A Large Proto-Mercury as the Aubrite Parent Body.

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Aubrites and their parent body (AuPB): Aubrites are achondrites generally considered to be samples of the silicate portion of a differentiated enstatite chondrite-like parent body [1]. Most aubrites are breccias, containing clasts of coarse-grained pyroxenite consisting of nearly FeO-free silicates and rare accessory minerals including Si-bearing Fe(Ni) metal and exotic Ca-Fe-Mg-sulfides which formed under extremely low fO_2. Among aubritic clasts, rare other lithologies including dunite, basalt (i.e. aubrite basalt vitrophyres [2], ABVs), and plagioclase-silica bearing rocks have been found [1]. This magmatic suite is consistent with igneous fractionation from a single mafic parental melt at IW-6 ± 1 [3]. The petrology of the igneous clasts, their very similar $D^{17}O$ values [4], and the strong depletions in siderophile and chalcophile elements characterizing aubrites [5], support a magma ocean stage on their parent body. ^{53}Mn-^{53}Cr isotope systematics measured on 7 aubrites suggest a main differentiation event at 4.562.5 Ga ± 1.1 Ma [6].

Ni and Co abundances in aubrites support an AuPB with a mass of 0.3 to 0.8 Earth mass: Ni and Co are excellent baro/oxybarometers as their metal/silicate partition coefficients ($D^{met/sil}$) are strongly correlated to P, decreasing over almost 3 orders of magnitude between 1 bar and 100 GPa, and to fO_2, with $D^{met/sil}$ increasing over 3 orders of magnitude between IW and IW-6. In order to construct a tool applicable to AuPB's redox conditions, we added recent experimental partitioning data obtained at highly reducing conditions to the database of [7], and parameterized Ni and Co $D^{met/sil}$ as a function of T, P, and fO_2 following a formalism identical to that of [7]. Our new model allows predicting confidently $D^{met/sil}$ for Ni and Co at $1 \text{ bar} \leq P \leq 60$ GPa, $\text{IW} \leq fO_2 \leq \text{IW-6}$, and $1550 \leq T \leq 4450$ K.

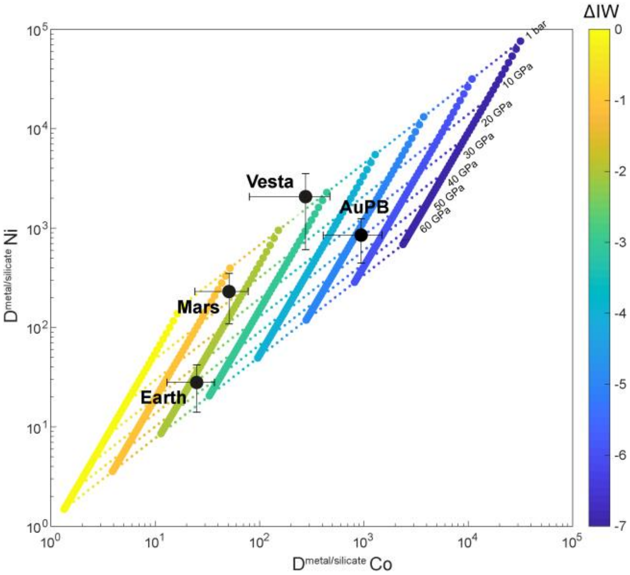

Fig. 1: Pressure (GPa) - fO_2 (ΔIW) space drawn by modelled Ni and Co $D^{met/sil}$ along the liquidus of a chondritic mantle, on which are plotted the core-mantle Ni and Co $D^{met/sil}$ calculated for the Earth, Mars, Vesta, and the AuPB.

