CHARACTERIZATION OF THE DISTRIBUTION OF SIDEROPHILE AND HIGHLY SIDEROPHILE ELEMENTS IN THE MILTON AND EAGLE STATION PALLASITES.

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Abstract

In an effort to better understand the distribution and fractionation behavior of siderophile (W) and highly siderophile elements (HSE), including Pt, Pd, Re, Os, Ru, Au, and Ir in natural occurring metal-silicate systems, the Milton and Eagle Station pallasite meteorites were studied using electron probe microanalysis, Laser Ablation Inductively Coupled-Plasma Mass Spectrometer (LA-ICP-MS), and isotope dilution of bulk metal and olivine separates. The high abundances of HSEs in bulk samples of Milton and Eagle Station pallasites enabled us to measure siderophile and HSE concentrations in ppt levels in both metal and silicate and then to calculate bulk partition coefficients ($D^{Metal/Silicate}$). Metal/Silicate partition coefficients for siderophile elements in Milton and Eagle Station agree with the proposed 10^2-10^4 range determined through laboratory experiments using synthetic materials (Borisov & Palme, 1997). The calculated $D^{metal/silicate}$ determined using *in situ* laser ablation techniques for HSE are generally on the order of 10^4-10^6.

Introduction

Meteorites are commonly classified into three major groups based on their chemical compositions, mineralogy, and textural appearance. These three groups are iron meteorites, stony meteorites, and stony irons. Iron meteorites consist primarily of nickel-iron alloy. These meteorites are believed to represent the cores of differentiated planetary bodies (Wagner, 1991). Stony meteorites are composed mainly of silicates. There are two main groups of stony meteorites, achondrites which are thought to be either the mantle or crust of a protoplanet or asteroid and chondrites that are thought to be among the most primitive solar system materials (Wagner, 1991). The third classification of meteorites is stony irons. These meteorites are composed of a mixture of iron/nickel metal and silicate phases. Stony irons include a particularly interesting group of meteorites termed pallasites. Pallasites consist of roughly equal parts metal and silicate (Mittlefehldt *et al.*, 1998). These meteorites are likely associated with the core-mantle boundary of a differentiated planetary body (Chen, Papanastassiou, and Wasserburg, 2002).

Pallasite meteorites can provide valuable information regarding the fractionation of siderophile and highly siderophile elements (HSE) between metal and silicate phases during the metal-silicate differentiation of a planet. This information may be used to predict the abundances of elements present in the silicate portion of protoplanets and asteroids, which have segregated metallic cores.

As discussed by D. Walker (2000), partition coefficients for HSEs are not adequately known from experiments and only poorly estimated by meteorite data. .Partition coefficients (D-values, $D^{metal/silicate}$) can be defined as values used to describe the ratio to which elements prefer one phase to another. These coefficients are useful in predicting the distribution behavior of elements into various phases such as that of magmatic systems. Siderophile and HSE are strongly partitioned into metal phases relative to silicates. . The degrees to which these elements prefer to partition into metal phases relative to silicates have been studied in several controlled laboratory experiments on synthetic materials doped with high abundances of siderophile and/or HSE (Kimura *et al.*, 1974; Borisov & Palme,1997; Holzheid *et al*, 2000). Most of these studies have determined low-pressure metal/silicate partition coefficients for siderophile elements ranging from 10^2 to 10^4 and $\geq 10^4$ for highly siderophile elements (Borisov & Palme, 1997). The results of these experiments are debated due to the tendency of the HSE to form microscopic nuggets in the silicate. Recent examination of HSE have shown that Pt and Pd, two HSE which lack the tendency of forming microscopic nuggets during crystallization, can have $D^{metal/silicate}$ in excess of 10^6, even at higher pressures where evidence suggests $D^{metal/silicate}$ should decrease (Holzheid, *et al*., 2000).

Because HSE tend to favor metal relative to silicate by a factor of at least 10,000, studies based on natural materials have been rare. In most instances, concentrations of HSE in silicate material have been too low to determine through *in situ* techniques. Concentrations of HSE in the silicate phases of some pallasite meteorites, however, may be determined in samples with sufficiently high HSE in the coexisting metal phases.

Samples

As stated by Horan *et al.* (2003), advances in mass spectrometry now permit high precision measurement of the concentrations of Re, Os, Ir, Ru, Pt, and Pd in chondrites. This is the case with pallasite meteorites as well. In order to determine high precision measurements of siderophile and HSE concentrations of in the silicate phase of the pallasites, high HSE concentrations must be present in the metal phase. This condition would allow a greater probability of *in situ* detection of HSE in silicates because with higher concentrations of HSE in metal phases, we would expect, based on the D-values determined in the experiments cited above, there to be greater concentrations in the coexisting olivines. After thorough review of pallasite meteorites, two non-genetically related pallasites were chosen for study. The two samples chosen are Eagle Station, which is genetically linked to Itzawisis and Cold Bay, forming the Eagle Station grouplet (Wasson and Choi, 2003), and Milton, which is not currently known to be genetically linked to any other pallasite (Jones *et al*, 2003). These two pallasites, Eagle Station and Milton, contain high concentrations of Ir relative to that of the main group pallasites (Jones *et al.*, 2003). R.H. Jones and the Institute of Meteoritics, University of New Mexico supplied the Milton specimen, and R. Clarke of the Smithsonian Institution supplied the Eagle Station specimen.

Analytical Methods

Samples of the Eagle Station and Milton pallasites were prepared for surface analysis by polishing using a 3 step procedure including 600 grit sanding paper, 0.3-micron aluminum polishing compound, followed by a 0.1-micron aluminum polishing compound to achieve a smooth, pit free surface. Polished samples were carbon coated and analyzed using a JEOL *JXA-8900* Electron probe Microanalyzer for major and minor elements in the metal phases (Fe, Ni, Co, Cu, and Cr) and olivine (Mg, Fe, Ca, Mn, Ni, Cr and Si). The following conditions were employed: accelerating voltage of 15 keV, 10 nA sample current, and a 5 μm diameter beam. Peak and background intensities were measured for all elements, and raw intensities were compared to intensities from natural standards, and corrected using a CIT-ZAF algorithm. Sampling traverses were selected in multiple olivine crystals and metal phases to detect zoning or other heterogeneity.

