Collected iron meteorites have sampled the cores of numerous (-70) parent bodies (1) of original diameters seemingly ~300 km as inferred from metallographic cooling rates. Three related types of basaltic achondrites are impact-brecciated crustal rocks, probably derived by partial melting of the interior of Vesta (2). Other achondrite types, derived from the voluminous mantles of such differentiated bodies, would be expected to be numerous, yet they are rare. Another dilemma is that asteroidal collisional evolution is not believed to have been extensive enough to liberate core fragments from such large bodies.

Consideration of how mesosiderites formed provides a logical link to the provenance of meteorites and to the representation of different types in meteorite collections. The conventional model of mesosiderites as breccias formed by impact of an iron body onto the surface of a basaltic-surfaced body (cf. 3) is not convincing. It cannot provide a sufficient quantity of finely integrated metal-rock mixtures in the 50:50 proportions observed, especially given the difficult requirement (for slow cooling) of subsequently burying this material and then re-excavating it from great depth. The petrographic textures and metallic network (4) requires invasion of the silicates by molten metal, which has led to models invoking impact melts (5). But a low-speed collision required to retain the projectile component would yield a minute quantity of impact melt. We propose that mesosiderites formed by the foundering of a basaltic crust through a substantially molten body to the metallic core. The incorporation of metal into the silicates occurred in the same fashion we believe accounts for pallasites.

Pallasites have slow cooling rates and are closely related to the IIIAB irons (6), which are thought to be formed in a parent-body core. Wood (7) proposed to form pallasites at the outer core boundary, where the overburden of olivine cumulates would submerge the bottom layer of olivine into the core. Wood originally calculated that all the olivine would be crushed, except for an infinitesimally thin layer of pallasites; this led him to a model of very small parent bodies. However, we find that for a 200 km diameter body, a 20 m thick layer of pallasites would form; Wood (8) now agrees.

Mesosiderites probably formed in a more thoroughly molten and/or larger parent body. The olivine compositions, rare-earth elements, dominant cumulate textures, etc. of mesosiderite silicates (cf. 9, 10) all imply that extensive partial melting of the body occurred. Such melting enriched the crust in iron-bearing rocks. The crust was brecciated and cracked by impacts. It then foundered and sank through the mostly molten, magnesium-enriched mantle, incorporating small amounts of olivine. Finally, cool crustal blocks floated at the core-mantle interface and quenched the iron, especially the portion that had invaded the interstices of the sunken breccia. Depending on relative melting temperatures of metal and silicates, this process accounts for observed metamorphic grades and evidence for melting of grain boundaries in mesosiderites (4). The parent body quickly froze, then cooled slowly through intermediate temperatures. Since bodies >30 km diameter developed extensive, insulating megaregoliths (11), we believe measured cooling rates were achieved on bodies only about 1/3rd the size calculated by Wood (7).

Of the differentiated asteroidal bodies, it is plausible that the mesosiderite parent should be the largest, the pallasite parents intermediate, and the iron parents smaller, in agreement with metallographic cooling rates. This reflects the degree to which bodies became molten, as governed by their volume/surface ratio. Only the mesosiderite parent was sufficiently molten.
to permit a foundering crust to reach the core. In the iron parents, melting was only sufficient to accumulate a metallic core with little silicate differentiation. Our model of forming stony-irons at core-mantle interfaces renders them readily available for sampling. Due to the strength of iron, collisions will strip away many weak, rocky mantles, exposing stony-irons to cratering, chipping, and delivery to Earth (cf. 12).

We now consider the collisional evolution of asteroids, the generation of megaregoliths on such bodies, collisional/dynamical mechanisms for transferring meteorites from asteroidal parent bodies to Earth, and spectral evidence concerning the composition of surface layers of asteroids. (We do not necessarily exclude origin of some meteorite types on comets, but cometary debris may not survive entry into the atmosphere.)

Scott (1) has graphically represented the frequency distribution of meteorite types. In particular, irons represent ~70 parent bodies while the more numerous chondrites represent only ~10 parents. Also, Wasson and Wetherill (13) have tabulated meteorite falls by type. We find that a model with chondrites coming from undifferentiated bodies (assumed to be ~90% of population at all sizes), achondrites from intact differentiated bodies, and iron-rich meteorites from cores whose mantles have been removed accounts for these statistics and agrees with the observed asteroid population.

