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Experimental Partitioning of Trace Elements into Schreibersite with Applications to IIG Iron Meteorites

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Abstract

Some of the defining characteristics of the IIG iron meteorite group are their high bulk P contents and massive, coarse schreibersite, which have been calculated to make up roughly 11–14 wt% of each specimen. In this study, we produced two datasets to investigate the formation of schreibersites in IIG irons: measurements of trace elements in the IIG iron meteorite Twannberg and experimental determinations of trace element partitioning into schreibersite. The schreibersite-bearing experiments were conducted with schreibersite in equilibrium with a P-rich melt and with bulk Ni contents ranging from 0–40 wt%. The partitioning behavior for the 20 elements measured in this study did not vary with Ni content. Comparison of the Twannberg measurements with the experimental results required a correction factor to account for the fact that the experiments were conducted in a simplified system that did not contain a solid metal phase. Previously determined solid metal/P-rich melt partition coefficients were applied to infer schreibersite/solid metal partitioning behavior from the experiments, and once this correction was applied, the two datasets showed broad similarities between the schreibersite/solid metal distribution of elements. However, there were also differences noted, in particular between the Ni and P contents of the solid metal relative to the schreibersite inferred from the experiments compared to that measured in the Twannberg sample. These differences support previous interpretations that subsolidus schreibersite evolution has strongly influenced the Ni and P content now present in the solid metal phase of IIG irons. Quantitative attempts to match the IIG solid metal composition to that of late-stage IIAB irons through subsolidus schreibersite growth were not successful, but qualitatively, this study corroborates the striking similarities between the IIAB and IIG groups, which are highly suggestive of a possible genetic link between the groups as has been previously proposed.

1. Introduction

Schreibersite ((Fe,Ni)₃P) is a common mineral in iron meteorites (Doan and Goldstein, 1969; Buchwald, 1975; Clarke and Goldstein, 1978). Its presence in iron meteorites ranges from micron-sized occurrences to centimeter-sized masses, and the term rhabdite has been used to describe its occurrence as small micron-sized crystals. In this study, we adopt the

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term schreibersite to refer to all occurrences of the mineral, including those formed during laboratory experiments.

The IIG iron meteorite group currently has six members and is especially rich in coarse, irregular, cm-sized schreibersite, though it also occurs in these irons as smaller lamellar and microprismatic phases (Hofmann et al., 2009; Wasson and Choe, 2009). Estimates of the schreibersite contents in IIG irons are about 11–14 wt% (Wasson and Choe, 2009), with bulk P compositions of the meteorites of 1.7–2.1 wt%, the highest of any iron meteorite group (Buchwald, 1975; Wasson and Choe, 2009). The abundant, large schreibersite phases in IIG irons have been suggested to have formed as a liquidus phase (Doan and Goldstein, 1968; Hofmann et al., 2009; Wasson and Choe, 2009). Formation from a melt is in contrast to the formation path believed to be responsible for the small schreibersite in many other iron meteorites, which is thought to have formed from subsolidus exsolution of P from the solid metal (Doan and Goldstein, 1968; Clarke and Goldstein, 1978). In order for schreibersite to crystallize from a Fe-Ni melt, the melt must be rich in P.

One way to enrich an Fe-Ni melt in P is through liquid immiscibility in the Fe-Ni-S-P system (Ulf-Møller, 1998; Chabot and Drake, 2000). Studies that have modeled the crystallization trends of iron meteorites have shown that S was likely an important component of the metallic liquid from which many iron meteorites solidified (e.g. Jones and Drake, 1983; Chabot 2004; Goldstein et al., 2009). An Fe-Ni metallic melt that contains S and P at the quantities needed to encounter the liquid immiscibility field will break down to form two separate immiscible liquids, one S-rich and one P-rich. Modeling of iron meteorite crystallization has suggested that liquid immiscibility may have been encountered by the IIAB and IIIAB groups (Ulf-Møller, 1998; Chabot and Drake, 2000; Wasson et al., 2007).

The IIG irons (Wasson and Choe, 2009) share many similarities in trace element compositions with the much larger IIAB iron meteorite group (Wasson et al., 2007), and the IIAB irons show evidence for being one of the most S-rich magmatic iron meteorite groups (Chabot, 2004; Wasson et al., 2007). Thus, Wasson and Choe (2009) hypothesized that the IIAB and IIG irons actually formed in the same asteroidal core, with the IIG irons forming from a late-stage Fe-Ni melt enriched in P due to liquid immiscibility in the Fe-Ni-S-P system. Such a formation history would explain the similarities in many trace elements between the IIG and IIAB irons and the presence of large amounts of schreibersite in IIG irons.

For this study, we devised an approach to investigate this hypothesis by examination of the partitioning of trace elements. First, we measured the trace elements present in the IIG iron Twannberg in both the solid metal and coarse schreibersite phases. Second, we conducted experiments to determine how trace elements partition into schreibersite when it forms as a liquidus phase. Lastly, we compared the iron meteorite measurements and the experimental results and considered the implications for the formation of the IIG and others iron meteorites. The next sections provide details of this overall approach and the results.

2. Methods

2.1. Twannberg Measurements

The IIG iron meteorite Twannberg was chosen for this study because of the previous extensive petrological and chemical characterization of the sample (Hofmann et al., 2009), and its representativeness of the IIG group as a whole (Wasson and Choe, 2009). The Twannberg meteorite, a collection of six paired masses found between 1984–2007 near Twann Mt. (Switzerland), is a large IIG iron, with a pre-atmospheric mass estimate of at least 11,000 kg (Hofmann et al., 2009). During their characterization, Hofmann et al. (2009) separated the schreibersite in Twannberg into three distinct classes, based on morphology as well as Ni content: 1) “Skeletal” – the largest (cm-sized) and lowest concentration of Ni (10.5 wt.%), 2) “lamellar” – elongated, mm-sized and moderately Ni-rich (17.2 wt.%) and 3) “microprismatic” – micron-sized crystals, highly enriched in Ni (23.9 wt.%). While the more Ni-rich and smaller “lamella” and “microprismatic” phases of schreibersite in Twannberg are thought to have formed via exsolution, Hofmann et al. (2009) suggested that the skeletal phase formed as a liquidus phase. As shown in Fig. 1, the Twannberg section used in our study contained clearly distinguished phases of solid metal and large, coarse schreibersite. We examined the section for evidence of lamellar and microprismatic schreibersite as well. A few cases of textures consistent with lamellar schreibersite were identified, but the features were too small for chemical measurements by our approach, and we avoided these few features in our analysis going forward. We did not identify microprismatic schreibersite in our section of Twannberg, though it is likely these phases are present and hence included in our analysis of the metal. Given the microprismatic schreibersite formed by exsolution, inclusion of this phase in our metal analysis is appropriate when we are interested in comparing our results to liquidus compositions. This section of Twannberg was cut into four sub-sections, with each sub-section mounted in epoxy and polished with alumina powder for analysis.

The Twannberg sub-sections were imaged and analyzed for Fe, Ni, and P abundances using a Hitachi TM 3000 desktop scanning electron microscope (SEM) with Bruker Q70+ silicon drift detector energy dispersive spectrometer (EDS) system at the Johns Hopkins University Applied Physics Laboratory. The Fe, Ni, and P concentrations of both the solid metal and coarse schreibersite phases were measured using counting times of 120 seconds for 5 analyses of each phase and were averaged to determine the major element composition of each phase. Magnification settings were varied to cover rectangular regions with dimensions of 150–500 μm per side and produced consistent results independent of the magnification. The energy resolution of the Hitachi TM 3000 is ~ 140 KeV at the full-width half-maximum of the Cu K alpha line. Calibration factors have been developed for the Hitachi TM 3000 at APL by comparing measurements to those obtained on a JEOL 8900L electron microprobe at the Carnegie Institution of Washington. For the limited elements measured in this study, calibration factors for Fe and Ni measurements were negligible and not applied, while P measurements used a correction factor of 1.15. For Fe and Ni, errors were estimated as the standard deviation of the multiple measurements. For P, the larger of either the calculated standard deviation of the multiple measurements or the difference between the original and corrected values was used as the error.

