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Planetary accretion and core formation inferred from Ni isotopes in enstatite meteorites

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Supplementary Information

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Samples and Analytical Methods

The enstatite chondrites, including MAC 88184 [EL3], MAC 02837 [EL3], GRO 95517 [EH3], Qingzhen [EH3], SAH 97096 [EH3] and Indarch [EH4], Itqiy [EH7] and the acid leachates of Indarch are from the dissolution in Zhu *et al.* (2021a). Bulk chondrite samples were dissolved in Teflon bombs + Evapo Clean at 140 °C using concentrated HF + HNO_3 (2:1) for 2 days and concentrated aqua regia (HCl + HNO_3, 3:1) at 140 °C for another 2 days following a protocol described in Inglis *et al.* (2018).

We performed the acid leaching for Indarch and tried to obtain its different phases. The sample solutions are from Zhu *et al.* (2021a), and related method is following Moynier *et al.* (2011). the magnetic fractions (from sample powders) were collected using a hand magnet and dissolved in aqua regia in Teflon bombs at 140 °C for 2 days. Note that the magnetic fractions were not pure metal and included other Fe-Ni-bearing minerals, such as troilite that can be also separated by magnet. After extraction of the magnetic fraction, the residual nonmagnetic fraction (mostly silicates and other sulfide) was then dissolved in cold 3 N HCl for ~6 hr to dissolve the sulfides. Since some Fe-Ni-bearing sulfide has been extracted in last step, only some Fe-Ni-poor sulfide was dissolved in this procedure. The final residues (mostly silicates) were dissolved in concentrated HF + HNO_3 at 140 °C for 2 days and concentrated aqua regia at 140 °C for another 2 days in Teflon bombs to completely dissolve the silicates.

We selected 14 enstatite achondrites for Ni isotope measurements in this study (Table 1). Twelve of them are main-group aubrites, with one anomalous aubrite Shallowater and another enstatite-rich EH7 meteorite, Itqiy. Note that, the three groups of enstatite meteorites can represent three different parent bodies based on their mass-independent $^{54}Cr/^{52}Cr$ compositions (Zhu *et al.*, 2021b). The petrological description for main-group aubrites and Shallowater can be found in Keil (2010), and that for Itqiy is introduced in (Patzer *et al.*, 2001). Except Shallowater and Itqiy, all the main-group aubrites in this study are breccia meteorites (Keil, 2010). Some of the aubrites, including Norton County, Bishopville, Bustee, Larned, Peña Blanca Spring, Aubres and Pesyanoe, are from the dissolution in Barrat *et al.* (2016). These meteorite samples were firstly powdered using a boron carbide mortar and pestle, and then the powers were dissolved in closed screw-top teflon vessels (Savillex) at about 130 °C for three days using 5 mL of concentrated HF, and 2 mL of concentrated HNO_3. The vessels were then opened. After evaporation to dryness of the acid mixture, approximately 2 mL of HNO_3 was added, and the vessels were capped and placed back on the hot plate and left overnight. Note that, Larned (sample powder) was leached in hot 6 N HCl (1 h, 120 °C), to dissolve all sulfides (including troilite) and the Fe-Ni metal, leaving residues composed essentially of silicate phases (mainly enstatite and sometimes diopside and plagioclase). Cumberland Falls, ALH 84007 and Shallowater are from the dissolution in Zhu *et al.* (2021b) that is the same as the protocol for the bulk enstatite chondrites in this study. The remaining aubrites, LAR 04316, Khor Temiki, ALHA 78113, were weighed and dissolved in Parr Bombs at Freie Universität Berlin. The samples were dissolved in a mixing acid of 3 mL conc. HF and 1 mL conc. HNO_3 at 180 °C for two days. After drying down, the samples were redissolved in 3 mL conc. HNO_3 at 180 °C for another two days; then no visible particles were observed in the sample dissolutions.

