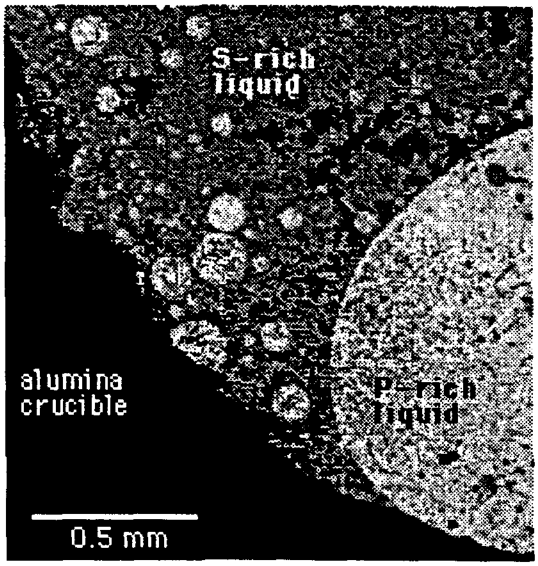

Fig. 1. A BSE image of an experimental run product showing the separation and settling of the denser P-rich immiscible metallic liquid.

implications for the crystallization method of the metallic cores. In order to match observed P values in iron meteorites, the core must crystallize in the presence of the P-rich liquid. The composition of the S-rich liquid, dictated by the liquid immiscibility field, has P contents much too low to reproduce P trends of iron meteorites. This suggests that inward core crystallization from the core/mantle boundary is not possible, since such a crystallization process would crystallize from the less-dense S-rich liquid that rises. This suggests outward core crystallization is necessary to reproduce observed P trends in iron meteorites.

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CRATERING ON THE GALILEAN SATELLITES: IMPLICATIONS FOR THE SIZE DISTRIBUTION OF CRATERING IMPACTS IN THE SOLAR SYSTEM.

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Galileo images of Europa, Ganymede, and Callisto reveal unexpected crater populations on all three bodies. Given the roughly lunarlike populations of craters larger than several kilometers in diameter seen in Voyager images, one might have expected that craters of order 100 m diameter would approach saturation (at least on Ganymede and Callisto), as is true of craters on both the lunar maria and the highlands and on other objects studied at these resolutions (e.g., Phobos and Ida) as well.

Instead, small craters are well below saturation on all three satellites. The situation is least clear for Ganymede, for which we so far have limited high-resolution images. But in four regions of Callisto, 100-m craters are undersaturated by a factor of about 20 and undersaturated in various parts of Europa by 1–2 orders of magnitude [1].

Certainly, ongoing processes of crater erosion and/or resurfacing contribute to their fewer numbers. On Callisto, there seems to be ongoing disaggregation of craters as well as infilling of small craters by widespread deposits; Europa exhibits ongoing resurfacing processes, especially ridge formation and localized upwelling and collapse, which erase small craters.

A straightforward interpretation is that the retention ages for 100-m craters on these bodies is of order 1–100 m.y., based on Shoemaker's [2] recent estimate of the cometary cratering rate, extrapolated to smaller sizes using the same size distribution (with "steep" differential exponent, −4 to 4.5) observed on the Moon, Gaspra, and—apparently—on the younger units of Uruk Sulcus on Ganymede.

However, there is little to no evidence concerning the actual size distribution of comets that would form craters <10 km in diameter on the Galilean satellites. In spite of arguments [3] that comets may be collisional fragments like the asteroids, with a steep size distribution, several lines of evidence suggest that small comets may be underabundant.

If the production population of small comets follows a shollower power-law, or even curves over, then the impact rate would be lower and inferred resulting ages older. There is a further complication. Secondary craters are thought to contribute only modestly to the numbers of observed craters on the Moon and other terrestrial bodies, away from the evident chains and rays of major primary craters. However, if the production population of small comets is very low in the Galilean satellites, it may be that secondary craters from observed, recent large craters >10 km in diameter actually dominate the numbers of craters 100 m in size. That would certainly complicate the relative age dating of geological units, because one would have to consider proximity of primary craters before assessing crater densities in terms of relative age. This possibility would make the absolute ages younger than if all craters were interpreted as primaries.

Obviously, if the few-small-comet alternative is correct, it would have implications for bodies other than the Galilean satellites (e.g., other outer solar system bodies where comets, rather than asteroids or circumplanetary objects, dominate the impactor population).

There is the oppourtunity, especially on Europa, to assess the secondary crater populations (in the absence of confusing primaries) from the several large craters and impact-maculae that have been imaged by Galileo. The results of these studies could clarify the nature of secondary cratering and perhaps even help us reassess the importance of secondary cratering on terrestrial bodies. Also, studies of catenae (crater chains due to impacts similar to Shoemaker-Levy 9 on Ganymede and Callisto) being imaged by Galileo may provide independent evidence concerning the numbers of cometary impactors too small to be estimated from Earth-based astronomical surveys.