Trace element analyses were conducted using a laser ablation ICP-MS system consisting of a 213 nm Nd:YAG laser coupled to an *Element 2*, magnetic sector ICP-MS. We used a small volume, in-house developed ablation cell for these measurements, which is continuously flushed with He (~1.2 mL/min) and Ar (~0.6 mL/min) throughout the analyses. Laser spot sizes range from 20-60μm for metal sampling and up to 160μm for olivine sampling. Laser repetition rates were set to optimize maximum signal intensity to ~10^6 cps. Time-resolved spectra included the acquisition of ~20 seconds of gas background followed by 40 to 80 seconds of signal. Analyses of unknowns were evaluated using a range of standard materials (i.e., NIST-610, NIST-612, Hoba iron meteorite, Filomena iron meteorite, BIRG-1g, and SRM-1158).

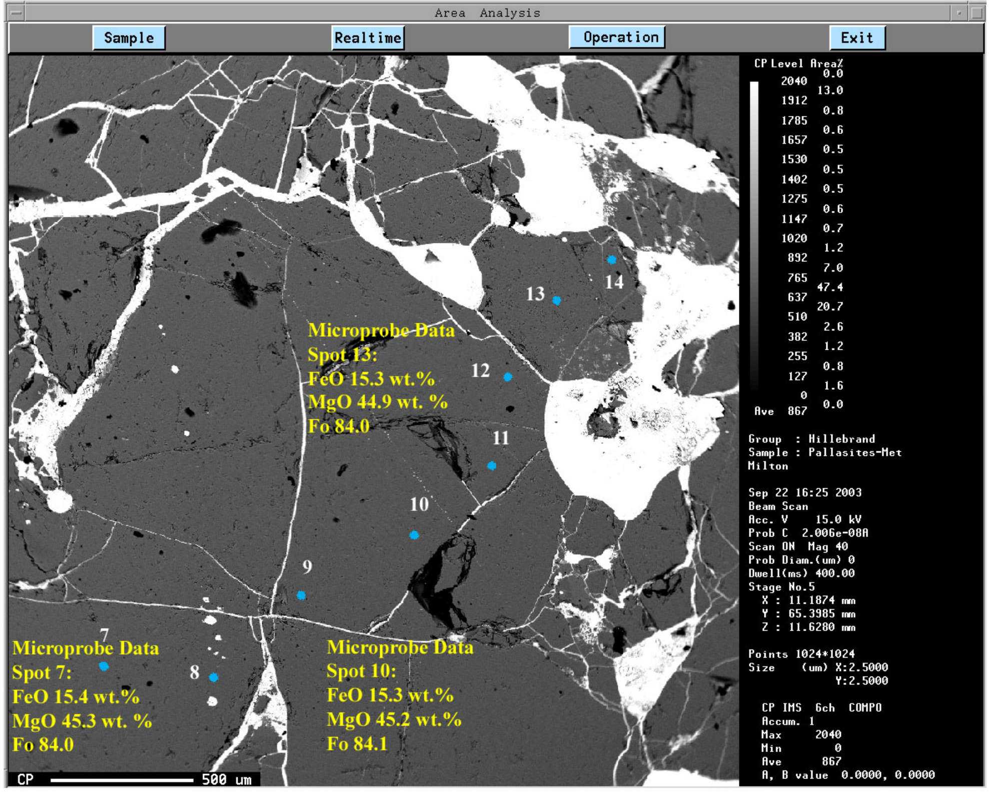
Siderophile and HSE concentrations were determined for sampling sites that were first examined via electron probe microanalysis. To avoid sampling inconsistencies during laser ablation, care was taken to avoid the numerous metal inclusions throughout the olivine. These inclusions were present in both pallasites. Backscatter images taken during the laser ablation, as well as photographs were used to aid the mapping of sampling locations (Figures 1 & 2). LA-ICP-MS data will be calibrated using several standards including iron meteorite Hoba, iron meteorite Filomena, Nist glass NIST-612, Nist glass NIST-610, and iron meteorite Coahuila. In order to minimize contamination during ablation, the olivine crystals in each pallasite were analyzed prior to the metals. Initial analyses of the Eagle Station and Milton pallasites were performed to optimize operational parameters prior to the final analysis.

Following the *in situ* analysis, the pallasites were sawed in smaller sections and prepared for the isotope dilution analysis of bulk metal and silicates. The olivines were separated from the metal phase by freezing for 2-minutes in liquid nitrogen followed by submersion in hot water. The difference in the contraction rates between metal and olivine was sufficient to cause cracking and separation of olivine from metal. The metal had all remaining olivine removed through use of a dental pick. Metal was then polished with a 0.3-μm aluminum-polishing compound and precisely weighed.

Presentation of Data

Data tables for the Electron probe analyses have been compiled and placed in the Appendix II-V. Error for electron microprobe measurements is calculated based on the counting statistics of the elements. Laser ablation mass spectrometry concentration data are presented in **Table 3**. Metal/silicate partition coefficients are found in **Table 4**. Due to the concentration variations in the olivine crystals of both Milton and Eagle Station, as well as the Eagle Station taenite, the data is presented as a range of concentrations. LA-ICP-MS detection limit filters for elements at the ppm levels in metals are $\geq 5\sigma$ above background signal. LA-ICP-MS detection limit filters for elements at the ppb-ppt levels are $\geq 2\sigma$ above background signal. Accuracy was controlled by the use of several standards including NIST-610, NIST-612, BIRG-1g, Filomena, and Hoba. Precision associated with these standards is in APPENDIX VI.

Figure 1. Backscatter Electron Image of Milton Olivine. White areas represent metal where as darker areas are olivine. Sampling points for the Electron Microprobe are labeled and included in Appendix III.



