Origin of Highly Siderophile and Chalcogen Element Fractionations in the Components of Unequilibrated H and LL Chondrites

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Abstract

Osmium isotopic compositions, abundances of highly siderophile elements (HSE: platinum group elements, Re and Au), the chalcogen elements S, Se and Te and major and minor elements were analysed in physically separated size fractions and components of the ordinary chondrites WSG 95300 (H3.3, meteorite find) and Parnallee (LL3.6, meteorite fall). Fine grained magnetic fractions are 268-65 times enriched in HSE compared to the non-magnetic fractions. A significant deviation of some fractions of WSG 95300 from the 4.568 Ga ^{187}Re - ^{187}Os isochron was caused by redistribution of Re due to weathering of metal. HSE abundance patterns show that at least four different types of HSE carriers are present in WSG 95300 and Parnallee. The HSE carriers display i) CI chondritic HSE ratios, ii) variable Re/Os ratios, iii) lower than CI chondritic Pd/Ir and Au/Ir and iv) higher Pt/Ir and Pt/Ru than in CI chondrites. These differences between components clearly indicate the loss of refractory HSE carrier phases before accretion of the components. Tellurium abundances correlate with Pd and are decoupled from S, suggesting that most Te partitioned into metal during the last high-temperature event. Tellurium is depleted in all fractions compared to CI chondrite normalized Se abundances. The depletion of Te is likely associated with the high temperature history of the metal precursors of H and LL chondrites and occurred independent of the metal loss event that depleted LL chondrites in siderophile elements. Most non-magnetic and slightly magnetic fractions have S/Se close to CI chondrites. In contrast, the decoupling of Te and Se from S in magnetic fractions suggests the influence of volatility and metal-silicate partitioning on the abundances of the chalcogen elements.

The influence of terrestrial weathering on chalcogen element systematics of these meteorites appears to be negligible.

1. Introduction

Main Components of unequilibrated ordinary chondrites, such as chondrules of variable size and fine grained matrix were likely formed at different physicochemical conditions, in different environments of the solar nebula (Scott and Krot, 2003). The observed mineralogy of the silicates, sulfides and metal phases in unequilibrated ordinary chondrites mostly reflects secondary processing of nebular solids and remaining gas (e.g., chondrule formation processes) or processes on the meteorite parent bodies (Scott et al., 1981; Nagahara, 1984; Hutchison et al., 1987; Alexander et al., 1989; Krot et al., 1997; Lodders, 2003). One of the key questions in understanding the genesis of chondrites is concerned with the possibility of whether or not chondrules and matrix formed from common dust precursors, as has been argued recently for some groups of carbonaceous chondrites (Bland et al., 2005; Hezel and Palme, 2008, 2010). Common dust precursors imply that compositional differences between chondrules and matrix arise from secondary processing in the nebula or, less likely, on the meteorite parent bodies. Similar REE patterns of sulfides from chondrule and matrix in LL3.1 chondrite Bishunpur (Kong et al., 2000) and complementary compositions of metal and chondrules in ordinary chondrites (Kong and Ebihara, 1997) indicate that the chondrules and matrix from unequilibrated ordinary chondrites may originate from a common reservoir. . What fraction of metal and sulfides from ordinary chondrites share similar or complementary trace element fractionations is not clear.

Study of the distribution of the highly siderophile (HSE: Re, Os, Ir, Ru, Pt, Rh, Pd and Au) and chalcogen elements (Te, Se and S) between different magnetic and size fractions, chondrules and matrix is useful to understand the origin and evolution of the precursors of chondrite components (Rambaldi, 1976; Kong and Ebihara, 1997; Walker et al., 2002; Archer et al., 2014; Kadlag and

Becker, 2015, 2016a, 2016b). Fe-Ni metal alloys in chondritic meteorites were interpreted to have formed either by direct condensation from nebular gas (Lodders, 2003; Campbell et al., 2005), by desulfurization of Fe bearing sulfides (Hewins et al., 1997), or by reduction of Fe^{2+} in silicates (Connolly et al., 2001). The siderophile and chalcogen element abundances in metal, sulfides and silicate phases reflect the origin of the metal and partitioning processes controlled by geochemical affinity of the elements and the state of chemical equilibrium between different phases.

Previous work has shown the existence different HSE compositions in different components and different mineral fractions of ordinary, carbonaceous and enstatite chondrites (Chou et al., 1973; Rambaldi, 1977b; Rambaldi et al., 1978; Grossman and Wasson, 1985; Kong et al., 1995; Kong and Ebihara, 1997; Humayun and Campbell 2002; Campbell and Humayun, 2003; Horan et al., 2009; Archer et al., 2014; Kadlag and Becker, 2015, 2016a and 2016b) Besides carrier phases with CI like HSE compositions, other phases that display depletions and enrichments of the slightly volatile HSE (Pd and Au) are also present in the components of ordinary, carbonaceous and enstatite chondrites (Horan et al., 2009; Archer et al., 2014; Kadlag and Becker, 2015, 2016a and 2016b). Because the Pd depleted HSE abundance pattern occurred in all classes of chondrites studied so far, the question arises whether this component was inherited from fractional condensation in the solar nebula or originated in secondary high temperature processes such as evaporation during chondrule formation or loss of metal enriched in moderately volatile HSE?

Besides CI chondrite-normalized abundance patterns of HSE, Re-Os isotopic systematics has revealed clear differences in Re/Os between different groups of chondrites (e.g., Walker et al., 2002). In comparison to carbonaceous chondrites, ordinary and enstatite chondrites are characterized by systematically higher Re/Os ratios and small differences in Re/Os between different groups of ordinary chondrites were observed (Walker et al., 2002; Fischer-Gödde et al., 2010). In case of correlated $^{187}\text{Os}/^{188}\text{Os}$ and Re/Os, as in most chondrite bulk rocks and metal rich components, these differences were established either in the early solar nebula or during the early metamorphic and aqueous alteration processes on the meteorite parent body (Becker et al., 2001; Walker et al., 2002;

Brandon et al., 2005; Rankenburg et al., 2007; Horan et al., 2009; Fischer-Gödde et al., 2010; Archer et al., 2014). Bulk rocks that are shifted from the 4.56 Ga Re-Os reference isochron may have been affected by later open-system behaviour (e.g., terrestrial weathering in case of meteorite finds), however, the causes of these shifts were not always clear (Becker et al., 2001; Kadlag and Becker, 2016a).

Different chondrite classes also show systematic differences in chalcogen element (S, Se and Te) abundances (Case et al., 1973; Wai and Wasson, 1977; Dreibus et al., 1995; Lodders, 2003). Because of a significant depletion of Te, the ordinary and EH chondrites show lower Te/Se compared to CI chondrites (Kallemeyn and Wasson, 1986; Wai and Wasson, 1977; Kadlag and Becker, 2015 and 2016b). The processes responsible for the depletion of Te in ordinary and enstatite chondrites may reflect spatially changing volatility of these elements in the solar nebula or on the meteorite parent bodies (Wai and Wasson, 1977; Schaefer and Fegley, 2009; Kadlag and Becker 2015, 2016a and 2016b).

In the quest to understand the influence of nebular and parent body processes on the origin and evolution of chondrite components, we have analyzed the ^{187}Re - ^{187}Os systematics, HSE, chalcogen and major elements in the components and variable size fractions of enstatite, carbonaceous and ordinary chondrites (Kadlag and Becker, 2015, 2016a and b). In the present contribution we are reporting the results of a systematic mass balance study of the ^{187}Re - ^{187}Os systematics, HSE, chalcogen, major and minor element abundances (Mg, Ca, Cr, Mn, Fe, Ni and Co) in components and mechanically and magnetically separated fractions of the unequilibrated ordinary chondrites WSG 95300 (H3.3, find, weathering grade A/B, Benoit et al., 2002) and Parnallee (LL3.6, fall, Dodd et al., 1967; Case et al., 1973; Chou and Cohen, 1973; Laul et al., 1973; Binz et al., 1976; Evensen et al., 1978; Afiattalab and Wasson, 1980). The objective of the present study is to constrain the fractionation processes of HSE and chalcogen elements, which occur in the solar nebula and meteorite parent bodies of unequilibrated H and LL chondrites.

2. Sample characterization and sample preparation

WSG 95300, a low-metamorphic-grade (H3.3) H chondrite contains organic matter, presolar grains and pristine chondrule textures (Lofgren and Le, 2002; Alexander et al., 2009). The unequilibrated LL3.6 chondrite Parnallee was studied extensively for its mineralogy and petrology. It contains exceptionally large chondrules (up to ~4 cm), and shows a low degree of aqueous alteration (Binns, 1967; Bridges et al., 1997; Lewis and Jones, 2014). Rock pieces of Parnallee (BM.34792, weight ~ 1g) and WSG 95300 (Split#68, weight ~ 0.6 g) were broken into fragments to separate components. Chondrules of different size were separated from these fragments using plastic tweezers. A sulfide-rich clast of ~1 mm size was found in the sample split of Parnallee processed in the present study (Fig. A1). A part of this clast was used for HSE and chalcogen element analysis and the remaining fraction was embedded in epoxy resin and polished for further petrographic study. The sulfide-rich clast is mostly composed of fine-grained troilite and contains minor irregular domains of orthopyroxene intergrown with traces of plagioclase and chromite (Fig. A1). Minor olivine occurs in contact with troilite near the edge of the clast. The silicate-rich domains show granular textures. Silicate-rich domains display fractured contacts with troilite and troilite veins, suggestive of the intrusion of sulfide liquid. After separation of chondrules and the clast, the remaining material (matrix and small broken chondrule fragments) was separated into three different grain size fractions: less than 80 μm (<80), 80-200 μm (80-200) and a coarse fraction of greater than 200 μm (>200). All size fractions were further divided into magnetic (M), slightly magnetic (SM) and non-magnetic (NM) fractions using a hand magnet.

