SIDEROPHILE ELEMENT FRACTIONATION IN METEOR CRATER IMPACT GLASSES AND METALLIC SPHERULES; D.W. Mittlefehldt[1], T.H. See[1] and E.R.D. Scott[2], [1]Lockheed-ESC, C23, 2400 NASA Road 1, Houston, TX 77058, [2]Planetary Geosciences Division, Dept. of Geology & Geophysics, SOEST, Univ. of Hawaii, Honolulu, HI 96822

Abstract - Meteor Crater, Arizona provides an opportunity to study, in detail, elemental fractionation processes occurring during impacts through the study of target rocks, meteorite projectile and several types of impact products. We have performed EMPA and INAA on target rocks, two types of impact glass and metallic spherules from Meteor Crater. Using literature data for the well studied Canyon Diablo iron [0], we can show that different siderophile element fractionations affected the impact glasses than affected the metallic spherules. The impact glasses primarily lost Au, while the metallic spherules lost Fe relative to other siderophile elements.

Stratigraphy / Geologic Setting - Meteor Crater is a small, bowl-shaped impact crater ~1.2 km in diameter and ~180 m deep located in the southern part of the Canyon Diablo Region of the Colorado Plateau in north-central Arizona. Formation of the structure is believed to have occurred ~49,000 years ago [1] when a IA iron meteorite ~30 m across, traveling at ~15 km/s collided with the Earth. The crater rim rises between 30-60 meters above the surrounding, low-relief Plateau. The somewhat squarish shape of the crater is the result of two perpendicular sets of vertical joints within the target strata. These strata consist of sandstones, siltstones and dolomites of Permian to Triassic age [2].

Only the upper portions of the Permian Coconino Sandstone, a crossbedded, clean-quartz sandstone, are exposed. Overlying the Coconino is the ~2.7 meter thick Permian Toroweap Formation composed of calcareous, medium- to coarse-grained sandstone and dolomite. Above the Toroweap lies the ~80 meters thick Permian Kaibab Formation composed of dolomitic limestone with minor amounts of calcareous sandstone. Above the Kaibab is a thin layer (~9-15 meters) of the Triassic Moenkopi Formation consisting of fine-grained sandstone and siltstone [2].

Sample Description - Three varieties of samples from Meteor Crater have been examined in this study. One type, Spherical Impact Glasses (SIG), occurred as dark, generally hollow, spherical glass beads ~0.5 cm in diameter. Small vesicles were visible on exterior surfaces, as were minor amounts of clastic detritus. In thin section the glasses exhibited varying degrees of crystallization (ranging from ~20% to >75% small, aphanitic crystals); vesicles ranged from circular to elliptical. Numerous, small circular Fe-Ni blebs were commonly scattered about the interior. The second sample type was the elongated Irregular Impact Glasses (IIG) which averaged ~1 x 2 cm in size. Macroscopically, these samples were reddish-brown in color, exhibited ropy to irregular exterior morphologies often containing larger spherical to elliptical vesicles in exterior surfaces. Exposed interior surfaces commonly exhibited larger white clasts. In thin section these samples were much more vesicular (≥50% of the surface area in several specimens) than the SIG samples. The IIG samples also exhibited higher degrees of crystallization and contained fewer metallic blebs than the SIG samples. Both sample types were clearly molten when formed. The third sample type was small, metallic spherules (MS) ~0.5-1.5 mm in diameter and weighing 0.7 to 13 mg. The metallic spherules possess an iron-oxide coating. The texture and mineralogy of these metallic spherules were classified in [3].

Analyses - We have performed electron microprobe analysis (EMPA) of the glass in the IIG and SIG samples as in [4]. The EMPA were purposefully targeted to avoid the Fe-Ni blebs contained in the glass. Bulk splits of the IIG and SIG samples were analyzed at JSC by instrumental neutron activation analysis (INAA) as in [4]. The MS samples were analyzed by INAA at UCLA in 1975 following the procedure of [5]. Following [6], we abraded the oxide coatings off of the metallic spherules prior to performing our analysis.

Discussion - In our previous work [4] we analyzed similar samples from Wabar Crater, Saudi Arabia in order to investigate mixing between the target lithologies and the projectile. The target lithology at Wabar is much less complex and is composed of sandstone with possibly some drift sand. Wabar Crater was formed by a IIIA iron meteorite projectile. In addition, Wabar Crater is small (~90 m diameter) compared to Meteor Crater.

