Does asteroid 4 Vesta, the Galilean moons, mode iron core predicated for Earth and terrestrial

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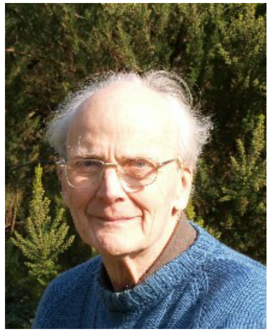
with watery 1 Ceres and record the Ringwood-construction now even apply to the other planets?



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DAWN mission observations have confirmed that Vesta, with a mean diameter of 530 km and mass only ~1/20,000 of Earth, was too small to experience appreciable magmatic resurfacing after accretion had ended.

With a 220 km diameter iron core and as the source of the HED meteorite family, Vesta offers to have preserved valuable clues as to how the Earth and the other terrestrials were built.

Setting the scene

Core formation in the terrestrial planets has long been attributed to the percolation of molten FeNi accreted from the (hot) solar nebula, either inward from the surface or from a magma ocean at depth.

But we now know [Halliday 2013, Craddock et al 2013] **that the 56Fe/54Fe ratio in Earth-mantle peridotites is still the chondritic one, ruling out that Fe has percolated through it.**

Ringwood-mode (RM) core formation

This means we must revert to A.E.(Ted) Ringwood's model for core formation [ANU papers and books, 1960-1978].

This uses the nebular H to reduce the hot FeO in lavas erupted at the protoplanet's volcanoes, generating lots of reaction water and subducting the iron in big lumps.

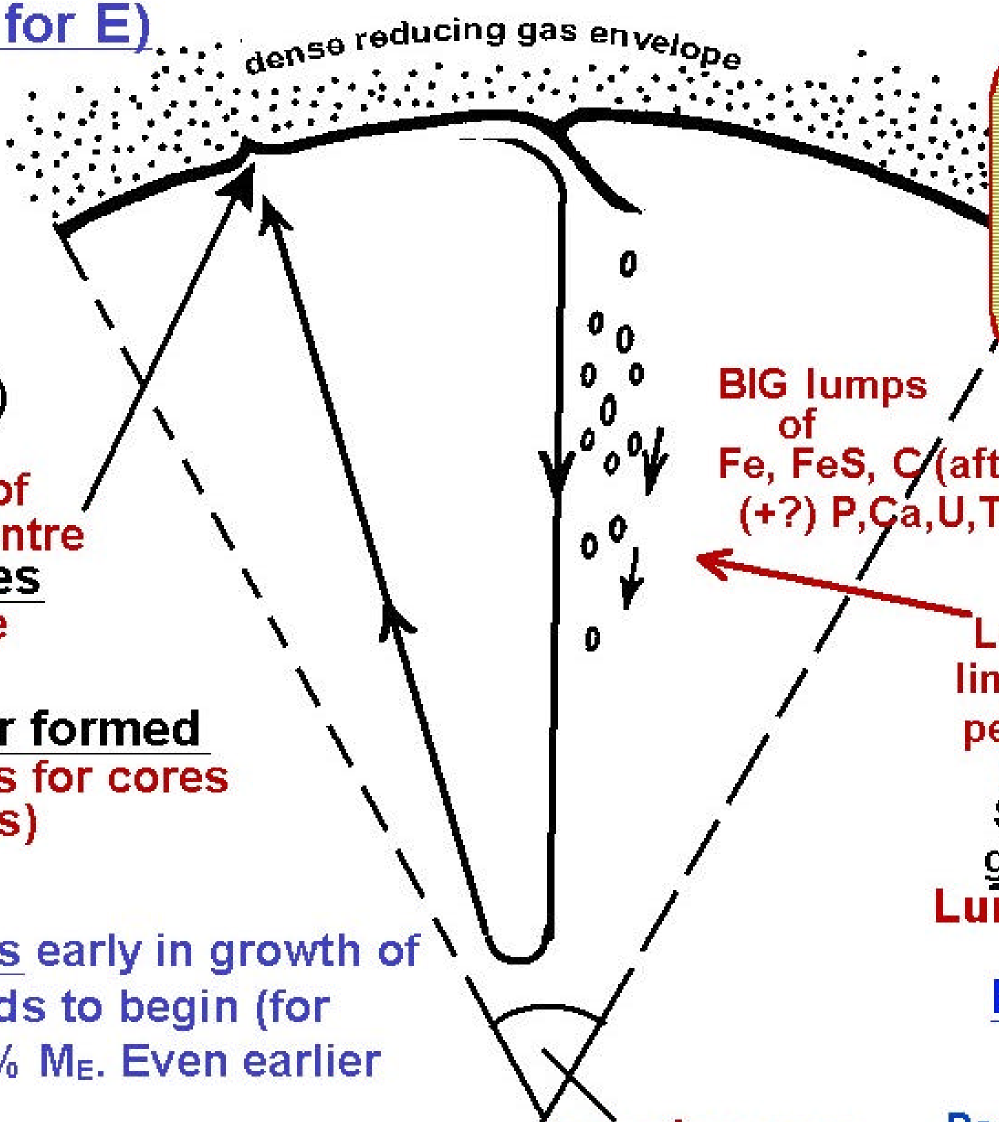
So the action is limited to while the nebula is present.