3. Analytical Techniques

All samples were digested in reverse aqua regia (2 HNO_3 : 1 HCl) in an Anton PaarTM High Pressure Asher System (HPA-S). A separation of the HSE and chalcogen elements from matrix elements was carried out by chemical separation procedures established in the Geochemistry

laboratories at Freie Universität Berlin (Fischer-Gödde et al., 2010; Wang et al., 2013; Kadlag and Becker, 2015). The isotope dilution method was used to obtain precise concentrations of Re, Os, Ir, Ru, Pt, Pd, Te, Se and S. Concentrations of the monoisotopic elements Rh and Au were determined by internal calibration using intensities of ^{101}Ru and ^{193}Ir , respectively. Concentrations of the major and minor elements Mg, Ca, Cr, Mn, Fe, Co and Ni were determined by an external calibration method. Different dilutions of the digested Smithsonian Institute Allende standard reference powder (USNM 3529, spilt 18, position 1) were used as an external matrix-matched calibration standard for major and minor elements, to correct for matrix effects (Kadlag and Becker, 2015).

Concentrations of all elements except Os were measured on the Element XR ICP-MS (Inductively Coupled Plasma Mass Spectrometer) at Freie Universität Berlin. Precise Os isotopic compositions and concentration of Os were determined on the Triton TIMS (Thermal Ionization Mass Spectrometer) at Freie Universität Berlin, using negative thermal ionization mass spectrometry. Detailed procedures of sample digestion, methods for chromatographic separation of elements and measurement protocols were described in Fischer-Gödde et.al. (2010), Wang et al. (2013) and Kadlag and Becker (2015) and references therein.

3.1 Analytical blanks

Total procedure blanks were determined with each set of digested samples. Average values of total procedure blanks for 12 digestions over the duration of the study were: Re = 1.9 ± 0.8 pg, Os = 1 ± 1 pg, Ir = 2 ± 1 pg, Ru = 2 ± 2 pg, Pt = 40 ± 30 pg, Rh = 9 ± 7 pg, Pd = 40 ± 20 pg, Au = 2 ± 2 pg, Te = 30 ± 10 pg, Se = 2.8 ± 0.5 ng and S = 7.6 ± 0.8 μg . Total procedure blanks contribute less than 5% for most of the components. Ruthenium, Rh and Pd required higher blank corrections in case of chondrules, non-magnetic fractions and the sulfide clast, but not more than 15%.

3.2 Repeatability of Standards

Repeatability of the corrected isotopic ratios of in-house HSE and chalcogen element standards during ICP-MS measurements at the Freie University Berlin was within 2% (2σ) over the period of analysis (except S which is $\sim 6\%$, 2σ). Repeatability of the interference- and mass fractionation-corrected $^{187}\text{Os}/^{188}\text{Os}$ ratio of the University of Maryland Os standard solution measured on the Triton N-TIMS at Freie Universität Berlin was 0.1138 ± 0.0001 ($n=8$, 2σ) for Faraday cup measurements and 0.1138 ± 0.0002 ($n=12$, 2σ) for electron multiplier measurements over the duration of a year. Higher uncertainties on the $^{187}\text{Os}/^{188}\text{Os}$ ratios for some samples stem from higher blank corrections (see Table 2).

4. Results

4.1 Major and minor element abundances

Major and minor element concentrations in the separated components of WSG 95300 and Parnallee and in the calculated bulk rocks are given in Table 1. Average bulk rock values of Parnallee and H3 (3.0-3.9) chondrites from the published literature are given for comparison. CI normalized element abundances of magnetic and slightly magnetic fractions of different grain size are shown in Fig. 1 and 2. The abundances and ratios of major elements show large variations among different fractions (Fig. 1, 2 and 3). Magnesium shows linear correlations with Mn and Ca in most components (Fig. 3a and b) and is enriched in slightly magnetic and non-magnetic fractions compared to other fractions indicating the predominance of olivine and pyroxene.

Magnesium abundances vary inversely with Fe (Fig. 3c). Chondrules, slightly magnetic and non-magnetic fractions show higher Mg/Fe than CI chondrites. Magnetic fractions and the sulfide clast display low Mg/Fe. Magnetic components of both meteorites show Ni/Fe higher than in CI chondrites, whereas other components show Ni/Fe lower than in CI chondrites (Fig. 3d). The Ni/Co ratio is nearly CI chondritic in most samples, except for the magnetic fractions of Parnallee, which

show substantial scatter and deviations in Ni/Co compared to CI chondrites (Fig. 3e). The Fe-S (Fig. 3f) variations indicate mixing between two end members, a high-Fe/S end member (magnetic fractions) and other components with low-Fe/S. This difference in Fe/S is likely due to the presence of Fe and S in different phases with different Fe/S (metal phase, silicates and troilite). Magnetic components show a higher metal/sulfide ratio compared to other components, which is reflected in higher Fe/S in the magnetic components (Fig. 3f).

4.2 ^{187}Re - ^{187}Os systematics

The concentrations of Re, Os, Re* (initial Re concentrations calculated from the measured Os isotopic compositions), $^{187}\text{Re}/^{188}\text{Os}$, $^{187}\text{Os}/^{188}\text{Os}$ and Δ_{Os} (the deviation of $^{187}\text{Os}/^{188}\text{Os}$ from solar system initial Os isotopic composition, a definition is given in the caption of Table 2) of analyzed components are listed in Table 2. The data are displayed in a ^{187}Re - ^{187}Os isochron diagram in Fig. 4. Components and size fractions of Parnallee show less deviation from the 4.568 Ga reference isochron (Smoliar et al., 1996, Archer et al., 2014) compared to components of WSG 95300. Components of WSG 95300 have systematically higher $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ compared to similar components of Parnallee. Note that, the bulk rock data on H3 and LL3 chondrites shows that some H3 chondrites have higher $^{187}\text{Os}/^{188}\text{Os}$ and $^{187}\text{Re}/^{188}\text{Os}$ than LL3 chondrites (Walker et al., 2002 and Fischer-Gödde et al., 2010). The differences in the bulk rock data between Parnallee and WSG 95300, mirror the behaviour of the component data in Fig. 4.

Magnetic fractions of both meteorites show the smallest deviations from the isochron compared to other components. However, magnetic fractions of Parnallee and WSG 95300 show substantial differences in their correlated $^{187}\text{Os}/^{188}\text{Os}$ and $^{187}\text{Re}/^{188}\text{Os}$ ratios. These differences between magnetic fractions of both meteorites are mainly responsible for the differences in $^{187}\text{Os}/^{188}\text{Os}$ and $^{187}\text{Re}/^{188}\text{Os}$ of the bulk rocks of Parnallee and WSG 95300 (Fig. 4, Table 2). Chondrule fractions of both meteorites lie on the isochron. Of note, the chondrule fraction of WSG 95300 shows ~ 8% higher

$^{187}\text{Os}/^{188}\text{Os}$ compared to the chondrule fraction of Parnallee. Slightly magnetic and non-magnetic fractions of Parnallee display only slight offsets from the 4.568 Ga isochron but show resolvable differences in $^{187}\text{Os}/^{188}\text{Os}$. Slightly magnetic and non-magnetic fractions of WSG 95300 and the sulfide clast of Parnallee show significant deviation from the 4.568 Ga isochron, which also affects the calculated bulk rock composition (Fig. 4). Therefore, the calculated bulk rock values of $^{187}\text{Os}/^{188}\text{Os}$ and $^{187}\text{Re}/^{188}\text{Os}$ of WSG 95300 display a greater deviation from the isochron compared to the bulk rock values of Parnallee.

4.3 HSE abundances

In Table 2, HSE abundances of analyzed components, bulk rock values calculated from the mass balance of all components, and average bulk rock data for H3 (3.2-3.9), LL3 (3.0-3.7), and CI chondrites from the literature are listed.

Magnetic fractions of both meteorites are enriched in the HSE compared to other fractions and CI chondrites (Fig. 5, Table 2). As in previous studies of ordinary chondrites (Rambaldi, 1977b; Rambaldi et al., 1978; Horan et al., 2009), HSE abundances of magnetic fractions (except Au in WSG 95300, which is enriched in the intermediate size fraction) show inverse relationships with the grain size (Fig. 1). In case of WSG 95300, magnetic fractions show unfractionated abundance patterns (Fig. 5a) of the HSE compared to CI chondrites (except in the smallest grain size fraction, in which Au is depleted compared to refractory HSE). Magnetic fractions of Parnallee show slightly fractionated abundance patterns, which are enriched in Ir and depleted in Re and Os compared to other HSE (Fig. 5b). Other fractions of both meteorites display lower HSE abundances and higher measured Re/Os ratios compared to CI chondrites and magnetic fractions (Fig. 4 and 5). Major and minor element variations (Fig. 3) suggest that HSE abundance patterns of slightly magnetic fractions represent a mixture of the HSE abundance patterns of non-magnetic and magnetic end members (Figs. 5, 6). CI normalized abundances of Pd and Au in non-magnetic fractions of both meteorites are depleted

compared to other HSE (Fig. 5). The chondrule fraction of WSG 95300 and the sulfide clast of Parnallee show depletions in Ru and Ir compared to other HSE, whereas the chondrule fraction of Parnallee shows nearly CI chondritic ratios and abundances of the HSE.

To summarize, four types of HSE abundance patterns have been observed: 1) HSE abundance patterns with nearly CI chondrite-like HSE ratios. 2) Abundance patterns with higher Re/Os ratios than in CI chondrites. 3) Depleted CI normalized Pd and Au abundances compared to other HSE, e.g. in non-magnetic fractions of both meteorites. 4) CI normalized Ir and Ru abundances are lower than abundances of other HSE, e.g. in the chondrule fraction of WSG 95300 and in the sulfide clast of Parnallee.

4.4 Chalcogen element abundances in the components

Chalcogen element abundances in the analysed fractions, in calculated bulk rocks and average bulk rocks from the literature are listed in Table 2. The chalcogen elements are depleted in nearly all fractions (except the sulfide clast) compared to CI normalized HSE abundances (Fig. 5 and 7). Most samples and the calculated bulk rock values show CI normalized abundances in the order $\text{Se} > \text{S} > \text{Te}$, which is inconsistent with the equilibrium condensation sequence in gas of solar composition (Lodders, 2003). With the exception of the magnetic fractions, all other fractions of both meteorites show a linear correlation between S and Se abundances and approximately CI chondritic S/Se (Fig. 7a). Selenium and S are decoupled in magnetic fractions and show lower S/Se ratio than CI chondrites. All fractions show systematically lower Te/Se ratio than CI chondrites, with magnetic fractions having higher Te/Se compared to other fractions (Fig. 7b). The systematics of Te/S is similar to Te/Se. Tellurium and S are decoupled in magnetic fractions and show a linear correlation in other fractions (Fig. 7c). Tellurium correlates with Pd in the fractions (Fig. 7e), although the data distribution indicates different mixing relations between non-magnetic and magnetic fractions in the meteorites.

