CONTRIBUTIONS OF ANTARCTIC METEORITES IN UNDERSTANDING THE INNER SOLAR SYSTEM: THE INTERPLAY OF SAMPLES AND PARADIGMS.

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Introduction: Antarctic meteorites number nearly 50,000 in world collections [1], and have provided significant contributions to our understanding of the Solar System. Collections include samples from the Moon, Mars, asteroid 4 Vesta, as well as dozens or even hundreds of other bodies from the asteroid belt or near Earth objects. This 50th anniversary of the Japanese Antarctic finds from Yamato Mountains [2] offers a chance to reflect on the contributions to planetary science. Antarctic meteorites have provided fundamental constraints on Solar System science in three major roles: A) unique samples of bodies (Mars and Vesta), B) complementary samples of bodies (Moon, together with Apollo and Luna), and C) foundational samples that have expanded the variety of known and documented materials in our sample collections. These have all contributed to the ideas and paradigms that have influenced the understanding of our Solar System.

Mars: The only samples available from Mars are meteorites and Antarctic meteorites played a central role in establishing the link between meteorites and Mars. EET 79001 and its glassy pods (Lith.C) allowed the initial connection to Mars atmospheric noble gases as measured by Viking [3]. Ten years later ALH 84001 played a central role in questions about the possibility of past life on Mars [4]. Robotic exploration of Mars and characterization of its surface has revealed connections between meteorites and Mars as well as distinct differences [5]. A multitude of missions has led to complementary data from missions and meteorites, and a robust understanding of Mars' geologic history.

Vesta: Lithologies in Antarctic HED meteorites record a detailed petrologic history of their parent body that includes early core formation, mantle differentiation, melting, volcanism, metamorphism, and impacts. For nearly 40 years HED meteorites have been linked to asteroid 4 Vesta because of the very close match in IR and visible spectra between the meteorites and the asteroid ([6], and references therein). This spectral link was strengthened with the discovery of a dynamic physical link between 4 Vesta and a family of asteroids that can be connected to Earth's orbit via resonances, such as the 3:1 mean motion resonance with Jupiter and the v6 secular resonance between Jupiter and Saturn [7,8]. This connection was dramatically strengthened by Hubble Space telescope images that revealed a large 400 km crater at the south pole of Vesta [9], a possible source crater of HEDs. The Dawn mission put much of the petrologic and geochemical information into context and showed where some lithologies may have originated, and identified lithologies represented in meteorites at the surface of the asteroid [10,11].

Moon: Lunar meteorites have provided a wealth of new information, requiring revision to some specific scenarios arising from studies of Apollo samples. *Age Of Basaltic Volcanism:* Evolved and young low Ti basalts provide evidence that the Moon maintained widespread active magmatism up to ~2.9 Ga *(e.g.,[12])*. In addition, low Ti basaltic meteorites, Asuka 881757, Yamato793169, MIL 05035 and MET 01210 have yielded the oldest ages for basalt of this composition – 3.8 to 3.9 Ga [13]. [14] emphasize that the gaps in the ages of Apollo basalt groups disappear when the ages of meteoritic basalts are included in assessments. *Crustal Evolution:* Studies of feldspathic lunar meteorites have revealed a rich compositional and petrologic diversity that is inconsistent with a simple picture of a flotation crust of ferroan anorthosite [15]. The Apollo high magnesium suite of plutonic rocks has not been identified in lunar meteorites, suggesting that this suite is of local, rather than global importance. On the other hand feldspathic clasts from highlands breccias yield Sr and Nd isochrons of 4.4 Ga, providing evidence for an ancient LMO [16]. Clasts in Y-86032 and MAC 88105 are among oldest and also record evidence for magma ocean and differentiation (not just an artifact of Apollo sampling bias). *Late Heavy Bombardment:* Impact melt clasts from meteoritic breccias allow testing of the lunar cataclysm hypothesis [17]. New high-resolution dating techniques have led to impact ages different from the cataclysmic spike at 3.85 Ga [18]. Evidence for the Lunar Cataclysm remains equivocal but many new highlands breccias will help resolve this important problem. *Global Significance Of Apollo Defined Units:* KREEP has been recognized as an important component in only a few lunar meteorites [19, 20]. High TiO_2 basalt is part of bi-modal Apollo basaltic volcanism, but has only rarely been observed in several meteorites.