This fits nicely with tackling the big problem of equipping the solar planets with their huge (>10^5-fold higher) mean specific orbital a.m., w.r.t. the a.m. of solar rotation (noted by Jeans 1919 and by a succession of others since). [The Nice and other SS models don't tackle it either!]

At EPSC-2013 I showed that this can indeed be done but only if the nebula is the mechanical agent. So construction has to be completed while it's present (5 Ma or less?).

Nebula-present core formation – Ringwood-mode

(pre~4561Ma? for E)



Cool nebula
(<600K)gives
high fO_2 silicate
Earth (Fe as FeO)

Chemical reduction of
FeO at upwelling centre
and other volcanoes
by nebular envelope

Solar System water formed
(~1000 earth-oceans for cores
of terrestrial planets)

Core formation starts early in growth of
body; overturn needs to begin (for
Europa) at about 1% M_E. Even earlier
for Vesta.
Finishes when nebula departs.

Opacity of dusty nebula
makes distance from the
Sun immaterial.
Heat for convection
onset is accretion
and radiogenic

BIG lumps
of
Fe, FeS, C (after Fe3C)
(+?) P,Ca,U,Th

Loading of descending
limb ensures convective
penetration and speeds
up core formation
So does release of
gravitational energy
Lumps descend in and
create flow so
NO PERCOLATION
or
HSE-STRIPPING
Partition across CMB later
(pressure evens up partition coeffs)

Implications of the Ringwood model

To provide Fe as FeO for planetary construction, thermodynamics specifies [Wood&Hashimoto 1993] that the protoplanetary disc must be very cool (<600K). That is provided by our EPSC2013 scenario.

In this scenario the proto-Sun travels through a second dust cloud (typical temp. only 10K) gathering dusty material to form the disc, and contaminating the above-tachocline part of the Sun, an unmixed star. [and picking up short-life 26Al, 41Ca from a stellar explosion source near the far end, so they haven't expired before construction ends.**]**

Dust-opacity of that disc made the formation of planetary bodies thermally independent of distance from the Sun.

The RM volcanism for core formation needs only localized melting in the body - far less than for its wholesale 'differentiation' – so it can form cores in much smaller bodies.

In these, the heating will be maintained by accretion and by the Fe-loaded 'conveyor belt', releasing gravitational energy. So it will cease soon after nebular departure, with very little volcanic resurfacing to hide what had happened.

What would a Ringwood-mode (RM) volcano look like?

I propose the following top-to-bottom profile of its axial character, bearing in mind that, for thermal reasons, volcanic fractionation processes habitually differ in detail from one volcano to the next and even between successive eruptions.

So detailed uniformity is not to be expected among the meteorites that sample them. They are sampling a process, NOT a single body of material.

Eucrite
Diogenite
Mesosiderite
Pallasite
Irons

The overall picture is that FeNi melt is produced by nebular reaction during eucrite melting and it trickles down to accumulate as the irons at the bottom.

Howardite is clearly a regolith material derived from eucrite and diogenite, so merely confirms the wider exposure of these.

The RM volcano profile

Eucrite volcanic melt compositions mark partial melting of the chondrite material that had built Vesta. FeNi metal present in some, and apatite [Sarafian et al 2013] indicating the water, record the action of the RM nebular process. Those eucrites that do not may postdate nebular departure.

Eucrite
Diogenite
Mesosiderite
Pallasite
Irons

Diogenite has more metal, presumably drained down from above, with a marked variability of its alloy composition [Gooley&Moore1976].

