Differentiation & Thermal Evolution
Meteorite Classification: Iron Meteorites

Undifferentiated Meteorites

Chondrites

- Carbonaceous Chondrites
- Ordinary Chondrites
- Rumuruti-Chondrites
- Enstatite-Chondrites

Differentiated Meteorites

Achondrites

- Primitive Achondrites:
  - Acapulcoites
  - Winonaites
  - Lodranites

Iron Meteorites

- (main groups)
  - IA
  - IIA
  - IIB
  - IIIA
  - IIIB
  - IVA
  - others

Stony-Iron Meteorites

- Pallasites
- Mesosiderites

- Martian Meteorites
- Aubrites
- Ureilites
- Angrites
- HED
- Lunar Meteorites

- SNC
  - Shergottites
  - Nakhliites
  - Chassigny
  - ALH 84001
  - Howardites
  - Eucrites
  - Diogenites

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Meteorite Classification

Basic Types of Meteorites:

- Stony (93% of falls)
- Irons (6% of falls)
- Stony-Irons (1% of falls)
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- **Undifferentiated (chondrites)** (stony meteorites; ~85% of falls; chemically similar to Sun)

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‘Primitive’ meteorites are stony meteorites and can be chondrites or special types of achondrites; the primitive meteorites are chemically similar to the Sun.
Iron Meteorites

Iron meteorites are largely composed of iron and nickel metal, thus they are believed to represent the cores of differentiated asteroids.

Though rare compared to stony meteorites, irons were fairly common in meteorite collections:

- they are resistant to weathering
- they are more resistant to ablation during passage through the atmosphere
- they were often easier to find because they look very distinct (stony meteorites, on the other hand, can often look like typical terrestrial rocks)

The Willamette meteorite, housed at the American Museum of Natural History, is the largest one to ever be found in North America. Transported to Oregon by glacial floods?
Stony-Irons meteorites are subdivided into 2 major types:

- **Pallasites**: composed of Fe-Ni metal and silicate (mostly olivine)
- **Mesosiderites**: composed of Fe-Ni metal and silicate (‘basaltic’; olivine, pyroxene)
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Because pallasites consist of metal and olivine, they are believed to represent **core-mantle components** in asteroids/planetesimals.
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Alternative hypothesis:
The solid cores were separated from the remaining (metal) melt and mantle by large impacts. The pallasites could come from many different bodies with different cooling histories.
Mesosiderites

Mesosiderites are composed of roughly equal portions of metal and silicate.

But the silicates are ‘basaltic’, suggesting mixing of deep metals with crustal silicates.
Evidence against a chondritic Earth

Ian H. Campbell & Hugh St C. O’Neill


Moderately volatile, lithophile elements (alkalis, halogens, boron) are depleted in bulk silicate Earth (BSE).

142Nd/144Nd ratio of terrestrial mantle is higher than chondritic values.

- Earth is non-chondritic

or

- Earth experienced early fractionation event w.r.t. Nd
Differentiation: Starting Material

If the bulk composition of Earth is non-chondritic, then this has major implications for our understanding of the evolution of Earth.

Although it raises many new questions, this idea could also solve some major paradoxes (see table below).

| Table 1 | The geochemical paradoxes of the mantle |
|---|---|---|
| Paradox | Chondritic solution | Non-chondritic solution |
| The $^{142}$Nd/$^{144}$Nd ratio of chondritic meteorites is $20 \pm 5$ parts per million less than that of rocks of terrestrial mantle origin. | A low-Sm/Nd hidden reservoir became isolated from the convecting mantle within 10 Myr of the Earth’s formation$^{15,61}$. | The Sm/Nd ratio of the primitive Earth was about 6% above the chondritic value$^{13}$. |
| Earth’s oldest rocks show evidence of being derived from a mantle with positive $\varepsilon_{\text{Nd}}$ and $\varepsilon_{\text{Hf}}$ before the formation of the first preserved continental crust. | Extensive continental crust formed before the first preserved continental crust and was recycled through the mantle$^{62}$ or there is a hidden basaltic low-Sm/Nd reservoir$^{15}$. | The Sm/Nd ratio of the primitive Earth was about 6% above the chondritic value$^{13}$. |
| The Ar concentration in the mantle is about half the value predicted from the chondritic model$^{63}$. | Only half of the mantle is degassed$^{63}$. | The collisional erosion hypothesis$^{13}$ predicts a K content of the mantle appreciably below that expected from the chondritic model. Alternatively, the Earth is not chondritic$^{16}$. |
| Nb/Ta and Nb/La values of both continental crust and depleted mantle lie below (Nb/Ta) and above (Nb/La) the primitive mantle values of 17.5 for Nb/Ta and 0.9 for Nb/La. | Hidden reservoir enriched in Nb, Ta and Nb with super-chondritic Nb/Ta and sub-chondritic Nb/La$^{64}$. | The Nb/Ta and La/Nb values of the primitive mantle lie between those of the depleted mantle (15.5 and 1.2) and the continental crust (12.5 and 2.2). |
| $^4$He production in oceans is less than that predicted from observed heat flow and about half that predicted from chondritic Earth model. | $^4$He stored in lower mantle that is separated by a boundary layer that transmits heat but not $^4$He (ref. 65). | Collisional erosion model predicts the Th–U content of the BSE to be about half the chondritic value$^{13}$. |
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*Silicate* melting is likely needed for significant melt migration; thus mantle-core separation likely requires higher temperatures (>1323K).
At high T, taenite (\(\gamma\)-Fe) is the stable phase.