Microprobe Data
Spot 13:
FeO 15.3 wt.%
MgO 44.9 wt. %
Fo 84.0

Microprobe Data
Spot 7:
FeO 15.4 wt.%
MgO 45.3 wt. %
Fo 84.0

Microprobe Data
Spot 10:
FeO 15.3 wt.%
MgO 45.2 wt.%
Fo 84.1

```
 CP Level Area%
              0.0
       2040
             13.0
       1912
              0.8
       1785
              0.6
       1657
              0.5
       1530
              0.5
       1402
              0.5
       1275
              0.6
       1147
              0.7
       1020
              1.2
        892
              7.0
        765
             47.4
        637
             20.7
        510
              2.6
        382
              1.2
        255
              0.8
        127
              1.6
          0
              0.0
 Ave    867

Group  : Hillebrand
Sample : Pallasites-Met
Milton

Sep 22 16:25 2003
Beam Scan
Acc. V    15.0 kV
Prob C  2.006e-08A
Scan ON  Mag 40
Prob Diam.(um) 0
Dwell(ms) 400.00
Stage No.5
  X : 11.1874 mm
  Y : 65.3985 mm
  Z : 11.6280 mm

Points 1024*1024
Size    (um) X:2.5000
             Y:2.5000

  CP IMS  6ch  COMPO
  Accum. 1
  Max     2040
  Min        0
  Ave      867
  A, B value  0.0000, 0.0000
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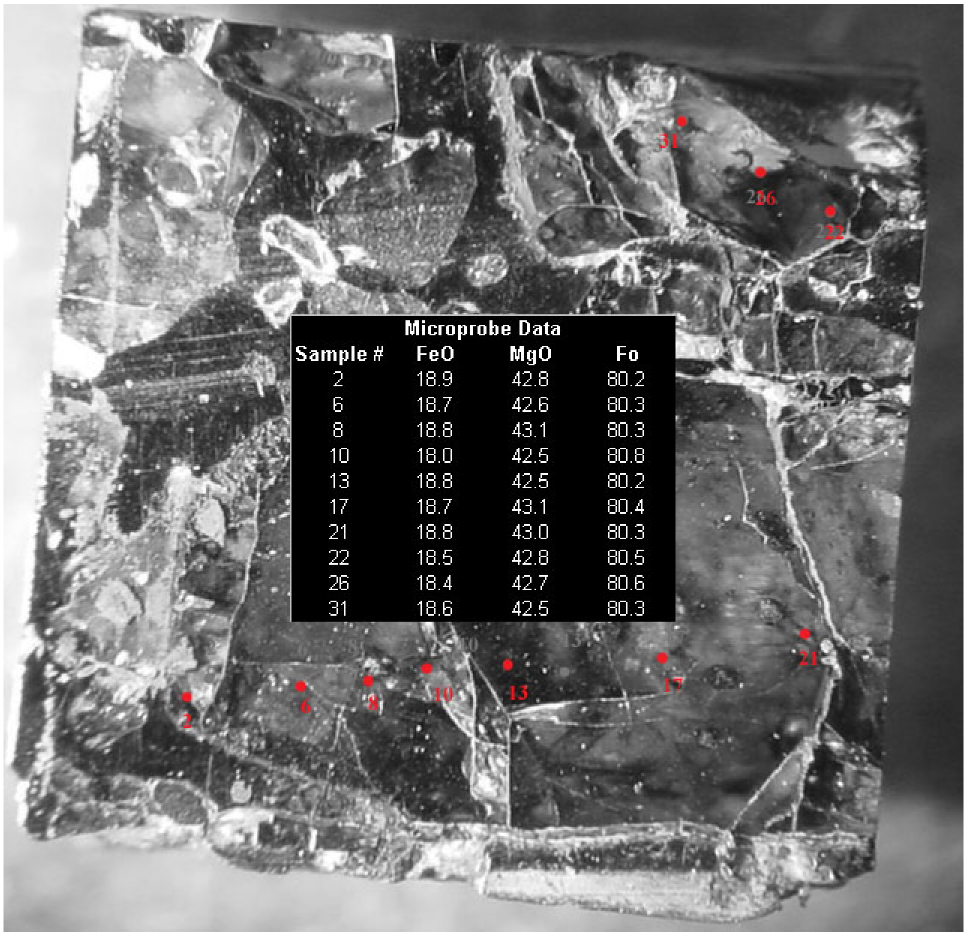
Figure 2. Photograph of Eagle Station with olivine sampling points labeled. Corresponding data is included in Appendix II



Microprobe Data

Sample #	FeO	MgO	Fo
2	18.9	42.8	80.2
6	18.7	42.6	80.3
8	18.8	43.1	80.3
10	18.0	42.5	80.8
13	18.8	42.5	80.2
17	18.7	43.1	80.4
21	18.8	43.0	80.3
22	18.5	42.8	80.5
26	18.4	42.7	80.6
31	18.6	42.5	80.3

Bulk olivine samples were prepared by removal of any visible metal flakes from the separated olivine crystals via hand picking. These crystals were then crushed with a hammer. After the olivines were crushed, a high-powered hand magnet was passed near the samples roughly 20 times to remove the remaining metal as well as olivine with metal inclusions. The remaining olivine was sorted manually for optically pure crystals through use of a microscope and dental pick. Olivine and metal separates were kept separate to prevent sample contamination. Isotope dilution techniques for the analysis of HSE in bulk olivine and metal samples are compiled in Appendix I.

Results

Electron probe microanalysis of olivines in Eagle Station and Milton shows that their Fo contents, (Fo = atomic % Mg / (atomic % Mg + atomic % Fe) x 100), were

84.1±0.4 (2σ) and 80.4±0.4 (2σ) respectively (Table 1). Our data for Milton is slightly higher than the value of 82.8 reported by Jones *et al.* (2003), whereas that for Eagle Station is comparable to the value, 79.8, reported in reported by Mittlefehldt (1998). Values reported from the microanalysis show slight deviations from average in the olivine crystals of both Eagle Station and Milton. Chemical zoning is not present in the olivine of either sample.

Table 1. Electron microprobe data summary for olivine and comparison to previously reported data.

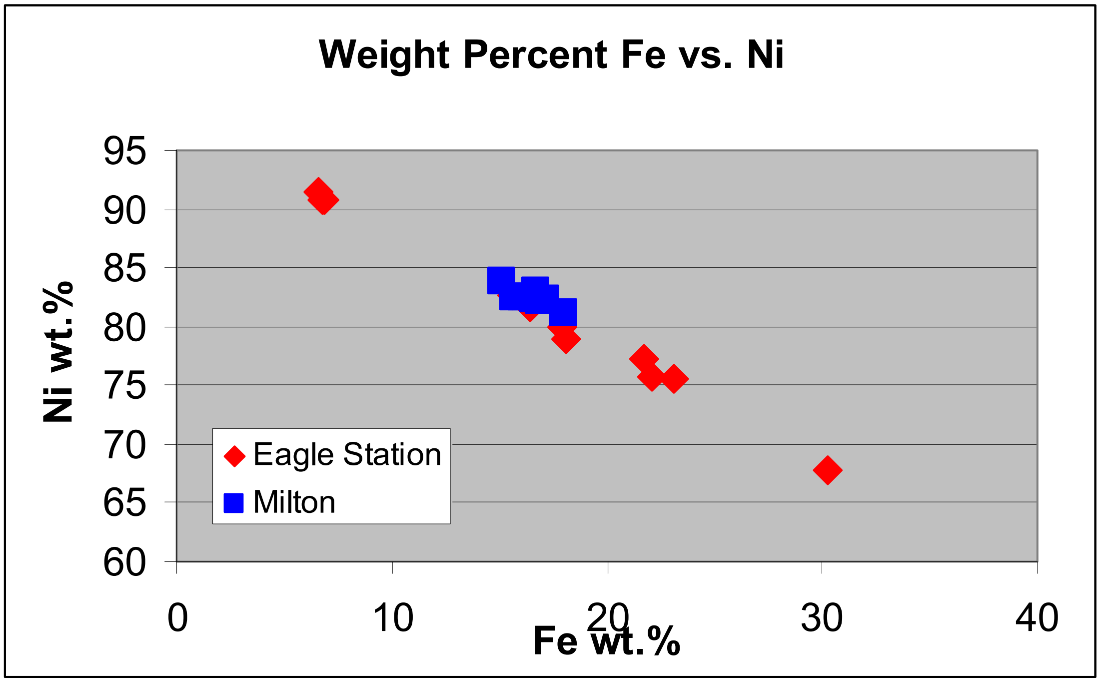
Milton	**MgO**	**MnO**	**CaO**	**SiO2**	**FeO**	**Cr_2O_3**	**NiO**	**Total**	**Fo**
Average Wt. %	45.2	0.13	0.17	39.2	15.2	0.06	0.05	100.1	84.1
St. Dev (2-sig.)	0.69	0.05	0.11	0.34	0.44	0.03	0.02		0.4
Jones *et al.* (2003)	44.3	0.13	0.12	39	16.4	0.09			82.8
Eagle Station	**MgO**	**MnO**	**CaO**	**SiO2**	**FeO**	**Cr2O3**	**NiO**	**Total**	**Fo**
Average Wt. %	42.7	0.19	0.05	38.7	18.5	0.03	0.05	100.25	80.4
St. Dev.	0.78	0.06	0.03	0.57	0.55	0.01	0.02		0.41
Mittlefehldt (1898)	49.1	0.2	0.1	38.7	19.0	0.0			79.8

Table 2. Average Electron probe microprobe data for taenite in Milton and Eagle Station.

Milton	**Cu**	**Fe**	**Cr**	**Ni**	**Co**
Average Wt. %	0.02	73.2	b.d.	14.9	0.66
St. Dev. (2-sig)	0.01	0.2	b.d.	0.1	0.02