Mesosiderite. Its brecciated character, incorporating E and D bits from above, suggests magma chamber convective overturn. It has even more metal than D, up to 4 cm size, that had resisted brecciation.

Pallasite. Essentially a mass of initially-angular high-mg typical cumulate olivines, surrounded by FeNi metal that has trickled down from above.

Irons. The final pool of FeNi metal at the bottom.

What does pallasite look like?

2 examples from the Imilac shower

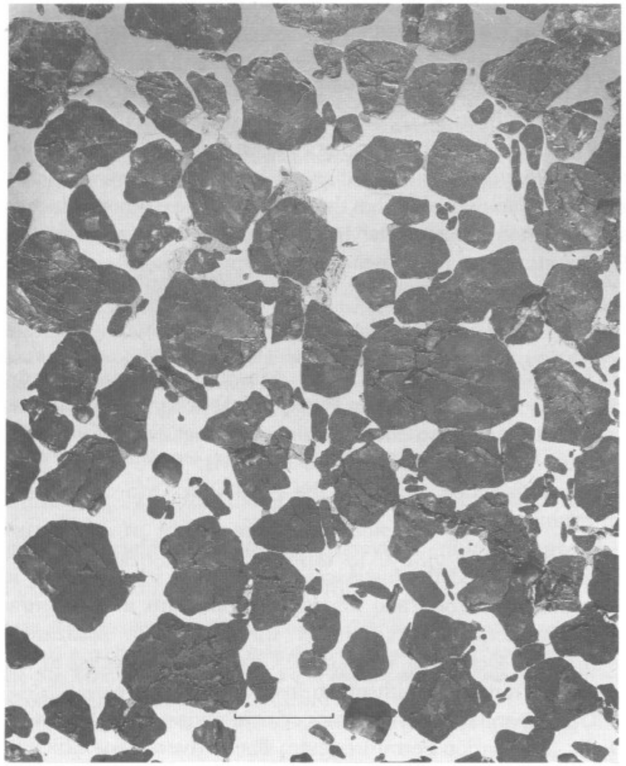
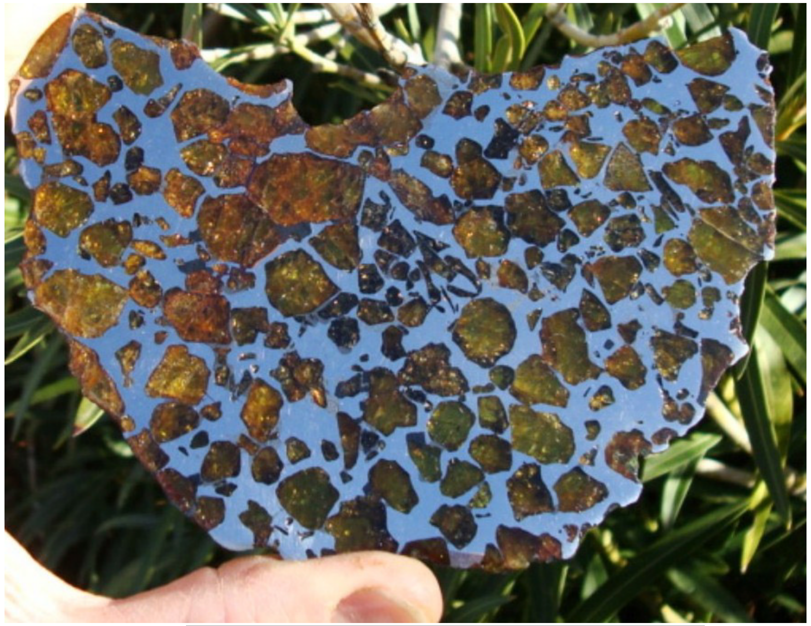


FIGURE 2-1.—Imilac, Chile (USNM#1333), pallasite. A polished surface of the Salta individual from the Imilac shower, emphasizing the relationship between metal and olivine. The dark, cracked, and somewhat angular fragmental material is olivine. The white to gray matrix is unetched metal. The slightly darker gray areas at olivine/metal interfaces are troilite or schreibersite. Scale bar 1 cm.

