FREMDLINGE IN CHONDRULES AND MATRIX OF THE NINGQIANG CARBONACEOUS CHONDRITE Xin Hua[1,2], Ying Wang[1], Weibiao Hsu[1], T. G. Sharp[3], [1]Purple Mountain Observatory, Nanjing, 210008, China (wbxu@pmo.ac.cn); [2]Dept. of Mechanical/Aerospace Engineering, Arizona State University, Tempe, AZ 85287; [3]Dept. of Geological Sciences, Arizona State University, Tempe, AZ 85287.

Introduction: We report here the petrographic and mineralogical studies of Fremdlinge in chondrules and matrix of the Ningqiang carbonaceous chondrite. Fremdlinge, or so-called opaque assemblages, were previously found in Ca-Al-rich inclusions (CAIs) of CV chondrites [1,2]. The mineralogy of Fremdlinge is very complex, containing phases apparently formed at high and low temperatures and under highly reducing and oxidizing conditions. Identified phases include Fe,Ni metals, sulfides, Fe-oxides, phosphates, silicates and Pt-metal grains. Fremdlinge were thought to be exotic objects incorporated into the host CAIs and thus represented the oldest solids in the solar system [1,2]. However, because of their complex mineral assemblages, their origin is not as readily explained. Other authors have argued for a local origin of these objects [3]. Ningqiang is an anomalous carbonaceous chondrite with many similarities close to CV3 meteorites. In this work, numerous relatively large Fremdlinge are observed in chondrules as well as in matrix of Ningqiang. We carried out a petrographic study of these objects in order to gain additional insights into their formation.

Results: In Ningqiang, Fremdlinge are relatively abundant and large. They occur as round objects, from 10 to 300 μm, with most having diameter > 100 μm, in chondrules (Fig. 1, 2) and in matrix. The major mineral phases are magnetite, Ni-rich metal, sulfide, and phosphate. The size of the individual mineral grains is ~ 10 μm (Fig. 3). Minor phases include silicates (olivine and pyroxene) and mesostasis (mixture of silicates and phosphates). Pt-metal nuggets are rare and appear only in magnetite as nano-grains (~ 150 nm) (Fig. 4). The magnetite contains a significant amount of Cr, but essentially no V. This is in contrast to magnetites of Allende Fremdlinge (V_2O_5 ~ 5%) [2]. Most phosphate grains are poor in Cl and rich in Ca, Fe. Fe metal is highly enriched in Ni, consistent with the previous observation in Allende [2]. Due to their small size, quantitative measurements of Pt-metal grains are not available. EDS analysis shows most of them are Os-rich Fe,Ni metal grains.

Discussion: The major mineral phases of Fremdlinge and their chemical compositions in Ningqiang chondrules are remarkably similar to those found in Allende CAIs. Magnetite is the dominant phase, and Fe-metal is highly enriched in Ni content (~ 65 %) with a notable amount of Pt (0.4 %). Both FeS and pentlandite are present with roughly equal amounts. Pt-group element-rich metallic phases are also observed in Ningqiang chondrules, but they are much smaller and less abundant than those in Allende CAIs. These observations suggest that Fremdlinge in Ningqiang chondrules could have formed by similar processes that generated the opaque assemblages in Allende CAIs.

Fremdlinge in CAIs were originally thought to have formed by nebular condensation of metal alloys, magnetite, and sulfides that were mechanically mixed at low temperature in the solar nebula [2]. Subsequently, the assemblages were incorporated into proto-CAI material and survived as inclusions in CAIs during a brief high temperature CAI formation event. This idea was further supported by the observation that the mineral phases of Fremdlinge have distinct O and Mg isotopic compositions from those of CAIs [4]. In this view, Fremdlinge would be the first objects formed in the solar nebula. It was also suggested that Fremdlinge may contain pre-solar materials. The potential candidates are Pt-metal grains. Some of them are highly enriched in Re, and others in Os. Their Re/Os ratios differ drastically from the cosmic value. In Ningqiang, we observed numerous Os-rich Fe, Ni nano-grains in Fremdlinge. Further isotopic analyses with an ion microprobe would help to address this issue.

Fremdlinge contain both highly reduced and oxidized mineral phases. This requires that the solar nebula change oxygen fugacity by many orders of magnitude during the condensation of these minerals. This would imply the solar nebula was highly heterogeneous and experienced violent turbulence. An alternative explanation is that the mineral phases of Fremdlinge are not relicts of nebular condensation, but formed by low temperature reequilibration (exsolution, oxidation and sulphidization) of homogeneous alloys within CAIs after their formation [3]. In this scenerio, Fremdlinge reflect the changing oxygen fugacity experienced by CAIs during slow cooling in nebular and/or planetary environments.

It is noticed that the mineral phases of Ningqiang Fremdlinge are commonly depleted in V. This may indicate that these objects formed in a different environment since the volatility of V is a strong function of oxygen fugacity. The observation of a large number of Fremdlinge in Ningqiang chondrules and matrix suggests that the formation of these objects was a rather common phenomenon which was closely

associated with the formation of CAIs and chondrules. Additional ion microprobe studies of oxygen isotopes and short-lived nuclides should provide a deeper understanding of the origin for this exotic object.

Acknowledgments: This work was supported by K. C. Wong Education Foundation (XH), Chinese NSF Grant 40325009 (WH), and ASU (TGS).

References: [1] El Goresy A., et al. (1978), *Proc. Lunar Planet. Sci. Conf. 9th*, 1279-1303. [2] Armstrong J. T., et al. (1985), *GCA*, 49, 1001-1022. [3] Blum J. D., et al. (1988) *Nature*, 331, 405-409. [4] Zinner E. K., et al., (1991) *EPSL*, 102, 252-264.