Decreasing T = conversion to kamacite (\(\alpha\)-Fe)

Taenite holds more Ni, and Ni diffuses into the grains.

Rate of diffusion is controlled by T, and by 500°C it effectively stops.
Crystallization of Iron Meteorites

The ‘classic’ phase diagram below is o.k. for general purposes, but the full story of cooling is much more complex and may be strongly affected by presence of elements such as P and S (see Goldstein et al., 2009).
Crystallization of Iron Meteorites

Temperature [°C] vs. Fe [%] diagram with various phases and reactions indicated:
- γ-Fe
- α-Fe
- α-Fe + Fe₃P
- Fe₃P + Fe₂P
- Fe₂P + (?)
Crystallization of Iron Meteorites

Previous studies have suggested the IIIAB irons may be from the same parent body as the pallasites.

However, new measurements on cooling rates in ‘cloudy zone’ and chemistry bring this into question (see Yang & Goldstein, 2006, Yang 2008).

Table 2. Cooling rate variations in iron meteorite chemical groups.

<table>
<thead>
<tr>
<th>Group</th>
<th>Cooling rate variation (°C/Myr)</th>
<th>Authors</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAB</td>
<td>2–3</td>
<td>Goldstein and Short (1967)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>63–980</td>
<td>Rasmussen (1989)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>25–70</td>
<td>Herpfer et al. (1994)</td>
<td>2</td>
</tr>
<tr>
<td>IIICD</td>
<td>87–480</td>
<td>Rasmussen (1989)</td>
<td>1</td>
</tr>
<tr>
<td>IIAB</td>
<td>0.8–10</td>
<td>Randich and Goldstein (1978)</td>
<td>3</td>
</tr>
<tr>
<td>IIIAB</td>
<td>1.0–10</td>
<td>Goldstein and Short (1967)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>21–185</td>
<td>Rasmussen (1989)</td>
<td>2</td>
</tr>
<tr>
<td>IVA</td>
<td>7–90</td>
<td>Goldstein and Short (1967)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2–96</td>
<td>Rasmussen (1982)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>19–3400</td>
<td>Rasmussen et al. (1995)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>100–6600</td>
<td>Yang et al. (2008a)</td>
<td>2</td>
</tr>
<tr>
<td>IVB</td>
<td>2–25</td>
<td>Goldstein and Short (1967)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>110–450</td>
<td>Rasmussen et al. (1984)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1400–17,000</td>
<td>Rasmussen (1989)</td>
<td>1</td>
</tr>
</tbody>
</table>

2. Taenite central Ni content method (includes effects of P on phase diagram and on diffusion coefficients for Ni in taenite).
3. Phosphide growth simulation.
After ~3 Myr, rate of heat generation from $^{26}$Al had dropped to ~12% and that from $^{60}$Fe had dropped to 25% of initial rates.

If chondrite parent bodies accreted 2-3 Myr (or longer?) after CAIs then there was likely not enough energy to melt them to the level that metal would be segregated from silicate.

(but what about the evidence we discussed that shows some chondrule formation overlapping with CAI formation?)

[See Kleine et al. (2005), GCA for discussion of iron, CAI, chondrule timing]
Cooling rates are important for understanding the potential sizes of the iron parent bodies.

Cooling rates would be expected to be very slow for cores of very large objects, so ‘historical’ view is that irons come from modest-sized bodies.

However, newer models suggest that iron and stony-iron parent bodies:

- accreted/melted shortly after CAI formation
- formed closer to Sun (1-2 AU)
- may have been much larger (1000 km?)
- were disrupted by grazing impacts (with planetesimals?)
- smaller fragments/bodies were then flung into the asteroid belt