

Preliminary results: After validating the method on terrestrial basalts, we studied a total of 65 meteorites (R, C and O chondrites, SNCs, HEDs, aubrites). H and L ordinary chondrites proved to be unsuitable for paleointensity studies. However, an upper limit of 1 µT can be set for the magnetizing field and former estimates around 50 µT must be definitively discarded. LL ordinary chondrites, with magnetization carried by tetrataenite, give paleofields in the range 0.1-1 µT. Rumuruti chondrites indicate a magnetizing field around 8 µT. A magnetic field of 15 µT may have been present during the cooling of the HED achondrite parent body. Martian meteorites give paleofields scattered between 1 and 24 µT that represent the Martian surface magnetic field of crustal origin after dynamo shutdown. Carbonaceous chondrites provided contrasted results, with possible record of strong field (mT) indicative of a T-tauri phase.

Limitations: A strong limitation is that the REM' method is calibrated for thermoremanent magnetizations (TRM), and that some meteorites probably carry shock remanent magnetizations (SRM). This is particularly true for Rumuruti chondrites, basaltic shergottites and some carbonaceous chondrites whose magnetic carrier (pyrrhotite) is totally remagnetized above 2.8 GPa [5]. This could also be the case for some SNCs, even if an impact related TRM cannot be excluded. What is the efficiency of SRM acquisition vs. TRM acquisition is an open question, but the paleointensities derived from these meteorites may be underestimated. Another limitation is the randomness of NRM directions that is the rule within OC, HED, and possibly carbonaceous chondrites, and leads to underestimated paleofields.

Perspectives: Much work remains to be done in the field of meteorite paleointensities and the REM' method may help in this task. Measurements on several individual mutually oriented chondrules are needed for carbonaceous and Rumuruti chondrites. More data are also needed on HEDs. Finally, more work is needed regarding the effect of shock on magnetization.

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AN IMPACT RELATED ORIGIN FOR THE FOLIATION OF ORDINARY CHONDRITES

J. Gattacceca[1], P. Rochette[1], M. Denise[2] and L. Folco. [1]CEREGE, Aix-en-Provence, France. E-mail: gattacceca@cerege.fr. [2]MNHN, Paris, France. [3]MNA, Siena, Italy.

Introduction: A large number of observations and anisotropy of magnetic susceptibility (AMS) measurements [e.g. 1] reveal the existence of a foliation in almost all chondrites, and a lineation in some of them. Accretional sedimentation, metamorphism, lithostatic compaction and impacts have been proposed as possible explanations, but the two former possibilities can be confidently ruled out [2]. Impacts and lithostatic compaction remain as the two possible explanations. The reason why no definitive conclusion could be reached is that the dataset of former studies was too limited to reach the necessary statistical significance in view of the numerous parameters that have a potential effect on petrofabric.

Our approach: We undertook a comprehensive study of ordinary chondrites petrofabric determined by AMS measurements. We performed AMS measurements on meteorites (mostly ordinary chondrites) with known metamorphism type and shock stage. H chondrites were discarded due to (shape) self demagnetization effects. After clarifying the influence of magnetic mineralogy on the AMS signal (using among other things image analysis), the 150 new AMS measurements and a review of the 60 published data allow a detailed discussion on the origin of petrofabric in meteorites, based on more than 200 data.

Preliminary results: Comparison of image analyses and AMS results indicate that the AMS signal in ordinary chondrites is due to the preferential orientation of the metallic grains (shape anisotropy).

Fabric consistency. The petrofabric appears to be remarkably consistent within a single meteorite, both in terms of orientation and intensity. This was evidenced for instance by measuring the AMS of 18 samples from Knyahinya L5 OC, and comparing the AMS and preferential grain orientation of several mutually oriented subsamples of individual chondrites.

Anisotropy degree vs. shock stage. The relation between the degree of AMS and shock stage depends on the magnetic mineralogy. For instance, LL ordinary chondrites that are rich in tetrataenite have a high AMS degree, due to the strong magnetocrystalline anisotropy of this mineral. As a consequence we focused our study on L chondrites whose main magnetic carriers are kamacite and taenite. Despite large variability for a given shock stage, it appears that gently shocked L chondrites (S1) have low AMS degree (<1.1), that AMS degree increases with shock stage up to S3, and that it tends to stabilize around 1.4-1.5 for higher shock stages.

Conclusions: These results clearly relate the petrofabric of ordinary chondrites to deformation/reorientation of metallic grains by compaction due to hypervelocity impacts. However, above shock stage S3 this process reaches a limit, and AMS measurements cannot be used to discriminate shock stages 3, 4, 5 and 6. This is likely due to an almost complete compaction by shock stage S3, and to annealing for the highest shock stage. We will also discuss preliminary measurements on Rumuruti chondrites, carbonaceous chondrites, and SNCs that indicate low AMS degrees (<1.1) with respect to ordinary chondrites, whereas HEDs show a large variability.

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DECOHERENCE TIME SCALES FOR METEOROID STREAMS

B. J. Gladman[1] and A. D. Pauls[1]. [1]Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada. Contact author e-mail: gladman@astro.ubc.ca

Introduction: We have explored [1] the orbital dynamics of a Earth-crossing objects with the intent to understand the time scales under which an `orbital stream' of material could produce time-correlated meterorite falls. These `meteorite streams' have been suggested to be associated with several well-known meteorite-dropping fireballs (Innisfree [2], Peekskill [3], and most recently Pribram [4]). These are distinguished from meteor streams by the fact that these streams would consist of huge numbers of objects large enough to drop recoverable meteorites. We have studied the statistical significance of some published claims for such meteoroid streams.

Statistical studies: We performed three different analyses of the statistical significance of the 'orbital similarity' in the published cases, in particular calculating how often orbits of the same level of similarity would come from a random sample of meteoroids with a similar pre-atmospheric orbital distribution. We found that in all cases the level of orbital coincidence (be it a single pair of nearby orbits or a cluster of similar orbits) observed is that expected from a random orbital distribution of Earth-crossing orbits which obey the known (a,e,i) distribution of Earth-crossing material. We conclude there is no statistically significant evidence for Earth-crossing meteoroid streams.