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RHENIUM-OSMIUM FRACTIONATION AND ISOTOPIC SYSTEMATICS IN ORDINARY CHONDRITES.

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We investigated Re-Os for whole rocks, sulfide, and metal from ordinary chondrites. Reproducible analyses for Re/Os in chondrites are obtained. Data on St. Séverin (LL6) show a large range in $^{187}Re/^{188}Os$ (0.31–0.78) and in $^{187}Os/^{188}Os$ (0.119–0.157). These results show an excellent correlation line on a ^{187}Re-^{187}Os evolution diagram. If this is considered to represent an internal isochron, the St. Séverin data indicate T = 4.76 ± 0.03 AE and initial $^{187}Os/^{188}Os$ (I_0) = 0.0943 ± 0.0003. By comparison, irons [1] show a precise isochron (T = 4.62 ± 0.01 AE, I_0 = 0.09563 ± 0.00011). The St. Séverin Re-Os age is distinctly older than that for irons (by ~140 ± 30 Ma) and older than the IVA and IVB irons (by ~110 ± 30 Ma). Whole-rock and metal-rich separates of H-group chondrites (H3 to H6: Dhajala, Lost City, Ucera, Olmedilla, and Guareña) yield small ranges in $^{187}Re/^{188}Os$ (0.42–0.47) and in $^{187}Os/^{188}Os$ (0.128–0.133). From this we calculate $(^{187}Re/^{188}Os)_{\odot}$ = 0.425 and $(^{187}Os/^{188}Os)_{\odot}$ = 0.1288 for the chondritic evolution (CHUR) line today. Metal-rich separates have 2–3× C_{Re} and C_{Os} than whole rocks, indicating that metal is the major Re-Os carrier. The chondrites plot close to the St. Séverin isochron; deviations of the chondrites from an isochron are larger (1–10‰) than deviations of the irons from their whole rock isochron (<3‰). For St. Séverin, Rb-Sr systematics indicate a small isotopic redistribution [2]. St. Séverin sulfide shows a young Re-Os model age (2.3 AE), indicating more recent element remobilization. The low Re-Os concentrations indicate that this phase is not important for the Re-Os systematics of the whole rock and metal-rich samples.

The new results on chondrites indicate that Re-Os fractionation events occurred very early in the solar system. As the predominant phase containing these elements is FeNi, this implies Re-Os fractionation between different pieces of metal in each meteorite; this could be the result of nebular processes, prior to or during accretion of the chondritic material, or the result of fractionation between metal and S-rich metal liquids in the chondrite parent bodies. We infer that the metal phases in stony meteorites have undergone melting and crystallization that produced the observed range in Re/Os and the apparent isochronous relations. Shock or nebular processes have also been suggested for siderophile-element fractionation [3].

If we consider the results on the chondrites as governed by the St. Séverin data to represent a time of Re-Os fractionation, in order to bring the Re-Os data into agreement with the ^{207}Pb-^{206}Pb ages of chondrites, an increase in $\lambda(^{187}$Re) by ~4.5% would be required. This also implies that, for irons, T = 4.41 AE. The interpretation of this wide (0.14 AE) time interval must depend on the processes that govern Re and Os fractionation. We propose that iron meteorites are the result of extended crystallization of molten FeNiS cores, formed early due to heating from ^{26}Al decay. These cores can be sufficiently insulated by silicate mantles (~30 km) to remain as liquids ~0.1 AE, before extensive FeNi fractional crystallization takes place. This suggests early differentiated and widely distributed planetary bodies with molten cores. Subsequent collisions could have provided impacting masses of molten FeNi and could explain the mesosiderites and possibly pallasites. This model appears to be in accord with Pd-Ag [4] and Hf-W [5]. It may be in conflict with the ^{129}I data [6] unless the IAB and IIE irons crystallized early (within <10^7 yr). The model may also be in conflict with evidence of ^{53}Mn in IIIAB phosphates and in pallasites [7,8]. However, we conclude that the Re-Os chronometry of meteorites must reflect a broader spectrum of chemical fractionation and the preservation of molten planetary cores over a time interval of ~10^8 yr.

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LOCAL SEGREGATION PROCESS OF CALCIUM-ALUMINUM-RICH MATERIALS IN UREILITES AND PRIMITIVE ACHONDRITES AND THEIR FORMATION MODEL.

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Ureilites and primitive achondrites are two groups of achondrites that have some of the characteristics of primitive materials, e.g., O isotopic anomalies [1] and high noble gas contents [2]. However, compared with carbonaceous and ordinary chondrites, these achondrites show depletion in Ca, Al, Fe, and S. This depletion is reflected in the mineralogy of these meteorites. Both groups consist primarily of olivine and low-Ca pyroxene with minor Cr-rich augite. Plagioclase is also found in primitive achondrites, but is very rare in ureilites. The origin of this depletion is the question addressed here.

