NWA 2999 AND OTHER ANGRITES: NO COMPELLING EVIDENCE FOR A MERCURIAN ORIGIN

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Introduction: In the past year, two abstracts [1, 2] on the angrite NWA 2999 have argued that the planet Mercury is the angrite parent body (APB). That angrites are not plausible candidates for Mercurian meteorites based on their high FeO contents and ancient ages has already been discussed by other authors (e.g., [3]). Unfortunately, this work has been overlooked, and the idea that angrites are from Mercury is beginning to be accepted by a number of scientists (e.g., [4]), and is solidifying in the public consciousness.

The original abstract on NWA 2999 [1] provides eight arguments for a Mercurian origin for angrites. Many of these arguments have been repeated by others [4]. The second abstract on NWA 2999 [2] focuses on one of the eight original arguments, which the authors of that abstract feel provides the most convincing argument for a planetary origin. In this poster, we will discuss all eight of the arguments from the original abstract [1], and explain why it is not plausible that Mercury is the angrite parent body.

ARGUMENT #1: "the virtual lack of Na implies a highly refractory planet (near the sun?)" [1]

This argument is based on the condensation model of Lewis (e.g., [6])– see Figure 1. As noted by numerous authors (e.g., [5]), angrites are enriched in Ca and Ti, and the plagioclase is pure anorthite.

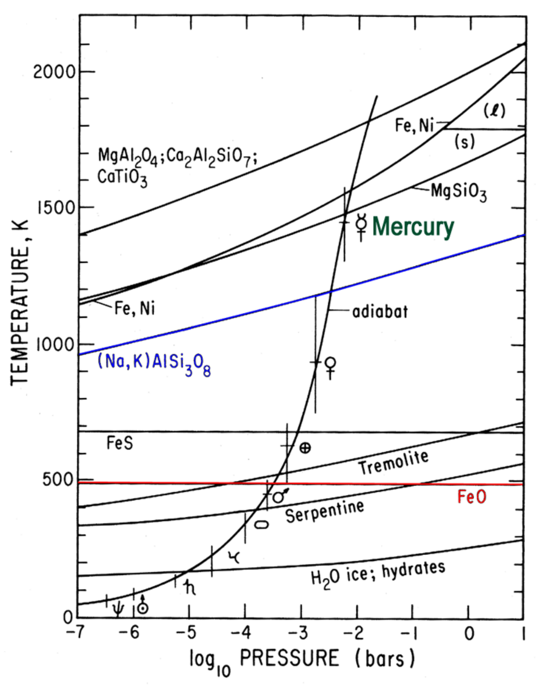


Figure 1 (left) shows equilibria for various phases in a system of cosmic composition with a superimposed solar nebula adiabat.

HOWEVER: Angrites are inconsistent with this model.

A) angrites are FeO rich (olivine in NWA 2999 is ~Fa_{40}), which is inconsistent with the Lewis model, as oxidation of Fe (red line) occurs at lower T than appearance of Na (blue line).

B) angrites are not more depleted than lunar rocks or eucrites in volatile elements, just in alkalis (e.g., [5] and [7]).

C) chondrites with the highest abundances of refractories (containing CAIs) are believed to come from the outer part of the asteroid belt (e.g., [8]), whereas chondrites with the lowest abundances of refractories are believed to come from the inner part of the asteroid belt, suggesting the opposite of argument #1.

ADDITONALLY: The chemistry of angrites is inconsistent with spectral data from Mercury.

A) Near-infrared and microwave spectroscopic observations suggest that Mercury's surface has $\leq$4 wt% FeO + TiO_2 (e.g., [9], [10], [11]), with a best estimate of ~1.2 wt% FeO [12], inconsistent with the high bulk FeO contents of angrites.

B) Mid-infrared spectroscopic observations suggest that an Na-bearing plagioclase, probably labradorite, is present on the Mercurian surface (e.g., [13], [14]), inconsistent with the anorthite typical of angrites.

C) At least some Na "hot spots" observed on Mercury (see Figure 2) appear to be related to surface features, suggesting that the Na is derived from rocks on the Mercurian surface [15].