Numerical studies: We also performed [1] extremely detailed numerical studies of the time evolution of the stream candidates. We find that if they were streams of objects in similar orbits to the observed fireballs then these streams of material would become `decoherent' (in the sense that the day of fall of meteorites of these streams become almost random) on times scales of a few tens of thousands to a few hundred thousand years. Thus, an extremely recent breakup would be required, much more recent than the cosmic ray exposure ages of the recovered falls in each case.

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THE ORBIT OF THE ORGUEIL METEORITE FROM HISTORICAL RECORDS.

Matthieu Gounelle[1,2], Pavel Spurny[3] and Philip A. Bland[4,2]. [1]CSNSM-Université Paris XI, Bâtiment 104, 91 405 Orsay Campus, France (gounelle@csnsm.in2p3.fr) [2]Department of Mineralogy, The Natural History Museum, London SW7 5BD, UK [3] Ondrejov Observatory, Astronomical Institute of the Academy of Sciences of the Czech Republic, 251 65 Ondrejov, Czech Republic [4]Department of Earth Science and Engineering, Exhibition Rd., Imperial College, London SW7 2AZ, UK

Introduction: Establishing a link between meteorites and their parent bodies is a key issue in planetary sciences. So far, the orbits of only four meteorites have been precisely established by photographic camera networks, while video technique and satellite observations have helped establish three less precise orbits. All these meteorites originate from the main asteroid belt.

The Orgueil meteorite is a CI1 chondrite that fell in southern France more than a century ago, May 14th 1864, shortly after 8 pm. Orgueil is a cornerstone and puzzling meteorite since it is chemically pristine but highly processed by hydrothermal alteration. The chemical composition of CI1 chondrites is virtually identical to that of the solar photosphere, defining the cosmic abundance [1]. Determining the orbit of Orgueil would help to constrain the origin of CI1 chondrites. We have used the primary records of the fireball observations across France to constrain a 'paleo-orbit' for the Orgueil meteorite, 140 years after it fell.

Results: Our orbit reconstruction is based on the cross-checked examination of all reported fireball observations, most of which can be found in Daubrée [2]. The atmosphere entry point is estimated to be H=70 km, Lo=0.26°W, La=44.29°N and the meteoroid terminal point is estimated to be H=19 km, Lo=1.34°E, La=43.89°N, after a luminous path of almost 150 km. The atmospheric trajectory we calculated is similar to that determined from Laussedat [3]. The argument of perihelion (326-332°), the longitude of ascending node (234.5°) and the inclination (1.3-2.7°) depend little on the fireball velocity, contrary to the semi-axis and eccentricity. The semi-axis varies from 2.4 AU to 13 AU and the eccentricity between 0.59 and 0.93. The identified orbits range from typical Apollo asteroid orbit (low entry velocity) to Jupiter family comets orbits (high entry velocity). We will discuss at the conference the likely velocity of the Orgueil fireball, and propose a most probable orbit for the Orgueil meteorite. Comparison with other meteorite orbits will be made [4,5], and constraints on the origin of CI1 chondrites will be proposed.

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ENTRY OF ALKALIS INTO TYPE-I CHONDRULES AT BOTH HIGH AND LOW TEMPERATURES.

J. N. Grossman[1] and C. M. O'D. Alexander[2]. [1]US Geological Survey, 954 National Center, Reston, VA 20192, USA, jgrossman@usgs.gov. [2]DTM, Carnegie Institution of Washington, 5241 Broad Branch Rd. NW, Washington, DC 20015, USA.

Introduction: Abundance of moderately volatile elements, including alkalis, is a key constraint for any chondrule formation model. A longstanding problem has been that alkalis may be mobile in asteroidal environments, obscuring the earlier nebular record and making it difficult to construct meaningful models.

The distribution of alkali elements in type-I (low-FeO) chondrules must be understood prior to modeling chondrule formation. Many type-I chondrules in primitive chondrites are zoned, with mesostasis near outer surfaces being richer in alkalis than that in cores. We have argued [1] that alkalis entered chondrules during parent-body processing at low temperature because Ca decreases as alkalis increase and alkalis correlate with water content. Others [2,3] explained the zoning by recondensation of alkalis into cooling chondrules. Type-I chondrules also have alkali contents that are related to mineralogy: pyroxene-rich chondrules (type IB) have higher alkali and Si contents than olivine-rich chondrules (type IA) [1,4]. The observation that Na in clinopyroxene (CPX) correlates with Na in surrounding glass, consistent with igneous partitioning [4], is evidence that alkalis were present in chondrules at high temperature. This has led to the conclusion that the process responsible for chemical zoning must be identical to that which produced differences between type IA and IB chondrules: recondensation of moderately volatile elements and Si into chondrules at supersolidus temperatures [4]. How can these conflicting observations be reconciled?

Experimental results: We have located zoned type-IA and IB chondrules in Semarkona that contain CPX quench crystals in regions of mesostasis with high alkali-element gradients. If alkali zonation was established prior to CPX crystallization, then a relationship should exist between the Na contents of CPX and glass within each chondrule. However, despite up to a factor of 10 difference in mesostasis Na content between chondrule surfaces and cores, CPX contains a uniform Na concentration consistent with igneous partitioning between the CPX and alkali-poor mesostasis found in the chondrule core. In addition, we have replicated the data of [4] showing a relationship between chondrule mineralogy and mesostasis alkali content (see also [1]).

Discussion: Both high- and low-T processes are required to explain the observed alkali distributions. Alkali zoning is produced *entirely* by low-T entry of alkalis (and other volatiles) into chondrules, accompanied by Ca loss. This zoning is superimposed on a high-T alkali signature possibly derived from condensation processes. When chondrules initially cooled, they were likely unzoned with respect to alkalis, as predicted by diffusion calculations. At this time, different types of chondrules had different alkali contents, which may be preserved in cores after low-T alkali entry on the parent body. Mineralogical zoning, including pyroxene-rich shells developed around type-I chondrules, is also a high-T effect *unrelated* to alkali zonation.