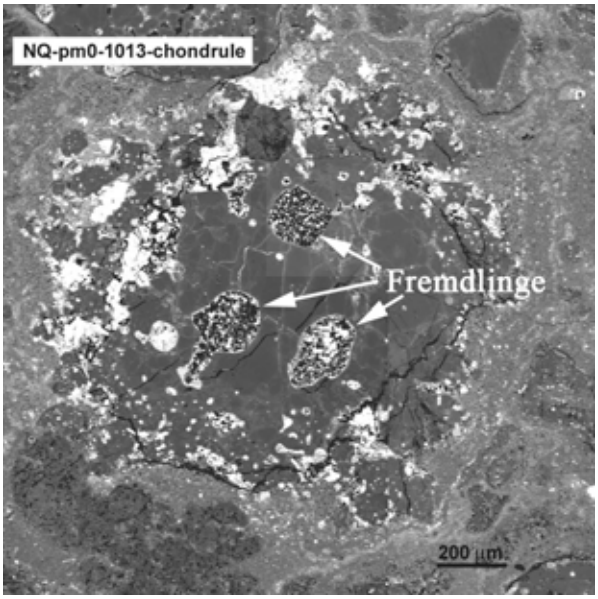

Fig. 1 BSE of an olivine chondrule of Ningqiang, containing three large Fremdling inclusions.

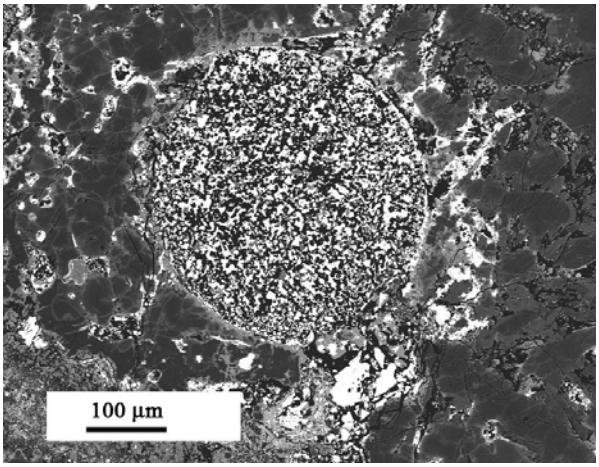

Fig. 2 A large round Fremdling inclusion (~ 300 μm) in a compound olivine chondrule of Ningqiang.

Table 1 Mineral chemistry of Ningqiang Fremdlinge

	Whit	Mt	Ol		Metal	FeS	Pn
SiO_2	0.02	0.03	34.88	Fe	32.74	65.4	47.9
TiO_2	0.00	0.03	0.00	Ni	65.01		16.9
Cl	0.03	0.00	0.00	Co	1.95		0.6
V_2O_5	0.00	0.02	0.05	Cr	0.14		
CaO	54.54	0.91	0.17	Pt	0.41		
MgO	0.00	0.17	25.41	S		35.4	35.1
FeO	2.16	86.39	39.47				
NiO	0.05	0.57	0.21				
Cr_2O_3	0.09	2.71	0.05				
P_2O_5	40.43	0.95	0.09				
Total	97.33	91.77	100.4		100.3	100.8	100.5

Whit: whitlockite; Mt: magnetite; Ol: olivine; Pn: pentlandite.

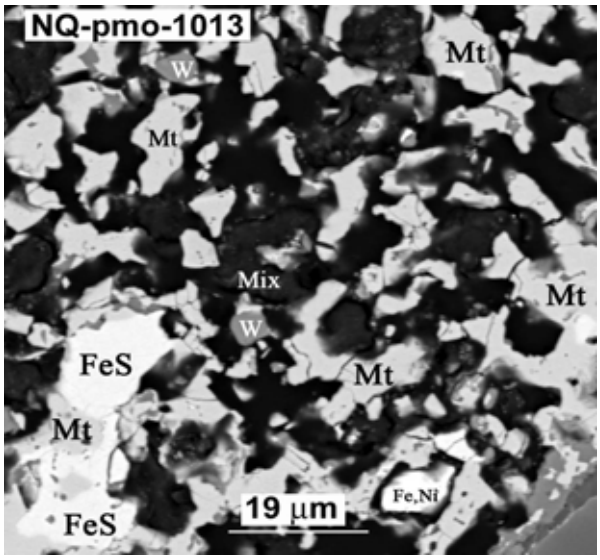

Fig. 3 The mineral assemblage of a Fremdling in a Ningqiang chondrule. W: whitlockite; Mt: magnetite; Mix: mixture of silicates and phosphates.

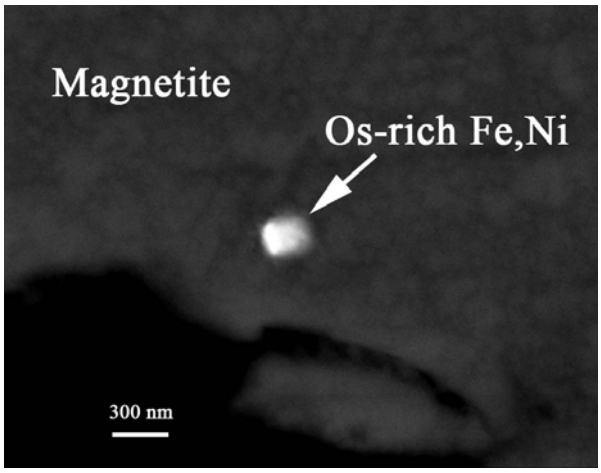

Fig. 4 BSE image of an Os-rich Fe,Ni nano-grain set in a magnetite grain. The scale bar is 300 nm.