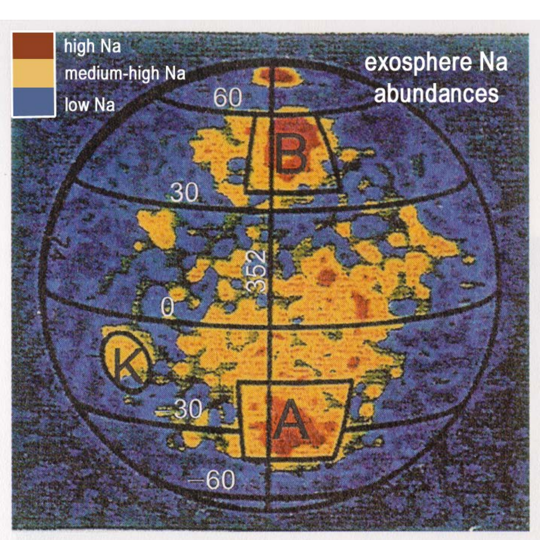
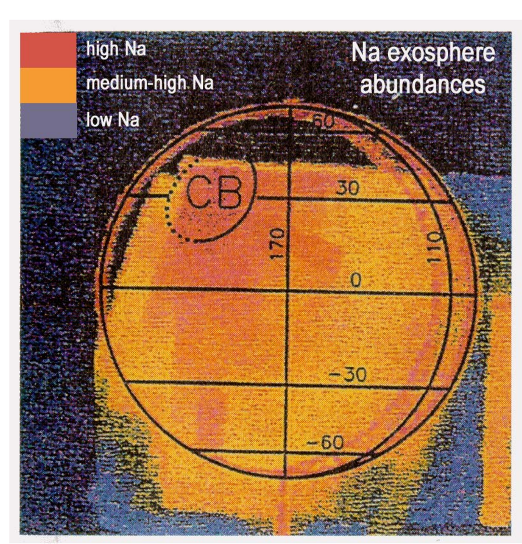


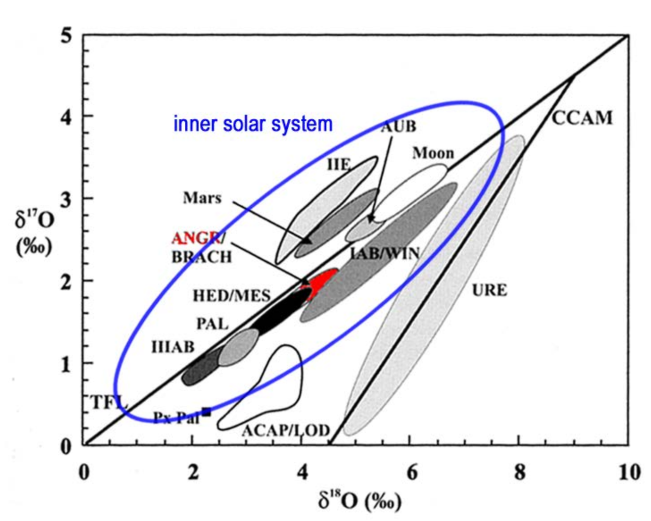
Figure 2a (left) and 2b (right) show Na abundances in Mercury's exosphere [15]. Abundances are high in radar bright spots A and B (left) and in the vicinity of the Caloris Basin (CB, right).



ARGUMENT #2: "oxygen isotopic compositions are close to and parallel to the TFL (like planetary rocks from Earth, Moon, Mars and Vesta)" [1]

HOWEVER: Being close to the TFL suggests only that the angrites formed in the inner solar system.

Figure 3 (right, [16]) shows that angrites (red) have unremarkable O-isotope compositions similar to the TFL, like HEDs, aubrites, winonaites, lodranites, brachinites, mesosiderites, and various iron groups. This has been interpreted to mean that all of the material that formed in the inner solar system (inside the orbit of Jupiter) has similar oxygen isotopic compositions [8].



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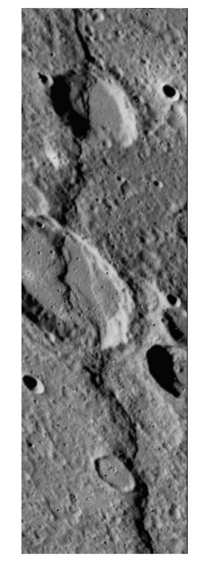
ARGUMENT #3: "preserved corona textures in NWA 2999 require a parent body capable of km-scale tectonic uplift of lithospheric material (by thrust faulting?)" [1]

The authors describe two types of corona features, which they call "symplectite" and "corona" [2].
Symplectite – described as "radial symplectitic intergrowths" of clinopyroxene (cpx) and spinel (sp) located between anorthite (anor) and olivine (ol) [2].
Corona – thin (10-20 µm) discontinuous rims of anor around sp grains in contact with cpx [2].