Trace element concentrations were measured by laser ablation inductively coupled plasma mass spectrometry (LA ICP-MS) at the University of Maryland, using the same approach as applied to the analysis of iron meteorites in previous studies (Walker et al., 2008; McCoy et al., 2011). Analyses were conducted using a single-collector ICP-MS (Element 2, Thermo Finnigan) coupled to a laser ablation system with an output wavelength at 213 nm (UP213, New Wave Research). The laser was operated at $\sim 3 \text{ J cm}^{-2}$. Ablation sampling was done in point mode using a spot diameter ranging from 80-250 μm and 7 Hz flash rate, with >10 analyses acquired for each of the solid metal and schreibersite phases. Data were collected for the following masses: ^{57}Fe , ^{59}Co , ^{61}Ni , ^{62}Ni , ^{69}Ga , ^{71}Ga , ^{73}Ge , ^{74}Ge , ^{75}As , ^{95}Mo , ^{97}Mo , ^{99}Ru , ^{101}Ru , ^{103}Rh , ^{105}Pd , ^{108}Pd , ^{121}Sb , ^{182}W , ^{183}W , ^{185}Re , ^{189}Os , ^{193}Ir , ^{195}Pt , and ^{197}Au . Analyses were carried out in blocks of twenty runs. Two runs of each of two standard reference materials bracketed the analyses of Twannberg: NIST 610 glass (Jochum and Stoll, 2008) and either the North Chile (Filomena) or Hoba iron meteorite (electronic annex of Walker et al., 2008), all with an 80- μm spot size. These standard reference materials provided the basis for determining calibration curves to constrain instrument drift and provide element concentrations. Element concentrations for Co, Ni, Ga, Ge, As, Mo, and Sb were standardized using the NIST 610 standard, and element concentrations for Ru, Rh, Pd, W, Re, Os, Ir, Pt, and Au were standardized using the North Chile (Filomena) or Hoba iron meteorite standard.

LA ICP-MS data were processed using the LAMTRACE (Van Achterberg et al., 2001) software program, which determines element concentrations using ratios of count rates for samples and standards, known concentrations in the standards, and the known concentration of an internal standard in the sample, in this case Ni as determined by the SEM measurements. For elements measured by two isotopes, the results were compared to confirm consistency in the measurements, and in general, the measurement from the isotope with the lower detection limit was used. Errors were calculated as the standard deviation of the multiple analyses made for each compositional phase.

Table 1 provides the compositional results for our Twannberg measurements. Measurements below the detection limit (defined as background plus three standard deviations of the background) or measurements where the error determined was greater than 100% are not reported in Table 1. Our compositional results are in good agreement with previously published measurements for Twannberg (Hofmann et al., 2009; Wasson and Choe, 2009), as shown in Table S1 of the supplemental material, and provide the first measurements for the concentrations of many elements in both the schreibersite and solid metal phases for Twannberg.

2.2. Laboratory Experiments

All experiments were conducted at the Johns Hopkins University Applied Physics Laboratory in a 1 atm Deltech vertical tube furnace using evacuated and sealed silica tubes, similar to the techniques used previously in our laboratory involving solid metal-liquid metal experiments (Chabot et al. 2007; 2009; 2017). At 1 atm, there is a large field in the Fe-Ni-P system where solid $(\text{Fe,Ni})_3\text{P}$ coexists in equilibrium with a P-bearing Fe-Ni metallic liquid (Raghavan, 1988), referred to as P-rich melt throughout this study. Experiments were

designed to take advantage of this simplified system with two phases and to produce equilibrium schreibersite and P-rich melt in each sample. The simplified two-phase system was highly conducive to producing run products with large schreibersite grains in equilibrium with large regions of P-rich melt, which enabled reliable determinations of trace element partitioning behaviors. The starting bulk composition and run temperature dictated the final composition and relative amounts of the two equilibrated phases. Because the experiments contained only two phases, schreibersite and a P-rich melt, comparing the experimental results to the iron meteorite measurements of solid metal and schreibersite required a correction factor, and this is discussed in detail in Section 3.3. Overall, two sets of experiments were conducted: a time series to investigate equilibrium partitioning behavior, and a series varying the Ni content of the bulk composition to investigate the effect of Ni on the equilibrium partitioning behavior.

Starting powders were mixed using commercially purchased powders of Fe, Ni, and P, along with a mixture of 25 trace elements. The trace elements were first mixed in a separate powder, with roughly equal concentrations of the following commercially purchased powders: V, Cr₂O₃, Mn, Co, Ni, Cu, Zn, Ga, Ge, As, Mo, Ru, Rh, Pd, Ag₂O, Sn, Sb, H₂WO₄, Re, Os, Ir, Pt, Au, PbO, and Bi. This trace element mixture was then mixed with the Fe, Ni, and P powders in acetone to dope each starting powder with ~100 ppm of each trace element. Previous work has demonstrated that doping at this level does not affect the solid metal-liquid metal partitioning behavior (Chabot et al. 2003, 2007). Starting powders were placed in a drying oven for ~3-4 hours. The bulk compositions for the starting powders mixed for each experiment are listed in Table S2.

Approximately 200 mg of the desired starting powder was placed directly in a high-purity silica glass tube. Samples were evacuated for 15 minutes and subsequently sealed under vacuum using an oxygen and acetylene torch. The sealed tube was hung in the vertical tube furnace at temperatures ranging from 950–1100°C for roughly 1–6 days. At the end of each experiment, the silica tube was removed from the furnace and briefly submerged in water to quench the experiment. Although the starting powders were placed directly in the silica tubes, the final run products showed no significant interaction with the glass tubes. Upon breaking the silica tube open after being quenched in water, the final experiments rolled easily out of the tube in the form of a small metallic ball. Samples were then mounted in epoxy and sliced with a diamond saw to obtain 3–4 cross-sections of each sample. Cross-sections were then re-mounted in epoxy and polished with alumina powder for analysis.

Experiments were first imaged and analyzed using the Hitachi TM 3000 desktop SEM/EDS, using the same procedures described in Section 2.1 for the Twannberg iron meteorite sample. As shown in the back-scattered electron (BSE) images of Fig. 2, experimental run products consisted of two clearly distinguished phases of schreibersite and quenched P-rich melt. The schreibersite phase had a homogenous Fe, Ni, and P composition, and the P-rich melt quenched to a dendritic texture typical for P-bearing quenched metallic liquids (Chabot and Drake, 2000; Corrigan et al., 2009). Figure 2B shows the distinct boundary between these coexisting phases, and Fig. 2C shows detail of the dendritic texture of the quenched P-rich melt phase. The Fe, Ni, and P concentrations of both the schreibersite and quenched P-rich melt phases were determined using counting times of 120 seconds, and approximately 9

analyses were acquired for each of the two phases in each sample. The average composition of the quenched P-rich melt was obtained by acquiring measurements over rectangular regions roughly 300–500 μm in length and width. The solid schreibersite phase was analyzed using a higher magnification, resulting in a rectangular analysis area of roughly 50 μm in length and width. The multiple measurements of each phase were averaged to determine the composition of each phase. Errors for Fe and Ni were estimated as twice the standard deviation of the multiple measurements, and errors for P were determined as described in Section 2.1.

Trace element concentrations were measured using the same LA ICP-MS methods as for the Twannberg IIG iron meteorite described in Section 2.1. The schreibersite phase of each experiment was analyzed by 5 measurements using a 55 μm diameter ablation spot size. To average over the P-rich melt with its quench texture, a 55 μm diameter ablation spot was moved at a rate of 20 $\mu\text{m s}^{-1}$ across the sample, resulting in a line scan. The length of each line varied depending on the characteristics of each experimental sample, but the length was generally between 800 and 1300 μm . Three or more line scans were conducted in the quenched P-rich melt phase of each experimental sample. Errors in the composition of each phase were calculated as twice the standard deviation of the multiple measurements. As with the Twannberg analysis, measurements below the detection limit or measurements where twice the error was greater than 100% error are not reported.

