THE TUCSON UNGROUPED IRON METEORITE: A STEP IN DECIPHERING ITS ENIGMATIC ORIGIN.

M. E. Varela[1], G. Kurat[2,3] , E. Zinner[4], and F. Brandstätter[2], [1]Instituto de Ciencias Astronómicas de la Tierra y del Espacio (ICATE) Av. España 1512 sur, J5402DSP, San Juan, Argentina, [2]Mineralogisch-Petrographische Abteilung, Naturhistorisches Museum, Burgring 7, 1010 Wien, Austria, [3] Department of Lithospheric Sciences, University of Vienna, Althanstrasse 14, 1090 Vienna, Austria (gero.kurat@univie.ac.at), [4]Laboratory for Space Sciences and the Physics Department, Washington University, St. Louis, MO 63130, USA.

Introduction: Tucson is an enigmatic ataxitic iron meteorite, an assemblage of reduced silicates [1] arranged in sub-parallel flow-like structures [2], embedded in reduced metal with dissolved Si and Cr [3]. Both, silicates and metal, contain a record of formation at high temperature (~1800 K) and fast cooling. The latter resulted in the preservation of abundant glasses [4] and fine-grained metal. The chemical composition of silicate and metal phases led Bunch and Fuchs [5] to point out that Tucson shows similarities with enstatite chondrites and achondrites. This possible relationship was also support by others [6]. However, Tucson silicates have also isotopic and chemical similarities with constituents from carbonaceous chondrites such as Bencubbin, Kakangari and Renazzo [7].

Results and Discussion: Silicate inclusions were studied in the thin section L3951 and the thick polished section Tucson B (NHM, Vienna). The petrology of the silicate inclusions (Fig. 1) indicates a paragenetic sequence that begins with olivine as the first mineral to form (+ glass). The Ca-Al-Si-rich liquid (glass precursor) is an early phase, that could have pre-dated and evidently co-existed with forsterite (e.g., in primary glass inclusions). Olivine and low-Al clinoenstatite are embedded in Al-rich orthoenstatite, the product of a reaction between early formed olivine and a Si-rich medium (likely a liquid) that resulted in rounded olivine relics. The mineral association Al-rich enstatite + anorthite + clinopyroxene is frequently accompanied by brezinaite with which these phases form symplectitic intergrowths. The particular growth feature of olivine, which shows crystal faces toward the liquid (=glass) but not toward the metal [4], clearly indicates that some metal was already present when olivine grew from the Ca-Al-Mg-rich liquid. Because metal is also present inside primary glass-bearing inclusions in olivine and surrounds the silicate inclusions, it must have been present during the formation of most constituents of Tucson.

We performed a compositional (major and trace element) study of all phases of the Tucson meteorite: primary glass inclusions in olivine, clear mesostasis glass [4], low-Al and high-Al pyroxenes [8], olivine, clinopyroxene, anorthite, and brezinaite.

All silicate phases are very poor in Fe and free of alkali elements. Glasses and Ca-rich pyroxene are rich in refractory trace elements and have unfractionated REE and Li abundances (~10 x CI REE), but are depleted in Sc, Ti, Nb, V, and the moderately volatile elements Cr and Mn (Fig. 2). Low-Ca pyroxene has trace element abundances correlated with Al-contents and fractionated abundance patterns. Trace element abundances are low and very similar in all olivines, with highly fractionated abundance patterns. Brezinaite is poor in trace elements and has a strongly fractionated abundance pattern with large positive abundance anomalies in Nb, V, Ti, Mn, and Zr.

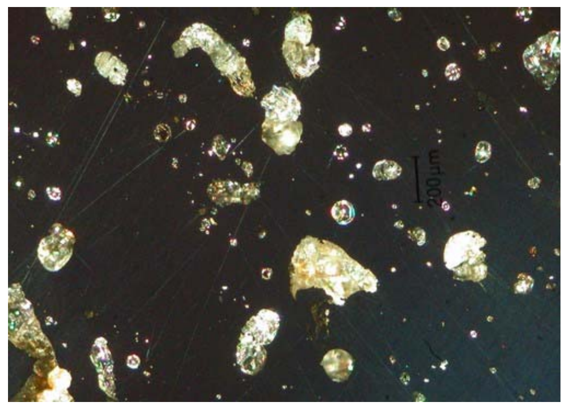

Fig.1: Silicate inclusions in Tucson metal (reflected light, crossed polarizers)

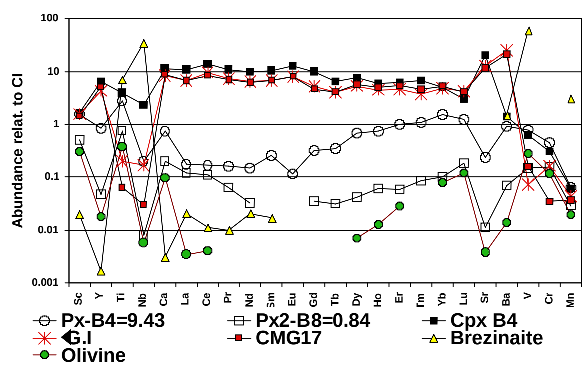

Fig. 2: CI-normalized trace element abundances in representative phases of the Tucson meteorite.