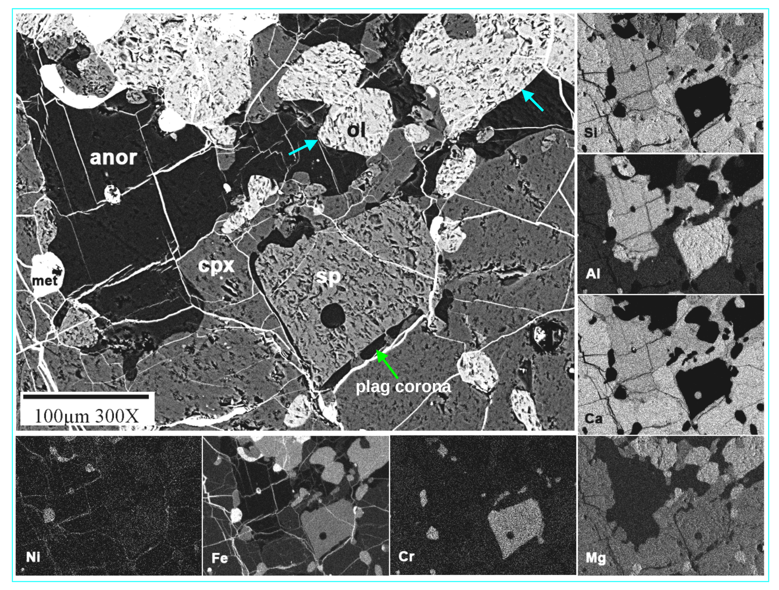
The authors conclude that these textures result from forward and reverse examples of a metamorphic reaction Fo+An=Al-Cpx+Al-Opx+Sp occurring at 870ºC and ~6.7 kb.

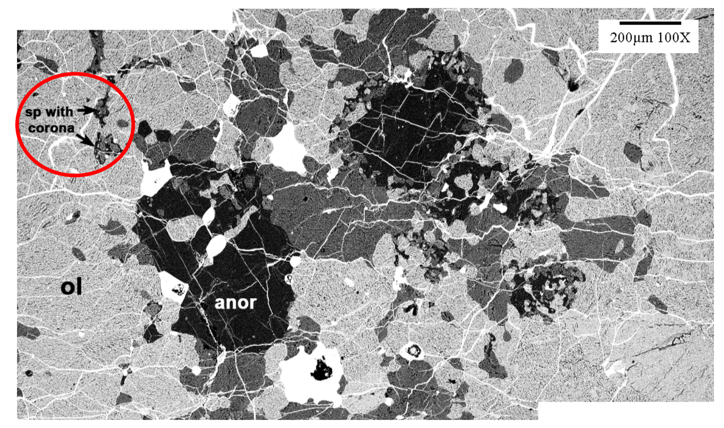


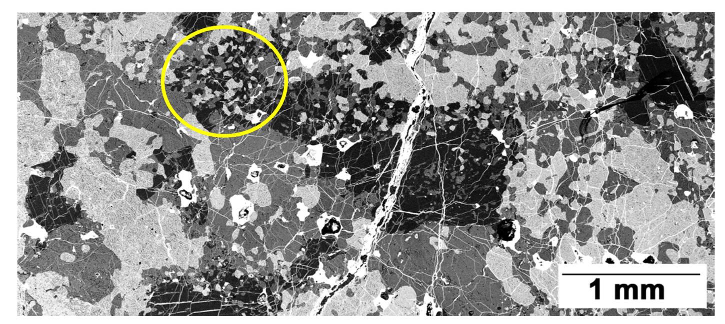
HOWEVER: There is no mechanism on Mercury to either bury material to, or exhume material from, the depths required by these metamorphic conditions.

On Mercury, we calculate that pressures of 6.7 kb occur at a depth of approximately 50 km. A model of thrust faulting along Discovery Rupes (see Figure 4 – right, [13]) concluded that the thrust faults on Mercury involved approximately 2 km of displacement and originated at a depth of 35-40 km [17]. This study also noted that the scarps formed after the period of heavy bombardment on Mercury (≤ ~4.0 Ga).