Table 2 provides the compositional results for eight distinct experiments, listing the composition of the schreibersite phase, the quenched P-rich melt phase, and the schreibersite/P-rich melt partition coefficient, D , calculated by dividing the wt% measurements from the two phases. The results in Table 2 represent two sets of runs. First, at a temperature of 1100°C, a time series study was conducted in the Ni-free Fe-P system (runs #LB14 – #LB21), with run durations varying from roughly 1–6 days. These runs show consistent and repeatable trace element partitioning behavior between the solid schreibersite and P-rich melt for experiments that were conducted for as little as 1 day. Figure 3 plots these time series results for a subset of the elements listed in Table 2, illustrating the equilibrium partitioning results achieved for runs of varying durations.

The second set of runs (#R1P1 – #R2P9) detailed on Table 2 varied the Ni composition in the system, using starting compositions with Ni contents that ranged from 10–40 wt%, as listed in Table S2. The motivation for this set of runs was to investigate the effect of Ni on the partitioning behavior of the trace elements, given that both the solid metal and schreibersite phases in iron meteorites span a large range of Ni contents (e.g. Doan and Goldstein, 1969; Buchwald, 1975; Clarke and Goldstein, 1978; Goldstein et al., 2009). The results from this set of experiments examining the effect of Ni are discussed in the next section.

In addition, while conducting the experiments, we also produced two runs that lacked schreibersite but that contained coexisting P-rich melt and $(\text{Fe,Ni})_2\text{P}$. In the Fe-Ni-P system, $(\text{Fe,Ni})_2\text{P}$ coexists in equilibrium with a P-bearing Fe-Ni metallic liquid at temperatures higher than the $(\text{Fe,Ni})_3\text{P}$ -liquid field (Raghavan, 1988). Thus, the temperature of these two runs were higher than we intended given the bulk Ni composition of the starting materials

and did not produce the desired phases for this project. Nevertheless, we analyzed these two runs using the same methods as applied to those runs that contained schreibersite, and the supplemental information contains a BSE image of a run product containing $(\text{Fe,Ni})_2\text{P}$ (Fig. S1) and a table of the measured compositions (Table S3). Figure S2 compares the partitioning behavior between $(\text{Fe,Ni})_3\text{P}$ /P-rich melt and $(\text{Fe,Ni})_2\text{P}$ /P-rich melt, which differs considerably for some trace elements. However, given that our motivation for this project is related to investigating schreibersite in iron meteorites, we do not discuss the runs that lacked schreibersite any further but rather provide the data in case they are of interest to future studies.

3. Results

3.1. Twannberg Results

Figure 4A plots the schreibersite/solid metal wt% element ratios measured from the large, coarse, “skeletal” schreibersite phases in the Twannberg sample, and Table 3 lists the ratio values. We were unable to resolve the composition of the few smaller, “lamellar” schreibersites identified in our section by our analytical methods. As mentioned previously, it is likely that our analysis of the solid metal phase includes “micropismatic” schreibersite phases, given these have been reported to exist in Twannberg (Hofmann et al., 2009). Since the micropismatic schreibersites formed by exsolution, including them in our analysis of the solid metal phase would be appropriate to compare to our experiments that involved liquidus conditions, but this is an important point to keep in mind as we use these compositional results going forward in this study. In Fig. 4A, the elements are arranged roughly in order of increasing compatibility in the schreibersite phase as measured in Twannberg. The highly siderophile elements Os, Ir, Pt, Re, and Au have very low concentrations in the Twannberg schreibersite, as listed in Table 1, resulting in ratios with large two-standard deviation errors. Previous Twannberg measurements of the trace element concentrations in schreibersite are limited, and our new measurements are in general agreement with the Ni and Co abundances reported by Hofmann et al. (2009) and listed in Table S1. The results shown in Fig. 4A are one of the two key datasets that we identified in the design of our project to investigate the formation of large schreibersites in IIG irons, and we will return to comparisons involving this dataset and implications for iron meteorites after introducing the experimental dataset in the next section.

3.2. Experimental Results

Figure 4B plots the schreibersite/P-rich melt wt% element ratios measured from the phases produced in our experiments and tabulated in Table 2. The order of the elements in the plot uses that determined for Fig. 4A, with increasing compatibility in the schreibersite phase in Twannberg. There are also a few additional elements included on Fig. 4B (Ag, Cu, Ge, Zn, and V) that were measured in our experiments but were at concentration levels too low in the natural iron meteorite Twannberg sample to measure by our analytical approach.

One of the main items we set up our experiments to investigate was the effect of Ni concentration on the trace element partitioning behavior. Our experiments covered a large range of Ni contents, from the Ni-free system to a system with ~40 wt% Ni in the bulk

starting composition, covering the Ni contents measured in the solid metal of nearly all iron meteorites (e.g. Chabot and Haack, 2006; Goldstein et al., 2009) except for two extremely Ni-rich irons, NWA 6259 with 42.6 wt% Ni (Wasson et al., 2011) and Oktibbeha County with 58.5 wt% Ni (Kracher and Willis, 1981). Figure 4B plots the results from these experiments with the wide-ranging Ni contents, and the results show remarkably consistent partitioning behavior across the entire range of Ni contents studied. From these results, we conclude that the Ni content of the schreibersite–P-rich melt system does not affect the trace element partitioning behavior of these 20 elements in this system.

Given the consistent partitioning behaviors across the full range of Ni contents, moving forward to compare the experimental results against the Twannberg iron meteorite measurements, it makes sense to combine all of the experimental results into a single, best determination of the partitioning behavior of each element. Table 3 provides the weighted averages and errors using the results from the five experiments plotted in Fig. 4B and the values and errors tabulated in Table 2 for each run. The calculated weighted average value is also plotted on Fig. 4B, demonstrating that it nicely represents the values determined from the individual experiments.

3.3. Comparing Twannberg and Experimental Results

The measured results from the Twannberg iron meteorite and the experimental samples are not directly comparable because the iron meteorite has solid metal and schreibersite and the experiments have P-rich melt and schreibersite. Thus, it is necessary to use existing knowledge about the partitioning behavior of these elements between solid metal and P-rich melt in the Fe-Ni-P system to enable such a comparison. A number of experimental studies have determined solid metal/liquid metal partitioning behaviors in the Fe-Ni-P system (e.g. Willis and Goldstein, 1982; Malvin et al., 1986; Corrigan et al., 2009), and Chabot et al. (2017) recently provided parameterizations of these experimentally determined partition coefficients for a number of elements. We used the parameterizations from Chabot et al. (2017) and a P concentration in the P-rich melt that ranged from 11–12 wt%, consistent with that measured in our experiments, to calculate $D(\text{solid metal}/\text{P-rich melt})$ partitioning values. We then divided the experimentally determined $D(\text{schreibersite}/\text{P-rich melt})$ values (the weighted averages in Table 3) by these $D(\text{solid metal}/\text{P-rich melt})$ values determined from the parameterizations to derive $D(\text{schreibersite}/\text{solid metal})$ values:

$$\frac{D(\text{schreibersite} / \text{P-rich melt})}{D(\text{solid metal} / \text{P-rich melt})} = D(\text{schreibersite} / \text{solid metal}) \quad (\text{Eq. 1})$$

Table 3 reports the results of applying this correction factor. The errors on the calculated $D(\text{schreibersite}/\text{solid metal})$ values in Table 3 were derived by considering both the errors on the parameterizations listed in Chabot et al. (2017) and the weighted average errors listed in Table 3 for the experimental schreibersite/P-rich melt values. Chabot et al. (2017) does not include parameterizations for either V or Zn in the Fe-Ni-P system, so there are no calculated schreibersite/solid metal values listed for these two elements in Table 3.

Figure 4C plots the calculated schreibersite/solid metal values, derived from the experimental measurements. For a few elements, previous experimental studies have determined schreibersite/solid metal partitioning values (Jones et al., 1993; Jones and Casanova, 1993; tabulated in Table S4 of supplemental material), but no errors were provided on those limited previous determinations. Our new results are generally consistent with the previous determinations, as shown on Fig. 4C.