Cratering and fragmentation of asteroids should produce ejecta roughly in proportion to the volumes of the parent bodies. We correct for the target strength, which affects both the volume of ejecta produced by an impact of given energy and the fraction of ejecta that exceeds escape velocity (cf. 14). We take target strength to be a function of both inherent composition (e.g., iron, stony, or weak-carbonaceous material) and of inferred collisional history (largely pristine rock or converted into weak megaregolith). Escaped ejecta fragments may yield meteorites, provided the parent bodies are located where perturbations will deliver fragments to Earth on timescales similar to or shorter than the collisional lifetime of such debris. The delivery processes are not completely understood (15, 16), but ~10% of stony asteroids may dynamically communicate with Earth. Other long-timescale delivery routes are available to irons, which are strong enough (as inferred from cosmic-ray exposure ages) to survive for ~10^9 yr; we choose 30% for the fraction of metallic asteroids that communicate. The volumetric sampling of meteorite falls depends also on the dynamical or collisional lifetimes of meteorites and on the Earth's atmospheric filter.

Interpretation of asteroid diameter-frequency statistics (17) and recent collisional models by Davis et al. (11) show that most asteroids larger than 30 km diameter survive over the age of the solar system. Table 1 approximately accounts for depletion of the original asteroid population by catastrophic disruption, based on timescales given in Fig. 11 of (11). Those left intact are observable today. We assume that differentiated bodies that would be "destroyed" according to the Davis et al. calculations for rocky bodies, will remain as exposed cores. In the table, we apply our dynamical communication percentages to obtain the predicted number of potential parent bodies of different types and sizes. We have also made approximate calculations of the relative yields from each body, using the logic outlined earlier.

Given that we sample about 10 chondrite parent bodies, inspection of Table 1 (column 9) shows that such bodies are ~100 km diameter. The two largest parents will dominate the meteorite population volumetrically, if they are of ordinary chondritic composition. Asteroids 6 Hebe and 532 Herculea are of the appropriate size, have possibly chondritic surface compositions (18), and may communicate with Earth (13). Our model predicts negligible sampling of chondritic (especially the predominant C-type) bodies
METEORITES FROM ASTEROIDS

Chapman, C.R. and Greenberg, R.

smaller than 80 km diameter.

In our model, it is rather unlikely that the third largest asteroid (Vesta) should have differentiated and also unlikely that it should communicate fragments to Earth. But evidently it did undergo a small degree of partial melting and it does communicate. Impacts should have sampled its crustal rocks (yielding eucrites, howardites, and diogenites) but not its deeper mantle rocks. Achondritic meteorites (Table 1, col. 1) should be dominated by basaltic achenorites from Vesta, plus a smaller sample of mantle rocks (e.g., chassignites) from several smaller differentiated bodies about 100 km in diameter. The largest examples of largely intact differentiated bodies (col. 8) may be olivine-rich asteroids 3 Juno, 7 Iris, and 15 Eunomia, but they are not located near known dynamical escape hatches from the asteroid belt.

The largest stripped cores are inconspicuous asteroids now about 40 km in diameter, derived by fragmentation of parent bodies originally roughly 100 km in diameter (col. 10); these are parent bodies for mesosiderites, pallasites, and IIIAB irons. Numerous smaller stripped cores, derived from bodies originally 25 to 50 km diameter provide the dozens of metallic meteorite types. The strength of metal-rich materials explains why iron parent bodies have been sampled that are only ~10% the diameter of the smallest rocky body sampled.

In summary, evidence concerning asteroidal surface compositions and collisional evolution can be reconciled with meteorite populations, provided: (a) < 10% of asteroids differentiated; (b) stony-iron meteorites were formed at core/mantle interfaces of bodies ~100 km in diameter, which were subsequently covered by a megaregolith, and then stripped of their crustal and mantle rocks by collisions; and (c) iron meteorites were formed in smaller, less completely molten bodies, a larger fraction of which have been stripped of their mantles. In this model, few meteorites are derived from the mantles of differentiated bodies, although several large bodies (~200 km diameter) with largely intact mantles may exist in the asteroid belt.

ACKNOWLEDGMENTS: We thank D. Davis, A. Planetary, P. Herbert, E. King, S. Widenschilling, L. Wiking, and J. W. for discussions. Supported by NASA Contracts NASA-36090, -3134, and -3208.


TABLE 1. ASTEROIDAL PARENT-BODIES FOR METEORITES

<table>
<thead>
<tr>
<th>Original Diameter (km)</th>
<th>Original</th>
<th>Non-Differentiated Bodies</th>
<th>Differentiated Bodies</th>
<th>Parent Bodies Communicating with</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total Number</td>
<td># Original (90% of 2)</td>
<td># Destroyed by Impact</td>
</tr>
<tr>
<td>&gt; 500</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>200-500</td>
<td>31</td>
<td>26</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>80-200</td>
<td>378</td>
<td>38</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>32-40</td>
<td>1554</td>
<td>155</td>
<td>77</td>
<td>77</td>
</tr>
</tbody>
</table>

* Note that the core is now ~3% of the diameter (column 1) of the original body.

** Vesta

© Lunar and Planetary Institute • Provided by the NASA Astrophysics Data System