For all sample solutions, Before the addition of a ^{61}Ni-^{62}Ni double spike, 1 % of the sample solutions were analysed for element mass fractions on a Thermo Instrument Element II Inductively Coupled Plasma Mass Spectrometer, housed at China University of Geosciences (Beijing). For stable isotope compositions, 400–800 ng of Ni were mixed with the double spike. The sample and spikes were heated in 6 N HCl in Teflon beaker at 120 °C over night for complete homogenisation. We employed a five-step column chemistry to purify the sample solutions, and the related method is described in Wu *et al.* (2019, 2022). The Ni yields of the entire purification procedure were >90 %, and the total Ni blanks were <1.2 ng, consistent with our previous work. After the column chemistry, conc. HNO_3 (0.6 mL) + 30 % H_2O_2 (0.3 mL) were added to the samples and heated at 130 °C overnight, for destroying any organics that may have potentially leached from the resin.

The Ni stable isotope measurements were performed on a Neptune Plus Multicollector-Inductively Coupled Plasma Mass Spectrometer housed at China University of Geosciences (Beijing). The methods are the same as those used in Wu *et al.* (2019, 2022). The instrument is equipped with nine Faraday Cups, and each cup are connected to a 1011 X amplifier. The signal intensities of ^{57}Fe, ^{58}Ni + ^{58}Fe, ^{60}Ni, ^{61}Ni, ^{62}Ni and ^{64}Ni were simultaneously measured using L3, L2, C, H1, H2 and H4 cups in static mode, respectively. We use standard sample + skimmer X cones for a high sensitivity measurement, which also includes an Aridus II desolvator equipped with an ice chamber (Wu *et al.*, 2020) and a 110 μL min^{-1} microconcentric PFA nebuliser (ESI). All the Ni isotope measurements are run in a low-resolution mode and at peak centre. The measurements yielded a ^{60}Ni (centre cup) signal of 10–15 V for both samples and standard solutions. Each measurement consisted of 45 cycles, with an integration time of 4.194 s for each cycle. Blank measurements with 15 cycles of 4.194 s were done and subtracted from the signals of sample solutions (off-line). Other instrumental parameters can be found in detail in (Li *et al.*, 2020). The data precision in study (2 s.d. uncertainty of ~0.02–0.06) are comparable to those in literature (Cameron *et al.*, 2009; Gall *et al.*, 2017; Klaver *et al.*, 2020; Saunders *et al.*, 2020, 2022; Wang *et al.*, 2021). All the measurements in this study were run in two sessions.

We also report the $\delta^{60/58}$Ni data for USGS reference materials, BHVO-2, BCR-1 and NOD-P, and these data consistent with literature data (Cameron *et al.*, 2009; Chernonozhkin *et al.*, 2016; Gall *et al.*, 2017; Klaver *et al.*, 2020; Saunders *et al.*, 2020; Wang *et al.*, 2021) and confirms the high-quality of our data. However, the $\delta^{60/58}$Ni datum for Allende (CV3; see Table S-1) does not overlap with the literature data (Gall *et al.*, 2017; Klaver *et al.*, 2020; Wang *et al.*, 2021), which may reflect sample heterogeneity. Similar inconsistencies were also found in other chondrites, *e.g.*, Orgueil [CI1], Karoonda [CK4] and Barratta [L4] (Gall *et al.*, 2017; Klaver *et al.*, 2020; Wang *et al.*, 2021).

Supplementary Table

Table S-1 Ni stable isotope compositions of chondrites and iron meteorites.