Figure 4C also plots the Twannberg schreibersite/solid metal measurements, the same results as shown in Fig. 4A. Figure 4C illustrates the extensive range of element partitioning behaviors in this system, which span roughly four orders of magnitude on the graph. Overall, there is good agreement between the Twannberg and experimentally derived values about which elements have the lowest schreibersite/solid metal partitioning values and which elements have the highest values. At the low end, the highly siderophile elements of Ir, Pt, Os, Au, and Re are very incompatible in schreibersite in both datasets, and the two datasets agree within the large errors associated with the Twannberg measurements. At the high end, both datasets show that Mo is compatible in schreibersite, with schreibersite/solid metal values >1 on Fig. 4C. These general agreements provide confidence in the overall approach and methods of our study.

For the elements on Fig. 4C with well-determined values in both datasets, there are a few elements that have similar values, within roughly a factor of two, between the experimental and Twannberg datasets: As, Co, W, Rh, and Mo. Employing the solid metal/P-rich melt parameterization model for determining the schreibersite/solid metal values for the experimental dataset can introduce some uncertainty in the determined values even beyond that captured by the error bars in Fig 4C. This is because the parameterization model is being applied to P-rich melts from Fe-Ni-P systems that contained P abundances that were too high to form solid metal and rather formed schreibersite, which is an extrapolation of the solid metal/liquid metal datasets on which the parameterizations of Chabot et al. (2017) are based. Thus, we interpret agreement within roughly a factor of two to be generally similar values given the approach of this study.

However, for other elements on Fig. 4C, there are larger differences between the schreibersite/solid metal values from the Twannberg and experimental datasets: Ga, Pd, Ru, Ni, and P. In particular, our experimental dataset shows Ni partitioning roughly equally between schreibersite and solid metal where the Twannberg measurements show that the schreibersite is considerably enriched in Ni relative to the solid metal. These discrepancies indicate that the elemental concentrations measured in the schreibersite and solid metal of Twannberg do not match equilibrium partitioning of elements into a schreibersite phase that formed on the liquidus.

Thus, overall, the Twannberg schreibersite and solid metal compositions resemble those expected by the experimental study for schreibersite that formed on the liquidus but the compositions also do not match the expected liquidus partitioning values in a few specific ways for some elements. This may indicate that the schreibersite in Twannberg formed largely as a liquidus phase but that it was also affected by further subsolidus chemical evolution, as posited in Hofmann et al. (2009). In the next section, we discuss this option

and other possible interpretations and implications of these results for the crystallization and chemical evolution of IIG irons.

4. Implications

One of the main motivations for this study was to test the hypotheses that the large “skeletal” schreibersite in IIG irons formed as a liquidus phase and that the IIG and IIAB irons formed in the same parent body core (Wasson and Choe, 2009). In the Fe-Ni-P system (Raghavan, 1988), as solid Fe-Ni metal crystallizes, the remaining melt becomes continually enriched in P until reaching the cotectic temperature, which depends on the composition of the system; in the binary Fe-P system (Okamoto, 1990), the eutectic temperature is at 1048°C and 10.2 wt% P. Once reaching this temperature, both solid Fe-Ni metal and schreibersite will crystallize as liquidus phases, forming from the P-rich melt. Our results suggest that the schreibersite in the IIG iron Twannberg has a chemical composition, relative to its neighboring solid metal phase, that largely resembles the composition that would be expected from formation as a liquidus phase, forming from the P-rich melt along with solid Fe-Ni metal. However, our results also suggest that the Twannberg composition differs in some important ways for a few key elements. Here we discuss two main items:

1. What may explain the chemical differences?
2. What does that mean for a potential genetic link between the IIG and IIAB irons?

In addition to potentially forming schreibersite as a liquidus phase from a P-rich melt, it is well established that schreibersite growth at subsolidus conditions in iron meteorites is a common occurrence and that it can have an important influence on the formation of the Widmanstätten pattern (e.g. Goldstein et al., 2009). The solubility of P in solid Fe-Ni metal decreases as the solid metal cools, leading to the exsolution of P and the formation of schreibersite at subsolidus conditions (Raghavan, 1988; Okamoto, 1990). Additionally, as the temperature decreases, the Ni content of the schreibersite continues to increase through the process of solid-state diffusion (Doan and Goldstein, 1969; Clarke and Goldstein, 1978). Thus, the fact that the Ni content measured in the schreibersite relative to the solid metal of the Twannberg sample is higher than that of the experiments is consistent with this well-established behavior. This higher Ni content suggests that the massive schreibersites in Twannberg either formed or continued chemical evolution at lower, subsolidus temperatures.

Subsolidus growth of schreibersite influences the Ni and P contents of the solid metal from which it forms, as Ni and P are major components in the schreibersite. The subsolidus growth of schreibersite will use P and Ni from the solid metal to create the schreibersite, leaving the resulting solid metal depleted in P and Ni relative to the composition of the solid metal that crystallized from the liquidus. This general behavior is very consistent with the difference shown on Fig. 4C between the P and Ni schreibersite/solid metal ratios in Twannberg compared to the experiments; Twannberg shows higher schreibersite/solid metal ratios for P and Ni than the experiments, consistent with subsolidus growth of schreibersite. Examination of our Twannberg sample (Fig. 1) by SEM did not show any evidence for depletions in Ni or P in the solid metal near the boundary with schreibersite. Additionally,

continued subsolidus chemical evolution could influence the chemistry of trace elements in Twannberg as well as affecting the P and Ni distributions. Returning also to a previous point, it is likely that our analysis of the solid metal phase of Twannberg contains micropismatic schreibersites that formed by exsolution. However, inclusion of these micropismatic schreibersites in the solid metal can not explain the observed mismatch between the higher schreibersite/solid metal ratios for P and Ni in Fig. 4C; inclusion of micropismatic schreibersites in the solid metal analysis would increase the P and Ni content reported for the solid metal, lowering the schreibersite/solid metal ratio for these elements, which is the opposite of what is seen in Fig. 4C.

Another large difference between the experiments and the Twannberg sample is the P content of the solid metal. At the liquidus, P solubility in the solid metal is high; at the Fe-P eutectic, Fe₃P forms that contains 15.6 wt% P along with solid metal that contains 2.8 wt% P (Okamoto, 1990). In contrast, the P content in the solid metal of Twannberg is 0.24 wt% P, even with the likely inclusion of some micropismatic schreibersites in that analysis. If the Twannberg solid metal originally formed with 2.8 wt% P and the current concentration of 0.24 wt% P is due solely to subsolidus schreibersite formation, mass balance implies that the amount of subsolidus schreibersite formed is 17% of the mass of the original solid metal that crystallized. This result is strikingly similar to the amount of schreibersite estimated to compose IIG iron meteorites, estimated at 11–14% (Wasson and Choe, 2009). Thus, the amount of schreibersite in IIG irons is generally consistent with having formed subsolidusly from a P-rich solid metal that formed near an Fe-P eutectic composition.

However, if the solid metal in IIG irons formed from a liquid with a composition near the Fe-P eutectic composition, where is all the schreibersite that formed as a liquidus phase? The Fe-P eutectic composition has 10.2 wt% P, which by mass balance would form roughly 42% solid metal with 2.8 wt% P and 58% Fe₃P with 15.6 wt% P. Formation of subsolidus schreibersite would be in addition to the schreibersite formed at the liquidus, bringing the final expected composition to 35% solid metal with 0.24 wt% P and 65% schreibersite with 15.6 wt% P. This is significantly more schreibersite than the roughly 11–14% observed in IIG irons (Wasson and Choe, 2009).

In considering the parental liquid composition of the IIG irons, we discuss the simplified Fe-P system, but it has been suggested that liquid immiscibility in the IIAB core in the Fe-Ni-S-P system led to the formation of the P-rich melt from which the IIG irons formed (Wasson and Choe, 2009). In this case, the P-rich melt that formed would also contain a few wt% S, which would also contribute to the evolution of the system. However, the system would still fundamentally be P-rich, such that schreibersite would be expected to be the dominant phase formed by the crystallization of such a P-rich melt and would be expected to be present at much higher abundances than the 11–14% observed in IIG irons (Wasson and Choe, 2009). Regardless of how the Twannberg massive coarse schreibersites originally formed, it is clear from the Ni and P contents that subsolidus growth or chemical evolution of schreibersite has affected the compositions of the solid metal and schreibersite phases present today. To that end, we considered two extreme end-member scenarios, to evaluate the range of effects on the IIG solid metal composition and how it compares to that of the IIAB group, proposed to have formed in the same asteroidal core (Wasson and Choe, 2009):

1. End-member Case 1: all of the schreibersite in Twannberg formed subsolidusly.
2. End-member Case 2: all of the schreibersite in Twannberg formed as a liquidus phase.