5. Discussion

5.1 The influence of mineral assemblages on element distribution between separated fractions

All studied fractions are mixture of variable proportions of silicates, sulfides and metal, which is reflected in the major element composition (Table 1, Fig. 3). Non-magnetic fractions are dominated by silicates (< 2 wt. % troilite, Fig. 3f), magnetic fractions are dominated by metal and contain minor proportions of sulfides (< 9 wt. % troilite, Fig. 3f) and silicates. Slightly magnetic fractions are mixture of these two end members (Fig. 3). Non-magnetic, slightly magnetic and chondrule fractions show a similar Fe/S ratio whereas magnetic fractions have a higher Fe/S ratio because of a higher proportion of metal. The sulfur content is exclusively controlled by troilite. All fractions of both meteorites show similar relationships for major and minor elements (Fig. 3) indicating that the influence of terrestrial weathering on these elements in WSG 95300 must be negligible.

Linear mixing relationships between Ca, Mn and Mg indicate the presence of variable proportions of pyroxenes, olivine and perhaps glass in all samples (Fig. 3a and b). The variable geochemical behaviour of Fe is reflected in the variation of Mg/Fe in the samples, $Mg/Fe_{\text{silicate rich}} > Mg/Fe_{\text{sulfide rich}} > Mg/Fe_{\text{metal rich}}$. The major element systematics indicates that the chondrule fraction of WSG 95300 contains a higher silicate-/metal ratio compared to the chondrule fraction of Parnallee (Fig. 3). Differences in the Ca/Mg and Mn/Mg of the non-magnetic fractions of the meteorites indicate that non-magnetic fractions of WSG 95300 contain a higher ratio of clinopyroxene/Mg silicates (e.g. Mg rich olivine) compared to the non-magnetic fraction of Parnallee (Fig. 3a and b). Calculated bulk rock values of major and minor elements in Parnallee and WSG 95300 are 20-30% lower compared to average bulk rock compositions of Parnallee and H3 (3.2-3.9) chondrites from the literature (Wiik 1966; Jarosewich, 1966, 1984, 1990; Kharitonova, 1969; Gopalan et al., 1976; Haramura et al., 1983; Fulton and Rhodes, 1984; MacPherson et al., 1993; Yanai et al., 1995). These

differences may either result from mineralogical heterogeneities in different bulk rocks or from incomplete dissolution of silicate phases in our study. The latter case is unlikely as we did not observe any undissolved residue in the sample solutions. Previous work on enstatite chondrites that applied the same techniques did not observe systematic shifts in major elements compared to literature data (Kadlag and Becker, 2015). In any case, because the main host phases of the HSE and chalcogen elements are metal and sulfides which dissolve completely in aqua regia, abundances of these elements should not be affected by incomplete digestion.

In ordinary chondrites, Fe-Ni metal alloys are the main host phases of Ni and Co (Larimer and Anders, 1970). Some magnetic fractions show large deviations of their Ni/Co from the CI chondritic value (Fig. 3e). Different metal-silicate partition coefficients (nickel is more siderophile compared to Co) of Ni and Co (Schmitt et al., 1989) may explain the variable Ni/Co in the magnetic fractions, however, most other fractions show nearly CI chondritic Ni/Co (Fig. 3e). Large deviations in Ni/Co and Ni/Fe occur in magnetic fractions of Parnallee (Fig. 3e and 8). The differences in the abundances and ratios of Co, Ni and Fe in magnetic fractions may also have been caused by the presence of different proportions of kamacite and taenite in the magnetic fractions. Higher Ni/Co and Ni/Fe in fine grained magnetic fractions of Parnallee indicate a higher taenite/kamacite ratio compared to coarse grained fractions (Fig. 1, 3e and 8). Magnetic fractions of WSG 95300 are closer to CI chondrites in their Ni/Co ratio (Fig. 3e and 8). The different Ni/Co between magnetic fractions of both meteorites may be a reflection of the slightly different metamorphic grades.

5.2 ^{187}Re - ^{187}Os systematics

All fractions of WSG 95300 have higher $^{187}\text{Os}/^{188}\text{Os}$ compared to similar fractions from Parnallee (Fig. 4), which likely represents the cause for the slightly higher $^{187}\text{Os}/^{188}\text{Os}$ of the bulk rocks of H3 chondrites compared to some LL3 chondrites (Walker et al., 2002 and Fischer-Gödde et al., 2010). The systematic differences between the bulk rocks suggest that the differences between the

different fractions and components were caused by processes that occurred before their accretion into the parent bodies and not by parent body alteration processes. The lower $^{187}\text{Os}/^{188}\text{Os}$ in the magnetic fractions of Parnallee compared to the magnetic fractions of the WSG 95300 may reflect the loss of Re enriched phases from the precursors of the magnetic fractions of Parnallee due to fractional condensation or slight differences in the metal-silicate partitioning of these elements in the solar nebula.

Some fractions of both chondrites show deviations from the 4.568 Ga isochron (Fig. 4, Table 2), indicating that the ^{187}Re - ^{187}Os systematics was disturbed more recently. The calculated bulk rock values also deviate from the isochron. The disturbance of the ^{187}Re - ^{187}Os systematics was likely caused by mobilization of Re and/or Os. Slightly magnetic and non-magnetic fractions of WSG 95300 show larger deviations from the isochron compared to similar samples of Parnallee (Fig. 4). Because WSG 95300 represents a meteorite find, the different behaviour compared to Parnallee, a meteorite fall, must be attributed to terrestrial weathering, which was also suggested in previous Re-Os studies of chondrites (Becker et al., 2001; Walker et al., 2002; Brandon et al., 2005; Rankenburg et al., 2007; Horan et al., 2009; Fischer-Gödde et al., 2010; Archer et al., 2014; Kadlag and Becker, 2015 and 2016a). Some slightly magnetic and non-magnetic fractions and the sulfide clast in Parnallee also show a resolvable deviation from the isochron, suggesting that the process of disturbance of the ^{187}Re - ^{187}Os system occurred on the parent body of LL3 chondrites. Processes such as aqueous alteration on the chondrite parent body (Palme et al., 1998; Becker et al., 2001; Walker et al., 2002; Lewis and Jones, 2014) might be responsible for the redistribution of Re and/or Os in different fractions.

To conclude, the major processes which are responsible for the variation in $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ in the samples are the early loss of Re-Os alloys from the precursors of HSE carriers of LL3 chondrites, for instance due to fractional condensation, followed by later small-scale redistribution of Re on the parent body. Fractions of WSG 95300, which have low Re and Os abundances were strongly affected by terrestrial weathering, which have induced Re mobilization.

5.3 HSE fractionation processes

All fractions of both meteorites display significant differences in the abundances of the HSE (Fig. 5). In the following sections processes for HSE fractionations in different fractions will be discussed.

5.3.1 HSE fractionation processes in magnetic fractions

The differences in the HSE abundances in the magnetic fractions of both chondrites were likely inherited from local nebular heterogeneities in the formation region of the different classes of the ordinary chondrites. Unfractionated abundance patterns of the magnetic fractions of WSG 95300 (Fig. 5) indicate that the HSE in these fractions were fully condensed from a gas of solar composition into Fe-Ni metal (Rambaldi et al., 1979; Lodders, 2003; Campbell et al., 2003).

Fine grained magnetic fractions of Parnallee are depleted in Re and Os compared to Ir and other HSE, indicating that Re-Os enriched refractory alloys may have been lost from metal precursor phases in Parnallee. The process may have been fractional condensation before most of the Fe and Ni condensed. Processes such as metal-silicate and solid metal-liquid metal partitioning may also change Re/Os, however, it would be more difficult to change Os/Ir by such processes, because of similar partitioning of Os and Ir in these processes (O'Neill et al., 1995; Chabot and Jones, 2003; Chabot et al., 2006). Another process that should be evaluated is the different partitioning of HSE during the exsolution of kamacite and taenite. Fine grained (< 80 and 80-150 μm) size fractions of magnetic components from Parnallee show higher Ni/Co compared to CI chondrites (Figs. 3e and 5), indicating that these fractions have a higher taenite/kamacite ratio. Coarse grained magnetic fractions have a lower taenite/kamacite ratio as their Ni/Co is lower (Fig. 3e). However, the HSE abundance patterns of coarse and fine metal fractions are not complementary to each other (which is required if these variations are only due to exsolution). Fine grained magnetic fractions show higher CI normalized Ir abundances compared to other HSE (Fig. 5 and 6), whereas coarse grained magnetic fractions are

almost unfractionated compared to CI chondrites. Previous studies of meteorite metal suggest that during Fe-Ni metal exsolution, Pt, Ir and Os were not fractionated from each other, even in highly equilibrated chondrites (Rasmussen et al., 1988; Hsu et al., 1998; Campbell and Humayun, 2003; Ash et al., 2007). Therefore, the magnetic fractions rich in Ir and depleted in Re, Os and Pt were more likely produced during earlier high-temperature processing (e. g., during fractional condensation).

Gold shows broad correlations with other HSE, however, Au/Ir in fractions of both meteorites scatters around the CI chondrite value (Fig. 6h). This scatter may reflect the redistribution of Au during aqueous alteration. In case of WSG 95300, these variations may also have been caused by the terrestrial weathering of metal. As Parnallee is a meteorite fall, mobilization of Au likely occurred by hydrothermal processes on the meteorite parent body (Binns, 1967; Bridges et al., 1997; Lewis and Jones, 2014).