Sample	**Group**	**$\delta^{60/58}$Ni (‰)**	**2 s.d.**	**2 s.e.**	***n***	**References**
CCs						
Orgueil	CI1	**0.21**	0.07			Cameron *et al*. (2009)
Orgueil	CI1	**0.19**		0.02		Steele *et al*. (2012)
Orgueil	CI1	**0.18**	0.04	0.02	4	Gall *et al*. (2017)
Orgueil	CI1	**0.02**	0.02	0.01	8	Klaver *et al*. (2020)
Orgueil	CI1	**0.12**	0.02	0.01	8	Klaver *et al*. (2020)
Orgueil	CI1	**0.14**	0.05	0.02	4	Zhu *et al*. (2022)
Orgueil Avg.		**0.14**	0.13			
Ivuna	CI1	**0.11**	0.02	0.01	8	Klaver *et al*. (2020)
Murchison	CM2	**0.21**	0.03			Cameron *et al*. (2009)
Murchison	CM2	**0.23**	0.07	0.04	9	Gall *et al*. (2017)
Murchison	CM2	**0.19**	0.03	0.01	8	Klaver *et al*. (2020)
Murchison Avg.		**0.21**	0.04			
Paris	CM2	**0.23**	0.02		4	Zhu *et al*. (2022)
Kainsaz	CO3.2	**0.20**	0.03	0.01	8	Klaver *et al*. (2020)
Felix	CO3.3	**0.31**	0.07			Cameron *et al*. (2009)
Ornans	CO3.4	**0.29**	0.08	0.03	9	Gall *et al*. (2017)
Ornans	CO3.4	**0.21**	0.02	0.01	8	Klaver *et al*. (2020)
Ornans Avg.		**0.25**	0.11			
Renazzo	CR2	**0.16**	0.03	0.01	8	Klaver *et al*. (2020)
Al Rais	CR2	**0.22**	0.02	0.01	8	Klaver *et al*. (2020)
Leoville	CV3.1	**0.30**	0.05			Cameron *et al*. (2009)
Kaba	CV3.1	**0.22**	0.04			Wang *et al*. (2021)
Allende	CV3.6	**0.24**	0.07	0.02	9	Gall *et al*. (2017)
Allende	CV3.6	**0.24**	0.03	0.01	8	Klaver *et al*. (2020)
Allende	CV3.6	**0.25**	0.04			Wang *et al*. (2021)
Allende	CV3.6	**0.23**	0.02	0.01	4	Zhu *et al*. (2022)
Allende	CV3.6	**0.35**	0.04			This study
Allende Avg.		**0.26**	0.10			
Karoonda	CK4	**0.28**	0.02	0.01	8	Klaver *et al*. (2020)
Karoonda	CK4	**0.39**	0.04			Wang *et al*. (2021)
Karoonda Avg.		**0.33**	0.16			
ECs						
GRO 95517	EH3	**0.28**	0.03	0.02	2	This study
Qingzhen	EH3	**0.27**	0.04	0.03	2	This study
SAH 97096	EH3	**0.26**	0.06	0.04	2	This study
Kota-kota	EH3	**0.20**	0.03	0.01	8	Klaver *et al*. (2020)
Kota-kota	EH3	**0.26**	0.04			Wang *et al*. (2021)
Kota-kota	EH3	**0.21**	0.04			Wang *et al*. (2021)
Kota-kota Avg.		**0.22**	0.07			
Abee	EH4	**0.19**	0.05			Cameron *et al*. (2009)
Abee	EH4	**0.25**	0.02	0.01	7	Klaver *et al*. (2020)
Abee Avg.		**0.22**	0.09			
Indarch	EH4	**0.27**	0.09	0.03	9	Gall *et al*. (2017)
Indarch	EH4	**0.29**	0.05	0.04	2	This study
Indarch	EH4	**0.19**	0.03	0.01	8	Klaver *et al*. (2020)
Indarch Avg.		**0.25**	0.11			

Table S-1 continued.

