

**INTERPRETING IMPACT-INDUCED HYDROTHERMAL GEOCHEMISTRY USING AUTHIGENIC MINERAL ASSEMBLAGES.** Z. E. Gallegos<sup>1</sup>, H. E. Newsom<sup>1</sup>, L. J. Crossey<sup>1</sup>, D. T. Vaniman<sup>2</sup>, G. R. Osinski<sup>3</sup>, P. Lee<sup>4,5</sup>. <sup>1</sup>Institute of Meteoritics, Univ. of New Mexico, Albuquerque, NM, USA ([zachegallegos@gmail.com](mailto:zachegallegos@gmail.com)); <sup>2</sup>Planetary Science Institute, Tucson, AZ, USA; <sup>3</sup>Univ. of Western Ontario, ON, Canada; <sup>4</sup>Mars Institute; <sup>5</sup>NASA Ames Research Center, CA, USA.

**Introduction:** Hydrothermal systems are prominent where a heat source interacts with the local hydrosphere. Ground and surface waters that undergo alteration due to this thermal disequilibrium can record the effects in the geologic record as complex, authigenic mineral assemblages. The deposition of these minerals allows for the study of hydrothermal systems that are dormant or even long extinct.

Impact-induced hydrothermal activity is a well proven process that accompanies a bolide impact of sufficient size/speed into a target with a hydrosphere of sufficient water/rock ratio. Currently, Earth harbors the only known examples of this impact process; however, impact cratering is the most ubiquitous geologic process throughout the rocky solar system.

*Hydrothermal regimes.* The smallest impact events may only record low temperature/diagenetic reactions. The very largest events, ‘plutonic cratering’, can record all four stages in hydrothermal evolution: rock dominated, vapor dominated, high temperature fluid, and low temperature fluid/diagenetic.

**Haughton Impact Structure:** The Haughton impact structure (HIS) lies on Devon Island, Nunavut territory (75°22’N, 89°41’W) within the Canadian Arctic Archipelago. The impact structure, ~23 km in diameter, is the result of an impact at 39 Ma (Late Eocene) [1]. The target area comprises mainly Paleozoic carbonate-sulfate sediments atop a gneissic basement.

*Hydrothermal deposits.* The Haughton impact structure is unique among the study sites in that the hydrothermal deposits are observable in outcrop on the surface. **Table 1** lists the hydrothermal minerals discovered at the HIS [1].

Quartz (SiO <sub>2</sub> )
Calcite (CaCO <sub>3</sub> )
Celestite (SrSO <sub>4</sub> )
Barite (BaSO <sub>4</sub> )
Fluorite (CaF <sub>2</sub> )
Pyrite (FeS <sub>2</sub> )
Marcasite (FeS <sub>2</sub> )
Goethite (α-FeO(OH))
Fibroferrite (Fe <sup>3+</sup> (SO <sub>4</sub> )(OH)•5H <sub>2</sub> O)
Ferrihydrite ((Fe <sup>3+</sup> ) <sub>2</sub> O <sub>3</sub> •0.5H <sub>2</sub> O)
Gypsum (CaSO <sub>4</sub> •2H <sub>2</sub> O)

**Table 1.** Hydrothermal mineral assemblage from the HIS.

**Manson Impact Structure:** The Manson impact structure (MIS) is located in Iowa, USA (42°35’N, 94°33’W). The impact structure, ~35 km in diameter, is the result of an impact at 74 Ma (Late Cretaceous). The target area consists of Mesozoic, Paleozoic, and Proterozoic sedimentary sequences atop a Proterozoic gneissic basement.

*Hydrothermal deposits.* The Manson impact structure is currently buried beneath a few tens of meters of post-impact sediments. Drill cores containing the hydrothermal mineral observed provide our only clue into the nature of these deposits. **Table 2** lists the hydrothermal minerals discovered at the MIS [2].