5.3.2 HSE fractionation processes in non-magnetic fractions

Non-magnetic fractions of both meteorites are depleted in Pd and Au compared to other HSE (Fig. 5). Depletions of Pd were also observed in previous work on H chondrite fractions (Rambaldi et al., 1978 and Horan et al., 2009). Several processes may account for the Pd depletion. In case of Parnallee, Ni and Co in non-magnetic fractions show similar depletions compared to refractory HSE (Fig. 5). The Pd depletion compared to refractory HSE may be because of incomplete condensation of Pd into Fe-Ni metal, or evaporation of Pd, Ni, Co and Fe from the HSE carriers of non-magnetic fractions of WSG 95300 and Parnallee, as discussed by Horan et al. (2009). Although, it is still difficult to distinguish between Pd depletion due to either incomplete condensation or evaporation processes, it is worth pointing out that Pd-Au depleted HSE carrier phases have been identified in the non-magnetic fractions of carbonaceous chondrites, EH chondrites and all ordinary chondrites groups (Archer et al., 2014; Horan et al., 2009; Kadlag and Becker, 2015a, b, and c).

5.3.3 HSE fractionation processes in the chondrules and in the sulfide clast

The chondrule fraction of Parnallee has a higher metal content compared to the chondrule fraction of WSG 95300 (Fig. 3d and e), which is also reflected in the differences in the HSE abundances in these fractions. Unfractionated and nearly CI chondritic abundances of the HSE in the chondrule fraction of Parnallee indicates that no fractionation of the HSE occurred during the heating, and melting and/or evaporation of metal in chondrules. The chondrule fraction of WSG 95300 and the sulfide clast in Parnallee show very similar HSE abundance patterns (Fig. 5). The HSE abundance pattern of the chondrule fraction of WSG 95300 is highly fractionated and complex (Fig. 5a). It shows higher Re/Os compared to other fractions and depleted Ir and Ru. These strongly fractionated refractory HSE patterns most likely represent nebular processing before accretion. The similarity of the HSE pattern of the chondrule fraction of WSG 95300 and the sulfide clast in Parnallee (Fig. 5b) is striking, given the different meteorites and chondrite groups. If the similar HSE composition of the sulfide clast and chondrule fraction of WSG 95300, indicates the origin of sulfide clast from similar parent body (similar to H chondrite), then likely that the sulfide clast formed after melting and fragmentation of the H chondrite type parent body and trapped into the Parnallee.

5.4 Chalcogen element systematics

Abundances of chalcogen elements in all fractions (except the sulfide clast) are depleted compared to HSE abundances and chalcogen element abundances in CI chondrites, (Fig. 5 and 7). This observation is consistent with partial condensation of more refractory elements and phase separation before accretion of the carrier phases into the parent body or evaporation of the volatile elements. Because of the similar volatility of S, Se and Te, the stronger depletion of Te compared to Se and S in most fractions is of particular interest, as it is also typical for bulk rocks of ordinary chondrites and also occurs in components and bulk rocks of enstatite chondrites (Binz et al., 1974; Wai and Wasson, 1977; Hertogen et al., 1983; Kallemeyn and Wasson, 1986; Kaczaral et al., 1988; Kong et al., 1997; Kadlag and Becker 2015, 2016a and 2016b).

5.4.1 Te loss during nebular or parent body processes?

All fractions show lower Te/Se compared to CI chondrites (Fig. 7b). Tellurium is depleted in the components and separated fractions of all H, L and LL chondrites (this study and Kadlag and Becker, 2016a). Here, we will evaluate the role of different processes which may be responsible for the depletion of Te.

We rule out terrestrial weathering as an important process for the depletion of Te on the basis of the preserved correlations between Te, Pd and Se (Fig. 7b and e) and the insolubility of TeO_2 in water (Greenwood and Earnshaw, 1984). Results from all fractions in this study show that although Te is depleted, it shows a linear correlation with Pd (Fig. 7e) and thus clearly behaves as a siderophile element, which is also suggested by the decoupling of Te from S in most fractions (Fig. 7c). The Te depletion could be explained by fractional condensation of metal and loss of Te into the gas phase from the ordinary chondrite formation region. However, this scenario appears inadequate to explain the lower Te/Se than CI chondrite in magnetic fractions, because gas-solid separation should also remove volatile Se and S (Fig. 7a). LL chondrites also show significant depletion in other siderophile elements compared to H chondrites (Table 1 and 2 and literature in the captions of Table 1 and 2), but LL and H chondrites display similar Te abundances. This observation indicates that the Te depletion in ordinary chondrites is independent of the process which resulted in the depletion of other siderophile elements (Fe, Ni, Co, Re, PGE and Au) in LL chondrites. Fractionation of Te from Se and S by volatility-controlled processes may be viable if the volatility of the elements changes because of changes in the physicochemical environment such as the total pressure or gas composition (Wai and Wasson, 1977). The results obtained in this study show that CI normalized Te abundances are lower in calculated bulk rocks compared to S and Se (Fig. 5 and 7), consistent with the calculated volatility sequence $\text{Te} > \text{S} > \text{Se}$ at low pressure conditions ($p = 10^{-6}$ bar) as suggested by Wai and Wasson (1977). However, relative differences in the CI normalized abundances of these elements are inconsistent with the slight differences in their condensation temperatures, e.g. abundances of Se and S in calculated bulk rocks are 35-38 % and 30-33 % of the Se and S abundances in CI chondrites,

respectively (Table 2). In contrast, Te abundances in the calculated bulk rocks are only 13-15 % of the abundances in CI chondrites (Table 2). Half-mass condensation temperatures of Se, S and Te at $p=10^{-6}$ bar are 684 K, 648 K and 600 K, respectively (Wai and Wasson, 1977). Therefore, the differences in the condensation temperature between Se and S, and Te and S are 36 K and 48 K, which are very similar to the condensation temperatures of these elements at the pressure $> 10^{-6}$. Therefore, changes in the volatility at lower pressure may not be the only reason for the Te depletion, as we also note changes in the geochemical properties of Te in different groups of chondrites. In the separated fractions of ordinary and enstatite chondrites Te behaves as a more siderophile element, whereas in similar fractions of carbonaceous chondrites it is a predominantly chalcophile element (Kadlag and Becker, 2015, 2016a and b). The combination of both changing geochemical behavior and volatility in response to changing physicochemical conditions may have played a role in the Te depletion processes.

Several previous studies suggested that larger quantities of Te compared to Se may have been lost during thermal metamorphism in meteorite parent bodies (Ikramuddin et al., 1977; Takahashi et al., 1978; Schaefer and Fegley, 2009). This process requires the loss of a gas phase and sufficient porosity and permeability for the gas to escape to space from meteorite parent bodies. However, it is rather unlikely that the linear correlation between Pd and Te in the analysed fractions would have been preserved after Te loss during metamorphism (Fig. 7e), and thus, we discard this possibility.

Considering all observations, the likely processes that may account for the depletion of Te is the strongly siderophile nature of Te in all fractions of these two meteorites and a change in the volatility of Te compared to Se and S during condensation of dust precursors or during the thermal processing in the context of chondrule formation.

5.4.2 S and Se variation in the components

Sulfur and Se both are considered to behave as truly chalcophile elements and condensed into FeS or as FeSe in the solar nebula (Lodders, 2003). In the present study, S and Se are correlating with each other in all, except the magnetic fractions (Fig. 7a). All magnetic fractions have lower S/Se ratios than CI chondrites and Se is decoupled from S in these fractions (Fig. 7a). The S-Ir diagram shows similarities with the S-Se diagram (Fig. 7d). Non-magnetic and slightly magnetic fractions show nearly CI chondritic S/Se and S/Ir and a linear correlation between these elements whereas in magnetic fractions they are decoupled from each other (Fig. 7d). The Se-Ir diagram (Fig. 6d) shows that the rocks represent a mixture of two types of components, nearly CI chondritic Se/Ir ratio in non-magnetic and slightly magnetic fractions and lower Se/Ir than CI chondrites in magnetic fractions. The decoupling of Se from S in magnetic fractions and the correlation of Se with Te and Ir in magnetic fractions indicate that Se behaves as a siderophile element in the phases in magnetic fractions (Figs. 7a, b and 6d). In case of the magnetic fractions of Parnallee (Fig. 8a), this conclusion is supported by the correlation of Ni/Co with Se/S, whereas the variation of Se/S in the magnetic fractions of WSG 95300 is independent of Ni/Co, and thus losses of S due to evaporation or weathering may have had a stronger influence on Se/S in this sample. Experimentally determined partition coefficients of S, Se and Te show that, the metal-silicate partition coefficients of Se and Te increase with increasing S concentration in metallic liquid (Rose-Weston et al., 2009), thus Te and Se should be more enriched in magnetic fractions due to higher S abundances compared to other fractions.

Calculated bulk rock S/Se values of both chondrites are lower than values of CI chondrites (Fig. 7a, Table 2). This may be explained if more S was lost compared to Se during high temperature melting processes in the solar nebula, for instance during chondrule formation. However, the chondrule fraction of WSG 95300 does not show a depletion of S compared to Se (Fig. 5 and 7a). Another possibility is the loss of S during metamorphism. Parnallee has a slightly higher metamorphic grade (petrologic type 3.6) and has lower calculated S/Se in its bulk rock compared to WSG 95300 (petrologic type 3.3). However, sulfides in non-magnetic and slightly magnetic fractions should be affected equally by S loss during metamorphism, yet they are apparently not as their S/Se are close to

the CI chondrite value. We thus favor that evaporation of S occurred preceding the accretion process, presumably during chondrule formation. The non-magnetic and slightly magnetic fractions may derive from dust that has escaped evaporation or may have shielded sulfide components from evaporative losses. Preserved correlations between S and Se in most fractions and similar S-Se systematics in the fractions of both meteorites (Fig.7a) indicates that the effect of terrestrial weathering on the S-Se systematics of WSG 95300 should be minor.

6. Conclusions

Differences in the HSE abundance patterns of different fractions of WSG 95300 and Parnallee indicate that dust precursors had different high-temperature condensation histories before their accretion. The chalcogen element systematics show similar behaviour of these elements in these meteorites. Tellurium is depleted compared to all elements, is decoupled from S and shows a linear correlation with Pd. Sulfur is decoupled from Se and Te in the magnetic fractions in which the different siderophile tendencies of these elements are obvious. Early stage loss of refractory HSE alloys from Parnallee is reflected in depleted Re and Os abundances in the magnetic fractions compared to other refractory HSE. The occurrence of HSE carrier phases which are depleted in Pd and Au compared to other HSE reflect the loss of Pd-Au enriched Fe-Ni metal alloys during high temperature processing, most likely in the nebula. Size-dependent HSE abundances in magnetic fractions of Parnallee indicate that the HSE are more concentrated in taenite compared to kamacite. However, the stronger enrichment of Ir compared to other HSE in the fine grained magnetic fractions is inconsistent with previous observations on the exsolution of ordinary chondrite metal, and thus requires other fractionation processes.