In aubrites and ABV, Ni and Co are mainly carried by the metal phase of metal/sulfide assemblages that make up ~ 0.7 vol% of the meteorites. We produced a compilation of all available Ni and Co analyses of aubritic samples. Once samples showing evidence for contaminated material are put aside from the database, bulk compositions are homogeneous, with a median values of 0.006 ± 0.003 wt% Ni and 2.8 ± 1.6 ppm Co in a population of 11 aubrites and 3 ABV. Under the hypothesis that metal/sulfides complexes formed by exsolution during the cooling of a silicate melt initially containing (Ca, Fe, Mg)S species [8,9], we consider the Ni and Co median values to be representative of the bulk silicate AuPB. We subsequently estimate 5.2 ± 0.1 wt% Ni and 2621 ± 191 Co in the AuPB's core using mass balance calculation and considering various AuPB bulk compositions. We finally calculate $D^{met/sil}$ of 846 ± 401 for Ni and 953 ± 545 for Co in the bulk AuPB.

We then model Ni and Co $D^{met/sil}$ along the liquidus of a chondritic mantle of terrestrial bodies to draw a P - fO_2 space in which we plot the Ni and Co $D^{met/sil}$ of the AuPB, together with $D^{met/sil}$ of Earth, Mars and Vesta, for which bulk silicate and core compositions are well constrained (Fig. 1). Calculated $D^{met/sil}$ indicates IW-2.2 and 41 GPa for the Earth, IW-1.5 and 7 GPa for Mars and IW- 2.3 and <1 bar for Vesta, in excellent agreement with both the fO_2 and P conditions estimated for core formation in these objects. Our estimation of Ni and Co $D^{met/sil}$ for the AuPB indicates an fO_2 of $\text{IW-}5.2^{+1.4}_{-1.8}$, consistent with the fO_2 of aubrites, and a P of 29^{+32}_{-21} GPa, intermediate between those obtained with the same method for Mars and the Earth, therefore suggesting an AuPB with an intermediate size between these planets.

Large proto-Mercury models match AuPB's inferred characteristics: Aubrites share similar exotic mineralogies with Mercury's lavas and are therefore regarded as potential analogues to Mercury's crust. It has however been assumed that they are not Mercurian meteorites, mostly based on chemical and physical arguments of asteroidal origin. Mercury has anomalously large core and small size relative to the other terrestrial planets, its mass being only ~6 % of the Earth's mass ($M_{\oplus}$) [10]. A long-standing idea holds that proto-Mercury once possessed a larger silicate mantle that was removed by an early giant impact(s) [11]. Hit-and-run impact simulations necessitate proto-Mercuries to be 4-5 times Mercury's actual mass (i.e. 0.2 - 0.3 $M_{\oplus}$) to be successful [12]. Moreover, N-body numerical simulations of solar system formation systematically predict bigger Mercury analogues, with 0.2 to 0.6 Earth masses ($M_{\oplus}$) [13,14]. All these models are consistent with P recorded by Ni and Co $D^{metal/silicate}$ in the AuPB (Fig. 1).

A chemical continuum between aubrites and Mercury's surface: All the rocks making up the silicate fraction of a planet are linked to their parent reservoir (i.e. the bulk silicate planet), by a combination of crystallization, melting, mechanical sorting and mixing processes. Given the well-established trends linking the Earth [15], Mars-SNC [16] and Vesta-HED data [17], we use here a similar cosmochemical framework to investigate a putative link between aubrites and Mercury. We plot all available chemical data (bulk aubrite data, excluding identified extraneous clasts and Shallowater, bulk ABV data, MESSENGER data) together. When plotted against Mg/Al, we observe a continuum for all major, minor and trace elements (Fig. 2). We interpret these global trends as illustrating the fractionation of mineral phases in a primitive magmatic episode of Mercury after the metal core was formed. In this context, aubrites would have been extracted from the shallow and sulfide-poor mantle of proto-Mercury and ABVs would sample its shallowest part. In contrast, the source of Mercury's lavas would be the deep and sulfide-rich mantle of proto-Mercury which became much shallower after the giant impact removing most of proto-Mercury's mantle.