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MAGNETISM IN THE UNIVERSE

A.P. Guimarães. Centro Brasileiro de Pesquisas Físicas, R. Xavier Sigaud 150, 22290-180 Rio de Janeiro, Brazil E-mail: apguima@cbpf.br.

Magnus magnes ipse est globus terrestris – "the Earth globe itself is a great magnet", wrote William Gilbert in 1600, in the *De Magnete*. This discovery is a remarkable advance in the knowledge about the Earth and in fact it represents one of the earliest recognitions of a global property of our planet, the second after the admission of its roundness. In the 400 years since the publication of the *De Magnete*, magnetism has been shown to be a widely prevalent natural phenomenon that acts in a vast range of scales, from the microscopic world to the distant galaxies.

The understanding of the magnetism of matter was made possible with the discovery of the relationship between electricity and magnetic phenomena in the XIX century, together with the introduction of Quantum Mechanics in the first decades of the XX century. The magnetism of our planet was found to be different from that of magnetite, with the proposal in 1919 of the dynamo model by the Irish physicist Joseph Larmor. This mechanism, active in many planets of the solar system, as well as in the Sun, is essentially based on the effect of electric currents circulating in the core of the astronomical body.

The Earth magnetism has undergone important modifications along the life of the planet, most significantly polarity reversals every few hundred thousand years. The magnetic activity of our planet has a wide range of effects, from the trapping of charged particles emitted by the Sun to the influence on the habits of uncountable living creatures that have evolved forms of sensing it.

The next source of magnetic activity, in an ascending astronomical scale is the Sun, where the same dynamo effect actuates. The cycle of magnetic activity of the Sun is correlated with the cycle of sunspots; every 11 years, a new cycle begins, and this is accompanied by a reversal of overall magnetic polarity. Around the sunspots, intense magnetic fields are observed.

Many other stars are known to be surrounded by magnetic fields. Neutron stars are the most remarkable objects from the magnetic point of view, since a class of these stars exhibit the largest magnetic fields found anywhere in the universe. These are the soft gamma ray repeaters (SGR), or magnetars, with fields 10^{15} stronger than those found on the Earth surface.

On the grand scale of the galaxies, magnetic fields have been detected and studied, with lines of fields that often parallel the arms in spiral galaxies. These are much weaker fields than those found on the surface of our planet, but which may have played a role in the shaping of the galaxies [1].

Magnetic fields may still hold the clue for important unanswered questions that refer to the large scale of the universe, such as the origin of high energy cosmic rays.

The study of magnetism and magnetic properties of materials has grown with a very rapid pace in the last decades, to a large extent stimulated by the development of magnetic recording media, a vital component of every computer. Magnetic recording density has doubled every two years since the 1950s!

Originally shrouded with mystery in the first days of civilization, magnetism still retains its appeal to our days, as a remarkable and fascinating natural phenomenon.

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OXYGEN ISOTOPES AND RARE EARTH ELEMENT ABUNDANCES OF REFRACTORY INCLUSIONS IN THE NINGQIANG METEORITE. H. Hiyagon[1], A. Yamakawa[1], Y. Lin[2] and M. Kimura[3]. [1]Department of Earth & Planetary Science, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan. E-mail: hiyagon@eps.s.u-tokyo.ac.jp. [2]Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, China. [3]Faculty of Science, Ibaraki University, Mito 310, Japan.

Introduction: As a part of the systematic study of refractory inclusions in the Ningqiang meteorite [1], we conducted ion microprobe analyses of oxygen isotopes and rare earth element (REE) abundances for selected inclusions of various bulk chemical compositions.

Samples and analytical method: So far, we analyzed the following inclusions: NQJ3-3-4 is a hibonite-bearing fluffy type A (FTA) inclusion, NQJ3-3-1.4 and NQJ3-5-9 are hibonite-bearing compact type A (CTA) inclusions, NQJ3-5-8, NQW1-1 and NQW1-16 are hibonite-free FTA inclusions, and NQW1-5 is a spinel-pyroxene-rich inclusion.

Oxygen isotopes and REE analyses were carried out using a CAMECA ims-6f ion microprobe at the University of Tokyo. The analytical conditions for O-isotopes are similar to those described in [2]. REE analyses were performed using an O^- primary beam of –22.5 keV energy, ~25µm in diameter and ~1nA beam intensity. Positive secondary ions were accelerated at 10keV. An energy filtering method was applied to reduce contributions of complex molecular ions. Synthetic REE standards were used to determine relative sensitivity factors for REE^+ and Ca^+ and production ratios of $REEO^+/REE^+$.

Results: *Oxygen Isotopes.* All the O isotope data are plotted along the CCAM line on the three-isotope diagram. They seem to be minerallogically controlled but show no correlation with the bulk chemical compositions of inclusions. Spinel, fassaite, olivine (in the rim) and diopside (in the rim) show highly ^{16}O-rich compositions with $\delta^{17}O \sim \delta^{18}O$ from –50 to –40 permil (for the first three) and from –40 to –30 permil (for diopside), respectively. One datum of perovskite (NQJ3-3-4), in contrast, shows a ^{16}O-poor composition ($\delta^{17}O$= +3.2 and $\delta^{18}O$= +10.4 permil). Melilite shows wide variations with $\delta^{17}O \sim \delta^{18}O$ near –40 permil (NQJ3-5-9) to >0 permil (NQJ3-3-4), suggesting partial equilibration with a ^{16}O-poor reservoir, possibly a nebular gas.

REE abundances. Most of the inclusions so far analyzed show almost flat REE patterns with some Eu anomalies (Group V or I or III [3]) except for NQW1-16, which shows depletion of HREE (Gd to Er and Lu) relative to LREE (La to Sm) (Group II). At present, we cannot find any systematic correlation between REE patterns and bulk chemical composition or petrographic type of the inclusions, possibly due to limited number of analyses. We will carry out more analyses to better understand the conditions and formation mechanisms of refractory inclusions.

