for the ^{53}Mn/^{55}Mn ratio is 6×10^{-7} corresponding to ≤4554 Ma.

Moore County: The ^{53}Cr excesses measured in Chr and Sil are essentially the same: $0.89 \pm 0.07\,\varepsilon$ and $0.86 \pm 0.07\,\varepsilon$ respectively. This suggests that MC has equilibrated Cr isotopes and, most likely, ^{53}Mn was extinct when the ^{53}Mn-^{53}Cr system closed in MC. This is consistent with a young Sm-Nd age of 4456 ± 25 Ma [8]. The upper limit for ^{53}Mn/^{55}Mn is $\sim 2.5 \times 10^{-7}$, which corresponds to an age of ≤4549 Ma.

Serra de Magé: In contrast to MC, the ^{53}Cr excesses measured in SM phases are different: $0.60 \pm 0.08\ \varepsilon$ in Chr and $0.77 \pm 0.07\ \varepsilon$ in Px. With ^{55}Mn/^{52}Cr ratios of 0.015 in Chr and of 4.54 in Px the slope of the isochron yields a ^{53}Mn/^{55}Mn of $(4.4 \pm 2.3) \times 10^{-7}$ and an age of 4552+2/–4 Ma. This suggests that Mn-Cr in SM closed relatively early in EPB history and that its young ^{147}Sm-^{143}Nd age of 4410 ± 20 [9] dates a secondary event. However, the ^{146}Sm/^{144}Sm ratio of 0.0068 ± 0.0016 [10] still reflects and is consistent with the older ^{53}Mn-^{53}Cr age.

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POTENTIAL FOR PRESERVATION AND RECOVERY OF FOSSIL IRON METEORITES FROM COAL, TRONA, LIMESTONE, AND OTHER SEDIMENTARY ROCKS.

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Although meteorites have fallen onto the Earth throughout geologic time, fossil meteorites or paleometeorites (i.e., those that fell long enough ago to have been buried and preserved in sedimentary rocks) are quite rare. Iron meteorites oxidize rapidly, surviving only a few hundred years in most environments. Only a few fossil meteorites are known and their discoveries were largely matters of chance. The Lake Murray (Oklahoma) octahedrite, found in a Cretaceous sandstone, is the oldest known paleoiron [1]. Heavily corroded on the exterior, its Fe-Ni core was unaltered despite its 120-m.y. terrestrial age. More than one dozen Ordovician "paleochrondrites" have been recovered from limestone quarries at Brunflo and Österplana, Sweden. These paleometeorites are heavily altered and have been largely replaced by barite and calcite [2,3].

An iron meteorite falling into a coal swamp will develop a rind of pyrite, siderite, or rust, which inhibits alteration of the interior of the meteorite. After coalification, an iron meteorite encased in coal will be preserved from further corrosion by the reduced state of the coal, particularly in a coal seam with a methane-dominated vapor phase. The discovery of native Fe in coal indicates that iron meteorites could survive for millions of years in coal seams. Native Fe has been reported in a Cretaceous coal from the Dutch Creek Mine, Pitkin County, Colorado, where it occurs at the coal/coke interface adjacent to an intruding felsic porphyry dike [4].

Other sedimentary environments that may have been conducive to paleometeorite preservation include those in which trona, limestone, sandstone, shale, gypsum, secondary kaolin, or salt were deposited. Trona, a sodium carbonate mineral, is particularly favorable to the preservation of metallic Fe, because of the relatively high pH and strongly reduced state of groundwater in contact with the trona beds.

Estimates of the present-day flux of meteorites range from 100 to 1000 metric tons of meteorites per day for the whole of the Earth's surface [5], about 1% of which is recoverable or macrometeorites, giving an average macrometeorite flux of 1.8×10^{-7} g/m^2 yr. About 5% of these meteorites are strongly magnetic (i.e., iron, or stony-iron meteorites). If coal accumulated at the rate of 0.1 mm/yr, then every million short tons of coal should yield about 300 g of magnetic macrometeorites. A large Western U.S. coal operation such as the Black Thunder Mine in Wright, Wyoming, which mines more than 36 million tons of coal per year, could yield about 10,000 g of magnetic macrometeorites per year. Similar theoretical yield estimates have been made for other sedimentary rocks.

By examining materials captured by existing large electromagnets (used to remove "tramp" Fe, such as drill bits, from the mineral stream) suspended over conveyor belts at coal mines, it should prove possible to recover fossil iron meteorites from the coal. Efforts to recover fossil iron meteorites by this method are underway at coal mines in Pennsylvania, Wyoming, and Montana, and at trona mines in the Green River Basin of southwest Wyoming. This recovery method potentially can be applied to other sedimentary rocks such as limestone and secondary kaolin, the mines of which also often employ tramp metal electromagnets.

