WILLY: A PRIZE NOBLE FREMDLING J.T. Armstrong, A. El Goresy, G.P. Meeker and G.J. Wasserburg, The Lunatic Asylum, Div. Geol. & Planet. Sci., Calif. Inst. of Tech., Pasadena, CA 91125

Among the most exotic and complex objects found in CAI are Fremdlinge [1]. The small size of these objects (typically << 50μm) has limited their petrologic and chemical investigation, and, to date, no isotopic analyses of individual Fremdlinge have been performed. The Allende CAI 5241 contains numerous Fremdlinge, two of which are of very large size (> 100μmϕ) and are contained in a single melilite grain. We report on a detailed petrologic and chemical investigation of "Willy", the larger of these Fremdlinge (~ 150μmϕ). Willy is composed primarily of a V-rich magnetite (V-mt), Ni-Fe metal, and troilite (FeS). Minor constituents include scheelite ($CaWO_4$), apatite, an Os-Ru alloy, MoS_2, and an unidentified Mg-, Fe-molybdate. Willy contains a complex fluffy core of V-mt, metal, FeS and other minor phases. The core is surrounded by a compact V-rich magnetite mantle. The mantle is surrounded by a rim composed of V-rich fassaite and V-rich spinels. This type of rimming is typical of oxide-bearing Fremdlinge in 5241 and other CAI as discussed in a companion paper [2].

V-mt, the most abundant phase in the Fremdling, occurs in two distinct morphologies. In the interior it is present as large single idiomorphic crystals up to 10μmϕ. In the exterior it is present as an anhedral, massive mantle, 2μm to 25μm wide, which surrounds the core. A typical composition of the V-mt is $(Fe^{+2}_{0.94}Mg_{0.06})(Fe^{3+}_{1.74}V_{0.18}Cr_{0.08})O_4$. The V-content is variable, containing up to 13% V_2O_3 and typically 4-6% V_2O_3, and is somewhat higher in the mantle than in the core.

Ni-Fe-metal, the most abundant phase in the core, is present as small subhedral crystals (< 10μm) [FeNi1] and as large oriented, crystals showing well developed [100] cleavage [FeNi2]. The skeletal crystals of FeNi2, which are loosely packed in rather porous areas, are oriented in distinctly different directions in each of several large (~ 50μm diameter) cells in the core. FeNi is clearly seen as rimming the idiomorphic V-mt crystals and thus clearly formed after the oxide. Additionally, FeNi2 is found growing around FeNi1. Both metal phases contain minute idiomorphic crystals of V-mt. The morphology of the FeNi2 is consistent with rapid growth. Compositionally, both metals are identical (typically, 61%Ni, 36%Fe, 2%Co, 0.4%Pt, 0.4%V, 0.2%Cr, 0.3%P). The metal is markedly enriched in Ni, Co, Pt, and P relative to normal metal in Allende. The main source of Pt in the inclusion appears to be a uniform concentration in FeNi rather than in distinct refractory blebs.

Sulfide is concentrated asymmetrically in a ring about the largest group of idiomorphic V-mt found in the interior, perhaps outlining the morphology of Willy in an earlier stage of growth. The sulfide is often found rimmed by FeNi and appears to have formed earlier than the metal. The sulfide is almost pure FeS with minor amounts of V, Cr, and Ni. Refractory metal alloy grains are found distributed throughout Willy and range in size from submicron blebs in the sulfides to ~ 3μm idiomorphic crystals often found at contacts between V-mt and FeNi. These grains are most frequently complex Os-Ru alloys poor in Pt. The platinum group elements are thus significantly fractionated in the FeNi and nuggets.

In one portion of Willy, extending from the interior of the V-mt mantle to the center of the Fremdling and separating two cells of the core is an assemblage of scheelite (~ 10x40μm), occuring as single idiomorphic crystals oriented to focm branching chains. This is the first reported occurrence of this mineral in any meteorite. Texturally, the mass of scheelite strongly resembles a common terrestrial occurrence as a pseudomorphic replacement of wolframite. Since the scheelite in Willy contains abundant submicron blebs of magnetite, typically $(Fe^{+2}_{0.82}Mg_{0.18})(Fe^{+3}_{1.60}V_{0.20}Cr_{0.20})O_4$, and is surrounded by V-mt and apatite, it may indeed represent a replacement of ferberite ($FeWO_4$) in a reaction with apatite or another Ca-rich phase. In any event, the texture indicates that the scheelite preexisted the formation of FeNi. The scheelite varies from $Ca(W_{0.87}Mo_{0.13})O_4$ at the center of Willy to $Ca(W_{0.96}Mo_{0.04})O_4$ at the contact with the V-mt mantle.