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ANOMALOUS NIR SPECTRA OF HIGH-Ca PYROXENES: POSSIBLE CORRELATION WITH EXSOLVED PHASES. E. J. Hoffman[1] and E.A. Cloutis[2]. [1]Physics Department, Morgan State University, Baltimore, MD 21251, USA (ehoffman@morgan.edu). [2]Department of Geography, University of Winnipeg, 515 Portage Ave., Winnipeg, Manitoba R3B 2E9, CANADA.

Introduction: Near-infrared (NIR) reflectance spectroscopy is a principal tool in the study of igneous planetary material whether remote or in the laboratory. Mössbauer spectroscopy has often provided a useful supplement in the lab and has now become a component of rover missions as well. It is thus ever more urgent to resolve outstanding spectroscopic ambiguities.

For high-Ca pyroxenes some NIR spectra show anomalous results ("Type B") as if Fe^{2+} ion were in the larger (M2) octahedral site where Ca^{2+} is known to be; in some cases samples of almost identical composition give contrasting NIR results [1]. Mössbauer spectra of such matched sets have also shown anomalous results, unexpectedly suggesting higher Fe^{3+} content than that found by chemical analysis [2]. We are continuing work coupling NIR and Mössbauer spectroscopy for matched sets of high-Ca pyroxenes and here present initial efforts toward testing the role of exsolved phases in producing the observed anomalies.

Materials: The samples are 36 terrestrial high-Ca pyroxenes in 12 sets of two or more each. Compositions within a set are very similar. A total of 12 samples show "normal" (Type A) spectra, 16 anomalous (Type B), and 8 intermediate or uncertain patterns. Compositions were determined by electron microprobe, with Fe^{2+} and Fe^{3+} by wet chemistry. Most of these have been previously published along with their NIR spectra [1, 4]. X-Ray diffraction (XRD) patterns exist for some of them and are being re-examined.

Procedure: Exsolved phases, in addition to pyroxene polymorphs, can include oxides, especially chromite [3]. Whether Fe-bearing silicate or oxide, these exsolved phases could account for the Mössbauer anomaly and perhaps for the unusual NIR absorption also. We are examining this possibility by considering composition, XRD, Mössbauer spectroscopy at low temperature, and more detailed microscopic analysis. Some experimental work may also be warranted.

Preliminary results, Cr content: Table 1 is consistent with the possibility that chromite exsolution plays a role.

Table 1. Cr per 6 O for 36 high-Ca pyroxenes

Samples:	All	Uncertain	Normal (A)	Anomalous(B)
n:	36	8	12	16
Mean:	0.00506	0.00175	0.00350	0.00756

The ratio of average Cr in anomalous to that in normal samples is 756/350 = 2.16, a highly suggestive figure.

Acknowledgements: We thank Jeremy Delaney and Bob Housley for helpful discussion.

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COMPOSITIONAL VARIATIONS AMONG CK CHONDRITES.

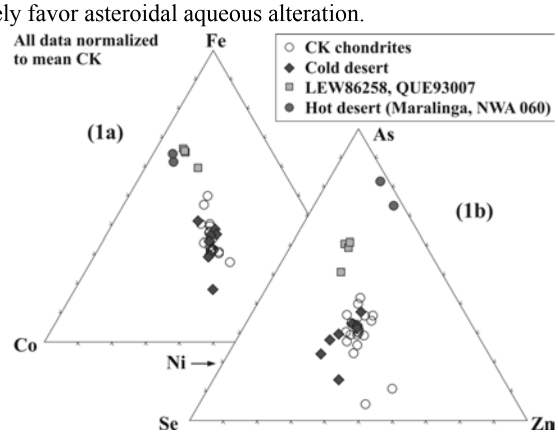
H. Huber, A.E. Rubin, G.W. Kallemeyn, and J.T. Wasson. Institute of Geophysics, University of California, Los Angeles, CA 90095-1567, USA. e-mail: hhuber@ucla.edu.

Although only two CK-chondrites are observed falls (Karoonda, Kobe), recoveries in Antarctica, Australia, and North Africa have produced a large group of about 30 distinct fall localities. The large variations in the abundance of several siderophile elements were previously ascribed to terrestrial weathering. Metal is rare in CK chondrites and the siderophiles are largely in sulfides and rare accessory phases such as Pt-Au-telluride that may be susceptible to weathering. Much of the Fe is present as magnetite. Other (e.g., nebular) processes were also thought to be able to account for the variations in CK siderophiles.

We have obtained additional bulk neutron-activation analysis data on CK chondrites and are again struck by the heterogeneous distribution of siderophiles. For example, ratios of siderophiles in EET99430 (CK4) to those in NWA060 (CK5) are Fe 0.94; Co 2.9; Ni 6.5; Ir 1.2; and Au 6.3. Interestingly, the more refractory elements Os and Ir are not affected by the depletion mechanism. The new data were combined with older UCLA data and plotted on triangular diagrams (Fig. 1).

We examined the following possible explanations for such variations: (1) they were established by processes such as metal-silicate fractionation in the solar nebula; (2) they were produced by impact mobilization of phases in the parent body; (3) they were produced during transport by aqueous phases in the parent body; or (4) they are the product of terrestrial weathering.

According to currently available data the fairly uniform distribution of Co and Se within sampling duplicates rules out the hypothesis that siderophile variations in different CK chondrites are due to impact mobilization of mineral phases on a scale of centimeters. Since most of the finds come from Antarctica and some from hot deserts (Maralinga, NWA 060) the question of site-dependent weathering arose. However, the group with low siderophile element contents (i.e., Co, Ni) contains samples from both hot and cold deserts (Fig. 1a); more consistent with a general loss in meta-sulfide components than by local weathering effects. The loss in Co and Ni is accompanied by depletions in the volatile elements As and Zn (Fig. 1b). The depletion of soluble elements such as Mg, Mn, and Na suggests aqueous transport either in the parent asteroid or during terrestrial weathering. The low Co/Fe and Ni/Fe ratios may reflect the immobilization of Fe in magnetite. We would expect more variations among replicates if terrestrial weathering was the primary effect; thus, we tentatively favor asteroidal aqueous alteration.