Asteroids: Antarctic meteorites have been integral to the establishment of new meteorite groups, and in fact remains one of the strongest drivers to continued recovery efforts. Diversity in the chondrite groups grew from Antarctic recoveries, such as CK and R chondrites [21,22], and CH chondrites which were established by studies of ALH 85085 [23]. More recent examples include G chondrites named for GRO 95551 [24], and Y chondrites named for the several members from the Yamato Mountains [25]. Significant members of all chondrite groups are represented in worldwide collections with a high number of CR chondrites among the ANSMET collection [26], and CI chondrites among the NIPR collection [27]. Achondrite groups have also been established and enhanced by Antarctic finds. One of the most compelling and spectacular examples is the lodranite-acapulcoite group. Initially established with largely ANSMET samples, this group now has significant members from all four major Antarctic meteorite collections - ANSMET, NIPR, EUROMET, and CHINAMET [28-31] – illustrating the potentially rich detail that can be discovered by pooling resources. Unique members of the aubrites, brachinites, ureilites, and non-Vestan eucrites are found among the Antarctic collections, and ungrouped irons and achondrites represent a significant fraction of recovery efforts. The ungrouped irons – first emphasized as a unique aspect of the ANSMET collection by [32] – continue to be found in new areas, and irons in general are a topic of broad interest internationally.

Antarctic meteorites are also intimately connected to, and provide “ground truth” for, sample return missions such as Stardust, Genesis, and Hayabusa [33]. The carbonaceous target asteroids of the OSIRIS-REx and Hayabusa2 missions share spectral and mineralogic features with numerous Antarctic carbonaceous chondrites [34,35]. These similarities should lead to new connections between meteorites and asteroids and a better understanding of relations between groups.

Influence on ideas: In addition to providing numerous new samples from the Solar System, Antarctic meteorite recovery has helped to challenge paradigms in planetary science. For example, the existence of dense collection areas was debated, but clearly there are many areas that have yielded thousands of meteorites. That larger bodies like planets can exchange mass was proved upon establishing the existence of lunar meteorites, followed shortly thereafter by martian meteorites. Views of a homogeneous solar nebula were dashed by recovery and documentation of numerous and diverse nebular materials amongst Antarctic meteorite collections. Availability of large amounts of meteoritic material in collections relaxed attitudes towards destructive analysis of traditionally more “unique and precious” meteorites such as Allende or others.

With such examples in mind, the future holds some tantalizing topics for consideration. As Antarctic meteorite collections grow, odds of recovering statistically rare samples increases. Continued meteorite recovery efforts in Antarctica may lead to recognition of a) Mercurian or Venusian (or even extrasolar) meteorites, which would address the uniqueness of the O and other isotopic similarity between enstatite meteorites and Earth and Moon, and/or b) missing portions of differentiated bodies (basalts from the aubrite and brachinite parent bodies and residues from the angrite parent bodies) thus leading to breakthroughs in understanding differentiation. Are H's, L's, LL's and R's from discrete bodies or stochastic samples of a continuous range of OC-like precursor nebular material? Can we discriminate multiple shower falls? Are there giant meteorites at depth in the ice sheet? Monitoring these and other questions into the future may reveal new or revised paradigms for how we view the Solar System.

Summary: The collection, distribution, and study of Antarctic meteorites has clearly provided fundamentally new materials, constraints, and ideas to Solar System science. They will continue to enhance our understanding of the origin of our solar system, nebular processes, differentiation processes, planetary dynamics, impact history, and the emergence of life and biochemical processes. As the Antarctic meteorite collections grow, so do the known number of parent bodies and unique materials that are otherwise not sampled by humans or robotic space exploration missions.

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