At Wabar we found that smaller, aeroballistically dispersed samples, akin to the SIG samples of this study, contained the highest percentage (~11%) of meteoritic materials, while the larger glass samples, similar to the IIG of this effort, possessed ~7% meteoritic component. The black and white melts discussed in [4] have no equivalents in Meteor Crater impactites. However, they contained ~4% and 0.4% meteoritic component, respectively. We concluded that the smaller, more meteorite-rich samples originated from the upper portion of the target near the impact point, while the larger samples originated from deeper within the target.

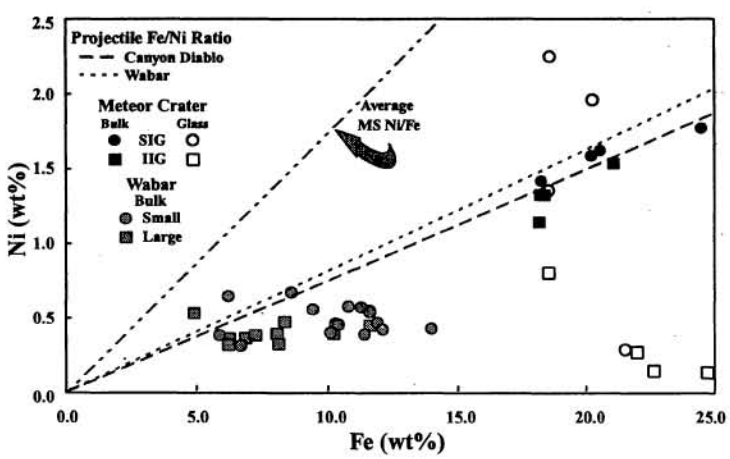

Figure 1 is a Ni vs. Fe diagram showing the bulk INAA analyses and the glass-only analyses collected via EMPA for the Meteor Crater impact glasses. Bulk analyses by INAA for Wabar impact glasses [4] are shown for comparison, as are Wabar and Canyon Diablo projectile Fe/Ni ratios and the average ratio for the Canyon Diablo metallic spherules. A general Ni-depletion, relative to the Wabar/Nejed projectile was observed for most of the Wabar specimens [4].

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The microprobe data show that all four of the IIG samples have fractionated Ni/Fe, within the glass, relative to Canyon Diablo projectile. The SIG samples, on the other hand, yield mixed results with one sample having Ni/Fe similar to the most depleted IIG samples, one SIG possessing essentially meteoritic proportions of Fe and Ni, and two samples exhibiting small degrees of Ni-enrichment relative to Fe within the glass. However, bulk Fe-Ni concentrations obtained by INAA analyses exhibit little deviation from the meteoritic ratio and suggest little siderophile element fraction on the scale of the bulk specimen.

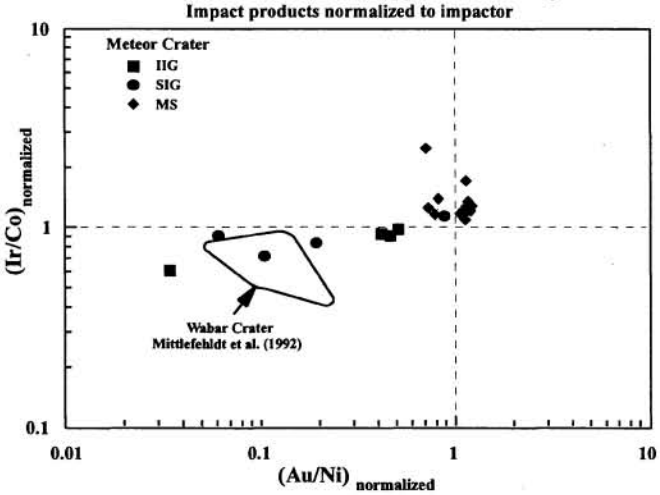
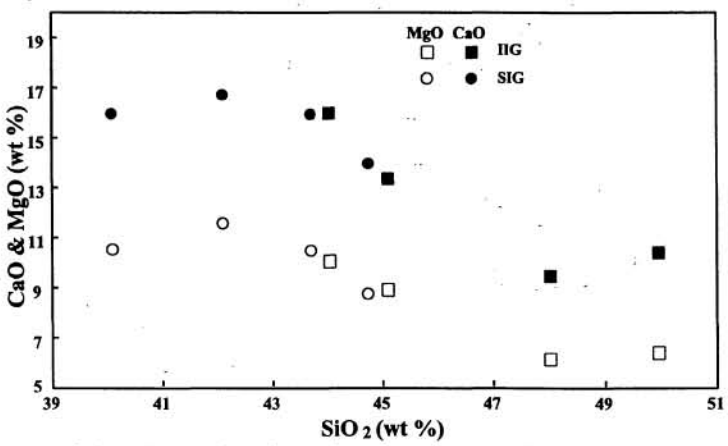