Rhenium is the most mobile element of all elements analyzed in this study and the only element which is strongly affected by terrestrial weathering, most likely during the rusting of metal. Components of meteorite falls also show resolvable disturbance of the Re-Os system, which must

have occurred by late processes on the parent body. Under such circumstances, ratios such as $^{187}\text{Re}/^{188}\text{Os}$ or Re/HSE may not be reliable to constrain early solar system processes.

The depletion of Te likely resulted from the highly siderophile nature of Te coupled with a change in the volatility compared to solar conditions. Parent body metamorphism or terrestrial weathering can be ruled out as causes for the Te depletion because under such circumstances correlations between Te and the HSE in chondrite fractions would not be preserved. The effect of terrestrial weathering on the chalcogen element systematics appears to be negligible, even in the meteorite find. The decoupling of S and Se in the magnetic fractions of the meteorites is likely reflects evaporative loss and incomplete condensation of S during chondrule formation.

HSE and chalcogen abundances and ratios in different fractions of unequilibrated chondrites from different classes show resolvable differences (this work, Kadlag and Becker 2015, 2016a and b) indicating that the nebular material that accreted to chondrite parent bodies was composed of components that formed in different compartments of the solar nebula. The precursors of planetary bodies may also have been influenced by these local differences in elemental abundances, thus the refractory and volatile element composition of the building materials of the terrestrial planets may not necessarily reflect the average inner solar system composition.

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References

- Afiattalab F. and Wasson J.T. 1980. Composition of the metal phases in ordinary chondrites: implications regarding classification and metamorphism. *Geochim. Cosmochim. Acta* 44, 431–446.
- Alexander C.M.O'D., Barber D.J. and Hutchison R. 1989. The microstructure of Semarkona and Bishunpur. *Geochim. Cosmochim. Acta* 53, 3045–3057.
- Alexander C.M.O'D., Newsome S.N., Fogel M.L. and Cody G.D. 2009. Deuterium enrichments-parent body products or a question of preservation? (abstract #2546) 40th Lunar Planet. Sci.
- Archer G.J., Ash R.D., Bullock E.S. and Walker R.J. 2014. Highly siderophile elements and ¹⁸⁷Re-¹⁸⁷Os isotopic systematics of the Allende meteorite: Evidence for primary nebular processes and late stage alteration. *Geochim. Cosmochim. Acta* 131, 402–414.
- Ash R.D., Luong R.J., McDonough W.F. and McCoy T.J. 2007. Trace element fractionation in kamacite and taenite in IVA irons. (abstract #2383) XXXVIIIth Lunar Planet. Sci.
- Becker H., Morgan J.W., Walker R.J., MacPherson G.J. and Grossman J.N. 2001. Rhenium–osmium systematics of calcium–aluminium-rich inclusions in carbonaceous chondrites. *Geochim. Cosmochim. Acta* 65, 3379–3390.
- Benoit P.H., Akridge G.A., Ninagawa K. and Sears D.W.G. 2002. Thermoluminescence sensitivity and thermal history of type 3 ordinary chondrites: Eleven new type 3.0-3.1 chondrites and possible explanations for differences among H, L, and LL chondrites. *Meteorit. Planet. Sci.* 37, 793–805.
- Binns R.A. 1967. An exceptionally large chondrule in the Parnallee meteorite. *Miner. Mag.* 36(279), 319–324.
- Binz C.M., Kurimoto R.K. and Lipschutz M.E. 1974. Trace elements in primitive meteorites-V. Abundance patterns of thirteen trace elements and interelement relationships in enstatite chondrites. *Geochim. Cosmochim. Acta* 38, 1579–1606.

599 Binz C.M., Ikramuddin M., Rey P., Lipschutz M.E. 1976. Trace elements in primitive meteorites- VI.
 600 Abundance patterns of thirteen trace elements and interelement relationships in unequilibrated
 601 ordinary chondrites. *Geochim. Cosmochim. Acta* 40, 59–71.
 602 Bischoff A., Geiger T., Palme H., Spettel B., Schultz L., Scherer P., Schlüter J. and Lkhamsuren J.
 603 1993. Mineralogy, chemistry, and noble gas contents of Adzhi-Bogdo - an LL3-6 chondritic breccia
 604 with L-chondritic and granitoidal clasts. *Meteoritics* 28, 570–578.
 605 Biswas S., Walsh T.M., Ngo H.T. and Lipschutz M.E. 1981. Trace element contents of selected
 606 Antarctic meteorites--II: Comparison with non-Antarctic specimens. *Mem. Nat. Inst. Polar Res.*
 607 (Tokyo), 20, 221–228.
 608 Bland P.A., Alard O., Benedix G.K., Kearsley A.T., Menzies O.N., Watt L.E. and Rogers N.W. 2005.
 609 Volatile fractionation in the early solar system and chondrule/matrix complementarity. *Proceedings of*
 610 *the National Academy of Sciences of the United States of America* 102, 13755–13760.
 611 Brandon A.D., Humayun M., Puchtel I.S. and Zolensky M.E. 2005. Re–Os isotopic systematics and
 612 platinum group element composition of the Tagish Lake carbonaceous chondrite. *Geochim.*
 613 *Cosmochim. Acta* 69, 1619–1631.
 614 Brearley A.J., Scott E.R.D., Keil K., Clayton R.N., Mayeda T.K., Boynton W.V. and Hill D.H. 1989.
 615 Chemical, isotopic and mineralogical evidence for the origin of matrix in ordinary chondrites.
 616 *Geochim. Cosmochim. Acta* 53, 2081–2093.
 617 Bridges J.C., Alexander C.M.O'D, Hutchison R., Franchi I.A. and Pillinger C.T. 1997. Sodium-,
 618 chlorine-rich mesostases in Chainpur (LL3) and Parnallee (LL3) chondrules. *Meteorit. Planet. Sci.* 32,
 619 555–565.
 620 Campbell A.J. and Humayun M. 2003. Formation of Metal in Grosvenor Mountains 95551 and
 621 comparison to ordinary chondrites. *Geochim. Cosmochim. Acta* 67, 2481–2495.
 622 Campbell A.J., Simon S.B., Humayun M. and Grossman L. 2003. Chemical evolution of metal in
 623 refractory inclusions in CV3 chondrites. *Geochim. Cosmochim. Acta* 67, 3119–3134.
 624 Campbell A.J., Zanda B., Perron C., Meibom A. and Petaev M.I. 2005. Origin and Thermal History of
 625 Fe-Ni Metal in Primitive Chondrites. *Chondrites and protoplanetary Disk*, Edited by A.N. Krot, E.R.
 626 D. Scott and B. Reipurth. ASP conf. series Vol. 341, 407–431.

627 Case D.R., Laul J.C., Pelly I.Z., Wechter M.A., Schmidt-Bleek F. and Lipschutz M.E. 1973.
628 Abundance patterns of thirteen trace elements in primitive carbonaceous and unequilibrated ordinary
629 chondrites. *Geochim. Cosmochim. Acta* 37, 19–33.

630 Chabot N.L. and Jones J.H. 2003. The parameterization of solid metal–liquid metal partitioning of
631 siderophile elements. *Meteorit. Planet. Sci.* 38, 1425–1436.

632 Chabot N.L., Campbell A.J., Jones J.H., Humayun M. and Lauer J.H.V. 2006. The influence of
633 carbon on trace element partitioning behavior. *Geochim. Cosmochim. Acta* 70, 1322–1335.

634 Chen J.H., Papanastassiou D.A. and Wasserburg G.J. 1998. Re–Os systematics in chondrites and the
635 fractionation of the platinum group elements in the early solar system. *Geochim. Cosmochim. Acta*
636 62, 3379–3392.

637 Chou C.-L. and Cohen A.J. 1973. Gallium and germanium in the metal and silicates of L- and LL-
638 chondrites. *Geochim. Cosmochim. Acta* 37, 315–327.

639 Chou C.-L., Baedecker P.A. and Wasson J.T. 1973. Distribution of Ni, Ga, Ge and Ir between metal
640 and silicate portions of H group chondrites. *Geochim. Cosmochim. Acta* 37, 2159–2171.

641 Connolly H.C. Jr., Huss G.R. and Wasserburg G.J. 2001. On the formation of Fe-Ni metal in
642 Renazzo-like carbonaceous chondrites. *Geochim. Cosmochim. Acta* 65, 4567–4588.

643 Delisle G., Schultz L., Spetter B., Weber H.W., Wlotzka F., Höfle H.-C., Thierbach R., Vogt S.,
644 Herpers U., Bonani G., Suter M. and Woelfli W. 1989. Meteorite Finds in the Frontier Mountain
645 Range in Northern Victoria Land, Antarctica. *Geol. Jahrb.* E38, 253–283.

646 Dennison J.E. and Lipschutz M.E. 1987. Chemical studies of H chondrites. II: Weathering effects in
647 the Victoria Land, Antarctic population and comparison of two Antarctic populations with non-
648 Antarctic falls. *Geochim. Cosmochim. Acta* 51, 741–754.

649 Dodd Jr. R.T., Van Schmus W.R. and Koffman D.M. 1967. A survey of the unequilibrated ordinary
650 chondrites. *Geochim. Cosmochim. Acta* 31, 921–951.

651 Dreibus G., Palme H., Spettel B., Zipfel J. And Wänke H. 1995. Sulfur and selenium in chondritic
652 meteorites. *Meteoritics* 30, 439–445.

653 Ebihara M. 1989. Rare earth and some other elements in acid-residues of unequilibrated ordinary
654 chondrites. *Proc. NIPR Symp. Antarct Meteorites* 2, 279–287.