(SmithsonianContrESci-0031)



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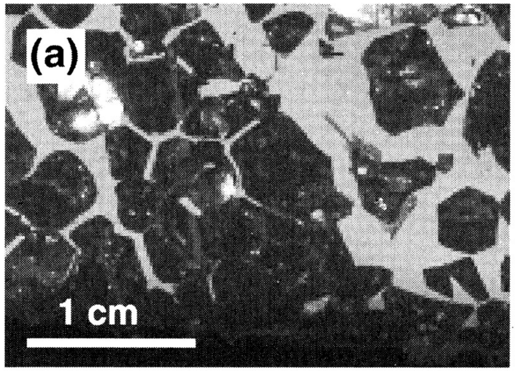
Rounding of the olivines, and their kamacite(?) borders may be due to Earth-entry or other heating.



(Hutchison 2004)

A rare example (Esquel) of the probable initial condition, with metal filling the narrow cracks between olivines.

What about the resulting reaction water?

The reaction mass-equation is FeO(72) + 2H(2) = Fe(56) + H_2O(18)
So, for every kg of Fe metal produced, there will also be 18/56 = 0.32 kg of water

For its 220 km core diameter, with a 10vol% of light element, the water generated would cover Vesta's 530 km diameter outer surface **to a depth of**

14.5 km. [Correction:- '30 km' in my abstract]

For precision this would need adjustments, **here ignored**, for:-

(1) The additional Fe (FeNi actually) still residing, globally, in the bottoms of the many volcanoes that never made it to a 'subduction' zone, and which are the sources of our iron meteorites;

(2) All the reaction water sequestered into the mineral structure of Vesta's mantle, during subduction;

(3) So we'll take the **mean water thickness to have been**

14.5 km by the time the nebula departed.

Before this moment, nebular opacity would have:-

(a) ensured that all this was frozen, shielding the crust from impacts, and

(b) would have prevented sublimation of the ice.

But then what?

On nebular departure and Vesta's exposure to solar radiation, the top of the ice would start to sublime,

and the lower 10km(?) would melt, with **<u>vigorous regolith-scouring deep water-current flows</u>** below the ice, Coriolis-deflected strongly at high latitude by Vesta's fast (5.3 hr) prograde rotation.

Circum-south polar spiral scoured channels outboard of Rheasilvia impact basin

(DAWN video - NASA)

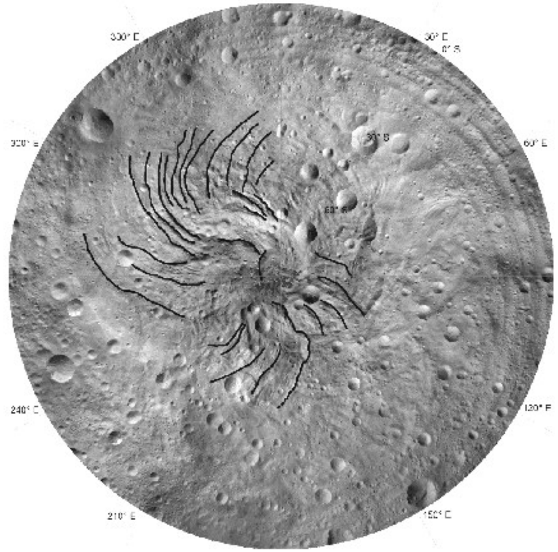


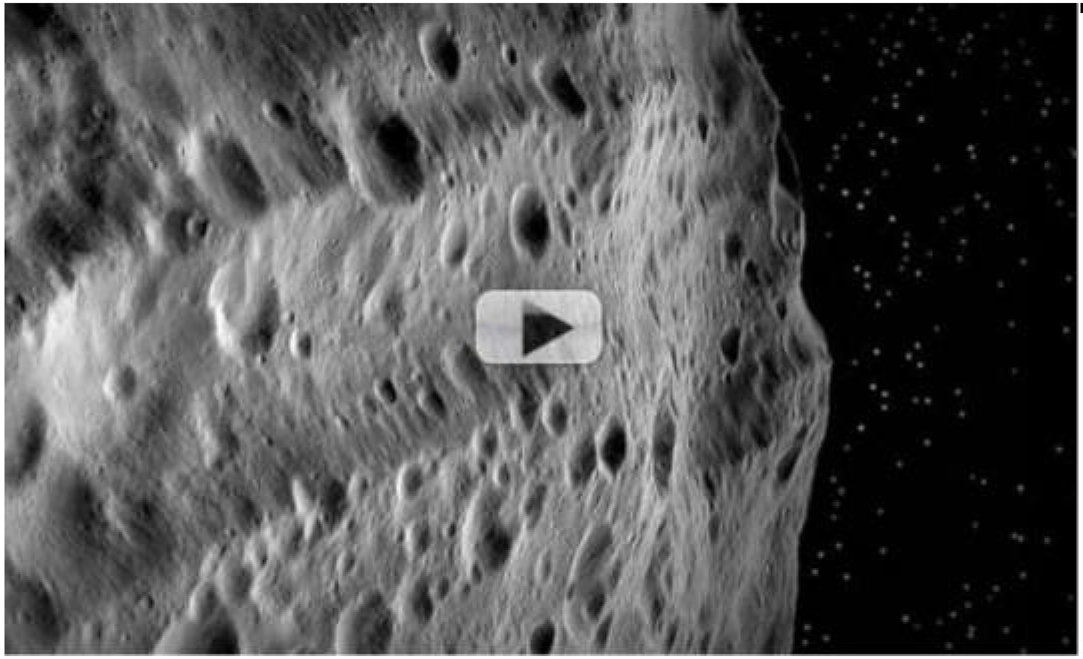
Figure 1: Stereographic projection of Vesta's southern hemisphere with curved features.