For Case 1, if all of the schreibersite formed from subsolidus growth, the composition of the solid metal formed at the liquidus would be the bulk composition determined by averaging the composition of the current solid metal and the current schreibersite weighted by their relative abundances from subsolidus formation. As discussed, by mass balance of the P content of the solid metal at the liquidus versus the current P content of metal in Twannberg, this results in values of 17% for the schreibersite composition and 83% for the solid metal composition. We applied this calculation to Twannberg, using the schreibersite compositions in Table 1 and the solid metal compositions listed in Wasson and Choe (2009). The reason we chose to use the Wasson and Choe (2009) Twannberg solid metal measurements over those we made in this study and listed in Table 1 is to make the comparison to the larger IIG (Wasson and Choe, 2009) and IIAB (Wasson et al., 2007) iron meteorite composition datasets as self-consistent as possible. Our Twannberg solid metal measurements are generally consistent with these previous studies, as detailed in Table S1.

Figure 5 plots the calculated bulk composition of Twannberg in comparison to IIG and IIAB irons for seven elements. Figure 5 also illustrates the similar elemental composition between the later crystallizing high-As members of the IIAB group and members of the IIG group, which are intriguingly similar in many elements to suggest evidence for being formed in the same core (Wasson and Choe, 2009). In particular, the Co vs. As data in Fig. 5A show a generally continuous trend between the solid metal in the IIAB and IIG groups. In contrast, the Ni vs. As data in Fig. 5B show that the solid metal of IIG irons has considerably lower Ni contents than that of IIAB irons.

However, the calculated bulk composition of Twannberg has higher Ni abundance than the solid metal alone, due to the inclusion of the Ni-rich schreibersite in the bulk calculation. The bulk Ni composition of Twannberg is very consistent with that of the later crystallizing, high-As IIAB irons, as shown in Fig. 5B. In contrast, the calculated bulk Co composition of Twannberg is lower than just the solid metal alone, due to the inclusion of the Co-poor schreibersite phase in the bulk calculation. The bulk Co composition of Twannberg differs significantly from IIAB irons with a similar As content, ruining the striking similarity of the solid metal of the two groups.

Other elements plotted in Fig. 5 are less diagnostic. As shown in Fig. 5C, the Ga contents in IIG irons are lower than IIAB irons, but they could also be consistent with the continuation of the IIAB trend to lower values. For Fig. 5D, the IIG W measurements are also consistent with the continuation of the IIAB trend to lower W values but, as noted by Wasson and Choe (2009), determinations of W in the IIG irons were near the detection limits, so interpretations based on IIG W data should be limited. Regarding Ir shown in Fig. 5E, Wasson and Choe (2009) explained that the Ir measurements for IIG data are high-precision measurements, noted the surprising factor of 10 variation among the IIG samples, but did not explain that variation.

The IIG irons appear to have Au abundances that are offset to lower values than a continuation of the IIAB trend would suggest, as shown in Fig 5F. Wasson and Choe (2009) assumed that the Au values were consistent with the IIAB irons and interpreted that the As IIG values were offset to higher values than the IIAB irons. The calculated bulk composition of Twannberg is lower in both Au and As than the solid metal measurement alone, but not in a manner to be consistent with the IIAB Au vs. As trend. Given the continuous nature of the Co vs. As trend in Fig. 5A between the IIAB and IIG irons and the similar schreibersite/solid metal ratio between our experiments and Twannberg in Fig. 4C, we chose to plot the irons in Fig. 5 against As rather than Au. Hence, for the end-member case where all the schreibersite formed subsolidus, the Twannberg bulk Ni content, and perhaps the bulk compositions of other elements such as As, W, and Ga, may be consistent with the late-stage IIAB irons, but in this same scenario, the Twannberg bulk Co and Au contents are not.

For Case 2, if all of the schreibersite in Twannberg formed from crystallization at the liquidus, the averaged bulk composition of Twannberg should represent the composition of the liquid that subsequently crystallized into the solid metal and schreibersite. This could represent the case where a pocket of P-rich liquid was isolated from the larger core and allowed to cool without any additions or outside influence. As cooling started, solid metal would crystallize, leaving the liquid enriched in P, and this would continue until a composition near the Fe-P eutectic was reached. Because Twannberg contains about 15% schreibersite, rather than the 58% schreibersite expected from a Fe-P eutectic composition liquid, the solid metal in this scenario must be a combination of solid metal formed prior to the eutectic as well as at the eutectic. Also, any significant chemical gradients in the solid metal must have been removed by equilibration of the solid metal during this scenario.

In this second case, the bulk composition for Twannberg plotted in Fig. 5 is not the original solid metal composition but rather the original liquid composition. Using the solid metal/liquid metal parameterization in Chabot et al. (2017), we calculated the solid metal that would coexist with this liquid metal composition, and that value is also plotted in Fig. 5. While the solid metal from this end-member case calculation is similar in As, Co, and Au values to the early formed, low-As IIAB irons, as shown in Fig. 5A and 5F, the calculated compositions for Ga, W, and Ir bear no resemblance to the low-As IIAB irons. Thus, this end-member case where the Twannberg bulk composition represents a trapped, P-rich melt composition does not suggest a relationship between the IIG iron Twannberg and the IIAB group.

Overall, neither of the end-member cases we considered, nor any combination thereof, are able to match all of the elements in Fig. 5 in such a manner that the IIAB and IIG compositions are explained as having formed in the same parent body core. However, the fact that the bulk composition of Twannberg does produce a Ni content that is consistent with the IIAB trend is intriguing, as is the consistency of the Co vs. As solid metal trend from IIAB to IIG. If the IIG solid metal was influenced by the subsolidus diffusion of Ni out of the solid metal and into the schreibersite while the Co concentration in the solid metal was unaffected, that would explain how the Co vs. As trend is continuous for the IIAB and IIG irons while also explaining why IIG irons have lower Ni contents than IIAB irons.

However, an explanation would still be needed for the lower Au contents of the IIG irons relative to that expected from the IIAB trend.

Additionally, if solid metal forms at the liquidus with schreibersite, the solid metal is expected to have much higher P concentrations than currently measured in IIG irons. This would require subsolidus growth of a P-rich phase, likely schreibersite, to produce the IIG solid metal P content measured today. Thus, at least some of the schreibersite in IIG irons must have formed subsolidus if any formed as a liquidus phase, just to explain the observed P content of the solid metal today. The large schreibersites in Twannberg are noted to be brittle, and Hofmann et al. (2009) speculated that the high abundance of brittle schreibersite might have facilitated the break-up of Twannberg during atmospheric entry. Similarly, Wasson and Choe (2009) noted that it seems probable that for IIG irons, the breakup in space and during atmospheric transit resulted in preferential fracturing in regions having high contents of brittle schreibersite, suggesting that the schreibersite contents in IIG irons may be appreciably lower than those in the original meteoroid. Thus, the amount of schreibersite originally present in the IIG parent body core may have been more than is present in the IIG samples we study today.

From examining these end-member scenarios, we are not able to provide a quantitative explanation to link IIAB and IIG irons to the same parent body core. However, our work corroborates the previous work of Wasson and Choe (2009) that there are striking chemical similarities among the IIAB and IIG groups that are suggestive of a genetic link between the IIAB and IIG irons. In addition, our study demonstrates that the subsolidus chemical evolution of schreibersite has affected the solid metal composition of IIG irons. Any future modeling attempts to link the IIAB and IIG compositions by crystallization in the same parent body core must include the effects of subsolidus schreibersite evolution on the chemistry to have the potential to be successful. Other efforts to demonstrate a common parent body for the IIAB and IIG irons, such as through W, Mo, Ru, or other isotopic similarities (e.g. Burkhardt et al., 2011; Budde et al., 2016; Kruijer et al., 2017; Bermingham et al., 2018) are well-motivated and highly worthwhile based on the work of Wasson and Choe (2009) and the additional results we have presented here.