655 Ebihara M. and Ozaki H. 1995. Re, Os, and Ir in Antarctic unequilibrated ordinary chondrites and
 656 implications for the solar abundance of Re. *Geophys. Res. Lett.* 22, 2167–2170.

657 Evensen N.M., Hamilton P.J. and O'Nions R.K. 1978. Rare-earth abundances in chondritic meteorites.
 658 *Geochim. Cosmochim. Acta* 42, 1199–1212.

659 Fischer-Gödde M., Becker H. and Wombacher F. 2010. Rhodium, gold and other highly siderophile
 660 element abundances in chondritic meteorites. *Geochim. Cosmochim. Acta* 74, 356–379.

661 Fulton C.R. and Rhodes J.M. 1984. The chemistry and origin of the ordinary chondrites: Implications
 662 from refractory-lithophile and siderophile elements. *J. Geophys. Res.* 89, B543–558.

663 Gopalan K., Rao M.N., Suthar K.M. and Venkatesan T.R. 1976. Rare Gases in the Dhajala Stone
 664 Meteorite. *Meteoritics* 11, 290–291.

665 Greenwood N.N. and Earnshaw A. 1984. *Chemistry of the elements*. Pergamon Press, Oxford, first
 666 edition: 911.

667 Grossman J.N. and Wasson J.T. 1985. The origin and history of the metal and sulfide components of
 668 chondrules. *Geochim. Cosmochim. Acta* 49, 925–939.

669 Haramura H., Kushiro I. and Yanai K. 1983. Chemical Compositions of Antarctic Meteorites I. *Mem.*
 670 *Nat. Inst. Polar Res. (Tokyo), Spec. Issue* 30, 109–121.

671 Hermann F. and Wichtl M. 1974. Neutronenaktivierungsanalytische Bestimmung von
 672 Spurenelementen in Meteoriten der Vatikanischen Sammlung. In: *Analyse extraterrestrischen*
 673 *Material*. (Editors W. Kiesel and H. Malissa Jun.), pp. 163–172. Springer-Verlag, Wien.

674 Hertogen J., Janssens M., Takahashi H., Morgan J.W. and Anders E. 1983. Enstatite chondrites: Trace
 675 element clues to their origin. *Geochim. Cosmochim. Acta* 47, 2241–2255.

676 Hewins R.H., Yu. Y., Zanda B. and Bourot-Denise M. 1997. Do nebular fractionations, evaporative
 677 losses, or both, influence chondrule compositions? *Antarct. Meteorite Res.* 10, 275–298.

678 Hezel D.C. and Palme H. 2008. Constraints for chondrule formation from Ca-Al distribution in
 679 carbonaceous chondrites. *Earth Planet. Sci. Lett.* 265, 716–725.

680 Hezel D.C. and Palme H. 2010. The chemical relationship between chondrules and matrix and the
 681 chondrule matrix complementarity. *Earth Planet. Sci. Lett.* 294, 85–93.

682 Horan M.F., Walker R.J., Morgan J.W., Grossman J.N. and Rubin A.E. 2003. Highly siderophile
683 elements in chondrites. *Chem. Geol.* 196, 5–20.

684 Horan M.F., Alexander C.M.O'D. and Walker R.J. 2009. Highly siderophile element evidence for
685 early Solar System processes in components from ordinary chondrites. *Geochim. Cosmochim. Acta*
686 73, 6984–6997.

687 Hsu W., Huss G.R. and Wasserburg G.J. 1998. Ion probe analyses of PGEs in metallic phases of
688 chondrites: implications for the origin of chondritic metals. (abstract #1939) XXIXth Lunar Planet.
689 Sci.

690 Humayun M. and Campbell A.J. 2002. The duration of ordinary chondrite metamorphism inferred
691 from tungsten microdistribution in metal. *Earth Planet. Sci. Lett.* 198, 225–243.

692 Hutchison R., Alexander C.M.O'D. and Barber D.J. 1987. The Semarkona meteorite: First recorded
693 occurrence of smectite in an ordinary chondrites, and its implications. *Geochim. Cosmochim. Acta*
694 51, 1875–1882.

695 Ikramuddin M., Matza S., Lipschutz M.E. 1977. Thermal metamorphism of primitive meteorites. V.
696 Ten trace elements in Tieschitz H3 chondrite heated at 400–1000 °C. *Geochim. Cosmochim. Acta* 41,
697 1247–1256.

698 Jarosewich E. 1966. Chemical analyses of ten stony meteorites. *Geochim. Cosmochim. Acta* 30,
699 1261–1265.

700 Jarosewich E. 1984. Bulk chemical analyses of Antarctic meteorites, with notes on weathering effects
701 on FeO, Fe-metal, FeS, H₂O, and C. *Smithsonian Contribution to the Earth Sciences* 26, 111–114.

702 Jarosewich E. 1990. Chemical analyses of meteorites: A compilation of stony and iron meteorite
703 analyses. *Meteoritics* 25, 323–337.

704 Kaczaral P.W., Dennison J.E., Verkouteren R.M. and Lipschutz M.E. 1988. On volatile/mobile trace
705 element trends in E3 chondrites. *Proc. NIPR Symp. Antarct. Meteorites* 1, 113–121.

706 Kadlag Y. and Becker H. 2015. Fractionation of highly siderophile and chalcogen elements in
707 components of EH3 chondrites. *Geochim. Cosmochim. Acta* 161, 166–187.

708 Kadlag Y. and Becker H. 2016a. ^{187}Os - ^{187}Os systematics, highly siderophile element and S-Se-Te
 709 abundances in the components of unequilibrated L chondrites. *Geochim. Cosmochim. Acta* 172, 225–
 710 246.

711 Kadlag Y. and Becker H. 2016b. Highly siderophile and chalcogen element constraints on the origin
 712 of components of the Allende and Murchison meteorites. Accepted in *Meteoritics and Planetary*
 713 *Science*.

714 Kallemeyn G.W. and Wasson J.T. 1986. Compositions of enstatite (EH3, EH4, 5 and EL6)
 715 chondrites: implications regarding their formation. *Geochim. Cosmochim. Acta* 50, 2153–2164.

716 Kallemeyn G.W., Rubin A.E., Wang D. and Wasson J.T. 1989. Ordinary chondrites: Bulk
 717 compositions, classification, lithophile-element fractionations, and composition-petrographic type
 718 relationships. *Geochim. Cosmochim. Acta* 53, 2747–2767.

719 Kharitonova V.Y. 1969. Chemical compositions of the Oesel, Kargapole, Dimmitt, Chico, and New
 720 Almelo chondrites from the collection of the Committee on meteorites of the USSR Academy of
 721 Sciences. *Meteoritika* 29, 91–100.

722 Kimura M., Hiyagon H., Palme H., Spettel B., Wolf D., Clayton R.N., Mayeda T.K., Sato T., Suzuki
 723 A. and Kojima H. 2002. Yamato 792947, 793408 and 82038: The most primitive H chondrites, with
 724 abundant refractory inclusions. *Meteorit. Planet. Sci.* 37, 1417–1434.

725 Kong P. and Ebihara M. 1997. The origin and nebular history of the metal phase of ordinary
 726 chondrites. *Geochim. Cosmochim. Acta* 61, 2317–2329.

727 Kong P., Ebihara M., Nakahara H. and Endo K. 1995. Chemical characteristics of metal phases of the
 728 Richardton H5 chondrite. *Earth Planet. Sci. Lett.* 136, 407–419.

729 Kong P., Mori T. and Ebihara M. 1997. Compositional continuity of enstatite chondrites and
 730 implications for heterogeneous accretion of enstatite chondrite parent body. *Geochim. Cosmochim.*
 731 *Acta* 61, 4895–4914.

732 Kong P., Deloule E. and Palme H. 2000. REE-bearing sulfide in Bishunpur (LL3.1), a highly
 733 unequilibrated ordinary chondrite. *Earth Planet. Sci. Lett.* 177, 1–7.

734 Krot A.N., Zolensky M.E., Wasson J.T., Scott E.R.D., Keil K. and Ohsumi K. 1997. Carbide-
 735 magnetite assemblages in type-3 ordinary chondrites. *Geochim. Cosmochim. Acta* 61, 219–237.
 736 Laul J.C., Ganapathy R., Anders E. and Morgan J.W. 1973. Chemical fractionations in meteorites-VI.
 737 Accretion temperatures of H-, LL-, and E-chondrites, from abundance of volatile trace elements.
 738 *Geochim. Cosmochim. Acta* 37, 329–357.
 739 Lewis J.A. and Jones R.H. 2014. Nephelinization and metasomatism in the ordinary chondrite
 740 Parnallee (LL3.6). (abstract #1661) 45th Lunar Planet. Sci.
 741 Lodders K. 2003. Solar system abundances and condensation temperatures of the elements.
 742 *Astrophys. J.* 591, 1220–1247.
 743 Lofgren G.E. and Le L. 2002. Experimental reproduction of type-1B chondrules. (abstract #1746)
 744 XXXIIIth Lunar Planet. Sci.
 745 MacPherson G.J., Jarosewich E. and Lowenstein P. 1993. Magombedze: A new H-chondrite with
 746 light-dark structure. *Meteoritics* 28, 138–142.
 747 Nagahara H. 1984. Matrices of type 3 ordinary chondrites-primitive nebular records. *Geochim.*
 748 *Cosmochim. Acta* 48, 2581–2595.
 749 O'Neill H.S.C., Dingwell D.B., Borisov A., Spettel B. and Palme H. 1995. Experimental
 750 petrochemistry of some highly siderophile elements at high temperatures, and some implications for
 751 core formation and the mantle's early history. *Chem. Geol.* 120, 255–273.
 752 Palme H., Borisov A. and Wulf A.V. 1998. Experimental determination of the oxidation sequence of
 753 refractory metals. (abstract #1611) XXIXth Lunar Planet. Sci.
 754 Rakenburg K., Bradon A.D. and Humayun M. 2007. Osmium isotope systematics of ureilites.
 755 *Geochim. Cosmochim. Acta* 71, 2402–2413.
 756 Rambaldi E. 1976. Trace element content of metals from L-group chondrites. *Earth Planet. Sci. Lett.*
 757 31, 224–238.
 758 Rambaldi E.R. 1977b. Trace element content of metals from H- and LL-group chondrites. *Earth*
 759 *Planet. Sci. Lett.* 36, 347–358.
 760 Rambaldi E.R., Cendales M. and Thacker R. 1978. Trace element distribution between magnetic and
 761 non-magnetic portions of ordinary chondrites. *Earth Planet. Sci. Lett.* 40, 175–186.