ADDITIONALLY: The observed textures in NWA 2999 are not consistent with the metamorphic reaction described by [2].







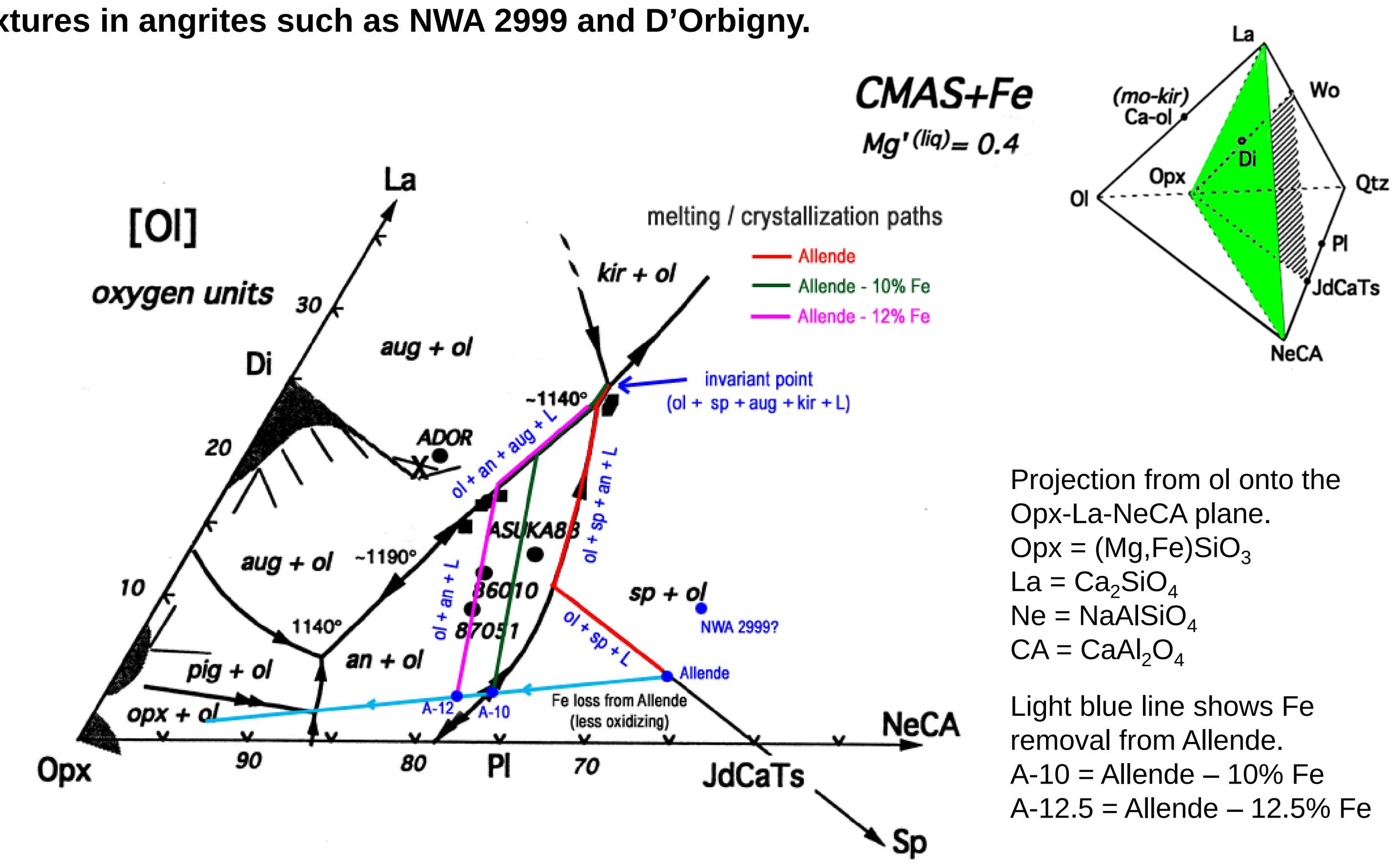
Figures 5 (top left), 6 (top right) and 7 (lower right) show backscattered electron (BSE) images of a poorly polished slice (not PTS) of NWA 2999. As shown in Figure 5, easily distinguishable phases are metal (met), ol, and anor. Sp and cpx are approximately the same shade of gray in BSE. EDS was used to confirm phase identification of these two phases.