As one final note, while our study does not provide a quantitative link between the IIG and IIAB solid metal compositions, our results do show that the solid metal compositions of iron meteorites can be considerably affected by the subsolidus formation of schreibersite. This result has important implications for modeling the crystallization trends within iron meteorites groups. The current solid metal composition in magmatic iron meteorites may have been influenced by both the fractional crystallization process and the subsequent chemical evolution of schreibersite, so attempting to match the compositions by only a fractional crystallization model may be inappropriate. This may be especially true for Ni, which diffuses strongly into schreibersite as the iron meteorite cools. Thus, previous studies to reproduce the Ni trends in iron meteorites by fractional crystallization only (e.g. Jones and Drake, 1983; Haack and Scott, 1993; Ulff-Møller, 1998; Chabot and Drake, 1999) may have been wrongly assuming that effects from subsolidus schreibersite evolution were negligible on the Ni solid metal composition. While Ni is clearly affected by schreibersite growth, whether the effects on other elements are indeed negligible or not is less clear. In the

future, crystallization models seeking to reproduce elemental trends in the solid metal compositions of iron meteorite groups should assess if elements should be excluded from the modeling efforts due to important effects on the final solid metal composition from schreibersite growth.

5. Summary

In summary, our study has produced two new datasets:

1. Measurements of trace elements in the solid metal and schreibersite phases of the IIG iron Twannberg.
2. Experimental determinations of trace element partitioning between a P-rich melt and schreibersite.

The Twannberg results identify a subset of trace elements that partition preferentially into the schreibersite. In particular, Mo has much higher concentrations in the Twannberg schreibersite than in the solid metal phase. However, the majority of the trace elements measured are present in higher concentrations in the solid metal phase of Twannberg than the schreibersite phase, in keeping with their classic siderophile nature.

The experimental results show that the Ni content of the schreibersite–P-rich-melt system does not affect the partitioning behavior of the 20 elements measured in this study. Given that iron meteorites can span a large range of Ni contents, with solid metal contents that range from 5 wt% to nearly 60 wt%, the fact that Ni content does not influence this partitioning behavior in this system is an interesting result and simplifies applying the results to interpret iron meteorites. Analysis of the experimental results show that Mo is the only trace element studied that partitions preferentially into schreibersite when schreibersite forms as a liquidus phase.

Comparison of the Twannberg measurements and the experimental results required applying published parameterizations of solid metal/liquid metal partitioning behavior (Chabot et al., 2017) to calculate schreibersite/solid metal behavior from the experiments that contained only equilibrium schreibersite and P-rich melt phases. Comparison of the two datasets show broad similarities between the schreibersite/solid metal distribution of elements, with Mo partitioning favorably in to the schreibersite phase in both datasets and the highly siderophile elements being incompatible in the schreibersite relative to the solid metal. These broad similarities are generally supportive of the hypothesis that the schreibersite in the IIG irons formed as a liquidus phase (Doan and Goldstein, 1968; Holfmann et al., 2009; Wasson and Choe, 2009).

However, important distinctions between the Twannberg and experimental datasets exist, notably for the major elements of Ni and P. The Twannberg solid metal contains lower Ni and P abundances relative to the coexisting schreibersite than suggested by the experimental data. This could be due to subsolidus growth of additional schreibersite, depleting the originally crystallizing solid metal in these elements. Calculation of the bulk composition of Twannberg that considered both the solid metal and schreibersite phases results in a bulk Ni composition that is consistent with late-crystallizing IIAB irons, supporting the proposed

genetic link between the IIAB and IIG groups (Wasson and Choe, 2009). However, the similarly calculated bulk composition for Co in Twannberg is not consistent with IIAB irons, even though the Co composition of the solid metal alone in Twannberg is consistent with that of late-stage IIAB irons. Subsolidus exchange of Ni into schreibersite could potentially explain the lower Ni in the solid metal of Twannberg while leaving the Co in the solid metal unaffected, but this explanation cannot account for the low P content of the Twannberg metal (0.24 wt% P) in comparison to the P content of solid metal that coexists with schreibersite as a liquidus phase (2.8 wt% P in the Fe-P system).

In conclusion, our study shows many similarities between the trace element composition of the schreibersite in IIG irons and that expected from formation as a liquidus phase, but there are also key differences, in particular between the Ni and P contents. The formation of schreibersite in IIG irons affects the trace element abundances in the solid metal of these irons, and it is possible that schreibersite formation and evolution can explain the already minimal differences between IIG irons and late-crystallizing IIAB irons, as suggested by Wasson and Choe (2009). Our attempts to quantitatively match the IIAB and IIG solid metal compositions using the results of this study were not successful, but our results do corroborate the striking qualitative similarities between late-stage IIAB irons and the IIG group and a possible genetic link between the two groups.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1. Section of Twannberg IIG iron meteorite (#36467) used in this study, displaying large phases of coarse schreibersite (i.e. “skeletal” schreibersite, Hofmann et al., 2009). Sample courtesy of Natural History Museum of Bern.

Fig. 2.

A) Backscattered electron image showing a typical run product (#R2P8) with coexisting schreibersite, $(\text{Fe,Ni})_3\text{P}$, and quenched P-rich melt phases. Due to the small compositional difference between these two phases, the coexisting schreibersite and quenched P-rich melt phases are best distinguished in BSE images by their distinctive textures. The bulk P-rich melt has a fine-grained dendritic quench texture, typical of quenched metallic liquids, and the schreibersite phase is compositionally homogeneous. B) Close-up images of the boundary between the schreibersite and quenched P-rich melt phases and C) the dendritic quench texture of the P-rich melt phase are shown.

Fig. 3.

Experimental partitioning data for Ru, Rh, Ir, and Pt versus run duration in days. Runs were held at constant temperature (1100°C) with identical starting compositions for durations ranging from roughly 1 to 6 days. These four elements were chosen to represent the varying partitioning magnitudes of all elements measured, as listed in Table 2, and they show consistent and repeatable partitioning values within error.

Fig. 4.

A) Partitioning data for 16 trace elements. Trace elements are ordered by increasing D in Twannberg. The red line with triangles corresponds to the partitioning values for Twannberg, and the shaded region is from the associated errors. B) Experimental partitioning data for 20 trace elements. Trace elements are ordered based off of (A), and run #LB19 was used to represent the Ni-free dataset as it provided measurements for the largest number of elements. The black line with upside-down triangles corresponds to the calculated weighted average of the five individual runs. C) Comparison of Twannberg and experimental results. Trace elements are ordered based off of (A). The red line with triangles corresponds to the partitioning values for Twannberg. The blue line with circles corresponds to the calculated

values for partitioning between schreibersite and solid metal, using the parametrizations provided in Chabot et al. (2017).

Fig. 5.

Compositions of IIAB (Wasson et al., 2007) and IIG (Wasson and Choe, 2009) irons plotted versus As for A) Co, B) Ni, C) Ga, D) W, E) Ir, and F) Au. The solid metal composition of the IIG iron Twannberg from Wasson and Choe (2009) is identified on each graph by the red square, along with the calculated bulk composition of Twannberg (blue triangle) and the calculated composition resulting for Case 2 considered in Section 4 of the text (green circle).

Table 1.Results from Twannberg analysis. All errors are $\pm 1\sigma$.

Element	Solid metal	Schreibersite
Fe (wt%)	93.6 ± 0.7	71.2 ± 0.9
P (wt%)	0.24 ± 0.07	15.3 ± 2.0
Ni (wt%)	3.5 ± 0.5	11.7 ± 0.3
Co (wt%)	0.46 ± 0.03	0.147 ± 0.007
Ga (ppm)	35 ± 4	2.2 ± 0.3
Ge (ppm)	47 ± 5	—
As (ppm)	20 ± 4	2.4 ± 0.3
Mo (ppm)	4.6 ± 0.5	31 ± 3
Ru (ppm)	0.4 ± 0.1	0.8 ± 0.1
Rh (ppm)	0.7 ± 0.1	0.7 ± 0.1
Pd (ppm)	1.6 ± 0.6	2.5 ± 0.1
Sb (ppm)	0.19 ± 0.04	0.04 ± 0.01
W (ppm)	0.06 ± 0.02	0.046 ± 0.008
Re (ppm)	0.009 ± 0.006	0.0011 ± 0.0004
Os (ppm)	0.12 ± 0.03	0.0020 ± 0.0006
Ir (ppm)	0.11 ± 0.02	0.0008 ± 0.0004
Pt (ppm)	0.24 ± 0.05	0.002 ± 0.001
Au (ppm)	1.16 ± 0.32	0.023 ± 0.015

Table 2.