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In addition to rimming scheelite, Fe-,Cl-apatite (~1.5%Cl) is found as submicron and μm-sized rounded subhedral grains and wormy-shaped inclusions in the V-mt mantle. In the center of the largest of the grains are included μm-size blebs of an as yet unidentified Mg-, Fe- molybdate. The wormy apatites contain included laths of molybdenite, MoS_2. No W was measured in either the molybdate or MoS_2. Fractionation of Mo and W is quite remarkable; however, the coexistence of both with apatite is striking and may indicate a genetic link of these elements with apatite.

Surrounding Willy, separating it from the melilite in 5241, is a 20μm wide rim of V-rich fassaite and a complex intergrowth of V-rich spinels. The fassaite is extremely variable in composition, ranging from 16% TiO_2, 0% V_2O_3 to 0% TiO_2, 12% V_2O_3. A typical composition is $Ca_{0.98}Fe_{0.02}Mg_{0.42}Al_{0.8}V_{0.04}Ti_{0.44}Si_{1.30}O_6$. The fassaite is reduced with typical Ti^{3+}/Ti=0.6-0.7. The spinels in the rim are Fe-, V-rich containing up to 25% V_2O_3. A typical composition is $(Mg_{0.44}Fe_{0.56})$ - $(Al_{1.26}V_{0.56}Cr_{0.14}Ti_{0.02}Si_{0.01})O_4$. The chemical and textural relationship between the V-rich magnetite rim and the V-rich fassaite mantle is significant. Both phases are separated in part by a reaction assemblage consisting of V-rich $MgAl_2O_4$, $FeAl_2O_4$ and a third V-rich spinel of unknown nature. The last two occur in an intimate intergrowth along (100) of the host $MgAl_2O_4$ thus indicating exsolution from a high temperature V-rich spinel solid solution. This reaction zone is < 20 μm wide confined to the V-mt-fassaite interface. The exsolution lamellae are clearly seen to be growing from a breakdown of the V-rich magnetite mantle, and are thus formed secondarily to it. Magnetite and metal veins in 5241 do not contain V, Co, Pt, or P and cannot be the source of the oxides and metal in Willy.

Discussion: The mineral assemblage comprising Willy is very complex and in extreme disequilibrium. Highly reduced phases are found in contact with highly oxidized phases and normally coexisting elements such as Mo and W are found to be fractionated into discrete phases. From the observed texture, a multi-stage sequence of formation of Willy can be deduced. In the interior, the first phases that appear to have formed are V-mt, scheelite or its ferberite precursor, and possibly apatite at high fO_2. Refractory metal nuggets of Os-Ru and perhaps Pt were presumably introduced after this stage. This was accompanied or followed by FeS formation, and then followed by two stages of FeNi formation at low fO_2 during which Pt was dissolved in the metal. The second stage of FeNi growth must have occurred quickly enough to permit the observed skeletal features. This was followed by formation of the V-rich magnetite mantle, further introduction of apatite and alteration of ferberite to scheelite under high fO_2. Finally, the V-rich fassaite rim formed followed by breakdown of V-rich magnetite to Fe-, V-rich spinels at low fO_2.

The difference in chemistry between the V-mt and FeNi (high V in magnetite; Ni, Co, Pt, P in both FeNi's) and the lack of any chemical zonation or resorption features at their contacts preclude the formation of magnetite by oxidation of metal or metal by reduction of magnetite. Similarly FeS is unlikely to have formed by sulfidization of metal or oxide. The fassaite spinel rim appears to have preceded inclusion of Willy into its CAI host [2]. In any event, the formation of Willy and other Fremdlinge clearly preceded the formation of the CAI.

The complex nature of Willy clearly precludes a simple origin by nebular condensation. Its formation history prior to inclusion into the CAI must have involved multiple stages with fO_2 varying by many orders of magnitude. The large size and fluffy nature of the interior may indicate that it is one of the few Fremdlinge that may have escaped thermal metamorphism and recrystallization after having been captured in the CAI. It thus may represent the precursor material for many of the smaller Fremdlinge, since numerous Fremdlinge studied exhibit many of the mineral and chemical features observed in Willy. The time and location of Willy's formation (intra- or extra-solar system) may be elucidated by planned isotopic analyses with the PANURGE ion microprobe. The size of this important Fremdling provides the first opportunity to obtain such important isotopic information.

Refs.: [1] Proc. 9th LPSC, 1279-1303 (1978; [2] El Goresy, et al., this vol. (1984)