A) No examples were found in this slice of NWA 2999 of the "symplectite" as described and illustrated in [2]. Instead, as shown in Figures 5, 6, and 7, anor is often found directly in contact with olivine – see blue arrows in Figure 5. This is inconsistent with the metamorphic reaction suggested by [2]. As shown in Figure 7, anor occurs both as very large (> 1mm) grains, and as complex intergrowths with ol, cpx, met and sp (e.g., region highlighted by yellow ellipse).

B) The "coronas" described by [2] are very common in this slice of NWA 2999 (see Figure 5 – green arrow and Figure 6 - red ellipse). However, they are not always in contact with cpx, but are frequently found completely enclosed in ol (Figure 6). This is not likely to be a sectioning artifact, as many examples were seen. This relationship is also inconsistent with the metamorphic reaction suggested by [2].

C) Similar "corona" textures were reported in D'Orbigny [18], with small hercynitic spinel grains "typically" [18] enclosed by cpx and plag. These are described as "symplectic borders" [18]. D'Orbigny is a clearly igneous rock that could not have experienced the metamorphism suggested by [2].

ADDITIONALLY: Not only is the pressure-change mechanism suggested by [2] implausible, it is unnecessary, because low-pressure crystallization can explain the observed disequilibrium textures in angrites such as NWA 2999 and D'Orbigny.



Projection from ol onto the Opx-La-NeCA plane.
Opx = $(Mg,Fe)SiO_3$
La = Ca_2SiO_4
Ne = $NaAlSiO_4$
CA = $CaAl_2O_4$

Light blue line shows Fe removal from Allende.
A-10 = Allende – 10% Fe
A-12.5 = Allende – 12.5% Fe

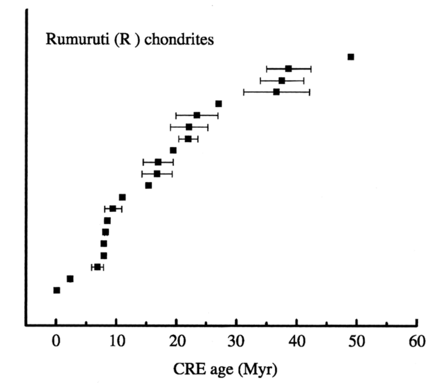
Figure 8 (above – after [19]) shows phase relationships relevant for angrites. The light blue line indicates the range of chondrite compositions, from highly oxidized on the right to reduced on the left, with variable amounts of Fe removed as metal. Red, green, and purple lines indicate liquid composition crystallization/melting paths for various bulk chondrite compositions. Most workers (e.g., [19]) believe that angrites formed by crystallization of partial melts of CV-like chondrites under oxidizing conditions. For such oxidized compositions (including the approximate NWA 2999 composition [2]), sp crystallizes before anor. As temperature decreases, anor becomes stable and can be produced at the expense of sp (e.g., green and red lines in Figure 8). We suggest that anor coronas around sp form by this process. In contrast, if the melt is more reduced, sp does not crystallize before anor, and such coronas wouldn't form. In addition, at lower temperatures (~1140ºC – near the minimum melt composition), anor becomes unstable and cpx + sp can crystallize together. This could form the symplectite textures observed by [2], and the complex intergrowth of phases seen in Figure 7.

ARGUMENT #4: "each angrite specimen is texturally different with a unique CRE age" [1]

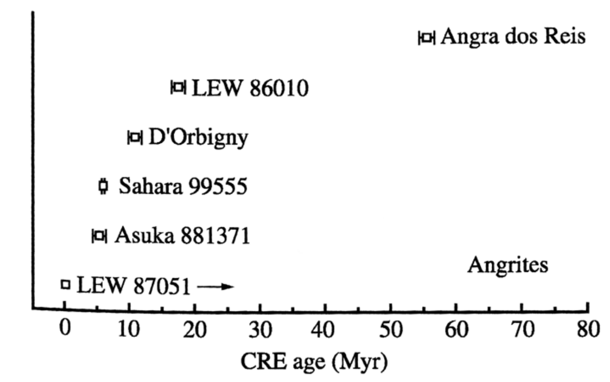
and

ARGUMENT #5: "the wide range in CRE ages (55 to <6.1 Ma) suggests that the parent body (APB) is large enough to be struck repeatedly and may till be extant" [1]

HOWEVER: Angrite CRE ages are totally unremarkable for a stony meteorite – there is no need for a planet-sized object.