Experimental partitioning results from the Fe-Ni-P system. All errors are $\pm 2\sigma$.

Run #	LB14	LB16	LB19	LB21	RIP1	RSP4	R2P8	R2P9
Temperature (°C)	1100	1075	1100	1100	1100	1075	1000	950
Duration (hours)	22	22	72	144	72	96	120	144
P-rich melt								
Fe (wt%)	89.6 $\pm$ 0.7	88.2 $\pm$ 2.2	88.2 $\pm$ 2.3	88.8 $\pm$ 2.0	74.6 $\pm$ 0.9	65.9 $\pm$ 1.1	51.4 $\pm$ 1.8	42.2 $\pm$ 1.0
P (wt%)	11.1 $\pm$ 1.5	11.3 $\pm$ 1.5	12.1 $\pm$ 2.1	12.2 $\pm$ 1.6	13.9 $\pm$ 2.2	13.5 $\pm$ 1.8	12.1 $\pm$ 1.8	12.0 $\pm$ 1.6
Ni (wt%)	—	—	—	—	10.9 $\pm$ 2.7	21.4 $\pm$ 1.6	33.6 $\pm$ 2.9	42.3 $\pm$ 1.7
V (ppm)	—	8.9 $\pm$ 1	—	—	11 $\pm$ 3	22 $\pm$ 3	7.2 $\pm$ 0.2	3.5 $\pm$ 0.4
Co (ppm)	134 $\pm$ 32	113 $\pm$ 21	122 $\pm$ 29	129 $\pm$ 16	294 $\pm$ 16	454 $\pm$ 18	645 $\pm$ 49	732 $\pm$ 45
Cu (ppm)	428 $\pm$ 178	275 $\pm$ 61	319 $\pm$ 35	231 $\pm$ 70	391 $\pm$ 66	620 $\pm$ 103	455 $\pm$ 77	216 $\pm$ 27
Zn (ppm)	—	—	—	—	53 $\pm$ 17	151 $\pm$ 47	120 $\pm$ 56	63 $\pm$ 6
Ga (ppm)	57 $\pm$ 10	25 $\pm$ 6	43 $\pm$ 3	35 $\pm$ 6	58 $\pm$ 13	68 $\pm$ 5	96 $\pm$ 22	58 $\pm$ 23
Ge (ppm)	180 $\pm$ 45	201 $\pm$ 43	168 $\pm$ 13	228 $\pm$ 45	127 $\pm$ 29	140 $\pm$ 16	180 $\pm$ 29	151 $\pm$ 67
As (ppm)	178 $\pm$ 110	215 $\pm$ 75	211 $\pm$ 51	220 $\pm$ 86	166 $\pm$ 37	294 $\pm$ 83	283 $\pm$ 96	225 $\pm$ 98
Mo (ppm)	117 $\pm$ 38	110 $\pm$ 18	122 $\pm$ 11	121 $\pm$ 21	155 $\pm$ 8	183 $\pm$ 8	260 $\pm$ 7	245 $\pm$ 32
Ru (ppm)	103 $\pm$ 20	94 $\pm$ 9	111 $\pm$ 12	94 $\pm$ 5	123 $\pm$ 13	157 $\pm$ 20	165 $\pm$ 9	147 $\pm$ 13
Rh (ppm)	95 $\pm$ 24	87 $\pm$ 2	84 $\pm$ 11	89 $\pm$ 10	91 $\pm$ 5	111 $\pm$ 0.2	145 $\pm$ 5	115 $\pm$ 11
Pd (ppm)	114 $\pm$ 84	109 $\pm$ 38	141 $\pm$ 13	163 $\pm$ 64	142 $\pm$ 37	188 $\pm$ 7	230 $\pm$ 68	160 $\pm$ 66
Ag (ppm)	—	15 $\pm$ 13	223 $\pm$ 205	—	311 $\pm$ 249	315 $\pm$ 123	553 $\pm$ 124	406 $\pm$ 189
W (ppm)	59 $\pm$ 10	69 $\pm$ 5	68 $\pm$ 15	63 $\pm$ 6	61 $\pm$ 1	76 $\pm$ 3	94 $\pm$ 7	83 $\pm$ 12
Re (ppm)	85 $\pm$ 23	90 $\pm$ 22	67 $\pm$ 12	84 $\pm$ 21	76 $\pm$ 12	110 $\pm$ 12	116 $\pm$ 16	85 $\pm$ 12
Os (ppm)	71 $\pm$ 17	94 $\pm$ 29	84 $\pm$ 30	86 $\pm$ 30	72 $\pm$ 15	87 $\pm$ 9	92 $\pm$ 7	70 $\pm$ 13
Ir (ppm)	130 $\pm$ 32	167 $\pm$ 50	116 $\pm$ 27	145 $\pm$ 49	119 $\pm$ 15	123 $\pm$ 3	153 $\pm$ 5	115 $\pm$ 23
Pt (ppm)	120 $\pm$ 26	167 $\pm$ 35	118 $\pm$ 33	144 $\pm$ 32	87 $\pm$ 18	91 $\pm$ 10	110 $\pm$ 13	87 $\pm$ 25
Au (ppm)	—	265 $\pm$ 166	224 $\pm$ 33	208 $\pm$ 111	210 $\pm$ 102	315 $\pm$ 76	377 $\pm$ 88	389 $\pm$ 219
Schreibersite								
Fe (wt%)	84.8 $\pm$ 2.7	84.6 $\pm$ 2.3	84.9 $\pm$ 1.3	84.9 $\pm$ 1.8	75.9 $\pm$ 2.1	69.0 $\pm$ 0.9	55.3 $\pm$ 1.8	44.1 $\pm$ 0.7
P (wt%)	15.2 $\pm$ 2.0	15.4 $\pm$ 2.0	16.5 $\pm$ 2.1	15.6 $\pm$ 2.0	15.8 $\pm$ 2.1	15.7 $\pm$ 2.0	15.6 $\pm$ 2.0	15.6 $\pm$ 2.0
Ni (wt%)	—	—	—	—	8.3 $\pm$ 2.1	15.4 $\pm$ 0.9	26.5 $\pm$ 1.1	36.9 $\pm$ 0.9

