THE ALLENDE PINK ANGEL: ITS MINERALOGY, PETROLOGY, AND THE CONSTRAINTS OF ITS GENESIS. John T. Armstrong and G. J. Wasserburg, Lunatic Asylum, Div. of Geol. and Planet. Sci., Caltech, Pasadena, CA 91125

Introduction. The Allende carbonaceous chondrite contains a variety of inclusions rich in Ca and Al (CAI). CAI are also commonly rich in Mg and Ti and poor in alkalis and volatiles, although the latter may be present in phases thought to be late-stage alteration products. There are other irregular, very fine-grained inclusions in Allende which are rich in Mg and Al and contain associated phases rich in sodium and halogens (MASHI). The origin of MASHI is unknown. It is not possible to assign them, a priori, as high temperature condensates as is done for a number of CAI. Although some work has been done to classify the various types of MASHI [1], a detailed investigation of the mineralogy, mineral chemistry, and isotopic systematics of an individual MASHI has not yet been reported. We report such a study of the "Pink Angel" - a ~ 2 cm diameter, zoned, fine-grained, oval MASHI isolated from an Allende fragment graciously provided us by D.P. Elston. The inclusion is composed of a large pinkish interior (90% of the total mass) surrounded completely by a whitish rim, ~ 400 μm wide, which is in sharp contact with the meteorite matrix.

Bulk composition and mineralogy. The bulk composition of the Pink Angel is given in Table 1. The bulk compositions of the rim and interior are distinct. The mineralogy and estimated modal abundances are given in Table 2. The major phases in the interior are spinel, sodalite, and grossular. The major phases in the rim are spinel, anorthite, and diopside. Very small amounts of a sodic plagioclase were detected both in the interior and the rim. However, nepheline was not observed in either the interior or the rim. A submicron phase rich in titanium observed throughout the rim may be perovskite. A glassy phase appears to be present, primarily in the rim.

Texture. The interior of the Pink Angel is a powdery, porous aggregate of spinel crystals (< 1 μm to 5 μm). Sodalite occurs in dense patches (10 to 60 μm) which appear to be a cement binding the interior together. Grossular is present as anhedral blebs (2 to 10 μm) mostly found on the exterior of sodalite. Grossular does not form rims around sodalite. Spinel normally is not found within sodalite or grossular grains,nor are scdalite and grossular found within spinel. The Pink Angel's interior shows no evidence of being an aggregate of grains with an "onion-skin" texture or zonation, in distinct contrast to the inclusions observed by Wark and Lovering [2].

The rim of the Pink Angel is a compact, non-friable, assemblage of spinel and fine-grained anorthite and diopside with very little void space. The spinel in the rim is considerably larger than that in the interior and is found primarily within anorthite. The concentration of spinel is greatest close to the rim-matrix boundary where it is commonly found as large (20 to 50 μm) anhedral grains. In the inner portions of the rim, spinel is found more commonly as individual, small (2 to 10 μm diameter), equant crystals, or large, convoluted, lacy aggregates of crystals. Diopside is commonly found in contact with anorthite and surrounding large (10 to 40 μm) cavities which may be primary.

Mineral composition. The mineral compositions of the Pink Angel phases are, with the exception of spinel, identical for the rim and interior (Table 3). The dominant spinel compositions are Fe-rich, but low-Fe spinels are found among the large spinel crystals at the rim-matrix boundary. Low-Fe spinels are present in low abundance in the inner portions of the rim, and absent in the interior of the inclusion. The minor element chemistry is similar for both high-Fe and low-Fe spinels and is similar to that found for low-Fe spinels in CAI. A number of very small (< 5 μm) patches (primarily in the rim, but also in the interior) yield identical results. Because of the homogeneous nature of this phase, we feel that it is an alumina-rich glass of composition similar to those reported by Marvin et al. [3]; although it is also possible that the "phase" is actually a homogeneous assemblage of submicron phases randomly distributed in patches throughout the inclusion. This glassy phase is similar in composition to the bulk rim (Table 1).

Constraints for genesis. The mineralogy, texture, and mineral chemistry of the Pink Angel provide a series of constraints regarding its possible modes of formation. The presence in the Pink Angel of low-Fe spinel, anorthite and diopside at the outside of the inclusion in contact with the matrix, and the high-Fe spinel, sodalite, and grossular in the inside of the inclusion argues against introduction of Fe and alkalis from the matrix previously proposed [4]. In no way can an inclusion such as the Pink Angel be considered a high temperature condensate. Concurrent formation of interior and rim would require extremely non-equilibrium processes.

The textural relations in the rim and possible presence of a glass suggest formation of the rim from a melt. This then implies that 1) material of distinct chemical composition coated the exterior as a melt, or 2) that the original object was flash-heated causing melting on the exterior with large matter loss (e.g., Na, Fe, and Cl) and addition of other elements (e.g., Ca and Si). The first mechanism appears more probable. A melt of bulk composition approximately that estimated for the rim would crystallize spinel first, followed by anorthite and then diopside [5], as is observed. In addition, the phase we have identified as glass is very similar to the estimated bulk rim in composition and may be residual primary liquid. The coexistence of spinel, anorthite, and diopside in equilibrium with liquid (in the Fe-free system) occurs at a temperature around 1230° to 1240°C [6]. For the rim to form from a melt, the interior would have to be exposed, at least briefly, to such temperatures. Neither sodalite nor grossular are stable at high temperatures. Sodalite decomposes quickly to nepheline + vapor at 1230°C in a closed, 1 atm, environment and at less than 950°C in an open environment. Grossular decomposes more slowly to wollastonite + gehlenite + anorthite at about 860°C at 1 atm. We carefully examined the boundary between the rim and the interior and did not observe any nepheline, wollastonite, or gehlenite, even at fine scale. Therefore, either the rim formed very quickly or we are in error about the rim being liquid.