Figure 2 compares the siderophile element fractionations of the IIG, SIG and MS samples. As was the case for Wabar Crater impact glasses [4], Au shows the strongest depletion among the siderophile elements in Meteor Crater impact glasses; Au/Ni ratios vary from ~1 to ~0.03 times that of the Canyon Diablo meteorite. The IIG samples *generally* have higher Au/Ni ratios than the SIG samples, although clearly there is a wide range in ratios for both sample types. Most of the SIG samples have impactor normalized Au/Ni ratios similar to those of Wabar Crater impact glasses.

Previous work on metallic spherules from Meteor Crater has shown that they contain projectile ratios of Co/Ni and Cu/Ni but are depleted in Fe [6]. Our MS samples show little fractionation in Ir/Co or Au/Ni from the projectile ratios (Figure 2). The most extreme Ir/Co ratio is ~2.3 times that of Canyon Diablo, and Au/Ni ratios are within 30% of Canyon Diablo. However, Ni/Fe ratios in MS are strongly fractionated relative to the projectile (Figure 1). Kelly*et al.* [6] concluded that Fe in the metal spherules was selectively oxidized in molten metal droplets in the atmosphere, and that some of the FeO was lost through vaporization. However, our metallic spherule samples have average Ga/Fe, Ge/Fe and As/Fe ratios of 1.6, 2.5 and 4.5 times those of Canyon Diablo meteorite, respectively. These are the most volatile of the siderophile elements we have analyzed, and the boiling point of As is undoubtedly >1000°K lower than that of FeO or Fe_2O_3. Therefore, oxidation and vaporization of Fe is probably too simplistic a model for Fe loss from the metallic spherule. Because oxide coatings were abraded off the metallic spherules by us and [6], it is possible that the Fe fractionation was generated at the time of sample preparation as follows: During impact, mm-sized metal droplets were sprayed out of Meteor Crater. Iron was oxidized during flight, and the iron oxides were concentrated on the outside of the droplets. During residence on the desert surface, some of this oxide coating was spalled off by weathering, and the remainder was removed by careful geochemists trying to avoid what appeared to be terrestrial weathering products. This process would give the *appearance* of Fe fractionation, when in fact, analysis of whole metallic spherules, including the oxide coating, would show that Fe was not fractionated. However, bulk analyses by EMPA [4] show that P is enriched relative to Fe in the metallic spherules. As P should be more susceptible to oxidation than Fe, the above model would predict that P/Fe, and especially P/Ni, ratios should be lower than those of bulk Canyon Diablo, contrary to observation. Clearly, however, the impact glasses and metallic spherules were affected by different fractionation processes; the former primarily lost Au while the latter lost Fe in preference to other siderophile elements.

Presently, we do not have bulk chemical compositions for the various target litholgies. However, we can deduce from the general lithologic descriptions of the target rocks that SiO_2 was a prominent component of the Moenkopi and Coconino, while CaO and MgO are dominant in the Kaibab. Figure 3 illustrates the relationships between SiO_2 and both CaO and MgO within the impact glasses. The increases in CaO and MgO within the SIG samples relative to the IIG suggest that the SIG samples contain larger proportions of the Kaibab limestone and dolomite. Based on the size, shape and petrography of the impact glasses, we expect that the SIG were formed higher in the target stratigraphy than the IIG [*e.g.* 4]. We infer, then, that the higher SiO_2 and lower CaO and MgO contents of the IIG samples reflect a larger component of Coconino sandstone, rather than the Moenkopi sandstone/siltstone. Verification of this awaits bulk chemical analyses of the various target lithologies.



References - [0] Wasson and Ouyang (1990) *CGA, 54*, 3175. [1] Sutton (1985) *JGR, 90*, 3690. [2] Shoemaker and Kieffer (1974) *Guidebook to the Geology of Meteor Crater, Arizona*. [3] Blau *et al.* (1973) *JGR, 78*, 363. [4] Mittlefehldt, *et al.* (1992), *Meteoritics, 27*, 361. [5] Scott (1978) *CGA, 42*, 1243. [6] Kelly *et al.* (1974) *GCA, 38*, 533.