UREILITE GEOCHEMISTRY AND SMELTING

P. Hudon and D.W. Mittlefehldt. NASA Johnson Space Center, 2101 NASA Road 1, Mail code SR, Houston, TX 77058 United States. E-mail: pierre.hudon1@nasa.gov

Introduction: Ureilites are ultramafic achondrites composed primarily of olivine and pyroxene, and containing 7-66 mg/g elemental C. Recent petrologic studies have supported carbon-silicate redox ("smelting") reactions as the major petrogenetic process responsible for the positive correlation between modal pigeonite and mg# and the negative Fe/Mn-mg# trend seen in mineral and bulk compositions of ureilites. In this model, ureilites with the largest mg# are the most reduced, experienced the highest temperatures, and formed at the lowest pressures, nearer the ureilite parent asteroid surface [1]. Ureilites with the highest mg# also have the most negative ^{17}O [2]. We did carbon content and isotopic composition, and petrologic studies of a suite of ureilites to test the smelting model [3]. One might expect that olivine core mg# would be negatively correlated with carbon content, and positively correlated with isotopic composition. Sadly, our results did not match these expectations.

Geochemistry: The strong negative correlation between ureilite bulk rock Fe/Mn and mg# is consistent with the smelting model, but requires that metal reduced from the silicates was lost during this process. This metal would have scavenged other siderophile elements, and should lead to strong negative correlations between, e.g. Co and mg#. Sadly, such is not the case. Early work on ureilites noted that the C-rich matrix (often called "veins") was enriched in siderophile elements. This could lead to scatter in trace siderophile element contents if variable proportions of the C-rich matrix were sampled for analysis. However, the distribution of Co-Fe in ureilite analyses shows sampling problems do not significantly impact the data.

Literature data on paired magnesian ureilites ALH 82130 and ALH 84136 (bulk mg# 90.7; olivine core mg# 95.2) yields averages of 58±2 mg/g Fe and 106±4 µg/g Co, while moderately ferroan ureilite PCA 82506 (bulk mg# 78.1; olivine core mg# 79.1) yields 138±2 mg/g Fe and 90±2 µg/g Co. Each of these ureilites is relatively homogeneous in Co content. The very similar Co contents at much different Fe contents indicate that removal of metal via a smelting process is not responsible for the difference in bulk rock or olivine core mg#.

Discussion: If the smelting process did not engender the differences in bulk rock Fe, how are they to be explained? The smelting model already required a heterogeneous ureilite parent body to explain the mg#- ^{17}O correlation [1]. We suggest that the oxidation state of the accreted silicates was also heterogeneously distributed – those ureilites with the most negative ^{17}O accreted more reduced silicates than those with a less negative ^{17}O [cf. 2]. Because there was little FeO in the protolith, the total cation/Si ratio of the silicate system was low, and hence the pyroxene/olivine ratio was high in the high mg# protolith compared to the low mg# protolith. Thus, the noted mg#-modal pyroxene correlation [1] may largely have been inherited from the protolith and survived partial melting. Heterogeneous accretion does not obviously explain the observation of fine-grained metal commonly included in pyroxene, but absent from olivine [1].

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SHORT-LIVED RADIONUCLIDES IN THE EARLY SOLAR SYSTEM: THE PROMISE AND THE PROBLEMS.
G. R. Huss. Department of Geological Sciences and Center for Meteorite Studies, Arizona State University, Box 871404, Tempe, AZ 85287-1404. gary.huss@asu.edu

Introduction: Short-lived radionuclides ($t_{1/2}$ < ~30 Ma) were present in the early solar system, but their initial abundances have since decayed away. These nuclides potentially provide a wealth of information about the early solar system. They provide information about the last input(s) of newly synthesized material into the solar system. They may provide high-resolution chronometers of early-solar-system events. They may have been a major heat source for metamorphism, melting, and differentiation in asteroids. They also provide a way to investigate the irradiation history of matter in the early solar system. As instrumentation and knowledge of early-solar-system materials improves, we are able to extract more of this information. In my talk, I will review what is and is not known about short-lived radionuclides.

Stellar Sources: Each type of star that ejects newly synthesized matter into the interstellar medium is a potential source of short-lived radionuclides to the early solar system. Each source produces different relative abundances of the various radionuclides, which serve to fingerprint the stellar source [e.g., 1]. We are getting closer to reliable estimates of the initial abundances of radionuclides in the early solar system, and may soon be able to confidently identify their source(s).

Chronology: ^{26}Al and ^{53}Mn have so far shown the most promise as chronometers, but ^{60}Fe also has potential. Identifying objects that have not been affected by metamorphism has been and continues to be a major challenge. Samples suitable for dating must also have a sufficiently large parent-daughter elemental fractionation. The current data indicate a 1-2 Ma time gap between the formation of CAIs and ferromagnesian chondrules [e.g., 2]. But the issue of whether differences in the initial abundances of short-lived radionuclides reflect time differences or isotopic heterogeneity in the nebula has not been resolved.

Heat Sources: ^{26}Al seems to have been sufficiently abundant to drive metamorphism in asteroids of up to ~100 km in diameter and to melt the interiors of larger asteroids [e.g., 3]. ^{60}Fe may also have been a significant heat source, but its initial abundance is not yet well constrained.

Irradiation History: ^{10}Be is produced efficiently by particle irradiation, but not at all efficiently in stars. Significant amounts of ^{10}Be were incorporated into CAIs when they formed [e.g., 4,5], so particle irradiation played a significant role in their history. Other radionuclides are also produced by particle irradiation. However, models that produce most of the short-lived radionuclides by irradiation [e.g., 6] are unlikely to be correct because to match the observed relative abundances, extreme conditions in the irradiating environment and a very specific structure of the CAI precursors are required [5]. In addition, the presence of ^{60}Fe in the early solar system requires a stellar input.

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PHASE EQUILIBRIUM EXPERIMENTS OF THE PARENT MAGMA FORMED NAKHLITES. N. Imae, National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515, Japan. E-mail: imae@nipr.ac.jp

Introduction: Nakhlites are clinopyroxenites and are one class of Martian meteorites. The most characteristic is that these are a cumulate igneous rock, suggesting that these experienced fractional crystallization between solid and melt in the Martian gravity field. Parent magma compositions of nakhlites have been obtained [e.g., 1]. However, the experimental studies of the phase relationship using a parent magma composition have not been sufficiently carried out [2], thus I examined it using the "NIM" composition obtained by [1] in detail in the present study. The study will play important role in understanding the crystallization processes of the parent magma formed nakhlites.