Eagle Station	**Cu**	**Fe**	**Cr**	**Ni**	**Co**
Average Wt.%	0.02	81.2	b.d.	16.8	0.69
St. Dev. (2-Sig)	0.02	14.19	b.d.	14.53	0.41

Data for metal phases (Table 2) reveal that the metal in Milton is a generally homogeneous taenite with 82.5±1.6 (2σ) wt. % Fe and 16.5±1.8 (2σ) wt. % Ni. Minor element concentrations in the metal phases include (in ppm): Co 8500±600 (2σ) and Cu 200±200 (2σ). In contrast, Eagle Station metal has a more heterogeneous composition, with an average Fe content of 81±12 (2σ) wt.% and a Ni content of 17±12 (2σ) wt.%. A plot of Fe wt.% vs. Ni wt.% indicates the degree of variance throughout the metal composition of Milton and Eagle Station. Minor elements in Eagle Station had concentrations of: Co 6900±400 (2σ) ppm and Cu 200±200 (2σ) ppm. Complete data tables for metal and olivine sampling using electron probe microanalyses are in Appendix II and Appendix V.

Figure 3. Fe wt.% vs. Ni wt.% of Eagle Station and Milton.



Concentration data for major, minor and trace elements compiled through LA-ICP-MS are provided in Table 3. Major element concentrations in olivine from both pallasites are homogeneous. Fe in Eagle Station and Milton olivine is 14±0.4 wt. % (2σ) and 11.8±.4 wt. % (2σ) respectively. These values are equal to those found in the Electron microanalyses. Heterogeneity of minor and trace elements in Eagle Station are pronounced. Seven sampling scans were taken over traverses mapped out in the olivines indicated significant heterogeneity. During the first two sampling points of Eagle Station, a Pt and Au rich metal or sulphide inclusion was sampled. Additional scans avoided this inclusion. The concentrations of Ru, Rh, Pd, W, Re, Os, Ir, Pt, and Au in Eagle Station's olivine vary as much as an order of magnitude over the traverse of the crystal. The most pronounced variations are for W and Ir. Over the seven scans, concentrations of Pd, W, and Ir ranged from 0.04-2.3ppb, 4-79ppb and 0.07-6.5ppb respectively (**Table 3**).

Table 3. LA-ICP-MS concentration data for Milton and Eagle Station olivines and metals

Table 3. Concentration data for olivines and metal.

(ppt)	**Eagle Station**		**Milton**			**Eagle Station**		**Milton**	
Olivines	**average**	**±**	**average**	**±**	**Metals**	**average**	**±**	**average**	**±**
Sc*	2.9	0.4	4	0.4	Fe %	80.5	4.7	82.5	0.3
V*	9.9	0.5	17	1	Co*	6660	668	8790	38
Cr*	156	34	574	133	Ni %	17.6	4.9	16.5	0.5
Mn*	1470	10	1230	10	Cu*	80	4	256	20
Fe %	14.4	0.22	11.8	0.17	Ga*	--	--	33	10
Co*	20	1	31	5	Ge*	129	132	55	9
Ni*	49	1	84	21	As*	75	44	7.2	1.5
Olivines	**min**	**max**	**average**	**±**	Mo*	--	--	14	2
Ru	600	1000	320	200	Ru*	2.3	1.4	31	5
Rh	100	1600	50	40	Rh*	2.4	1.3	5	1
Pd	40	2300	280	180	Pd*	3.5	0.5	5.2	0.1
W*	4000	79000	14.2	0.1					
Re	100	2000	610	310	W*	46	53	1.2	0.1
Os	10	150	180	40	Re*	0.5	--	5.1	0.6
Ir	10	190	130	20	Os*	18	13	51	3
Pt	70	6500	140	40	Ir*	14	11	45	2
Au	20	620	120	0.03	Pt*	1.6	1.9	33	1
Scans	7		5		Au*	--	--	130	130

*Concentrations in ppm

Red: Inclusion w/ Pt=510±175ppt and Au=390±330ppt

Metal in Eagle Station exhibits similar levels of heterogeneity. Fe composes 80.5±0.3 wt. % of the taenite. This value is slightly lower than the 81±6 wt. % reported in the electron microanalysis, appendix V. Ni and Co also have similar concentrations to that of the electron microanalysis. Ranges of concentrations can vary as much as two orders of magnitude, as is the case with Pd, W, and Pt. W has the largest degree of variation, ranging from 4000-79000 ppt. The large variations in siderophile and HSE concentration in Eagle Station poses significant problems when calculating D-values. With a wide range of concentration values throughout the sample, the metal/silicate D-values will depend on which values are used. Since it is impossible to determine what values are in equilibrium, $D^{metal/silicate}$ for Eagle Station is presented as an average value.

