

μm) chondritic particles. W7027C5 exceeded the dimensions of the x-ray beam, thus we underestimate the total Fe present and can infer only a lower limit on its density. The mean particle density is 1.2 g/cc, suggesting a density of about 1 g/cc is appropriate for orbital evolution and entry heating models. References: (1) Flynn G. J. and Sutton S. R. (1988) *Meteoritics* **23**, 268–269. (2) Fraundorf P. *et al.* (1982) *LPS* **13**, 225–226.

Excess fission xenon in meteorites. T. D. Swindle,¹ C. M. Hohenberg,² R. H. Nichols,² C. T. Olinger² and D. H. Garrison.³ ¹Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA. ²McDonnell Center for Space Science, Washington University, St. Louis, MO, USA. ³NASA/JSC, Houston, TX, USA.

All gas-rich lunar highland breccias, and some other lunar samples, contain excess fission xenon, xenon which was apparently produced by decay of ²⁴⁴Pu and ¹²⁹I within the moon, and then somehow incorporated near the surfaces of grains within the regolith (1). Finding the same effect in a gas-rich meteorite might be useful both to determine the timing of asteroidal regolith exposures and to constrain models of incorporation of excess fission xenon on the Moon.

Xenon matching many characteristics of lunar excess fission xenon has been identified in two howardites. In Kapoeta, grain-size separates reveal a surface-correlated fission-like component (2), although ordinate-intercept plots give a composition closer to H-Xe than to a true fission xenon component. In Bholghati, a lightly-bound (low-temperature) fission-like component has been found in stepwise heating (3), although the spectrum is again uncertain. These data, along with data from two other gas-rich meteorites, have been re-analyzed to try to pin down the fission composition.

For the Kapoeta data, three individual data sets [two grain-size separate experiments (2) and stepwise heating data (2, 4)] define linear correlations on three-isotope plots of ¹³⁶Xe/¹³⁰Xe vs. ¹²⁶Xe/¹³⁰Xe. Assuming that there are two components, and that one component is solar xenon plus a fission component, the composition of the assumed fission component can be calculated from the values of the correlation lines at ¹²⁶Xe/¹³⁰Xe = 0.0263 (the solar value). A weighted average of the three compositions is consistent with either H-Xe or ²³⁸U fission. For Bholghati, a similar analysis gives a composition close to ²³⁸U for ¹³²Xe/¹³⁴Xe/¹³⁶Xe, but with anomalously high ¹³¹Xe. Combined, these suggest the possibility of U fission, which would suggest that the component was acquired more recently than 4Ga ago. However, Kapoeta and Bholghati have “fission” components with ¹²⁹Xe/¹³⁶Xe of 0.73 ± 0.48 and 0.80 ± 0.26, respectively, which suggests an earlier acquisition (since the progenitor, ¹²⁹I, has such a short half-life).

In each stepwise heating experiment on Pesyanoe (5, 6) and Fayetteville (7), a low-temperature step is enriched in heavy (fission-derived) xenon isotopes, although in some cases, the enrichment is apparently generated by terrestrial contamination. Since the data do not define linear correlations, the decomposition was done assuming a mixture of SUCOR, an appropriate fission-poor temperature step (which also contains some SUCOR) and the unknown component. Choosing the appropriate fission-poor component is somewhat arbitrary, but two Pesyanoe samples analyzed by (5) seem most consistent with ²⁴⁴Pu fission, while the Fayetteville data could be consistent with either ²⁴⁴Pu or terrestrial contamination.

In summary, there is clear evidence for excess fission xenon in meteorites. However, the present data are not sufficiently precise to determine the progenitor with accuracy for any class of meteorite, suggesting the need for more work. References: (1) Swindle T. D. *et al.* (1986) *Origin of the Moon*, p. 331. (2) Garrison D. H. *et al.* (1987) *Meteoritics* **22**, 382. (3) Swindle T. D. *et al.* (1989) *LPS* **20**, 1095. (4) Rowe M. W. (1970) *GCA* **34**, 1019. (5) Marti K. (1969) *Science* **166**, 1263. (6) Shukolyukov Yu. A. *et al.* (1983) *Geochem. Int.* **20**, 96. (7) Manuel O. K. (1967) *GCA* **31**, 2413.

Asteroidal sources of dust at the Earth's orbit. Mark V. Sykes. Steward Observatory, Univ. of Arizona, Tucson AZ 85721, USA.