Run #	LB14	LB16	LB19	LB21	R1P1	RSP4	R2P8	R2P9
V (ppm)	—	13 ± 3	2.5 ± 1.7	—	18 ± 0.9	24 ± 2	7.9 ± 2	4.2 ± 0.8
Co (ppm)	—	83 ± 6	—	—	307 ± 30	346 ± 42	540 ± 47	818 ± 77
Cu (ppm)	—	91 ± 42	98 ± 44	62 ± 7	131 ± 8	120 ± 6	121 ± 11	63 ± 6
Zn (ppm)	—	—	—	—	—	—	—	7.9 ± 5
Ga (ppm)	7.2 ± 6.3	5.4 ± 5.2	4.2 ± 1.2	4.1 ± 0.1	4.7 ± 1	4.3 ± 1	4.8 ± 1	5.4 ± 2
Ge (ppm)	22 ± 21	—	14 ± 12	12 ± 8	13 ± 2	14 ± 1	17 ± 4	20 ± 3
As (ppm)	48 ± 45	—	32 ± 24	27 ± 1	25 ± 2	25 ± 0.8	34 ± 7	29 ± 3
Mo (ppm)	—	89 ± 17	93 ± 14	95 ± 12	137 ± 21	128 ± 4	221 ± 45	239 ± 22
Ru (ppm)	91 ± 15	76 ± 10	100 ± 13	101 ± 4	166 ± 26	136 ± 14	165 ± 30	134 ± 11
Rh (ppm)	56 ± 9	55 ± 11	49 ± 6	51 ± 6	82 ± 16	67 ± 6	110 ± 20	87 ± 15
Pd (ppm)	29 ± 5	36 ± 23	29 ± 12	31 ± 4	36 ± 3	34 ± 4	40 ± 10	39 ± 3
Ag (ppm)	—	—	5.6 ± 2.3	3.6 ± 0.6	4.5 ± 0.7	—	7.8 ± 3	10 ± 5
W (ppm)	46 ± 10	57 ± 8	65 ± 11	63 ± 4	69 ± 10	88 ± 7	101 ± 20	86 ± 9
Re (ppm)	56 ± 14	48 ± 13	55 ± 10	71 ± 2	95 ± 14	157 ± 5	111 ± 34	87 ± 20
Os (ppm)	33 ± 3	32 ± 14	46 ± 9	35 ± 6	59 ± 21	90 ± 11	103 ± 30	107 ± 16
Ir (ppm)	35 ± 4	37 ± 29	33 ± 10	35 ± 1	64 ± 12	66 ± 8	79 ± 19	63 ± 7
Pt (ppm)	14 ± 4	—	12 ± 4	12 ± 1	20 ± 5	25 ± 2	21 ± 5	19 ± 4
Au (ppm)	—	—	3.1 ± 1.9	2.1 ± 0.4	3.7 ± 0.9	4.0 ± 1	4.3 ± 1	3.3 ± 0.9
D(schreibersite)/(P-rich melt)								
P	1.37 ± 0.26	1.36 ± 0.25	1.32 ± 0.28	1.35 ± 0.25	1.13 ± 0.23	1.17 ± 0.22	1.29 ± 0.25	1.30 ± 0.24
Ni	—	—	—	—	0.77 ± 0.27	0.72 ± 0.07	0.79 ± 0.08	0.87 ± 0.04
V	—	1.47 ± 0.44	—	—	1.64 ± 0.46	1.09 ± 0.17	1.10 ± 0.22	1.20 ± 0.26
Co	—	0.73 ± 0.14	—	—	1.04 ± 0.12	0.76 ± 0.10	0.84 ± 0.10	1.12 ± 0.13
Cu	—	0.33 ± 0.17	0.31 ± 0.14	0.27 ± 0.09	0.34 ± 0.06	0.19 ± 0.03	0.27 ± 0.05	0.29 ± 0.05
Zn	—	—	—	—	—	—	—	0.13 ± 0.07
Ga	0.13 ± 0.11	—	0.10 ± 0.03	0.12 ± 0.02	0.08 ± 0.03	0.06 ± 0.02	0.05 ± 0.02	0.09 ± 0.05
Ge	—	—	0.09 ± 0.07	0.05 ± 0.03	0.10 ± 0.03	0.10 ± 0.01	0.09 ± 0.03	0.13 ± 0.06
As	—	—	0.15 ± 0.12	0.12 ± 0.05	0.15 ± 0.04	0.09 ± 0.02	0.12 ± 0.05	0.13 ± 0.06
Mo	—	0.81 ± 0.20	0.76 ± 0.13	0.79 ± 0.17	0.88 ± 0.14	0.70 ± 0.04	0.85 ± 0.18	0.98 ± 0.16
Ru	0.88 ± 0.23	0.81 ± 0.14	0.89 ± 0.15	1.07 ± 0.07	1.35 ± 0.25	0.87 ± 0.14	1.00 ± 0.19	0.91 ± 0.11
Rh	0.59 ± 0.18	0.63 ± 0.13	0.58 ± 0.11	0.57 ± 0.09	0.90 ± 0.19	0.60 ± 0.06	0.76 ± 0.14	0.76 ± 0.15

Run #	LB14	LB16	LB19	LB21	R1P1	RSP4	R2P8	R2P9
Pd	0.26 ± 0.19	0.33 ± 0.24	0.21 ± 0.08	0.19 ± 0.08	0.25 ± 0.07	0.18 ± 0.02	0.17 ± 0.07	0.24 ± 0.10
Ag	—	—	—	—	0.014 ± 0.012	—	0.014 ± 0.006	0.03 ± 0.02
W	0.78 ± 0.22	0.82 ± 0.13	0.96 ± 0.27	1.00 ± 0.11	1.13 ± 0.16	1.16 ± 0.11	1.07 ± 0.23	1.04 ± 0.19
Re	0.66 ± 0.24	0.53 ± 0.19	0.83 ± 0.21	0.84 ± 0.21	1.25 ± 0.27	1.43 ± 0.16	0.96 ± 0.32	1.02 ± 0.27
Os	0.46 ± 0.12	0.34 ± 0.18	0.55 ± 0.22	0.40 ± 0.16	0.82 ± 0.34	1.03 ± 0.16	1.12 ± 0.33	1.53 ± 0.37
Ir	0.27 ± 0.07	0.22 ± 0.19	0.29 ± 0.11	0.24 ± 0.08	0.54 ± 0.12	0.54 ± 0.06	0.52 ± 0.13	0.55 ± 0.12
Pt	0.11 ± 0.04	—	0.11 ± 0.04	0.08 ± 0.02	0.23 ± 0.07	0.27 ± 0.04	0.19 ± 0.05	0.22 ± 0.08
Au	—	—	0.014 ± 0.009	0.010 ± 0.006	0.02 ± 0.01	0.013 ± 0.006	0.010 ± 0.004	0.008 ± 0.005

Table 3.

Experimental partitioning results compared to Twannberg results.

Element	Weighted average [*]	Calculated ^{**}	Twannberg ^{***}
	D (schreibersite)/(P-rich melt)	D (schreibersite)/(solid metal)	D (schreibersite)/(solid metal)
P	1.25 ± 0.11	10.07 (1.12, 0.91)	64 ± 19
Ni	0.83 ± 0.03	0.94 (0.02, 0.02)	3.3 ± 0.4
V	1.15 ± 0.12	—	—
Co	0.91 ± 0.06	0.67 (0.20, 0.12)	0.32 ± 0.03
Cu	0.24 ± 0.02	0.16 (0.06, 0.04)	—
Zn	0.13 ± 0.07	—	—
Ga	0.07 ± 0.01	0.011 (0.006, 0.003)	0.06 ± 0.01
Ge	0.100 ± 0.009	0.019 (0.005, 0.004)	—
As	0.11 ± 0.02	0.09 (0.02, 0.01)	0.12 ± 0.03
Mo	0.74 ± 0.04	3.14 (0.94, 0.66)	6.71 ± 0.98
Ru	0.94 ± 0.07	0.50 (0.21, 0.13)	1.91 ± 0.55
Rh	0.65 ± 0.05	0.46 (0.14, 0.09)	0.96 ± 0.22
Pd	0.19 ± 0.02	0.23 (0.06, 0.04)	1.60 ± 0.60
Ag	0.015 ± 0.005	0.13 (0.10, 0.03)	—
W	1.11 ± 0.07	0.83 (0.34, 0.22)	0.74 ± 0.27
Re	1.16 ± 0.10	0.10 (0.05, 0.030)	0.12 ± 0.09
Os	0.94 ± 0.11	0.033 (0.027, 0.012)	0.017 ± 0.007
Ir	0.50 ± 0.04	0.20 (0.009, 0.005)	0.007 ± 0.004
Pt	0.20 ± 0.02	0.012 (0.006, 0.003)	0.009 ± 0.006
Au	0.011 ± 0.003	0.006 (0.001, 0.001)	0.02 ± 0.01

^{*} Weighted average calculated from experiments LB19, R1P1, R5P4, R2P8, and R2P9, with $\pm 2\sigma$ errors.

^{**} Calculated using the weighted average from the first column and the solid metal/P-rich melt parametrizations of Chabot et al. (2017). Listed with $\pm 2\sigma$ errors (-2σ error, $+2\sigma$ error) derived from uncertainties from both the weighted average in the first column and the uncertainties of the published Chabot et al. (2017) parameterizations.

^{***} Twannberg errors are $\pm 1\sigma$.