Concentrations of Ru, Rh, Pd, Re, Os, Ir, Pt and Au in Milton olivine generally range between 50-700 ppt. Concentrations of Ru, Rh, Pd and Re are quite heterogeneous, varying up to 50% in some cases, though to a lesser degree than in Eagle Station. In contrast to Eagle Station, olivine concentrations of Os, Ir, Pt, and Au are fairly homogeneous through out the sampling locations each varying only by roughly ±20% throughout the olivine crystals. Elements such as Ru, Rh, and Pd in Milton olivine are very heterogeneous. These elements vary as much as ±80% throughout the sampling sites. Metal in Milton is relatively is relatively homogeneous with respect to siderophile and HSE concentrations. Concentrations of Co, Ni and Fe determined through both LA-ICP-MS and electron microanalysis agree. Siderophile element variation is less than ±20% throughout the sampled metal with some elements such as W, Co, Cu, and As having deviations from average of less than ±14% (**Table 3**). All HSE in Milton are homogeneous, relative to Eagle Station, through the metal. These elements vary only slightly with Ru, Re, and Os varying under 17% and Rh, Ir, Pt, and Au varying less than ±8% in the taenite.

The relative homogeneity of Milton, with respect to Eagle Station, allows calculation of D-values for this system. Metal/silicate D-values values were calculated by combining the concentration data of five separate olivine scans with an average metal composition (**Figure 4**). Calculated $D^{metal/silicate}$ for Milton and Eagle Station are compiled in **Table 4**.

Figure 4. Metal/Silicate D-values of HSE in Milton based on five LA-ICP-MS sampling scans.

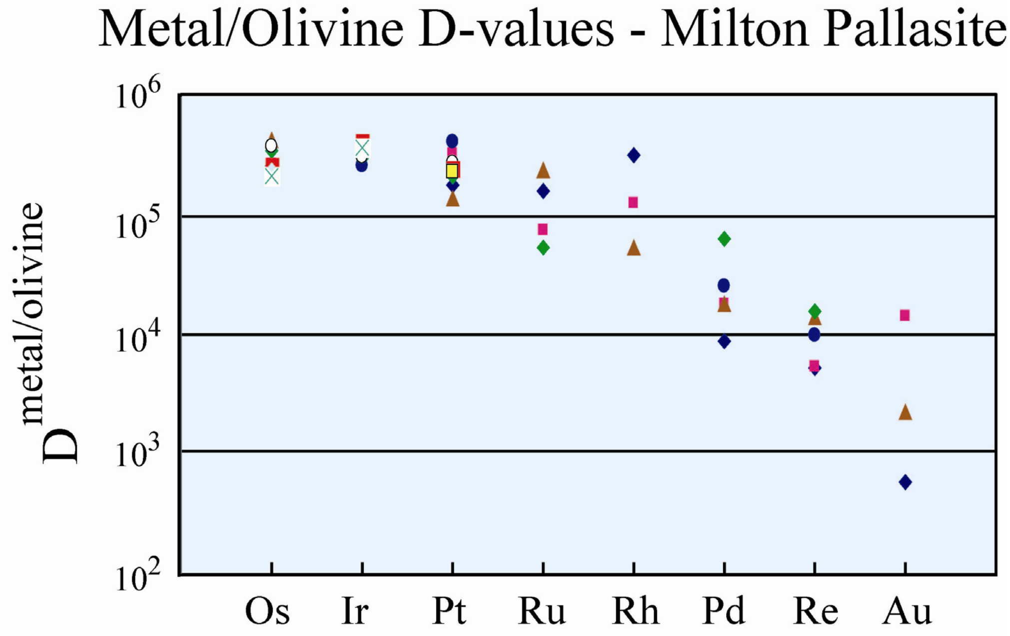
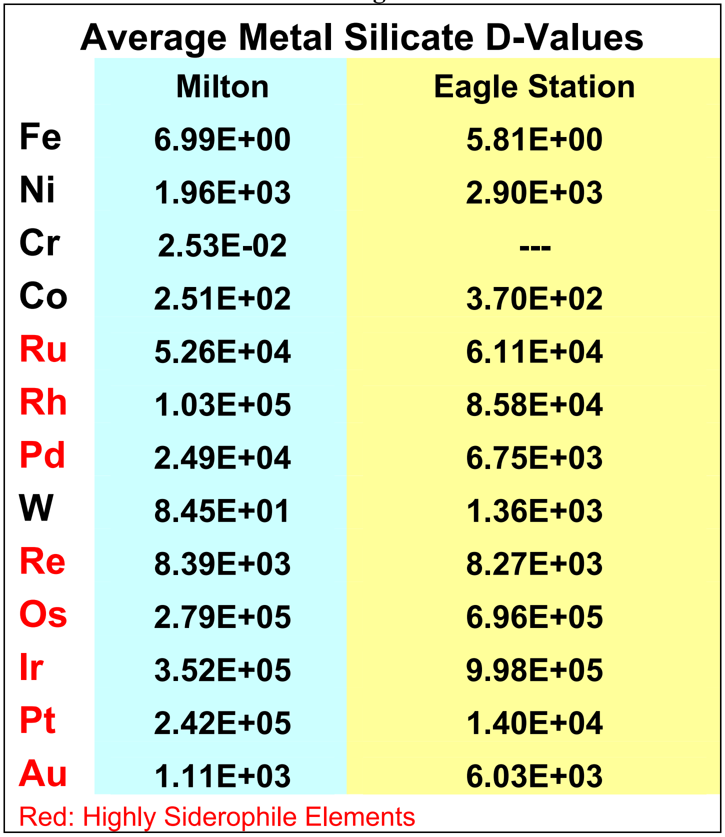


Table 4. Calculated Average Metal/Silicate D values.



Average Metal Silicate D-Values

	Milton	Eagle Station
Fe	6.99E+00	5.81E+00
Ni	1.96E+03	2.90E+03
Cr	2.53E-02	---
Co	2.51E+02	3.70E+02
Ru	5.26E+04	6.11E+04
Rh	1.03E+05	8.58E+04
Pd	2.49E+04	6.75E+03
W	8.45E+01	1.36E+03
Re	8.39E+03	8.27E+03
Os	2.79E+05	6.96E+05
Ir	3.52E+05	9.98E+05
Pt	2.42E+05	1.40E+04
Au	1.11E+03	6.03E+03

Red: Highly Siderophile Elements

Milton possesses higher $D^{metal/silicate}$ than Eagle Station for Ni, Ru, W, Os, Ir, and Au. Fe, Rh, Pd, Re, and Pt have higher $D^{metal/silicate}$ in Eagle Station. Rhenium and gold have average $D^{metal/silicate}$ which are, in some cases is lower than 10^4. $D^{metal/silicate}$ for Eagle Station could be presumably higher or lower than would be expected for HSE due to the extreme heterogeneity of the sample. Still, both Eagle Station and Milton possess metal/silicate D-values for siderophile and HSE that are broadly similar to those of experiments based on synthetic materials (Borisov A. & Palme H., 1997). All of the HSE $D^{metal/silicate}$ fall within the proposed 10^4-10^6 range with the exception of Re, Au, and possibly Pd. Siderophile elements, including Ni, Co, and W in both pallasites fall within the 10^2-10^4 range with the exception of W in Milton which had a $D^{metal/silicate}$ of 8.5×10^1.