Experiments: A gas mixing vertical furnace was used for the experiments. Glass with the composition of "NIM" [1] was prepared using the reagent grade powder of oxides or carbonates: SiO_2, MgO, FeO, CaO, Al_2O_3, TiO_2, Na_2CO_3, and K_2CO_3. Powdered glass was pressed into the pellet, held with Pt-wire loop of 0.2 mm in diameter, and put into the furnace under the FMQ condition at fixed temperature. 23 experiments were carried out at temperatures ranging from 1010 to 1265 ^{o}C for durations ranging from a few to ~100 h. Polished sections of run products were studied using an electron probe microanalyzer (JXA-8200).

Results: The first phase appeared below 1240 ^{o}C, corresponding to liquidus temperature, is euhedral abundant small titanomagnetites of 2 μm in size. The TiO_2 content is 20 ~ 30 wt%. The second phase appeared below 1140 ^{o}C is euhedral abundant small augites of 2~5 μm in size. The composition is $En_{14-37}Fs_{21-55}Wo_{30-42}$. The third phase appeared below 1130 ^{o}C is irregular shaped scarce larger olivines of 10 μm in size. The composition is Fa_{50-73}. These titanomagnetites, augites and olivines in a run are compositionally homogeneous, irrespective of grains. The difference of the crystallization temperature of augite and olivine is small to be 10 ^{o}C. Augites trap smaller sized titanomagnetites of a few μm. Olivines trap larger sized interstitial melts of 20 μm as well as small titanomagnetites. Solidus temperature is 1030 ^{o}C.

Discussions: There are common characteristics between the run products in some runs and nakhlites: morphologies, constituting minerals and the compositions of these. The crystallization of three cumulative minerals of augites, olivines and titanomagnetites has been reproduced. The composition of augites is $En_{37}Fs_{21}Wo_{42}$ at the run on the condition of 1100 ^{o}C and 27 h. It is nearly identical with the composition of augite phenocryst cores in nakhlites ($En_{36}Fs_{25}Wo_{39}$) [3]. Trapped melts in olivines observed in many runs seem to correspond to the rounded vitrophyric inclusion in nakhlites [1]. Small titanomagnetite inclusions observed in augites in many runs are also seen in nakhlites.

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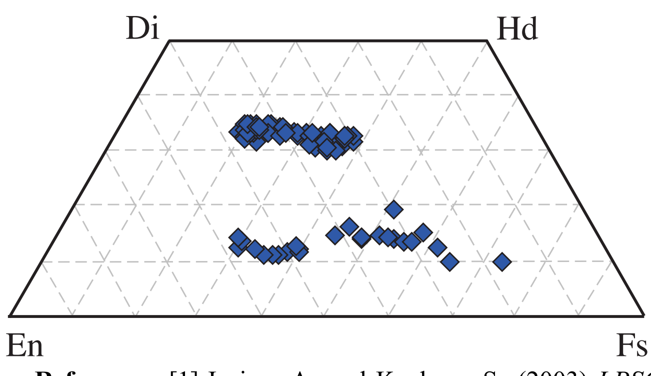
PETROLOGY AND REDOX STATE OF BASALTIC SHERGOTTITE NWA 3171. A. J. Irving[1], C. D. K. Herd[2], S. M. Kuehner[1], D. A. Gregory[3] and A. A. Aaronson[4], [1]Earth & Space Sciences, Univ. of Washington, Seattle, WA 98195; irving@ess.washington.edu, [2]Earth & Atmos. Sciences, Univ. of Alberta, Edmonton, Alberta T6G 2E3, [3]St. Thomas, Ontario, [4]Lagrange, Texas

Discovery: Algerian basaltic shergottite NWA 3171 is a fresh, 506 gram, greenish-gray stone partially coated by thin, black fusion crust exhibiting flow orientation.

Petrography: The sample consists mainly of subequal amounts of prismatic pyroxene and glassy maskelynite. Pyroxenes are zoned from cores of subcalcic augite ($Fs_{19.3}Wo_{33.1}$; FeO/MnO = 26.4) or pigeonite ($Fs_{29.9}Wo_{12.1}$; FeO/MnO = 28.2) to pigeonite rims (as ferroan as $Fs_{72.9}Wo_{9.8}$; FeO/MnO = 39.9), a pattern similar to that in Shergotty and Zagami. Maskelynite exhibits patchy compositional heterogeneity ($An_{41.5}Or_{3.7}$ - $An_{54.4}Or_{1.3}$). Accessory phases are ulvöspinel, ilmenite, chlorapatite, merrillite, pyrrhotite, Na-K-Al-Si-rich glass, silica (formerly stishovite, judging from radial fractures around some grains), rare baddeleyite, and rare barite and calcite (probably of terrestrial origin). Minor rusty staining occurring around ulvöspinel grains, and along thin, black (shock-produced?) veinlets across the specimen, appears to be a complex mixture of iron hydroxide and Si-Al-Ca-Mg-Cl-K-Br(?)-bearing phases (possibly pre-terrestrial). This specimen is not obviously paired with any of the other four African evolved, olivine-free basaltic shergottites NWA 480, NWA 856, Zagami or NWA 1669 [1].

Oxygen Fugacity: The compositions of coexisting ulvöspinel and ilmenite imply an oxygen fugacity during crystallization of 1.4 log units below the QFM buffer, similar to the values determined for other basaltic shergottites, specifically Shergotty, Zagami and Los Angeles [2].



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KAIDUN AMAZES AGAIN: UNEXPECTED UOC CHONDRULE.

M. A. Ivanova, A.V. Ivanov, and N. N. Kononkova, Vernadsky Institute of The Russian Academy of Sciences, Kosygin St. 19, Moscow 119991, Russia. E-mail: venus2@online.ru.