These curved features suggest that the diogenitic regolith in the floor of the Rheasilvia basin was still subject to scouring water flows after the impact. The older, quasi-equatorial grooves are also seen.

(VestaCoriolisatRheasilvia Ottoetal EPSC2013)

A close-up view of the present surface

Eventually, all the ice and water would vanish by sublimation and evaporation, exposing the crustal regolith surface to general inter-asteroidal bombardment, as we see it now.



(DAWN video – NASA)

This image confirms that this cratering postdated the deep grooving of the regolith by deep-water currents. Development of such deep regolith suggests glacial action for a major interval while nebular opacity was keeping frozen all the water being generated at Ringwood-mode volcanoes.

Widmanstätten fabric in 'irons'

Composed of taenite and kamacite, this example is from the Gibeon shower, Namibia. (courtesy Wikipedia).

Formation of this mm-scale structure is thought to require **very slow cooling**, although similar structures at the micrometre scale are formed very rapidly in the lab.

Extreme extrapolation has led to the view that this slowness can only be found **in the iron cores** of asteroids, meaning that 'iron' meteorites must have come from broken-open cores – a very difficult achievement, especially when solid. **S, P, Ca & C**, (all potentially included in irons by the Ringwood model - Panel 1) may reduce the slowness.

Our analysis prefers that the slowness demanded may be no slower than prevailed at the bottom of a Ringwood-mode volcano, whence the irons and stony-irons are readily ejected as meteorites. The lack of mantle-like meteorites (*Burbine etal* 1996**) is then also explained.**

Extreme extrapolation of any physical process always carries the risk that a factor, formerly negligible, becomes the controlling one.

Was Earth built in the same way as Vesta?
Some core-construction links

Ringwood-mode core formation would cease in all terrestrial-type bodies at nebular departure, leaving their mantles replete with reaction water - but still containing some FeO.

For Earth, we see the results in the mantle's 7.5 wt%FeO. And the water both in the 4374 Ma detrital zircons from water-requiring granitoids [Valley et al 2014]; and in its still-continuing abundance in water-rich ringwoodite in the TZ at the bottom of the upper mantle [Pearson et al 2014].

Vesta has hydroxyl in its regolith, and apatite in eucrites.

In smaller bodies (less gravity) the Ringwood process would run slower, leaving more FeO in their mantles to put into their volcanic products. Eucrites (Vesta) have ~18 wt% FeO, nearly double that of MORB on Earth's East Pacific Rise [Cottrell & Kelly 2011].

EPSC2014onVestaRingwoodCol3-Concl.lwp

Main conclusions

- Ringwood-mode core formation needs nebular presence for the reaction, so it would cease in all terrestrial-type bodies at nebular departure, leaving their mantles replete with reaction water and a high fO_2 - but still containing some FeO.
- Bar the Moon, Vesta and all the other terrestrials with iron cores, including the Galilean moons of Jupiter, were likely made similarly, with Europa offering a near-perfect water-iron ratio for the reaction.
- The Moon's highly depleted HSEs and dryness show that it alone experienced core formation by melt percolation. These resulted from its high assembly-temperature; and its dryness from post-nebular time of formation.
- We predict that 1 Ceres has an iron core, whose formation would explain the water/ice volume present, although extraneous acquisition of it is not impossible.

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