Sample	Group	δ$^{60/58}$Ni (‰)	2 s.d.	2 s.e.	*n*	References
ECs (continued)						
St. Mark's	EH5	**0.18**	0.02	0.01	15	Klaver *et al.* (2020)
MAC 88184	EL3	**0.21**	0.08	0.05	2	This study
MAC 02837	EL3	**0.35**	0.03	0.02	3	This study
Khairpur	EL6	**0.29**	0.08	0.03	9	Gall *et al.* (2017)
Khairpur	EL6	**0.21**	0.02	0.01	11	Klaver *et al.* (2020)
Khairpur Avg.		**0.25**	0.12			
Atlanta	EL6	**0.21**	0.03	0.01	8	Klaver *et al.* (2020)
Hvittis	EL6	**0.22**	0.02	0.01	7	Klaver *et al.* (2020)
Yilmia	EL6	**0.21**	0.02	0.01	8	Klaver *et al.* (2020)
OCs						
A 10224	L3	**0.24**	0.01		3–5	Chernonozhkin *et al.* (2016)
Ceniceros	L3.7	**0.20**	0.03	0.01	8	Klaver *et al.* (2020)
Barratta	L4	**0.31**	0.05	0.02	9	Gall *et al.* (2017)
Barratta	L4	**0.19**	0.03	0.01	8	Klaver *et al.* (2020)
Barratta Avg.		**0.25**	0.16			
Bruderheim	L6	**0.51**	0.07	0.03	5	Gall *et al.* (2017)
Chainpur	LL3.4	**0.28**	0.10			Cameron *et al.* (2009)
Chainpur	LL3.4	**0.28**	0.04			Wang *et al.* (2021)
Chainpur Avg.		**0.28**	0.00			
Parnalee	LL3.6	**0.20**	0.03	0.01	8	Klaver *et al.* (2020)
A 09135	LL3	**0.15**	0.02		3–5	Chernonozhkin *et al.* (2016)
Parnalee	LL3	**0.16**	0.05	0.02	4	Gall *et al.* (2017)
Chelyabinsk	LL5	**0.27**	0.03	0.01	8	Klaver *et al.* (2020)
Dhurmsala	LL6	**0.22**	0.02	0.01	8	Klaver *et al.* (2020)
Kilabo	LL6	**0.25**	0.03	0.01	8	Klaver *et al.* (2020)
St. Severin	LL6	**0.24**	0.05		5	Gall *et al.* (2017)
A 09436	H3	**0.20**	0.04		3–5	Chernonozhkin *et al.* (2016)
Bremervorde	H3	**0.26**	0.05	0.03	5	Gall *et al.* (2017)
Buzzard Coulee	H4	**0.17**	0.03	0.01	8	Klaver *et al.* (2020)
Kernouve	H6	**0.37**	0.08	0.04	4	Gall *et al.* (2017)
Irons						
Negrillos	IIA	**0.31**	0.03	0.01	6	Gall *et al.* (2017)
North Chile	IIA	**0.36**	0.05	0.02	6	Gall *et al.* (2017)
Arispe	IC	**0.20**	0.06	0.03	5	Gall *et al.* (2017)
Clark County	IIIF	**0.30**	0.05	0.02	6	Gall *et al.* (2017)
Duel Hill	IVA	**−0.06**	0.06	0.02	6	Gall *et al.* (2017)
Gibeon	IVA	**0.31**	0.06	0.03	6	Gall *et al.* (2017)
Sikhote Alin	IIAB	**0.30**	0.06	0.03	6	Gall *et al.* (2017)
Charcas	IIIA	**0.23**	0.07	0.03	6	Gall *et al.* (2017)
Henbury	IIIA	**0.29**	0.07	0.03	6	Gall *et al.* (2017)
Coahuila	IIAB	**0.36**		0.04		Cameron *et al.* (2009)
Henbury	IIIAB	**0.24**		0.07		Cameron *et al.* (2009)
Bristol	IVA	**0.28**		0.05		Cameron *et al.* (2009)
Hoba	IVB	**0.33**		0.06		Cameron *et al.* (2009)
Santa Clara	IVB	**0.32**		0.03		Steele *et al.* (2011)
Nantan	IICD	**0.32**	0.03	0.02	3	Gueguen *et al.* (2013)
Gibeon	IVA	**0.26**	0.05	0.03	3	Gueguen *et al.* (2013)
Sikhote Alin	IIAB	**0.23**	0.10		3–5	Chernonozhkin *et al.* (2016)
Chinga	IVAB	**0.24**	0.03		3–5	Chernonozhkin *et al.* (2016)
Elga	IIE	**0.24**	0.04		3–5	Chernonozhkin *et al.* (2016)
Darinskoe	IIC	**0.23**	0.04		3–5	Chernonozhkin *et al.* (2016)

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