Introduction: The Kaidun meteorite is a unique breccia containing a broad variety of extraterrestrial materials formed in many different times, places, and ways. It contains EH3-5, EL3, CV3, CM1-2, and R chondrite clasts, new C1 and C2-type lithologies, unique alkaline-enriched clasts, impact melt products, phosphide-bearing clasts, vein- and cavity-filling materials, new enstatite-bearing clasts, and Ca-rich achondrite materials, but no OC [1]. It has been proposed that the parent body of Kaidun is Phobos [2]. Here we report results on an unusual Kaidun OC chondrule, including its petrography, mineralogy, bulk chemistry and oxygen isotopic compositions.

Results: A rounded 5mm object occurs in the main carbonaceous chondrite material of Kaidun [1]. Texturally the object is similar to POP chondrules and consists of Ol and Px embedded in mesostasis. Opaque minerals are chromite, kamacite, taenite, and pentlandite. Peripheral Ol grains are large and contain inclusions of glassy material and tiny crystals of Pl and Cpx. Central Ol grains are smaller and lack inclusions, but have Ca-Px reaction zones along boundaries. The central part also contains cavities filled with glass, pure calcite, and phyllosilicates.

Ol (Fa25) and Opx (Fs24 Wo2) are varied in composition, Ol is very zoned, PMD of Fa is 32 %, and correspond to L type. Px is present as Opx, pigeonite and augite. Main correlations of elements in Ol and Px resemble Ol and Px of UOC. Glass has plagioclase composition (Ab50 An47). Pl from inclusions in Ol is more Na-rich (Ab63 An35). Phyllosilicates in cavities fall in the smectite mixing line on the Fe-Al+Si-Mg diagram.

Like porphyritic chondrules from UOC, the chondrule is enriched in refractory lithophiles and depleted in siderophiles [3]. Compared to them, the chondrule is more depleted in K, Na, and siderophiles. The REE pattern has an unfractionated character and negative Eu anomaly. Oxygen isotopic composition is unusual, with ^{18}O=8.32 ‰ and ^{17}O=5.02 ‰ [4]. This is similar to the anomalous ordinary chondrite Dhofar 535. The chondrule falls at the ^{16}O-rich end of the oxygen isotopic diagram, continuing the line of ordinary chondrites.

Discussion: This chondrule from UOC with anomalous oxygen isotopic compositions is the first such found in Kaidun. Based on texture and bulk chemistry – lithophile-siderophile fractionation and REE pattern – the chondrule likely crystallized in space, before or during metal-silicate fractionation. The periphery crystallized quickly and Ol grains caught melts during crystallization; the central part crystallized more slowly, forming reaction boundaries and caverns. In the Kaidun parent body, the chondrule experienced aqueous alteration that lead to formation of calcite and smectite in cavities. This also may explain the chondrule's depletion in K and Na. It appears that ordinary chondrite-type material also took part in the formation of the Kaidun breccia.

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ARE MCCs DHOFAR 225 AND DHOFAR 735 OF CM3-TYPE?
M.A. Ivanova[1], L.V. Moroz[2], M. Schmidt[3,4], U. Schade[4], F. Brandstaetter[5], M.A. Nazarov[1] and G. Kurat[5]. [1]Vernadsky Institute of Geochemistry and Analytical Chemistry, Kosygin St. 19, Moscow 119991, Russia (venus2@online.ru). [2]German Aerospace Center, D-12489 Berlin, Germany. [3]Heidelberg University, D-69120 Heidelberg, Germany. [4]BESSY GmbH, D-12489 Berlin, Germany. [5]Natural History Museum, A-1014, Vienna, Austria.

Introduction: Dhofar 225 (Dh-225) and Dhofar 735 (Dh-735) are metamorphosed carbonaceous chondrites (MCC) with some similarities to the Antarctic MCCs B-7904 (CM) and Y-86720 (CM) [1]. Based on our previous data and new results obtained using in situ synchrotron IR microspectroscopy (SIRM) we discuss the possible genesis of Dh-225 and Dh-735 by dehydration of matrix phyllosilicates. In addition, we studied a new Ca,Fe-oxysulfide [2].

Results: In texture and petrography, Dh-225 and Dh-735 are similar to CM chondrites [1]. However, Dh-225 contains the first Ca,Fe-oxysulfide found in nature [2]. Its best-fit stoichiometry and low analytical total indicate a formula of $(Ca_{4.66}\ Fe^{2+}_{0.34})5Fe^{3+}_{6}S_5O_9$. Another possible formula is $Ca_4Fe^{2+}_5S_4(OH)_4O_3$, but the Ca,Fe-oxysulfide inclusions appear to lack OH because they are stable under the electron beam. Moreover, absorption bands of structural OH at 2.7 µm were not detected in these grains by SIRM.

Matrices of Dh-225 and Dh-735 are very fine-grained, similar to the MCC's, have high EPMA totals, are depleted in Fe and S, and contain small grains of olivine, troilite, taenite, and tetrataenite [1,2]. The bulk composition of Dh-225 is low in H_2O (1.76 wt.%) and Fe. No signatures of O-H bonds (in structural OH and/or bound H_2O) at 2.7-3 µm were detected in the Dh-225 and Dh-735 matrices by SIRM, suggesting a lower content of hydrated phases, phyllosilicates and tochilinite, as compared to those in CMs. The O-H absorption bands were identified by SIRMs in the matrix spectra of CMs Cold Bokkeveld, Murray and Mighei, and in tochilinite inclusions of Murray, studied for comparison. Further evidence for the dehydrated state of the Dh-225 and Dh-735 matrices is the position and shape of strong bands around 10 µm due to Si-O vibrations, being consistent with fine-grained Fe-rich olivine. The positions and shapes of the Si-O bands in the IR spectra of the typical CM2 matrices are different, being consistent with mixtures of Fe-rich and Mg-rich phyllosilicates.