Os data taken from the isotope dilution analysis of bulk metal and olivine samples of Eagle Station and Milton show taenite concentrations similar to those found using LA-ICP-MS. Os concentrations determined by isotope dilution analysis are 15,099 ppb for Eagle Station and 46,554 ppb for Milton metal (**Table 5**). Os concentrations of Eagle Station and Milton determined using LA-ICP-MS are 21000ppb and 51000ppb respectively. Os data for the iron meteorite Coahuila has also been gathered via isotope dilution analyses in previous experiments. This meteorite will be used as a standard to further calibrate the LA-ICP-MS concentration data of Milton and Eagle Station. The Os concentration in Coahuila is 11500ppb. This differs from the isotope dilution concentration by only 1400ppb. The Os concentration taken from Eagle Station during isotope dilution places it well within the range of values suggested by LA-ICP-

MS. Os in Milton taenite, as determined by isotope dilution, agrees within 9% of the concentration determined by LA-ICP-MS. Concentrations of Os in both Milton and Eagle Station olivine were larger when taken through isotope dilution of the samples. *In situ* analysis of Eagle Station and Milton determined the Os concentration to be 0.01-0.15 ppb and .18 ppb respectively. Values found during analysis of bulk olivine samples show an Os concentration of 12.24 ppb in Eagle Station and 24.60 ppb in Milton. A large difference exists between the Os $D^{metal/silicate}$ of both Milton and Eagle Station. For both meteorites the difference is approximately two orders of magnitude, which can be attributed to metal inclusions and impurities in the olivines after sample separation and purification. These existing inclusions would raise the concentration of Os detected in the olivine phase, thus lowering the calculated $D^{metal/silicate}$.

Table 5. Comparison of Os concentrations and $D^{metal/silicate}$ calculated from LA-ICP-MS and isotope dilution of bulk metal and silicates.

Sample	**Isotope Dilution Os (ppb)**	**LA-ICP-MS Os (ppb)**
Coahuila 1	10123	11500
Coahuila 2	10119	11100
Eagle Station Metal	15099	21000
Eagle Station Olivine	12.24	.01-.15
Milton Metal	46554	51000
Milton Olivine	24.6	0.18
$D^{metal/silicate}$		
Eagle Station	1.23E+03	6.96E+05
Milton	1.89E+03	2.79E+05

$^{187}Os/^{188}Os$ ratios were also determined during the bulk analysis of Eagle Station and Milton (**Table 6**). These ratios show that Eagle Station metal is in isotopic equilibrium with olivine. This isotopic equilibrium could indicate mixing during the formation of the meteorite or metal contamination during the purification process. This, however, is not the case for Milton. Milton metal and olivine have significantly different $^{187}Os/^{188}Os$ ratios. The metal has an $^{187}Os/^{188}Os$ ratio of 0.1371 and the olivine 0.1308. This difference indicates the absence of metal/silicate contamination during crystallization.

Table 6. Isotopic ratios of Coahuila, Milton, and Eagle Station determined through isotope dilution of bulk samples.

Sample	**$^{187}Os/^{188}Os$**
Coahuila 1	0.14152±0.02
Coahuila 2	0.14155±0.02
Eagle Station Metal	0.12477±0.02
Eagle Station Olivine	0.1251±0.2
Milton Metal	0.13711±.02
Milton Olivine	0.1308±0.2

Conclusions

It is now possible to determine concentrations of siderophile and HSE of some pallasite meteorites directly through use of *in situ* techniques such as laser ablation. This data can in turn be used to determine the metal silicate partition coefficients of siderophile and HSE in naturally occurring systems with coexisting metal and silicate phases. Though this is the case, several meteorites did not crystallize in equilibrium and may be heterogeneous. The chemical heterogeneity of metal and silicate phases in pallasite meteorites can lead to difficulties in calculating $D^{metal/silicate}$ due to the wide range of concentrations throughout various sampling locations, such as those found for Eagle Station. Metal/silicate partition coefficients obtained for Siderophile and most HSE in Milton, a relatively homogeneous pallasite, and Eagle Station, a relatively heterogeneous pallasite, are both broadly similar to values found in synthetic systems.