The range of CRE ages for R chondrites (Figure 9a-left) is comparable to those of angrites (Figure 9b-right) [20]. These ranges are similar to those of ordinary (1-80 Ma) and enstatite chondrites (0.5-90 Ma) [20] and clearly do not require a large parent body.



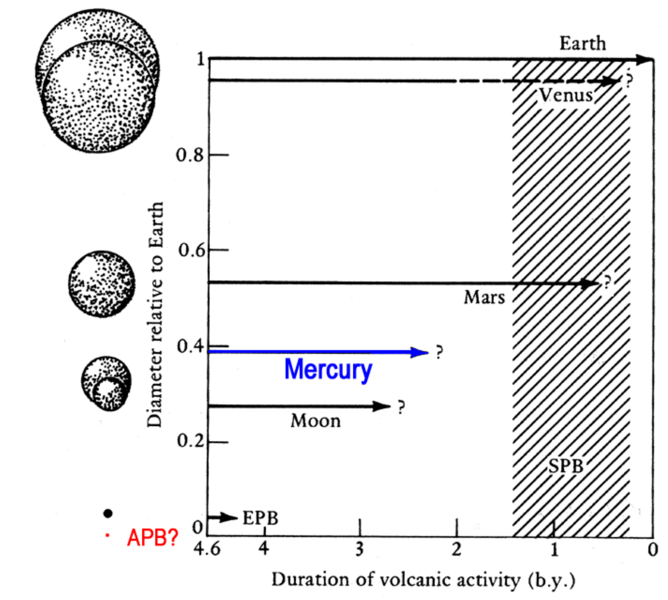
ARGUMENT #6: "very ancient formation ages (>4.555 Ga) imply very rapid core segregation and cooling following APB accretion (consistent with contraction?)" [1]

HOWEVER: Very ancient formation ages argue AGAINST an origin on a large parent body.

A) As shown in Figure 10 (right, [21]), larger planetary objects remain geologically active for longer periods of time.

B) Lunar and martian samples show a wide range of crystallization ages, with only a few Apollo samples having ages >4.3 Ga [22].

C) Angrites are among the oldest materials dated, implying that the APB was very small (e.g., [3], [18]).



ARGUMENT #7: "dynamical calculations predict that ~1% of material ejected from Mercury could reach Earth" [1]

HOWEVER: We have far more angrites in our collection than expected from dynamical calculations for mercurian ejecta.

A) More rigorous modeling [23] indicates an efficiency of transport from Mars to Earth about 15 times greater than from Mercury to Earth. With over 30 martian meteorites, we would expect only 2 or so mercurian meteorites.

B) Just because material can reach Earth from Mercury, doesn't mean that the material must be angritic. Some other type of meteorite is just as likely.

ARGUMENT #8: "the limited shock effects may mean that some angrites, including NWA 2999, were ejected by spallation; others may be impact melts (could vesicles in some quenched specimens be trapped impact rock vapor?)" [1]

HOWEVER: Limited shock effects argue for a smaller parent body, not a larger one (e.g., [24]).

A) In order to be ejected from a planet, material must be accelerated to greater than escape velocity. Dynamical models suggest that to reach Earth any mercurian ejecta would have had to have been accelerated more than martian ejecta [3]. Thus any martian meteorite should have been shocked at least as intensely as martian meteorites, unlike angrites.

B) It is unlikely that some angrites are heavily shocked impact melts, while others show minimal shock effects. A continuum of shock effects would be more probable.

C) All angrites could be impact melts. However, this is inconsistent with the plutonic textures of some of these rocks.

Why angrites are not from Mercury:

The high FeO and TiO_2 contents and low alkali contents in angrites are inconsistent with spectral measurements of the composition of Mercury's surface.

The bulk FeO content (33 wt%) and abundance of metal (8%) reported for NWA 2999 [2] are inconsistent with Mercury's huge metal core, which requires both efficient segregation of Fe-metal from silicates, and removal of FeO from silicates.

Ancient crystallization ages for the angrites are inconsistent with formation on a planet-sized object, which would have remained geologically active, with remelting for at least 1 Ga (based on the smaller Moon).

There is no mechanism on Mercury that will enable material to be buried to, and exhumed from, the great depths required for the metamorphic reactions proposed by [2] to explain disequilibrium textures observed in NWA 2999. These disequilibrium textures more plausibly result from normal crystallization processes.