The isotope composition of selenium in chondrites constrains the depletion mechanism of volatile elements in solar system materials

Hauke Vollstaedt [a,b,*], Klaus Mezger [a,b], Ingo Leya [c,b]

[a] *Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland*
[b] *Center for Space and Habitability, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland*
[c] *Institute of Physics, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland*

A B S T R A C T

Solar nebula processes led to a depletion of volatile elements in different chondrite groups when compared to the bulk chemical composition of the solar system deduced from the Sun's photosphere. For moderately-volatile elements, this depletion primarily correlates with the element condensation temperature and is possibly caused by incomplete condensation from a hot solar nebula, evaporative loss from the precursor dust, and/or inherited from the interstellar medium. Element concentrations and interelement ratios of volatile elements do not provide a clear picture about responsible mechanisms. Here, the abundance and stable isotope composition of the moderately- to highly-volatile element Se are investigated in carbonaceous, ordinary, and enstatite chondrites to constrain the mechanism responsible for the depletion of volatile elements in planetary bodies of the inner solar system and to define a $\delta^{82/78}$Se value for the bulk solar system. The $\delta^{82/78}$Se of the studied chondrite falls are identical within their measurement uncertainties with a mean of $-0.20 \pm 0.26‰$ (2 s.d., $n = 14$, relative to NIST SRM 3149) despite Se abundance depletions of up to a factor of 2.5 with respect to the CI group. The absence of resolvable Se isotope fractionation rules out a kinetic Rayleigh-type incomplete condensation of Se from the hot solar nebula or partial kinetic evaporative loss on the precursor material and/or the parent bodies. The Se depletion, if acquired during partial condensation or evaporative loss, therefore must have occurred under near equilibrium conditions to prevent measurable isotope fractionation. Alternatively, the depletion and cooling of the nebula could have occurred simultaneously due to the continuous removal of gas and fine particles by the solar wind accompanied by the quantitative condensation of elements from the pre-depleted gas. In this scenario the condensation of elements does not require equilibrium conditions to avoid isotope fractionation. The results further suggest that the processes causing the high variability of Se concentrations and depletions in ordinary and enstatite chondrites did not involve any measurable isotope fractionation. Different degrees of element depletions and isotope fractionations of the moderately-volatile elements Zn, S, and Se in ordinary and enstatite chondrites indicate that their volatility is controlled by the thermal stabilities of their host phases and not by the condensation temperature under canonical nebular conditions.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

Moderately- and highly-volatile elements are depleted in almost all materials of the inner solar system including the carbonaceous chondrites (e.g., Davis and Richter, 2014 and Palme, 2001). Only the CI chondrites closely match solar abundances for

all elements except the extremely volatile elements such as the rare gases, H, C, O, N, and Li (e.g., Palme and O'Neill, 2003). Specifically, abundances of moderately-volatile elements show a positive correlation with condensation temperature (T_C), indicating that T_C is the primary factor controlling moderately-volatile element concentrations in chondrites (Palme and O'Neill, 2003; Wasson and Kallemeyn, 1988). The moderately-volatile elements comprise elements with 50% T_C between 1060 and 664 K, ranging between the condensation of Mg-silicates and FeS from a gas of solar composition (Palme and O'Neill, 2003; Table 1). With the exception of S, all elements in this group are trace elements and condense by dissolution into already condensed major phases such

* Corresponding author at: Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland. Fax: +41 31 631 4843.
E-mail addresses: hauke.vollstaedt@geo.unibe.ch (H. Vollstaedt), klaus.mezger@geo.unibe.ch (K. Mezger), ingo.leya@space.unibe.ch (I. Leya).

Table 1

Moderately-volatile elements and calculated 50% equilibrium condensation temperatures (T_C) for a gas of solar composition (Lodders, 2003; Palme and O'Neill, 2003).

Element	50% T_C (K)
Au	1060
Cu	1037
K	1006
Ag	996
Ga	968
Na	958
Cl	948
B	908
Ge	883
Rb	800
Cs	799
Bi	746
F	734
Pb	727
Zn	726
Te	709
Sn	704
Se	697
S	664

as silicates, metal, and sulphides (Palme and O'Neill, 2003). Several processes have been proposed to explain the depletion of volatile elements in chondrites with respect to the bulk solar system. These processes may have occurred prior to or during condensation and/or during evaporation caused by a heating event. Since depletion of moderately- to highly-volatile elements is observed in all meteorite groups except CI chondrites, this depletion must be a very early and universal process. To record the characteristic volatile element fractionation observed in chondrites, a physical separation of gas and dust in the solar nebula must have taken place. The nebular temperature at which the meteoritic and planetary volatile-element depletion was established is estimated to be higher than 1400 K (Humayun and Cassen, 2000).