Suggestions for Future Work

"Rhenium and the platinum group elements are valuable tracers of the processes responsible for small- and large-scale differentiation of terrestrial planets. Despite this, much of our current knowledge of the phases that control the distribution of these elements is empirical, and subject to considerable uncertainty" (Brenan *et al.,* 2003). Understanding the degree to which these HSEs fractionate between the metal core and silicate mantle/crust during planetary differentiation can give us a better understanding of the core/mantle differentiation of planetary bodies including Earth. Promoting our understanding this partitioning behavior can also shed light on theories explaining the over abundance of siderophiles and HSE in the mantle and crust relative to chondrites (Holzheid *et al*., 2000; Walker, 2000). This study has shown that in general, partitioning behavior of siderophile and HSE elements in Milton and Eagle Station pallasites behave similar to that of experiments using synthetic materials. Completion of the isotope dilution analysis of the remaining siderophile and HSE for Coahuila, Milton and Eagle Station will allow a greater accuracy and understanding of the metal/silicate partition coefficients in these natural systems. Additional laser ablation using homogeneous standards with lower siderophile and HSE concentrations, such as the iron meteorite Coahuila, will be helpful in further constraining the metal/silicate partition coefficients of Eagle Station and Milton. Also, characterizing the chemical composition of additional pallasite meteorites through isotope dilution and LA-ICP-MS to calculate metal silicate partition coefficients may help our understanding of the partitioning behavior of elements between metal and silicates.

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APPENDIX I

Isotope dilution methods of bulk metal and silicates

- Samples and spikes added to quartz Carius tubes
    - Addition of Re-Os Spike
    - Addition of HSE Spike
    - Samples Dissolved in 2:1 mixture of HNO_3 and HCL
- Sample solution Sealed in quartz Carius tubes
    - Heated at 285 degrees for 12 hours
    - Samples frozen and tube unsealed
    - Samples placed in centrifuge tube
- CCl_4 added to centrifuge tube
    - Sample mixed via shaking for 1-2 minutes
- CCl_4 pipette out of centrifuge tube and placed in HBr
    - 1.5 Ml CCl_4 added to centrifuge, shaken and removed
    - Repeated 3 times
- Hbr solution heated on hot plate for 4 hours
- Hbr dried to roughly 40µg
    - Pipetted onto cap
- Cap micro distilled for two hours at 195 degrees
- Sample pipetted onto a platinum filament
    - Filament coated with Barium Hydroxide and loaded into mass spectrometer

APPENDIX II

Eagle Station Olivine Electron Probe Microanalysis Data (Weight %)

	MgO	MnO	CaO	SiO2	FeO	Cr2O3	NiO	Total	Fo
Detection Limit Wt. %	**0.01**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.03**		
Sample #	**Wt %**	**Wt %**	**Wt %**	**Wt %**	**Wt %**	**Wt %**	**Wt %**	**Wt %**	
2	42.81	0.19	b.d.	38.88	18.85	b.d	b.d	100.77	80.2
3	41.45	0.22	b.d.	37.86	18.53	b.d	0.05	98.13	79.9
4	42.51	0.18	b.d.	39.02	18.45	b.d	0.04	100.21	80.4
5	42.76	0.23	0.05	38.71	18.35	0.03	b.d	100.13	80.6
6	42.59	0.17	b.d.	38.55	18.68	b.d	b.d	100.01	80.3
7	42.97	0.12	b.d.	39.06	18.78	0.04	0.04	101.01	80.3
8	43.06	0.19	b.d.	38.90	18.84	b.d	0.07	101.07	80.3
9	42.45	0.24	0.04	38.93	18.87	b.d	b.d	100.52	80.0
10	42.48	0.16	b.d.	38.83	18.04	b.d	b.d	99.53	80.8
11	42.94	0.17	b.d.	39.01	18.92	b.d	b.d	101.07	80.2
12	43.24	0.23	0.08	38.66	18.97	b.d	b.d	101.20	80.3
13	42.79	0.18	b.d.	38.88	18.84	b.d	b.d	100.70	80.2