762 Rambaldi E.R., Wänke H. and Larimer J.W. 1979. Interelement refractory siderophile fractionation in
 763 ordinary chondrites. 10th Proc. Lunar Planet. Sci. 997–1010.

764 Rasmussen K.L., Malvin D.J. and Wasson J.T. 1988. Trace element partitioning between taenite and
 765 kamacite; relationship to the cooling rates of iron meteorites. *Meteoritics* 23, 107–112.

766 Rose-Weston L., Brenan J.M., Yingwei F., Secco R.A. and Frost D.J. 2009. Effect of pressure,
 767 temperature, and oxygen fugacity on the metal-silicate partitioning of Te, Se and S: Implications for
 768 earth differentiation. *Geochim. Cosmochim. Acta* 73, 4598–4615.

769 Rieder R. and Wänke H. 1969. Study of trace element abundances in meteorites by neutron activation.
 770 In: *Meteorite Research* (ed. P. M. Millman), 75–86.

771 Schaefer L. and Fegley B. Jr. 2009. Volatile element chemistry during metamorphism of ordinary
 772 chondritic material and some of its implications for the composition of asteroids. *Icarus* 205, 483–496.

773 Schmitt W., Palme H. and Wänke H. 1989. Experimental determination of metal/silicate partition
 774 coefficients for P, Co, Ni, Cu, Ga, Ge, Mo, and W and some implications for the early evolution of
 775 the Earth. *Geochim. Cosmochim. Acta* 53, 173–185.

776 Scott E.R.D. and Krot A.N. 2003. Chondrites and their components. *Treatise on Geochemistry*.
 777 Editors Davis A.M., Holland H.D. and Turekian K.K. Vol.1, 143–200.

778 Scott E.R.D., Taylor G.J., Rubin A.E., Okada A. and Keil K. 1981. Graphite-magnetite aggregates in
 779 ordinary chondrite meteorites. *Nature* 291, 544–546.

780 Smith C.L., Laeter de J.R. and Rosman K.J.R. 1977. Mass spectrometric isotope dilution analyses of
 781 tellurium in meteorites and standard rocks. *Geochim. Cosmochim. Acta* 41, 676–681.

782 Smoliar M.I., Walker R.J. and Morgan J.W. 1996. Re–Os ages of group IIA, IIIA, IVA, and IVB iron
 783 meteorites. *Science* 271, 1099–1102.

784 Takahashi H., Gros J., Higuchi H., Morgan J.W. and Anders E. 1978. Volatile elements in chondrites:
 785 metamorphism or nebular fractionation? *Geochim. Cosmochim. Acta* 42, 1859–1869.

786 Wai C.M. and Wasson J.T. 1977. Nebular condensation of moderately volatile elements and their
 787 abundances in ordinary chondrites. *Earth Planet. Sci. Lett.* 36, 1–13.

788 Walker R.J., Horan M.F., Morgan J.W., Becker H., Grossman J.N. and Rubin A.E. 2002.
 789 Comparative ^{187}Re – ^{187}Os systematics of chondrites: implications regarding early solar system
 790 processes. *Geochim. Cosmochim. Acta* 66, 4187–4201.
 791 Wang Z., Becker H. and Gawronski T. 2013. Partial re-equilibration of highly siderophile elements
 792 and the chalcogens in the mantle: A case study on the Baldissero and Balmuccia peridotites massifs
 793 (Ivrea Zone, Italian Alps). *Geochim. Cosmochim. Acta* 108, 21–44.
 794 Wasson J.T., Rubin A.E. and Kallemeyn G.W. 1993. Reduction during metamorphism of four
 795 ordinary chondrites. *Geochim. Cosmochim. Acta* 57, 1867–1878.
 796 Wiik H.B. 1966. On the genetic relationship between meteorites. Arizona State University Special
 797 Contributions 18.
 798 Yanai K., Kojima H. and Haramura H. 1995. Catalog of the Antarctic Meteorites collected from
 799 December 1969 to December 1994, with special reference to those represented in the collections of
 800 the National Institute of Polar Research. National Institut of Polar Research, Tokyo, pp. 44–76.

Fig.1 CI chondrite normalized abundances of a) S, Se and Te, b) HSE, c) Fe, Ni and Co, d) Cr, Ca, Mg, Mn and Fe of magnetic fractions of WSG 95300 as a function of grain size. CI chondrite normalized abundance variations of e) S, Se and Te, f) HSE, g) Fe, Ni and Co, h) Cr, Ca, Mg, Mn and Fe in magnetic fractions of Parnallee with grain size. Au is decoupled from the HSE in magnetic fractions of WSG 95300 and shows a similar size-dependent behavior like S, likely caused by terrestrial weathering. Differences in the HSE and Ni and Co variation likely result from kamacite-taenite exsolution.

Fig.2 CI chondrite normalized abundances of a) S, Se and Te, b) HSE, c) Fe, Ni and Co, d) Cr, Ca, Mg, Mn and Fe of slightly magnetic fractions of WSG 95300 as a function of grain size. CI chondrite normalized abundance variations of e) S, Se and Te, f) HSE, g) Fe, Ni and Co, h) Cr, Ca, Mg, Mn and Fe in slightly magnetic fractions of Parnallee with grain sizes. Rhenium and Au are decoupled from other HSE in fractions of WSG 95300, due to redistribution during terrestrial weathering.

Fig.3 Variation of major elements a) Ca-Mg, b) Mn-Mg, c) Mg-Fe, d) Ni-Fe, e) Ni-Co and f) Fe-S in the fractions of WSG 95300 and Parnallee. Crosses: WSG 95300, diamonds: Parnallee. M: magnetic, SM: slightly magnetic and NM: non-magnetic. CI chondrite data is shown by the red circle. Black symbols show the calculated bulk rock values from a mass balance of all analyzed fractions. Gray symbols show the average literature bulk rock data for Parnallee and H3 chondrites (sources are mentioned in the caption of Table 1 and 2). Error bars are smaller than the symbol size for most elements except for Ca, which has larger errors. Significant variations in the abundances of major elements in the fractions are observed, which is mainly due to the variable proportions of metal, silicate and sulfide phases in different fractions. Linear variation between Ca, Mn and Mg (a and b) indicate the predominance of a silicate phase in the fractions. Variations in the abundances of the siderophile elements Fe, Ni and Co (d and e) in the samples likely reflect metal-silicate-sulfide partitioning and kamacite-taenite exsolution. The Fe/S plot shows the predominance of Fe-Ni metal over sulfide (FeS) in magnetic fractions.

Fig.4 ^{187}Re - ^{187}Os isochron diagram of separated fractions of WSG 95300 and Parnallee. Literature bulk rock data of H3 and LL3 chondrites (Walker et al., 2002; Fischer-Gödde et al., 2010) is shown by the gray shaded area. The 4.568 Ga reference isochron is based on data in Smoliar et al. (1996) and Archer et al. (2014). Large deviation of slightly magnetic and non-magnetic fractions of WSG 95300 from the reference isochron likely reflects Re mobilization during terrestrial weathering. Non-magnetic, slightly magnetic and sulfide clast fractions of Parnallee show slight deviations from the isochron, presumably resulting from oxidation processes on the meteorite parent body. Magnetic fractions of both chondrites show substantial variation in $^{187}\text{Os}/^{188}\text{Os}$ and $^{187}\text{Re}/^{188}\text{Os}$, which reflect the fractionation of Re/Os in the solar nebula before accretion of chondrite parent bodies.

Fig.5 CI chondrite normalized abundances of HSE, chalcogen elements and Ni, Co and Fe in fractions of WSG 95300 and Parnallee. Elements are ordered from left to right in increasing order of volatility based on the 50% condensation temperature in solar gas (Lodders, 2003). Different symbol sizes of the same fractions represent different grain sizes (numbers in the legend indicate the size fractions). Sources of literature data are mentioned in captions of Tables 1 and 2. HSE abundances in magnetic fractions show inverse size-dependent variation. Magnetic fractions of Parnallee show higher HSE abundances compared to the magnetic fractions of WSG 95300.

Fig.6 a) Re-Ir, b) Os-Ir, c) Pt-Ir, d) Se-Ir, e) Pd-Ir, f) Ru-Ir, g) Rh-Ir and h) Au-Ir variation in the fractions of WSG 95300 and Parnallee. Osmium, Ru, Pt, Pd and Rh show linear correlation with Ir, with nearly CI chondritic ratios of these elements with Ir. Magnetic fractions of Parnallee show lower than CI chondritic ratios of Re/Ir, Os/Ir, Ru/Ir, Pt/Ir, Pd/Ir, and Rh/Ir.

Fig.7 a) S-Se, b) Te-Se, c) Te-S, d) S-Ir and e) Pd-Te variation in the fractions of WSG 95300 and Parnallee. Selenium is more siderophile in magnetic fractions (a) compared to other fractions whereas Te is siderophile in almost all fractions therefore showing a linear correlation with Pd (e), higher

Te/Se (b) in magnetic fractions and decoupling from S. Arrows on the upper part of (a) and (d) show the deviation of magnetic fractions from the CI chondritic composition, mainly due to sulfur loss, which may have occurred during chondrule formation. Despite of variation in the concentrations, fractions of both meteorites show similar systematics of chalcogen elements indicating that the influence of terrestrial weathering on these elements is negligible.

Fig.8 a) Ni/Co-Se/S and b) Ni/Fe-S/Fe variations in the fractions of WSG 95300 and Parnallee. Fractions of Parnallee show significant variation in the Ni/Co with nearly constant Se/S, likely due to the exsolution of kamacite and taenite, in addition to metal-silicate partitioning. Higher Se/S in the magnetic fractions of WSG 95300 either reflect higher metal-silicate partition coefficients of Se or loss of S from this fraction during terrestrial weathering

Fig.A1 Fragment of a sulfide clast in Parnallee. The dominant mineral phase is troilite of variable grain size (light gray, T). O = olivine, P = plagioclase, py = pyroxene and, C = chromite. Fe-Ni metal is very rare.