Collisional dust production in the asteroid belt is evidenced by the zodiacal dust bands discovered by the Infrared Astronomical Satellite (1). Small particles are removed from the asteroid belt by radiation forces, including Poynting-Robertson drag which secularly reduces their

semi-major axes. The spatial distribution of particles deriving from the dust bands at a given time is defined by a torus having a squarish radial cross-section. Particle number densities increase toward the edges and are maximum at the “corners” (the locus of pericenters and apocenters of the particle orbits). As the particle orbits decay and their eccentricities decrease, the radial width of the torus decreases. Secular gravitational perturbations cause the tori to be inclined with respect to the ecliptic plane with an angle and ascending node which are a function of semi-major axis. Eventually these tori come within 1 AU of the sun and are intercepted by the earth. The result is an annual modulation in the flux of interplanetary dust as the earth samples different locations within a given torus. Only tori having low proper inclinations are likely to have their maximum densities sampled. The initial density and orbital elements of the dust in their source region will determine the amplitude of modulation at the earth's orbit and the ecliptic longitude of peak flux of dust deriving from that source. The principal asteroidal sources of modulations in the interplanetary dust flux at the earth's orbit is expected to derive from the low-inclination α and β bands, which have been associated with the Themis (C-type) and Koronis (S-type) asteroid families, respectively (2). By determining the components of interplanetary dust which are varying, and the longitudes of their maximum spatial density, it will be possible to identify material from these and possibly other source regions in the asteroid belt, thereby determining the mineralogies associated with specific asteroid taxa. References: (1) Low F. J. *et al.* (1984) *Astrophys. J. (Letters)* **278**, L19–L22. (2) Sykes M. V. (1989) *Icarus*, submitted.

Chemical compositions of Fremdlinge from an Allende inclusion. P. Sylvester, B. Ward and L. Grossman.* Department of Geophysical Sciences, The University of Chicago, Chicago, IL 60637, USA. *Also Enrico Fermi Institute.

Fig 6 is a Type B1 calcium-, aluminum-rich inclusion (CAI) from the Allende meteorite. It contains numerous metal-magnetite-sulfide-phosphate aggregates known as “Fremdlinge”. We have determined the bulk chemical compositions of nine, tiny (0.2–10.5 μg) Fremdlinge from this inclusion by INAA. The refractory siderophiles are fractionated from one another relative to C1 chondrites. For example, Re/Os ratios range from 0.82–1.02 times C1 values. Ir/Pt ratios vary from 0.4–1.7 times chondritic. W and Mo show both enrichments and depletions relative to C1 chondrites. In cases where both are depleted, the W depletion is larger. This is opposite to what is expected from condensation from an oxidizing gas, a model used previously (1) to explain W and Mo depletions in Fremdlinge and bulk CAIs. W was probably removed from Fremdlinge during secondary alteration (2).

It is not possible to successfully model these data assuming condensation of all the refractory siderophiles into a single phase. In such a model, Re/Os and Ir/Pt ratios are never less than the chondritic ratios, because Re is slightly more refractory than Os and Ir is more refractory than Pt. If the condensing alloy is fractionated at high temperatures, alloys that subsequently condense will have Re/Os ratios less than chondritic. At the temperature of removal of early alloy, however, insignificant Ir will have condensed, so that subsequently condensing alloys will never have subchondritic Ir/Pt ratios. Similar problems are found for other element ratios.

An alternative model that explains all the fractionations of the refractory siderophiles assumes condensation of three alloys with different crystal structures. At high temperatures, W and Mo are known to form complete solid solutions in an alloy with a bcc structure, whereas Re, Os and Ru form complete solid solutions with one another in alloys which have hcp structures and Ir, Pt and Rh do so with fcc structures. Thus, solar nebular condensation calculations were used to compute the relative proportions of W and Mo in one alloy, Re, Os and Ru in another alloy and Ir, Pt and Rh in a third. Fractionations between elements that condense in the same alloy are explained by removal of an early, high temperature condensate, equilibration of subsequent condensates over a range of temperatures and mixing of the latter with some of the previously removed early condensate. Fractionations between elements that condense in different alloys are then simply explained by mixing different proportions of the 3 alloys. During formation of each Fremdling, mixing of many individual condensate grains occurred in the nebula and/or during CAI melting. References: (1) Fegley B. and Palme

H. (1985) *EPSL* 72, 311–326. (2) Palme H. *et al.* (1989) *LPSC* 20, 814–815.

Association of diogenites and cumulate eucrites in Yamato 791439 and their genetic link. Hiroshi Takeda and O. Hidaka. Mineralogical Inst., Faculty of Science, Univ. of Tokyo, Hongo, Tokyo 113, Japan.