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HIBONITE-BEARING SPHERULES WITH EXTREMELY ALUMINOUS PYROXENE AND LARGE TITANIUM-50 ANOMALIES.

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Hibonite-silicate spherules are texturally simple objects, yet they are interesting and important because they typically contain relict hibonite and have large isotopic anomalies. We have studied both of the known glass-free, hibonite-pyroxene spherules, one from Murray (CM2) and one, first described by [1], from Y 791717 (CO3). They consist of assorted ragged, rounded, subhedral, and euhedral hibonite plates (~2 wt% TiO_2^{tot}) enclosed in Al-rich pyroxene that has up to ~80 mol% CaTs ($CaAl_2SiO_6$) component. In the Yamato spherule, Y17-6, chemical variations in the pyroxene are small, but in the Murray sample, MYSM3, the pyroxene is very strongly zoned, from 80 mol% diopside to ~80 mol% CaTs. The Mg-Si-Al relationships in the spherule pyroxenes are similar to those observed in fassaite from type B refractory inclusions. Abundances of MgO and SiO_2 are strongly correlated with each other and are anticorrelated with Al_2O_3, reflecting a strong anticorrelation between the diopside and CaTs components of the pyroxene. Contents of TiO_2^{tot} in the pyroxene are low (mostly <5 wt%) and, in contrast with previous results for type B fassaite, on a plot of MgO vs. TiO_2^{tot} we observe a great deal of scatter rather than a tight anticorrelation, possibly reflecting different relative distribution coefficients for Ti^{3+} and Ti^{4+} in the aluminous pyroxene of the spherules than in fassaite in type B inclusions. Chondrite-normalized REE patterns for pyroxene are similar to those of type B fassaite, but with lower abundances (e.g., La at 3–4× CI). Previously described hibonite-silicate spherules [2,3] have ^{26}Mg deficits but the present samples do not. Furthermore, the pyroxene in Y17-6 has excess ^{26}Mg while the hibonite it encloses does not, indicating that the two phases either had different initial ^{26}Al/^{27}Al ratios, or different initial ^{26}Mg/^{24}Mg ratios. The Ti isotopic compositions of the present samples are highly unusual: $\delta^{50}Ti = 101 \pm 17$‰ in MYSM3 and -69 ± 16‰ in Y17-6, both well outside the range (0–22‰) previously observed in hibonite-silicate spherules [2,3] and among the largest ^{50}Ti anomalies reported for any refractory inclusion.

The textures indicate that hibonite crystallized first but, based on the calculated bulk compositions of both spherules, it is not the liquidus phase in either sample, suggesting that the hibonite in both samples is relict. The presence of ragged hibonite grains in MYSM3 and, in Y17-6, rounded hibonite grains and a lack of isotopic equilibrium between pyroxene and hibonite support this conclusion. The spherules crystallized from liquid droplets that probably formed as a result of the melting of solid precursor grains that included hibonite. The heating events were too short and/or not hot enough to melt all the hibonite. The droplets cooled quickly enough that CaTs-rich pyroxene crystallized metastably instead of anorthite. Based on the observed heterogeneity in isotopic composition, it is unlikely that the precursors of the present samples formed in the same reservoir as each other or as the previously described hibonite-silicate spherules, providing further evidence of the isotopic heterogeneity of the early solar nebula.

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DISCOVERY OF IMPACTITE AT THE ODESSA METEORITE CRATER.

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The Odessa meteorite craters were formed by the hypervelocity impact of a type IAB iron meteorite [1] about 50,000 yr ago [1,2] in the high plains region of western Texas. The extraterrestrial nature of the Odessa craters was established by the presence of thousands of meteorite fragments [3], the morphology of the main crater [4], and by the existence of tons of microsopic meteoritic material surrounding the crater [5]. To this evidence we now add the discovery of small pieces of impactite containing metallic spherules found in the soil surrounding the Odessa craters.

The impactite at the Odessa craters was discovered during a preliminary examination of the magnetic fraction of soil samples from around the main crater. The impactite seems to be an ubiquitous component of the magnetic fraction of the soil within 300 m of the main crater's rim.

The impactite at the Odessa craters occurs as very small (<2 mm, typically ~200–500 μm), very fragile, dark, vesicular particles. No ponderable fragments of impactite are known to have been recovered from the Odessa site.