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Table 1. Concentrations of major and minor elements in the separated fractions of WSG 95300 (H3.3) and Parnallee (LL3.6)

Sample	Mg (%)	Ca (%)	Cr (%)	Mn (%)	Fe (%)	Co (%)	Ni (%)
<i>WSG-95300</i>							
WSG-NMC (> 80 μm)	15.5	1.0	0.2501	0.1882	8.9	0.0041	0.052
WSG-NMF (< 80 μm)	13.9	0.8	0.232	0.1751	9.5	0.0077	0.133
WSG-M (< 80 μm)	3.5	0.09	0.164	0.0687	38.2	0.177	3.10
WSG-M (80-200 μm)	6.5	0.6	0.213	0.1157	37.7	0.155	3.05
WSG-M (> 200 μm)	8.2	0.67	0.2558	0.1339	31.3	0.114	2.27
WSG-SM (< 80 μm)	12.8	1.0	0.2474	0.1804	14.9	0.0219	0.43
WSG-SM (80-200 μm)	11.8	1.0	0.2648	0.1881	14.0	0.0207	0.44
WSG-SM (> 200 μm)	10.7	0.62	0.2090	0.1489	13.9	0.0269	0.563
WSG-chondrules	9.3	0.9	0.252	0.2185	7.5	0.0055	0.13
WSG-cal bulk	10.2	0.7	0.2328	0.1525	19.6	0.0559	1.116
H-Bulk ^a	13.7	1.17	0.29	0.22	26.0	0.07	1.47
<i>Parnallee</i>							
Parn-NMC (> 80 μm)	13.8	1.1	0.2716	0.2112	9.4	0.0030	0.051
Parn-NMF (< 80 μm)	13.8	0.92	0.2663	0.2123	10.6	0.0035	0.066
Parn-M (< 80 μm)	3.7	0.2	0.212	0.078	14	0.113	5.56
Parn-M (80-200 μm)	9.6	0.5	0.260	0.1579	23.1	0.087	2.90
Parn-M (> 200 μm)	10.2	0.85	0.2532	0.1716	23.1	0.123	1.61
Parn-SM (< 80 μm)	13.6	1.0	0.2816	0.2141	11.6	0.0069	0.225
Parn-SM (80-200 μm)	11.9	1.0	0.2749	0.1999	11.9	0.0073	0.242
Parn-SM (> 200 μm)	12.9	1.2	0.2810	0.2184	12.7	0.0090	0.339
Parn-chondrules	8.5	0.68	0.2185	0.1403	13.8	0.0502	0.69
Parn-sulfide clast	1.0	0.00	0.024	0.0189	41.3	0.0018	0.08
Parn-cal bulk	11.0	0.92	0.2513	0.1812	14.4	0.0364	0.6009
Parn -lit bulk ^a	15.4	1.21	0.38	0.2713	18.5	0.0674	0.97
CI Bulk ^b	9.59	0.91	0.26	0.19	18.28	0.050	1.06

^a Bulk rock data for H3 chondrites and Parnallee from Wiik (1966), Jarosewich (1966, 1984, 1990), Kharitonova (1969), Gopalan et al. (1976), Haramura et al. (1983), Fulton and Rhodes (1984), MacPherson et al. (1993), Yanai et al. (1995).

^b Data for CI chondrites from Lodders (2003).

Table 2. HSE, chalcogen abundances and ¹⁸⁷Re-¹⁸⁷Os isotopic systematics of separated fractions of WSG 95300 (H3.3) and Parnallee (LL3.6)

Sample	Weight (mg)	Re (ng/g)	Os (ng/g)	Ir (ng/g)	Ru (ng/g)	Pt (ng/g)	Rh (ng/g)	Pd (ng/g)	Au (ng/g)	Te (ng/g)	Se (ng/g)	S (mg/g)	¹⁸⁷ Os/ ¹⁸⁸ Os	¹⁸⁷ Re/ ¹⁸⁸ Os	Δ _{Os}
<i>WSG-95300</i>															
WSG-NMC (> 80 μm)	24.2	3.2	19	16	25	31	6	14	4	1	585	2.09	0.128 ± 0.002	0.82 ± 0.02	-321 ± 14
WSG-NMF (< 80 μm)	10.3	10.2	59	46	71	97	17	40	11	25	2585	6.44	0.130 ± 0.002	0.84 ± 0.01	-314 ± 10
WSG-M (< 80 μm)	6.7	206.0	2496	2327	3710	5100	822	2725	308	1525	16065	23.06	0.12820 ± 0.00009	0.3978 ± 0.0005	15.7 ± 0.5
WSG-M (80-200 μm)	18.1	168.1	2010	1858	2748	3873	576	2070	845	983	14722	28.84	0.12823 ± 0.00007	0.4031 ± 0.0002	11.8 ± 0.3
WSG-M (> 200 μm)	21.5	136.4	1610	1447	2153	3089	468	1513	603	804	12611	24.15	0.12801 ± 0.00007	0.4084 ± 0.0002	5.5 ± 0.3
WSG-SM (< 80 μm)	22.7	31.4	259	229	352	783	73	249	34	85	6013	14.58	0.1295 ± 0.0002	0.583 ± 0.001	-118 ± 1
WSG-SM (80-200 μm)	19.6	55.7	218	194	306	403	64	266	108	94	5496	13.66	0.12800 ± 0.00009	0.4864 ± 0.0005	-56.3 ± 0.5
WSG-SM (> 200 μm)	51.0	30.5	302	289	435	570	88	356	138	114	5077	12.53	0.1287 ± 0.0003	1.233 ± 0.002	-639 ± 2
WSG-chondrules	6.0	6.9	58	32	52	145	22	141	17	12	1945	4.95	0.138 ± 0.002	0.57 ± 0.02	-25 ± 15
WSG-cal bulk	625	68	736	670	1003	1422	215	742	282	350	7400	15.79	0.1286 ± 0.0004	0.551 ± 0.003	-101 ± 2
H3-bulk ^a		68	836	729	1197	1544	246	967	259	338	7737	19.96	0.128 ± 0.002	0.42 ± 0.02	-4 ± 13
<i>Parnallee</i>															
Parn-NMC (> 80 μm)	35.6	3.19	40	37	54	64	11	19	5	18	1618	4.12	0.1227 ± 0.0007	0.385 ± 0.006	-30 ± 4
Parn-NMF (< 80 μm)	15.9	4.8	55	53	73	92	15	28	10	33	2863	6.59	0.122 ± 0.001	0.420 ± 0.009	-63 ± 7
Parn-M (< 80 μm)	0.9	239	2898	4578	6120	7514	1437	5128	1185	1955	19560	22.61	0.1271 ± 0.0004	0.398 ± 0.003	5 ± 2
Parn-M (80-200 μm)	12.8	102.9	1357	2009	2595	3490	503	2080	371	838	14741	29.35	0.12388 ± 0.00008	0.3656 ± 0.0005	-2.0 ± 0.5
Parn-M (> 200 μm)	39.9	73.5	990	902	1327	1908	284	1131	279	577	8383	19.18	0.12284 ± 0.00006	0.3579 ± 0.0002	-6.3 ± 0.3
Parn-SM (< 80 μm)	28.7	12.34	145	150	208	287	43	141	34	122	4571	10.02	0.1254 ± 0.0003	0.409 ± 0.002	-22 ± 2
Parn-SM (80-200 μm)	26.1	14.4	162	148	220	297	50	151	32	137	8033	18.04	0.1254 ± 0.0003	0.429 ± 0.002	-37 ± 1
Parn-SM (> 200 μm)	50.6	15.5	175	159	251	337	53	218	47	187	6611	15.44	0.1261 ± 0.0001	0.4279 ± 0.0009	-29.5 ± 0.8
Parn-chondrules	9.4	40.1	475	415	638	883	133	641	137	580	9397	18.83	0.1272 ± 0.0002	0.407 ± 0.002	-2 ± 1
Parn-sulfide clast	6.8	4.8	41	37	61	95	18	81	11	167	134896	306.31	0.129 ± 0.004	0.57 ± 0.03	-113 ± 23
Parn-cal bulk	1087	30	370	342	514	713	108	464	103	297	8031	17.63	0.1256 ± 0.0003	0.410 ± 0.002	-20 ± 2
LL3-lit bulk ^a		31	407	350	460	714	114	444	140	813	9407	20.00	0.1282 ± 0.0006	0.41 ± 0.01	2 ± 6
CI-bulk ^b		36.6	449.5	418.4	627.2	871.4	130	567.4	148.8	2310	21300	54.10	0.12641	0.40073	-4.50

Uncertainties on isotopic ratios are 2σ. Bold ¹⁸⁷Os/¹⁸⁸Os ratios are analysed using Faraday cup and other ratios are obtained from electron multipleir measurements. Deviation of the Os isotopic composition (Δ_{Os}) from a 4568 Ma isochron is calculated by the following relation.

$\Delta_{Os} = (^{187}\text{Os}/^{188}\text{Os}_{\text{sample}} - (0.09517 + 0.07908 \times ^{187}\text{Re}/^{188}\text{Os}_{\text{sample}})) \times 10^4$, where 0.09517 is the ¹⁸⁷Os/¹⁸⁸Os ratio at 4.568 Ga and 0.07908 is the slope of a primordial 4568 Ma isochron (Archer et al., 2014).

^a Average LL3 and H3 bulk values from Rieder and Wänke (1969), Case et al. (1973), Hermann and Wichtl (1974), Binz et al. (1976), Smith et al. (1977), Biswas et al. (1981), Dennison and Lipschutz (1987), Brearley et al. (1989), Delisle et al. (1989), Ebihara (1989), Kallemeyn et al. (1989), Bischoff et al. (1993), Wasson et al. (1993), Ebihara and Ozaki (1995), Chen et al. (1998), Kimura et al. (2002), Walker et al. (2002), Horan et al. (2003) and Fischer-Gödde et al. (2010).

^b CI-bulk is the average CI chondrites data from Dreibus et al. (1995), Walker et al. (2002), Fischer-Gödde et al. (2010) and Wang et al. (2013).