Crystallization and impact histories of the HED parent body have been deciphered from the mineralogy and chemistry of a suite of the Yamato achondrites (Y75032 group) intermediate to diogenite and cumulate eucrite (Takeda and Mori, 1985). A new specimen Y791439, 51 has been investigated by electron microprobe and compared with the Y75032 group. The shock textures and mineral chemistry indicate that Y791439 belongs to the Y75032 group but contains more clasts of cumulate eucrites. One characteristic of Y791439 is that cumulate eucrites such as Fe-rich as Serra de Magé (SM) and Moore Co. (MC) with larger amounts of plagioclase, are abundant as clasts and pyroxene fragments. The exsolution textures of inverted pigeonites and chemistry of such clasts are similar to SM. Six clasts of this kind up to 2.8×2.3 mm in size have been found in the thin section. Two pyroxene fragments contain thick (001) exsolution lamellae similar to MC.

Pyroxene compositions in Y791439 fall in a limited range from mg number = $Mg \times 100 / (Mg + Fe) = 70$ to 50. The chemical variation of pyroxenes is larger than that of the monomict Y75032 group. The Mg-rich end is an Fe-rich diogenite-like pyroxene ($Ca_2Mg_{66}Fe_{31}$) common in Y75032, but the range extends more to the Fe-rich side. Y791439 contains pyroxene clasts ($Ca_{11}Mg_{53}Fe_{36}$) texturally like that in MC and small fragments of ordinary eucrites such as Juvinas. Chemical compositions (An mol%) of all plagioclase fragments fall between 93 to 87 and the range is smaller than that of the diogenite-rich members of the Y75032 group. Chromite crystals are present in pyroxenes and show intermediate chemistry to cumulate eucrite trends.

An versus mg number of the clasts distribute along cumulate eucrite (mg 63.5, An 91.5) to ordinary eucrite (mg 48.7, An 88.0) crystallization trend. This trend contrasts with that of diogenite-rich members such as Y791466, which shows an An-variation trend with nearly constant mg number. Y791439 sampled more cumulate eucrite components, especially of the MC-type, than diogenitic ones, but the Binda-type are also present. Y791439 shows a more polymict nature than the other Y75032 group, but the lithic variability is more limited and large lithic clasts are more abundant than normal howardites. The association of large amounts of smaller numbers of clast types suggests that it sampled by an impact three or four layers of the layered crust or pluton produced by the crystal fractionation, but did not sample deeper Mg-rich diogenites as in howardites and diogenites. Y791439 may best be classified as a polymict cumulate eucrite with small diogenitic and rare ordinary eucrite components. The presence of such a link material is a good indication of their genetic relationship.

We thank NIPR for the sample. References: Takeda H. and Mori H. (1985) *Proc. Lunar Planet. Sci. Conf.* 15th, C636–C648.

Lunar regolith: Its characterization as a potential resource for a lunar base. Lawrence A. Taylor. Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996, USA.

The entire lunar surface is covered by a layer of fragmental and unconsolidated rock material—the “regolith”. In fact, all of the 382 kg of lunar samples returned by the 9 lunar missions were collected from this. The unconsolidated nature of the regolith makes it relatively easy to move, mine, and otherwise manipulate. Indeed, the rocks, minerals, and regolith on the moon will be the raw materials with which to construct a lunar base.

The soil, the finer fraction (<1 cm) of the unconsolidated regolith, was formed by three basic processes: 1) simple *comminution*—disaggregation of rocks and minerals into smaller particles by micrometeorites (which are also incorporated into the soil); 2) *agglutination*—the welding of lithic and mineral fragments together by the glass resulting from micrometeorite-produced impact melt; and 3) solar-wind *spallation and implantation*. The soil consists of rock, mineral, and glass fragments and agglutinates. The glasses are of two origins: 1) impact melt and 2) volcanic magma, explosively discharged and with coatings of volatile components. The presence of solar-wind H and C caused an “auto-reduction” of the soil during impact melting to produce single-

domain (40–330 Å) Fe⁰ in the agglutinitic glass. Unfortunately this abundant native Fe metal in the soil is too fine-grained for easy concentration; beneficiation, involving grain-size coarsening, will be necessary to bring this native Fe up to “ore” grade. The single-domain signature, “ I_0/FeO ”, was recognized by McKay *et al.* (1974) as a measure of the quantity of agglutinitic glass and maturity (exposure age) of a soil. Morris (*et al.*, 1976) performed measurements of this parameter on numerous soils, thereby providing invaluable data for use in surveying soils for particular raw materials. In fact, this I_0/FeO is also indicative of the solar-wind content of the soil—higher maturity indicating greater amounts of H, He, C, *etc.*