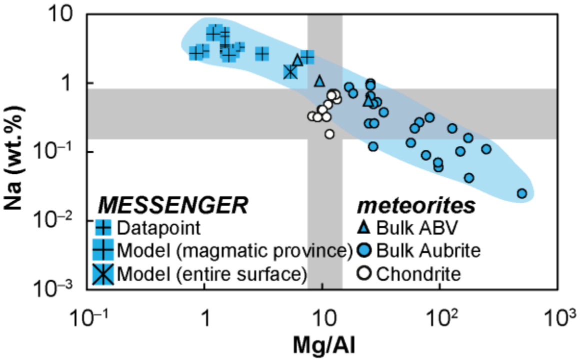

Fig. 2: Na abundances measured in bulk aubrites (except Shallowater, compiled with the MetBase software), bulk ABV, and at Mercury's surface by MESSENGER plotted as function of Mg/Al.

E-type asteroids as the secondary aubrite parent body: E-type asteroids are rubble pile asteroids with reflectance spectra and low densities consistent with an aubritic composition [18]. They are located in the innermost belt, forming a large proportion of the Hungaria population, and encountered among the Apollo near-Earth asteroid group. Their orbits are consistent with the fall dates and the long cosmic ray exposure ages of aubrites, supporting the idea that they are the immediate source body of these meteorites [19]. E-type asteroids represent a total mass of ~1.46×10^{18}kg, which represents only a few ppm of the material that would be stripped out by a giant impact on a large proto-Mercury. The age of aubrites coincides with an early epoch during which the Sun's wind, magnetic field strength and rotation rate each greatly exceeded their present-day value. We propose that following a giant impact, this early wind would have provided sufficient drag upon ejected debris to remove them from Mercury-crossing trajectories [20] and generated a tailwind upon debris, propelling them to greater orbital radii, possibly as far as the asteroid belt.

Implications for inner solar system early history: In the scenario of a giant impact occurring onto a large proto-Mercury and sending some small debris up to the Hungaria region, it is likely that large amounts of ejected debris are gravitationally captured by the inner planets during their outward course. [21] calculated that up to 20% of escaped particles could collide with Venus, and about 5% with Earth. If proto-Mercury was 0.3 to 0.8 Earth masses and lost most of its mantle, that would potentially represent ~ 1% to 2.5% Earth mass of aubritic material accreting to the Earth.

References: [1] Keil K. (1997) *Chemie der Erde, 70*, 295–317. [2] Fogel R. A. et al. (2005) *Geochim. Cosmochim. Acta 69*, 1633–1648 [3] Righter K. et al. (2016) *Am. Mineral. 101*, 1928–1942. [4] Barrat J. A. et al. (2016) *Geochim. Cosmochim. Acta 192*, 29–48. [5] Lodders K. et al. (1993) *Meteorit. Planet. Sci.* 28, 538–551. [6] Zhu K. et al. (2021) *Geochim. Cosmochim. Acta 308*, 256–272. [7] Fischer R. A. et al. (2015) *Geochim. Cosmochim. Acta* 167, 177–194. [8] Namur O. et al. (2016) *Earth Planet. Sci. Lett.* 448, 102–114. [10] Hauck S. A. et al. *JGR*, *118*, 1204–1220. [11] Benz W. et al. (1988) *Icarus 47*, 516–528. [12] Chau A. et al. (2018) *Astrophys. J. 865*, 35. [13] Chambers J. E. (2001) *Icarus 152*, 205–224. [14] Lykawka P. S. and Ito T. (2017) *Astrophys. J. 838*, 106. [15] Palme H. and O'Neill H. S. C. (2014) *Treatise on Geochemistry*. [16] Righter K. and Chabot, N. L. (2011) *MAPS 46*, 57–176. [17] Righter K. and Drake M. J. (1997) *Meteorit. Planet. Sci.* 944, 929–944. [18] Fornasier S. et al. (2008) *Icarus 196*, 119–134. [19] Gaffey M. J. et al. (1992) *Icarus 100*, 95–109. [20] Spalding C. and Adams F. C. (2020) *Planet. Sci. J. 1*, 7.