A fundamental issue in the genesis of the MASHI is the origin of the halogen-rich phases. We feel that the most likely precursor structure for the Pink Angel interior was a droplet formed of aggregate spinels and devitrified glasses related in composition to the CAI. We consider that the Pink Angel precursor was modified in a second event with major element transport to form its existing interior structure. This event was probably prior to rim formation. This requires a halogen- and alkali-rich gas phase which removed most of the original glass and produced the low temperature assemblage. The spinels are considered to be possibly chemically-modified residues of the original material. The existence of sodalite without nepheline in the interior indicates that it was formed in an environment of high halogen partial pressure. If the interior was in contact with a liquid rim, this contact had to occur for an extremely short time or in a closed environment to prevent halogen escape. Thus, it appears that an important portion of the formation of the Pink Angel, before incorporation into the Allende matrix, had to have occurred at a substantial HCl pressure. The solar nebula does not appear to be an obvious site for such processes. A condition where moderate confining pressures are possible, such as a planetary body rich in alkalis and halogens, merits consideration.

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The problem of the origin of alkali-, halogen-rich phases in CAI and MASHI must not be ignored. Such phases must have been formed either in a very low temperature nebular process or on a planetary body prior to incorporation of the inclusions into the meteorite matrix. If we wish to consider the CAI and the MASHI to be part of a common family with an origin in the solar nebula, then it will be necessary to describe reasonable chemical-physical states in the nebula which can produce the observed assemblages.

Ref:[1]Cf. Clarke et al., Smith.Cont.Ear.Sci. 5,1(1970); Wark,Astr.Sp.Sci. 65, 275(1979). [2]Wark & Lovering,Proc.LSC 8th,95(1977). [3]Marvin et al.,EPSL 7, 346(1970). [4]Grossman,GCA 39,433(1975). [5]Stolper,this vol.(1981). [6]Yang et al.,Am.J.Sci. 272,161(1972). Div. Contrib. No. 3556(382)

TABLE 1. Bulk and glassy phase compositions

	BULK*			GLASSY
	Total	Interior	Rim	PHASE
Na_2O	6.8	7.5	0.6	0.3
MgO	13.5	13.6	12.7	7.7
Al_2O_3	52.1	53.0	43.9	39.0
SiO_2	16.3	15.1	26.8	29.8
Cl	1.9	2.0	0.1	-
CaO	3.8	2.9	12.4	17.7
TiO_2	0.1	0.1	0.2	2.6
V_2O_3	0.2	0.2	0.2	0.2
Cr_2O_3	0.2	0.2	0.1	-
FeO	5.0	5.3	3.0	2.4

*Based on modal abundances

TABLE 2. Modal abundances

	Rim	Interior
Fe-rich spinel	30%	60%
Fe-poor spinel	10%	-
Anorthite	40%	5%
Diopside	15%	< 1%
Sodalite	2%	30%
Grossular	< 1%	5%
"Glass"	2%	< 1%
Plagioclase	< 1%	< 1%
Ti-rich (Perovskite?)	< 1%	-

TABLE 3. Pink Angel mineral chemistry (range or typical measured compositions)

SPINEL	Low-Fe Rim	High Fe Rim/Interior
mol% $MgAl_2O_4$	93-99	74-87
mol% $FeAl_2O_4$	8-1	24-14
wt% Cr_2O_3	0.09-0.37	0.07-0.76
wt% V_2O_3	0.24-0.50	0.11-0.51
wt% TiO_2	0.09-0.70	0.06-0.44

GARNET	Rim/Interior
mol% Grossular	94-99
mol% Andradite	0-2
mol% Pyrope	0-3
mol% Almandine	1-3
wt% Na_2O	0-0.14
wt% TiO_2	0-0.41

PLAGIOCLASE	Anorthite Rim	Plagioclase Rim
mol% $NaAlSi_3O_8$	0-1	10-45
wt% Fe	0.07-0.37	0.22-0.37

PYROXENE	Rim
mol% Wo	43-50
mol% En	41-51
mol% Fs	0.2-4
wt% Al_2O_3	0.65-6.64
wt% Na_2O	0-0.09
wt% V_2O_3	0-0.17
wt% TiO_2	0-0.85

SODALITE*	Typical Interior
Na_2O	18.2
K_2O	0.8
CaO	0.1
FeO	0.2
Al_2O_3	33.2
Cr_2O_3	0.1
V_2O_3	0.1
SiO_2	38.3
TiO_2	0.1
Cl	7.5
Total	98.6

*Under normal analysis conditions, sodalite undergoes severe Na,K and Cl loss.