Quartz (SiO <sub>2</sub> )
Calcite (CaCO <sub>3</sub> )
Ferroactinolite (Ca <sub>2</sub> (Mg <sub>2.5-0.0</sub> Fe <sup>2+</sup> <sub>2.5-5.0</sub> )Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub> )
Analcime (NaAlSi <sub>2</sub> O <sub>6</sub> •H <sub>2</sub> O)
Garnet (Ca <sub>3</sub> Fe <sub>2</sub> Si <sub>3</sub> O <sub>12</sub> & Ca <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub> )
Laumontite (Ca(AlSi <sub>2</sub> O <sub>6</sub> ) <sub>2</sub> •4H <sub>2</sub> O)
Prehnite (Ca <sub>2</sub> Al(AlSi <sub>3</sub> O <sub>10</sub> )(OH) <sub>2</sub> )
Epidote (Ca <sub>2</sub> Al <sub>2</sub> (Fe <sup>3+</sup> ,Al)(SiO <sub>4</sub> )(Si <sub>2</sub> O <sub>7</sub> )O(OH))
Wollastonite (CaSiO <sub>3</sub> )
K-feldspar (adularia) (KAlSi <sub>3</sub> O <sub>8</sub> )
Pyrite (FeS <sub>2</sub> )
Goethite (α-FeO(OH))
Molybdenite (MoS <sub>2</sub> )
Phlogopite (KMg <sub>3</sub> (AlSi <sub>3</sub> O <sub>10</sub> )(F,OH) <sub>2</sub> )
Chlorite (Mg,Fe) <sub>3</sub> (Si,Al) <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub> (Mg,Fe) <sub>3</sub> (OH) <sub>6</sub>
Corrensite (Ca,Na,K)(Mg,Fe,Al) <sub>9</sub> (Si,Al) <sub>8</sub> O <sub>20</sub> (OH)•10(H <sub>2</sub> O)
Illite (K,H <sub>3</sub> O)(Al,Mg,Fe) <sub>2</sub> (Si,Al) <sub>4</sub> O <sub>10</sub> [(OH) <sub>2</sub> ,(H <sub>2</sub> O)]

**Table 2.** Hydrothermal mineral assemblage from the MIS.

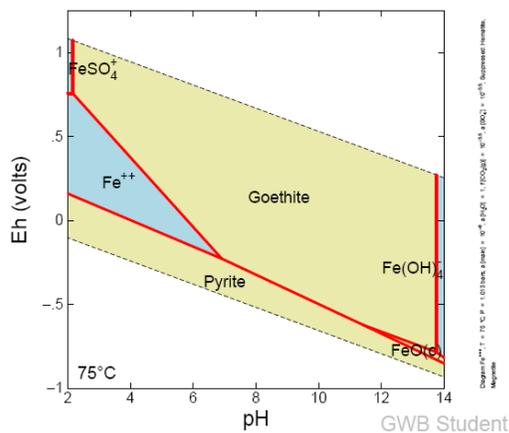
**Chicxulub Impact Structure:** The Chicxulub impact structure (CIS) is centered off the northern coast of the Yucatán Peninsula (21°24’N, 89°31’W). The impact structure, ~180 km in diameter, is the result of an impact at 66 Ma (Cretaceous-Paleogene boundary). The target area comprises Mesozoic carbonate-evaporite sediments atop Paleozoic crystalline basement.

*Hydrothermal deposits.* The CIS is another impact structure currently buried, in this case beneath ~1 km of post-impact sediments; drill cores provide evidence for hydrothermal deposits. **Table 3** lists the hydrothermal minerals discovered at the CIS [3,4].

Quartz (SiO <sub>2</sub> )
Calcite (CaCO <sub>3</sub> )
Apatite (Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> (F,Cl,OH))
Francolite ((Ca,Mg,Sr,Na) <sub>10</sub> (PO <sub>4</sub> ,SO <sub>4</sub> ,CO <sub>3</sub> ) <sub>6</sub> F <sub>2-3</sub> )
Garnet (Ca <sub>3</sub> Fe <sub>2</sub> Si <sub>3</sub> O <sub>12</sub> )
Sphene (CaTiSiO <sub>5</sub> )
Magnetite (Fe <sub>3</sub> O <sub>4</sub> )
Chalcopyrite (CuFeS <sub>2</sub> )
Bornite (Cu <sub>5</sub> FeS <sub>4</sub> )
Molybdenite (MoS <sub>2</sub> )
Rutile or Anatase (TiO <sub>2</sub> )
Limonite (FeO(OH)·nH <sub>2</sub> O)
Albite (NaAlSi <sub>3</sub> O <sub>8</sub> )
K-feldspar (KAlSi <sub>3</sub> O <sub>8</sub> )
Scapolite (Na, Ca, K) <sub>4</sub> (Al <sub>3</sub> (Al, Si) <sub>3</sub> Si <sub>6</sub> O <sub>24</sub> )(Cl, CO <sub>3</sub> , SO <sub>4</sub> , OH)
Epidote (Ca <sub>2</sub> Al <sub>2</sub> (Fe <sup>3+</sup> , Al)(SiO <sub>4</sub> )(Si <sub>2</sub> O <sub>7</sub> )O(OH))
Gypsum (CaSO <sub>4</sub> ·2H <sub>2</sub> O)
Halite (NaCl)
Chlorite (Mg,Fe) <sub>3</sub> (Si,Al) <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub> (Mg,Fe) <sub>3</sub> (OH) <sub>6</sub>