Our examination of the polished sections of the impactite shows the individual impactite particles exhibit a range of morphologies that fall between two endmember types. At one end the impactite particles are characterized as being very vesicular in nature, with some particles being dominated by void spaces. These particles often have relic mineral grains in addition to the metallic spherules embedded in the matrix. We refer to particles of this type as having a type I morphology (Fig. 1). At the other end the impactite particles are characterized by having a solid matrix that lacks any vesicles or relic mineral grains, with the matrix tending to be homogeneous in regions that contain the metallic spherules, but which may appear different in different regions of the same particle. We refer to particles of this type as having a type II morphology.

The mechanical strength of the impactite particles is very low. The particles are easily crushed by hand. Not all of the metallic inclusions are spherical. Many of them are irregular in shape and often resemble partial spherical shells or dumbbells. The irregular shapes are more commonly found in the more vesicular type I impactite.

Microprobe analysis of the metallic spherules in the impact show that (1) the Ni and Co abundances for all the spherules are significantly enhanced compared to the bulk composition of the Odessa meteorite; (2) the Co abundance is positively correlated with the Ni abundance up to a Ni abundance of about 50%, beyond which point the Co abundance is negatively correlated; (3) spherules in type I particles have Ni abundances in the range of 15–30%, whereas spherules in type II particles have Ni abundances that range from 20–70%; and (4) the elemental abundances of spherules within each particle are relatively similar with no particle containing spherhules that span the entire range of measured abundances. The features 1 and 2 are common characteristics of impactite spherules from other craters, as well as being characteristic of the metallic cores of deep-sea spherules [6].

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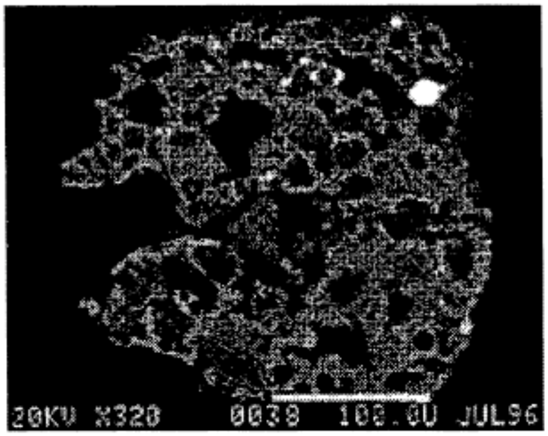

Fig. 1. BSEM image of a type I impactite particle. The metallic spherules appear as the white regions. Relic mineral grain can be seen in the lower left of the particle.

RHENIUM-OSMIUM ISOCHRON FOR IA METEORITES: FURTHER REFINEMENT OF THE THENIUM-187 DECAY CONSTANT.

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In the past few years substantial improvements were made to Re-Os techniques: (1) the application of NTIMS [1] gave about a five-fold gain in precision of the $^{187}Os/^{188}Os$ ratio and (2) the employment of the Carius tube digestion [2] and the mixed spike technique [3] yielded a similar gain in precision of the $^{187}Re/^{188}Os$ ratio. Together, these modifications resulted in increases of Re-Os isochron precision by an order of magnitude: Smoliar et al. [3] reported Re-Os isochrons with ±0.18% and ±0.28% slope uncertainties (IIA and IIIA isochrons, correspondingly); Shen et al. [4] reported a similarly precise (±0.23%) isochron for IIA irons, in good agreement with the result of [3].

However, the achieved high resolution cannot be used for precise comparison with other dating systems, since high uncertainty of the Re decay constant ($1.64 \times 10^{-11}y^{-1} \pm 3\%$ [5]) does not permit a precise calculation of isochron age from isochron slope. Recently, several attempts were made to refine this value: ($1.666 \times 10^{-11}y^{-1} \pm 1.2\%$) [3], ($1.660 \times 10^{-11}y^{-1} \pm 1.6\%$)

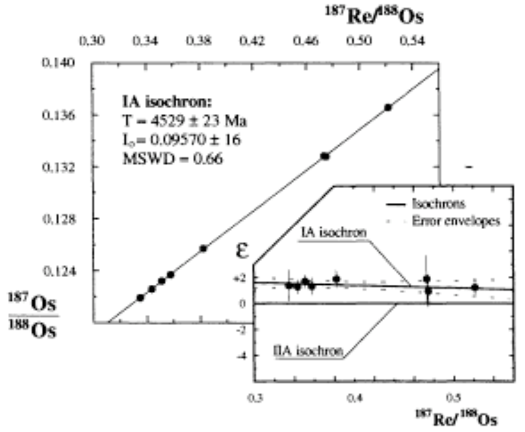

Fig. 1. Rhenium-osmium isochron for IA meteorites. The inset shows the data in ε form. ε values were calculated as absolute vertical deviation from the reference line (IIA isochron [3]) × 10^4. Error bars take into account errors in both $^{187}Os/^{188}Os$ and $^{187}Re/^{188}Os$ ratios.