Discussion: Dh-225 and Dh-735, the first non-Antarctic MCC meteorites, expand the MCC group and have similar oxygen isotopic compositions [2]. They apparently have experienced heating after aqueous alteration. No water-bearing mineral was detected in their matrices, indicating that phyllosilicates were dehydrated. The materials were heated above 245 ^oC, since tochilinite disintegrates into troilite and oxides at 245 ^oC. The absence of this phase distinguishes MCCs from CMs. The presence of dolomite in Dh-225 and Dh-735 indicates an upper limit of the temperatures reached of ~700 ^oC. Although all MCCs underwent aqueous alteration followed by heating to different degrees [3], they may be considered as CM3 chondrites according to the general characteristics of the petrological type 3 chondrites. However, the meteorites differ from CMs also in the bulk abundances of some refractory, (enriched in Ti and Al), siderophile (depleted in Ni and Fe), and moderately volatile elements (enriched in P and K). It is unlikely that these differences in bulk chemistry are the result of metamorphism, therefore Dh-225 and Dh-735 may represent a separate group of carbonaceous chondrites of type 3 (also supported by oxygen isotopes).

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U-Th-Pb SYSTEMATICS IN CHONDRITES

E. Jagoutz, R. Jotter, A. Kubny, W. Zartman, G. Dreibus
Max Planck Institut für Chemie Planetology

Introduction: Over the past 30 years continuous improvements have been made in the analytical capabilities to measure Pb isotopic composition. Since the return of the first lunar samples by the Apollo 11mission, chemistry Pb blanks have been lowered from ~1ng to ~1 pg . Also, the increased sensitivity of the mass spectrometer now makes it possible to measure quite precisely the isotopic composition of 100 pg of Pb. However, most of the existing U-Th-Pb data for meteorites were obtained prior to these significant improvements, and mainly on bulk rock samples before very clean mineral separates were available.

U-Th-Pb isotope systematics in chondrites have always presented us with an unsolved problem in cosmochemistry. Although their Pb-Pb isochrons give ages close to 4.55 Ga, the U-Pb and Th-Pb systems are heavily disturbed. In most cases they contain more radiogenic Pb than can be accounted for by the present U and Th concentrations. The origin of this so-called excess Pb component has been under discussion for many years.

Results: We present here the results of a study, in which we have measured U, Th, and Pb isotope systematics in fragments and mineral concentrates from four different chondrites (Pantar H5, Leighton H3/5, Rumuruti and Zag). In particular, we designate the fragments as being of dark or light lithology, and identify the mineral concentrates as plagioclase or sulfide. Also, included are the fused crusts of two of the chondrites. Although the dark lithology has been shown to be enriched in volatile elements, such as Cl Br, K, compared to the light lithology, we do not find the dark lithology to be preferentially enrichment in radiogenic Pb.

Discussion: While on a ^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb diagram the samples lie close to a 4.57 Ga Pb-Pb isochron, they are heavily disturbed on a ^{206}Pb/^{204}Pb vs. ^{238}U/^{204}Pb diagram. In the latter diagram about half of the data plot above a 4.57 Ga reference isochron, indicating that the Pb is more radiogenic than would be produced by the measured ^{238}U/^{204}Pb ratio. However, at least one sample does plot significantly below the reference isochron and suggests the possibility of some internal re-distribution of Pb. In the ^{208}Pb/^{204}Pb versus ^{232}Th/^{204}Pb diagram the samples plot only on or above the reference isochron, implying that disturbed systems only gained radiogenic Pb.

Conclusions: While some of the excess Pb could be explained by the infiltration of terrestrial Pb into the chondrites, many aspects of these data cannot be explained this way. Nonetheless, the Pb re-distribution must be a young event, possible related to shock metamorphism at the time of excavation from the parent body. Such data hold promise of giving better insight into the mechanism and timing of Pb re-distribution. We plan to extend this study to other meteorites and an examination of the relationships within coexisting mineral suites.

TERRESTRIAL AGES OF METEORITES USING ^{14}C AND $^{14}C/^{10}Be$: SOME NEW RESULTS FROM ANTARCTICA.

A. J. T. Jull[1], L. R. McHargue[1], S. La Motta[1], J. A. Johnson[1], K. J. Kim[2] and R. C. Reedy[2]. 1NSF-Arizona AMS Laboratory, University of Arizona, Tucson, AZ 85721, USA. E-mail: jull@email.arizona.edu. 2 Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131. Email: rcreedy@unm.edu

Introduction: It is important to determine the terrestrial age, or residence time, of a meteorite on the surface of the Earth, as this gives us useful information which can be applied to studies of infall rates, meteorite distributions, weathering of meteorites and meteorite concentration mechanisms. The study of the terrestrial ages of these meteorites gives us useful information concerning the storage and weathering of meteorites and the study of fall times and terrestrial age. We would expect that weathering of meteorites and their eventual destruction would be a function of the terrestrial age. In addition, weathering would affect trace-element composition. However, a direct connection of weathering rates to the terrestrial survival times of meteorites was initially shown by Wlotzka et al. [1] and later by Bland et al. [2,3].

Terrestrial ages of meteorites have been determined by the concentration of ^{36}Cl, ^{14}C or ^{41}C, measured independently or also in combination. With measurement of more than one radionuclide, we can correct for shielding effects [4-6]. At our laboratory, we make measurements of ^{14}C and $^{14}C/^{10}Be$. We previously considered that the production rate of $^{14}C/^{10}Be$ should be reasonably constant at ~2.5 to 2.6 [7,8]. Recently, we have also undertaken some modeling calculations [9] to determine if we can assume a constant production rate of ^{14}C and ^{10}Be.

The smaller size of many Antarctic meteorites may result in lower $^{14}C/^{10}Be$ ratios. We have obtained more than 200 ^{14}C terrestrial ages on Antarctic meteorites, from many different sites.

Trends in terrestrial ages: The trends in terrestrial age are that some sites exhibit older terrestrial ages than others. The Allan Hills Main icefield, Elephant Moraine and Queen Alexandra Range tend to have many meteorites beyond the range of ^{14}C (>40kyr). Other Allan Hills sites and the Yamato region show a much younger age distribution. It is important to be able to understand differences in the production rates of ^{14}C. We will discuss our results in terms of recent modeling calculations for ^{14}C and ^{10}Be [9]. We have also studied the terrestrial-age distributions of various achondrites and compared the age distributions to ordinary chondrites.

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