Raw Materials. In order to consider habitation on the Moon, it is necessary to have abundant **WATER**. *Ilmenite* and possibly spinel are starting materials from which oxygen can be easily extracted by reduction processing (Gibson and Knudson, 1988). Solar-wind hydrogen is abundant (≈ 100 ppm) in lunar soil and is easily recovered by heating to 600 °C (Carter, 1985). Another valuable solar-wind component of the soil is **helium** (≈ 40 ppm) which is the most prized of the reactants for nuclear fusion—in fact, it may be the only true economic “ore” on the Moon (Kulcinski, 1988). **Native Fe** is abundant in mare basalts and soils, particularly in the agglutinates. Volcanic glass beads possess abundant coatings of **volatile elements** (*e.g.*, Cl, Na, Zn, S). Concentrations of this material occur in certain deposits, such as in the Apollo 17 “orange soil” (74220). **Sulfur** is also abundant in the soil in the mineral troilite (FeS). Several metals can be extracted from the soils and rocks, such as Al, Si, Ti, Co, Ni, *etc.* As a bulk material, lunar soil can be used as housing *insulation against cosmic rays*, as well as within space vehicles. Perhaps *agglutinitic glass* can be concentrated by magnets (attraction of single-domain native Fe) and used for the fabrication and casting of certain structures. And of course, there is always the use of lunar soil as feed for making *cement* (à la T. D. Lin, 1988). The numerous potential uses for lunar regolith and soil only await fertile imaginations. References: Carter (1985) *Lunar Bases & Sp. Act. 21st Century*, 571. Gibson M. A. and Knudson C. W. (1988) *Proc. Space 88*, ASCE, 400. Kulcinski G. L. (1988) *Univ. Wisc. Press*, 20 pp. Lin T. D. *et al.* (1988) *Proc. Space 88*, 146. McKay D. S. *et al.* (1974) *PLSC* 5, 887. Morris R. V. (1976) *PLSC* 7, 315.

Twenty years since Apollo 11: What have we learned about the Moon?

Stuart Ross Taylor. Lunar and Planetary Institute and Australian National University.

Before the Apollo landing on 20 July 1969, facts about the moon were restricted to information about the lunar orbit, angular momentum and density. Speculations about composition and origin were effectively unconstrained. Statements that running water carved the lunar rilles, that many of the large craters were volcanic calderas, that ice was present in a permafrost layer, that the maria were full of dust, that the maria were only a few million years old, that the lunar highlands were composed of granite or covered with volcanic ash-flows, that a ‘lunar grid’ reflected tectonic stress patterns, that tektites came not only from the Moon, but from the crater Tycho, and that the Moon was essentially a primitive undifferentiated object, were all published in the serious scientific literature.

The Apollo data immediately swept away much of this speculation. The maria were shown to be composed of basaltic lava flows, with ages close to 4 billion years. The postulated calderas were all due to meteoritic impact, the lunar highlands were mainly composed of anorthosite, the highland plains were ejecta sheets from large basin impacts, the ‘lunar grid’ was an artifact of the overlapping basin ejecta patterns, and tektites were terrestrial.

By 1974 the major conclusions about the evolution of the Moon had been established. At least 50% of the Moon was shown to have been melted, either during or shortly following accretion. The 100 km thick feldspathic highland crust had crystallised and floated on this ‘magma ocean’. The interior had crystallised by about 4.4 billion years into a zoned sequence of cumulate minerals. The enigmatic ‘KREEP’ was shown to be derived from the final few percent of residual melt from this magma ocean, thus accounting for the extraordinary near surface concentrations of the incompatible elements. The mare basalts represented partial melts derived from this zoned interior, erupting up to a billion years later as radioactive heating induced mantle melting. Prob-