Silicate inclusions in iron meteorites may hold a clue to the process that produced this depletion. Wasserburg et al. [3] found a K-feldspar-rich area in a IIE iron meteorite and Takeda et al. [4] found Na-plagioclase and Cr-diopside rich areas in two PTSs of silicate inclusions in the Caddo County IAB iron meteorite (PTSs B2A and B3A). To understand this differentiation process, we performed mineralogical analyses by EPMA of a third PTS of Caddo County (B1A). We propose that ureilites and primitive achondrites underwent almost the same minor differentiation process that caused local migration of Ca-Al-rich material and yet preserved primitive characteristics.

B1A shows textures, grain sizes, and modal abundances of minerals similar to those in Acapulco. This area is finer-grained (0.2–1.5 mm in size) than B2A and B3A. Olivine (25.98 vol%) and opx (39.92 vol%) are the most dominant minerals, while plagioclase (20.39 vol%) and minor augite (5.34 vol%) fill interstices between the mafic silicates together with troilite, FeNi metal, chromite, and Ca-phosphate. In B1A, veinlike plagioclase 0.2–0.4 mm in size enclosing augite run into the finer-grained mafic silicate-rich region. Finer-grained silicates (0.2–0.5 mm) are concentrated on one side of B1A. Grain size gradually increases (0.2 mm–>1.5 mm) from one side of the PTS to the other. The plagioclase vein (9 cm in length) can be interpreted as a channel collecting Ca-Al-rich melt from the surrounding areas and supplying the melt into the plagioclase-augite-rich area.

Opx ($Wo_{2.3}Wo_{90.7}Fs_{7.0}$) is uniform in composition from grain to grain, but augite has two dominant compositions ($Wo_{40.7}En_{56.0}Fs_{3.3}$ and $Wo_{45.2}En_{53.8}Fs_{1.0}$). The composition of plagioclase is $Or_{2.0}Ab_{69.8}An_{28.2}$–$Or_{2.9}Ab_{73.5}An_{23.6}$. The Zn content of chromite ($Chr_{93}Hy_4Ulv_3$) coexisting with troilite and FeNi metal is 1.7–2.2 wt%. Chikami et al. [7] suggested that chromites in primitive achondrites and ureilite contain significant Zn, while HED chromites do not contain detectable Zn content. The Zn content in B1A shows that it underwent only a minor differentiation process and that Zn is still retained in the chromite structure.

To date, ureilites containing Cr-rich-augite like that in Caddo County include in Y 74130 and MET 78008, but these samples do not contain plagioclase. Chikami et al. [8] found augite rims on pigeonite and olivine grains in Hammadah al Hamra 126 and Y 74123 ureilites. These augites might be remnants of Ca-rich materials that drained away through interstices. Augite and plagioclase-rich areas in B2A and B3A of Caddo County are regions where such Ca-Al-rich material is concentrated. Yugami et al. [5] plotted modal abundances of primitive achondrites and H7 chondrite on the opx-olivine-(augite + plagioclase + phosphate) diagram to indicate the differentiation trend. The material enriched in Na-rich plagioclase, Cr-rich augite, and Ca-phosphate found in Caddo County is an endmember partial melt of the differentiation trend of the Winonaite/IAB group. Thus, PTSs of Caddo County show us how Ca-Al-rich material can migrate even in PTS scale by a local segregation mechanism. Hence, Caddo County may be a missing link between primitive achondrites/ureilites and primitive materials.

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Δ^{17}O IN THE NEBULAR GAS: EVIDENCE FOR A TEMPORAL UPWARD DRIFT.

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Refractory inclusions (RI) in Allende and other carbonaceous chondrites are the oldest objects known. They are also the materials that, on a diagram of δ^{17}O vs. δ^{18}O, have the most negative Δ^{17}O ($\equiv \delta^{17}O - 0.52 \times \delta^{18}O$) values. Clayton and coworkers [e.g., 1] found that carbonaceous chondrite (CC) samples other than chondrules form an array (the CCAM line) with slope 0.94 (the chondrule array is steeper), much higher than the slope of 0.52 generated by mass-fractionation processes. As one proceeds up the CCAM line, nebular formation temperatures decrease, implying that the arrow of time points in this direction. The Δ^{17}O values of early formed RI are ≈ −20‰; those of low-temperature, high-FeO samples reach −2‰.

The O in whole-rock samples or chondrules of unequilibrated ordinary chondrites (UOC) also form arrays with slopes >0.52. However, with the exception of rare RI that could be xenoliths, the lowest Δ^{17}O values are about 0‰. At the other extreme, we [2] measured Δ^{17}O values of 4–7‰ in Semarkona and Ngawi magnetite, the highest values known in material of solar-system origin.