Yin et al. (2005) studied the moderately-volatile element depletion in interstellar dust and rocky material of the inner solar system and argues for an inheritance of the depletion pattern from the interstellar medium (ISM). In his conceptual model, interstellar dust grains acquired an outer layer of condensed ice and other volatiles in the cold and dense molecular cloud stage. During the collapse of the dense molecular cloud and the formation of the early solar system, adiabatic compression or passage of shock waves take off and vaporize/sublimate the icy mantle. The re-condensation and re-equilibration of the gas with the entrained dust grains was prohibited by rapid grain growth in the solar nebula, reducing the surface area per unit mass and removing them from contact with the gas before complete recondensation occurs. The variable proportions of refractory grains and volatile-rich mantle constitute the ultimate chemical heterogeneities observed in different reservoirs of the solar nebula at different scales (Yin et al., 2005). However, different extents of volatility-related element fractionation in grains from the ISM and carbonaceous chondrites as well as a uniform isotopic composition of the solar system argue against an element and isotope record in chondrites produced by dust and gas fractionation in the ISM (Palme, 2001).

Models for a loss of volatile elements prior to or during condensation from the solar nebula suggest a progressive removal of gas as condensation and aggregation proceeded leading to a higher depletion of volatile elements with low T_C. Different mechanisms have been proposed describing the possible separation of the gas from dust. Similar to the model of Yin et al. (2005), Larimer (1967) suggested that the limitation of surface area by grain aggregation may lead to a kinetic limitation of volatile-element condensation

that depends on the diffusion of the elements into grains. In this scenario, volatile elements condense partially from the solar nebula. Wasson and Chou (1974) and Wai and Wasson (1977) proposed that the separation occurred continuously during the cooling of the solar nebula and consequent condensation due to one or a combination of processes including i) the shrinkage of particle orbital radii due to solid–gas interactions and induced deceleration of particles, ii) the removal of gas from the surface of the solar nebula by wind and photons whereas particles were retained and settled towards the midplane, and iii) the entrainment of gaseous and/or fine dust condensates of volatile elements with the nebula gas during the final dissipation of gases from the nebula. These qualitative arguments have been supported and quantified in model simulations (e.g., Cassen, 2001). Here, the chemical fractionation patterns are the natural result of the inherently coupled evolution of condensing and coagulating solids from a nebula of diminishing mass cooling from a hot initial state. However, to exactly reproduce the moderately- to highly-volatile element abundances with $T_C < 800$ K as observed in meteorites, mixing with material having a composition similar to that of CI chondrites is additionally required (Humayun and Cassen, 2000; Larimer, 1967; Wolf et al., 1980).

The latter observation led other authors to explain the element pattern in chondrites by a two- or multi-component model where a volatile-depleted phase, devoid of all highly-volatile elements <700 K T_C, variously depleted in moderately-volatile elements, and completely retaining the refractory elements >1200 K T_C, is mixed with a CI-like phase to explain the chemical fractionation in chondrites (Alexander, 2005; Anders, 1964). The amount of the CI-like component roughly correlates with the amount of matrix in chondrites whereas the volatile-depleted component originates from the coarse grained fraction, mainly consisting of chondrules (Wolf et al., 1980). The partial loss of gaseous volatiles during the chondrule formation process then explains the smooth relationship between CI-normalized moderately-volatile element abundance and T_C (Alexander, 2005). Bulk meteorites are therefore considered to represent a mixture of undepleted matrix and volatile-depleted chondrules, which are thought to be residues from partial vaporization of CI-like material (Alexander, 2005). Also impacts on the chondrite parent bodies have been considered to result in a redistribution and depletion of volatile elements (Kadlag and Becker, 2015 and references therein). However, heating experiments on fragments of the Allende CV and Murchison CM chondrites showed depletions of volatile elements in the residues that are inconsistent with the origin by thermal processing of CI-like material (Wulf et al., 1995). Also, other studies argued that Mn/Na ratios are constant and CI-like within ±15% (1 r.s.d.) in all chondrite groups, that Se/Zn ratios are constant and CI-like within ±5% (1 r.s.d.) in all carbonaceous chondrites despite significant absolute variations in element abundances, and that Au/Co significantly correlates with Ga/Co ratios in carbonaceous chondrites (Dreibus and Palme, 1996; Palme and O'Neill, 2003; Xiao and Lipschutz, 1992). The authors from these studies inferred from the data that no net evaporative loss of these elements could have occurred under oxidizing conditions on the chondrite parent bodies. Further, Bland et al. (2005) studied minor and trace element abundances in the fine-grained matrix of a variety of carbonaceous chondrites and found that matrix elements are characteristic for a given chondrite group and depleted with respect to CI but enriched relative to bulk compositions, particular in volatile siderophile and chalcophile elements. They inferred that complementary and non-monotonic depletions of volatile elements with decreasing T_C between matrix and chondrules best explain the monotonic trace element pattern observed in bulk carbonaceous chondrites. Accordingly, Bland et al. (2005) proposed that matrices of carbonaceous chondrites formed from material that has been volatile-depleted before the chondrule for-