The distribution of trace elements between olivine and co-existing glass closely follows the experimentally determined distribution coefficients (Fig. 3), with four notable exceptions: La and Ce, Ti, and V. The high abundance of La and Ce in olivine could be the result of terrestrial contamination, which is also evident in many other minerals and glasses. The high distribution values for Ti and V – the result of very low abundances in glass - indicate that olivine is not in equilibrium with its co-existing glass inclusion and mesostasis glass.

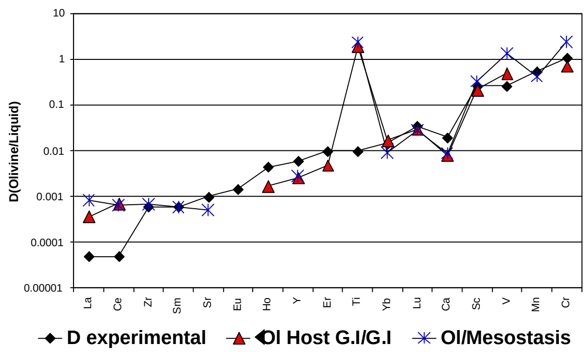

Figure 3: Distribution of trace elements between co-existing olivine and glass in Tucson silicate inclusions compared to experimentally determined olivine-liquid distribution coefficients (black diamonds, [9]).

However, because most other elements do behave very well, the petrographic finding that olivine grew from the liquid it now carries as glass inclusions [4] is strongly supported. Apparently, Ti was removed from the liquid=glass after olivine formation and re-equilibration was not possible (fast cooling). In contrast to olivine, pyroxenes in Tucson are compositionally very inhomogeneous, both in major and trace elements (Fig. 2). Their abundance patterns are fractionated, indicating chemical exchange reactions attempting equilibration with a vapor, liquid or solid (e.g., rock) system [8].

Calculation of the composition of a theoretical liquid in equilibrium with the Ca-poor, Al-rich pyroxenes shows that this liquid must have had refractory trace element abundances of around 10 x CI. The compositions of Ca-rich clinopyroxene and anorthite also indicate derivation from a liquid with refractory element abundances of ~8 – 20 x CI and 7 x CI, respectively. However, the trace element abundances of a liquid in equilibrium with Al-poor clinopyroxene appear to be very low and indicate an environment similar to that from which enstatite meteorites originated (xenocryst?). Tucson seems to contain silicates from two different sources. Both of them come from highly reduced environments and from environments very poor in volatile elements.

The Sc deficit in glasses signals fractionation via a refractory phase that scavenged Sc before the liquid formed [4]. In a cosmochemical setting this indicates early condensation of a highly refractory phase, such as corundum, hibonite, and perovskite. The two order of magnitude deficits in the abundances of Ti and Nb in all Tucson glasses – but not minerals – indicate loss of these elements from glasses after silicate formation. This could be achieved if Ti and Nb became chalcophile, moved out of the glass, and entered brezinaite.

Our previous results [4, 8] compel us to challenge the igneous model previously proposed for the formation of Tucson silicates inclusions [6]. Our new data support this effort and suggest that all silicates phases, have a simple, one-step nebular origin. These phases keep a record of the early highly reducing and increasingly oxidizing conditions during their evolution, before they became trapped in the metal.

The refractory and reduced silicates of the Tucson iron are embedded in a refractory and reduced metal, which has high and almost unfractionated abundances of refractory siderophile elements at ~3 – 9 x CI, low contents of volatile siderophile elements, and high contents of Si and Cr [e.g., 10]. Trace element abundances in Tucson metal also are governed by volatility (as they are in glasses). An origin by direct condensation from solar nebula gas seems to be likely. Such an origin has been predicted [14] and has also been favored by previous investigators of relatives of Tucson, such as Bencubbin and ALH 85085 [e.g., 7, 12, 13, 15, 16].

Conclusions: Tucson is the result of co-precipitation of metal and silicates from the solar nebula gas and precipitation of metal before silicates – in accordance with theoretical condensation calculations for high-pressure solar nebula gas [17].

Acknowledgement: Financial support was received from FWF, Austria (P16420-N10, P20226-N10), from CONICET (PIP 1645), Agencia (PICT212) and CONICET-FWF and CONICET-NSF International Cooperation Projects, Argentina, and NASA.

References: [1] Cohen (1905) Meteoritenkunde, Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Band III, 88-100; [2] Buchwald (1975) Handbook of Iron Meteorites. Univ. California Press, Berkeley, 3 vol., 1418 pp; [3] Wai and Wasson (1969) *GCA* 33, 1465-1471; [4] Varela et al., (2008) *LPS* XXXIX, Abstract #1373; [5] Bunch and Fuchs (1969) 54, 1509-1518; [6] Nehru et al. (1982) *Proc. LPSC* 13th, *JGR*. 87, Suppl., A365-A373; [7] Prinz et al., (1987) *LPS* XVIII, 800-801; [8] Varela et al., (2009) *MAPS* 44, A210; [9] Green, (1994) *Chemical Geology* 117, 1-36; [10] Wänke et al., (1983) *Phil. Trans. R. Soc. London* A 303, 287; [12] Newsom and Drake (1979) *GCA* 43, 689-707; [13] Weisberg et al. (1990) Meteoritics **25**, 269-279; [14] Grossman and Olsen (1974) *GCA* **38**, 173-187. [15] Meibom et al. (1999) *JGR* **104**, 22,053–22,059; [16] Cambell and Humayun (2004) *GCA* 68, 3409-3422; [17] Ebel (2006) In Meteorites and the Early Solar System II, Lauretta and McSween (eds.) University of Arizona Press, 253-277.