**Table 3.** Hydrothermal mineral assemblage from the CIS.

**Geochemical Modeling.** The mineral assemblages produced in hydrothermal processes contain a record of the fluid composition and the P/T conditions during alteration and precipitation that can be evaluated through geochemical modeling. Constraints on mineral stability such as temperature, activities, activity ratios, and Eh/pH (*Figure 1*) can be used to constrain the characteristics of the hydrothermal chemistry.



**Figure 1.** Eh/pH diagram of pyrite→goethite observed in hydrothermal deposits from the HIS (*Figure 1*). (Log activity Fe<sup>+++</sup> = -3, temp = 195°C, in the presence of CO<sub>2</sub> and SO<sub>4</sub>)

#### Discussion:

*Comparative mineralogy.* Every impact hydrothermal system has a unique geochemical signature related to 1) impact size, and therefore hydrothermal system complexity and maturity, and 2) the composition of the target rocks through which the hydrothermal fluids once flowed.

The heat source of an impact hydrothermal system is the result of impact energy transferred to melt rocks and stratigraphically uplifted basement material. An impact with greater size will result in a higher temperature, longer lived heat source. The mineralogy produced at the CIS is indicative of the impact size in mineral complexity and presence of high temperature andradite garnet. The HIS and MIS have fewer altered phases than the CIS, and there is a lack of high temperature minerals in the HIS. The increase in impact size also relates to an increase in sample depth, with the CIS sampling more basement material than the HIS and MIS. Target composition is reflected in the hydrothermal mineralogy; the HIS hydrothermal system sampled mostly chemical sedimentary rocks, while the mineralogically complex hydrothermal systems of the MIS and CIS sampled more continental and basement material respectively.

*Haughton as an Analogue for Gale Crater.* The use of analogue sites in planetary science provides essential training and testing environments; Haughton is ideal for analogue studies of Martian exploration. NASA hosts an initiative at the impact structure called the Haughton-Mars Project. The goals of this project are to understand the geology of the crater and also to use the environment as a testing ground for future planetary exploration [5].

Haughton and Gale crater are both complex impact structures, and they both contain deposits from post-impact fluvial and lacustrine processes. Whether Gale contains impact-induced hydrothermal deposits, as Haughton does, remains to be proven. The recent discovery of iron-rich sediments on Mars, by ChemCam and APXS [6,7], possibly with iron-rich cementation, as well as elevated manganese abundances [8] indicate fluid driven diagenetic and possible hydrothermal alteration/transportation processes within Gale.

**Conclusions:** Understanding the geochemistry of impact-induced hydrothermal systems, based on mineral assemblages, provides a glimpse into fluids that deposited those minerals. Through geochemical modeling experiments utilizing Eh-pH diagrams, temperature/activity diagrams, and activity ratio diagrams, the characteristics of impact-induced hydrothermal fluids can be interpreted.

**References:** [1] Osinski G.R. *et al.* (2005) *Meteoritics & Planetary Science*, 40, Nr 12. [2] McCarville P. & Crossey L.J. (1996) *The Manson Impact Structure*, GSA Special Paper 302. [3] Zucher L. & Kring D.A. (2004) *Meteoritics and Planetary Science*, 39, Nr 7. [4] Nelson *et al.*, LPSC 2010. [5] Lee P. and Osinski G.R. (2005) *Meteoritics & Planet. Sci.*, 40, Nr 12. [6] Williams R.M.E. *et al.* (2013) *Science*, v340 no.6136. [7] Blaney D.L. *et al.*, LPSC 2014. [8] Lanza N.L. *et al.*, (2014) *GRL* 41.16.