14	42.93	0.18	b.d.	38.89	18.55	b.d	b.d	100.56	80.5
16	42.07	0.16	b.d.	38.45	18.35	b.d	b.d	99.05	80.4
17	43.06	0.22	0.04	38.66	18.74	0.03	b.d	100.79	80.4
18	42.77	0.16	0.08	39.39	18.62	b.d	b.d	101.05	80.4
19	41.77	0.17	0.04	38.22	17.70	b.d	b.d	97.91	80.8
20	42.96	0.25	0.04	38.87	18.38	b.d	b.d	100.54	80.7
21	43.03	0.17	0.03	38.92	18.82	b.d	b.d	101.01	80.3
22	42.79	0.24	b.d.	38.56	18.46	b.d	b.d	100.06	80.5
23	42.83	0.20	0.03	38.85	18.51	b.d	b.d	100.42	80.5
24	42.98	0.18	0.06	38.73	18.57	0.03	b.d	100.54	80.5
25	42.80	0.20	0.05	38.40	18.55	0.04	b.d	100.03	80.4
26	42.72	0.17	0.06	38.65	18.35	0.03	0.04	100.02	80.6
27	42.65	0.16	0.07	38.73	18.33	0.03	0.04	100.00	80.6
28	43.01	0.16	0.07	38.71	18.53	b.d	b.d	100.52	80.5
29	42.67	0.19	0.06	38.59	18.35	0.03	b.d	99.89	80.6
30	43.05	0.19	0.07	38.84	18.38	0.04	b.d	100.58	80.7
31	42.54	0.24	b.d.	38.68	18.58	b.d	b.d	100.09	80.3

	MgO	MnO	CaO	SiO2	FeO	Cr2O3	NiO	Total	Fo
Average Wt. %	42.7	0.19	0.05	38.7	18.5	0.03	0.05	100.3	80.4
Standard Dev. (2-sig.)	0.2	0.03	0.01	0.2	0.1	0.01	0.01		0.2

b.d.= Below Detection Limit

APPENDIX III

Milton Olivine Electron Probe Microanalysis Data (Weight %)

	MgO	MnO	CaO	SiO2	FeO	Cr2O3	NiO	Total	Fo
Detection Limit Wt.%	**0.01**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.03**		
Sample #	**Wt %**	**Wt %**	**Wt %**	**Wt %**	**Wt %**	**Wt %**	**Wt %**	**Wt %**	
3	45.13	0.14	0.16	38.98	15.51	0.07	0.06	100.04	83.84
4	44.79	0.11	0.08	39.00	14.95	0.04	b.d	98.99	84.23
5	44.87	0.16	0.19	39.35	14.81	0.04	b.d	99.41	84.38
6	45.25	0.14	0.24	39.02	15.49	0.07	b.d	100.20	83.89
7	45.27	0.15	0.26	39.07	15.41	0.09	b.d	100.25	83.97
8	45.39	0.17	0.13	39.18	15.18	0.08	b.d	100.16	84.21
9	45.81	0.12	0.18	39.30	15.17	0.06	b.d	100.65	84.33
10	45.21	0.13	0.23	39.30	15.25	0.08	b.d	100.20	84.09
11	45.45	0.13	0.17	39.35	15.04	0.06	b.d	100.22	84.35
12	45.81	0.13	0.14	39.41	15.37	0.06	b.d	100.92	84.16
13	44.88	0.08	0.13	39.40	15.30	0.04	b.d	99.84	83.95
14	44.93	0.08	0.10	39.41	15.43	0.06	0.05	100.06	83.85
	MgO	**MnO**	**CaO**	**SiO2**	**FeO**	**Cr2O3**	**NiO**	**Total**	**Fo**
Average Wt. %	45.2	0.13	0.17	39.2	15.2	0.06	0.05	100.1	84.1
St. Deviation (2-sig.)	0.2	0.02	0.02	0.2	0.1	0.02	0.03		0.2

b.d.= Below Detection Limit

APPENDIX IV

Milton Electron Probe Microanalysis Metals Data (Weight %)

Milton Taenite

Detection Limit Wt.%	0.01	0.02	0.01	0.03	0.02	
Sampling #	**Cu**	**Fe**	**Cr**	**Ni**	**Co**	**Totals**
1	b.d.	83.8	b.d.	15.1	0.84	99.8
2	b.d.	83.0	b.d.	16.7	0.84	100.5
3	b.d.	82.1	b.d.	16.9	0.81	99.8
4	0.02	82.4	b.d.	17.1	0.83	100.3
7	b.d.	82.4	b.d.	16.6	0.88	99.8
8	b.d.	82.4	b.d.	15.7	0.88	99.0
9	b.d.	82.5	b.d.	16.1	0.88	99.5
10	b.d.	81.1	b.d.	18.0	0.88	100.0
	Cu	**Fe**	**Cr**	**Ni**	**Co**	**Totals**
Average Wt. %	0.02	82.5	b.d.	16.5	0.85	99.8
Standard Deviation (1-sig)		0.8		0.9	0.03	

b.d.= Below Detection Limit

APPENDIX V

Eagle Station Electron Probe Microanalysis Metals Data (Weight %)

Eagle Station Taenite

Detection Limit Wt.%	0.01	0.02	0.01	0.03	0.02	
Sample #	**Cu**	**Fe**	**Cr**	**Ni**	**Co**	**Totals**
6	0.03	75.8	b.d.	22.0	0.47	98.3
7	0.02	81.9	b.d.	16.4	0.70	99.0
8	0.02	82.7	b.d.	15.6	0.71	99.0
10	0.00	90.7	b.d.	6.7	0.99	98.5
11	0.04	67.8	b.d.	30.3	b.d	98.3
16	0.03	77.2	b.d.	21.7	0.49	99.4
17	0.02	81.6	b.d.	16.5	0.68	98.8
18	0.02	79.9	b.d.	17.9	0.55	98.4
19	0.02	78.9	b.d.	18.1	0.59	97.6
20	0.02	75.6	b.d.	23.1	0.46	99.3
21	b.d.	91.5	b.d.	6.6	0.98	99.1
22	b.d.	90.8	b.d.	6.9	0.96	98.7
	Cu	**Fe**	**Cr**	**Ni**	**Co**	
Average Wt.%	0.02	81.2	b.d.	16.8	0.69	98.7
Standard Deviation (1-Sig)	0.01	6		6	0.2	0.5

b.d= Below Detection Limit

APPENDIX VI

St. Dev. And RSD for Standards

Standard	Standard St. Dev.	Standard rsd
BIR-1g	2.7	1.6%
NIST-612	0.5	3.9%
NIST-610	0.3	6.7%
Filomena	2.2	12.1%
Hoba	0.6	17.2%
SRM1158	1.5	11.0%