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Chemical and physical studies of type 3 chondrites—VI: Siderophile elements in ordinary chondrites

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Abstract—The abundances of Fe, Ni, Co, Au, Ir, Ga, As and Mg have been determined by instrumental neutron activation analysis in 38 type 3 ordinary chondrites (10 of which may be paired) and 15 equilibrated chondrites. Classification of type 3 ordinary chondrites into the H, L and LL classes using oxygen isotopes and parameters which reflect oxidation state (Fa and Fs in the olivine and pyroxene, and Co in kamacite) is difficult or impossible. Bulk compositional parameters, based on the equilibrated chondrites, have therefore been used to classify the type 3 chondrites. The distribution of the type 3 ordinary chondrites over the classes is very different from that of the equilibrated chondrites, the LL chondrites being more heavily represented. The type 3 ordinary chondrites contain 5 to 15 percent lower abundances of siderophile elements, and a compilation of the present data and literature data indicates a small, systematic decrease in siderophile element concentration with decreasing petrologic type. The type 3 ordinary chondrites have, like the equilibrated ordinary chondrites, suffered a fractionation of their siderophile elements, but the loss of Ni in comparison with Au and Ir is greater for the type 3 chondrites. These siderophile element trends were established at the nebula phase of chondritic history and the co-variation with petrologic type implies onion-shell structures for the ordinary chondrite parent bodies. It is also clear that the relationship between the type 3 and the equilibrated ordinary chondrites involves more than simple, closed-system metamorphism.

INTRODUCTION

THE CHONDRITIC METEORITES are aggregates of material that accreted in the solar nebula 4.6 Ga ago and have escaped subsequent planetary processing. During accretion, several chemical and physical processes occurred which produced the many chondritic classes. Classification of these meteorites therefore, not only provides a descriptive label for the meteorite, but it also has genetic relevance. The classification scheme for chondrites has, over the last 160 years, evolved into one incorporating bulk chemical data (UREY and CRAIG, 1953; UREY, 1961; AHRENS *et al.*, 1968; KALLEMEYN and WASSON, 1981; SEARS *et al.*, 1982b), the oxidation state of the Fe (as reflected in metal abundance, metal composition and silicate composition (PRIOR, 1920; KEIL, 1962; SEARS and AXON, 1976; AFIATTALAB and WASSON, 1980; KEIL and FREDRIKSSON, 1964; FREDRIKSSON *et al.*, 1968) and the relative abundances of the three isotopes of oxygen (CLAYTON *et al.*, 1976). Thus there are 2 classes of enstatite chondrites (EH and EL), 4 classes of carbonaceous chondrites (CI, CM, CV, and CO) and 3 classes of ordinary chondrites (H, L and LL).

On the basis of trends in bulk composition, four important element fractionating processes appear to have occurred; three of them, or perhaps all, occurred while the chondritic material was dispersed in the nebula. The processes that occurred are those which: (1) produced the lithophile element proportions appropriate to the carbonaceous, ordinary and enstatite values; (2) produced the siderophile element differences between the H, L and LL classes of ordinary chondrite, the EH and EL classes of enstatite chondrite and the CV and CO classes of carbonaceous chondrite; (3) affected elements with volatility intermediate between that of Au and Cd; (4) affected elements of volatility equal and greater to that of Cd. Possible mechanisms for achieving these fractionations have been well-reviewed (*e.g.* ANDERS, 1971; WASSON, 1972; SEARS, 1978). While there is controversy over the details of the processes responsible for fractionations 1, 3 and 4 above, there seems widespread agreement that process 2 involved the physical separation of metal and silicate.

Of the elements in the present study, Ir, Co, Fe, Ni, Au and As all had their present abundances in ordinary chondrites determined primarily by the metal-silicate fractionation. However, superimposed on this was a process which caused siderophile element ratios to differ from class to class by small but significant amounts. The present abundance of Ga and As were also determined in some part by process 3 above. This process has been identified with partial or complete loss of volatiles during chondrule formation, and with continual separation of gas and dust during condensation (WASSON, 1977; ANDERS, 1977).

During or after accretion, most chondrites experienced an episode of metamorphism (DODD, 1969). VAN SCHMUS and WOOD (1967) defined six petrologic "types" that summarize textural and the mineralogical variations which are presumed to reflect various degrees of metamorphic alteration. The least metamorphosed ordinary chondrites are members of petrologic type 3, types 1 and 2 being carbonaceous chondrites which have been aqueously altered (MCSWEEN, 1979). A variety of physical and chemical evidence enables division of type 3 into types 3.0 to 3.9, where the type < 3.2 are virtually unmetamorphosed, primitive aggregates (SEARS *et al.*, 1980; HUSS *et al.*, 1981; AFIATTALAB and WASSON, 1980). It is not clear whether metamor-

Table 1. Details of the samples analyzed in the present paper and some literature data.

Meteorite*	Source and Cat. No+	Class	Petrologic Type	Weathering	Fa@	Fs@	References†			Footnotes#
							Class	pet. type	Fa,Fs	
ALHA 76004	MWG	LL	3.2-3.4	A	17.3 ± 9.7	12.1 ± 8.0	1	3	1	g
77013	UNM (2)	L	3.5	B	18.7 ± 3.8	20.5 ± 7.9	27	3	27	
77015	MWG (23,25)	L	3.5	C	8.9 ± 5.5	13.2 ± 7.9	4	5	6	a
77167	MWG (11)	L	3.4	C	20.1 ±11.8	7.4 ± 6.4	4	5	6,7	a
77176	UNM (2)	L/H	3.2	B	12.4 ± 8.3	12.2 ± 8.9	5	3	4	
77197	UNM (2)	L	3.6	A/B	24.4 ± 3.0	12.3 ± 5.1	5	3	4	
77214	MWG (14,38)	L	3.4	C	19.6 ±12.7	10.3 ± 5.6	4	5	6	a
77216	MWG (38,39)	L	3.7-3.9	A/B	24	16	4	3	4	b
77249	MWG (11,21)	L	3.4	C	18.9 ± 7.9	11.0 ± 6.6	4	5	6	a
77260	MWG (22,23)	L	3.4	C	15.9 ± 7.2	10.8 ± 9.1	4	5	6	a
77278	MWG (31,40)	LL		A	26.8 ± 6.4	14.1 ± 4.5	4	5	6,7	
					16.6 ± 2.4	18.3 ± 3.8			6	
77299	MWG (44,45)	H	3.7	A	17.1 ± 5.7	13.7 ± 6.7	4	5	1	
					26.5 ± 2.0	15.7 ± 2.7			6	
77304	MWG (40,44)	L	3.8	B	25.5 ± 0.92	16.7 ± 6.3		3	1	
78038	MWG (12,14)	L	3.4	B	22.5 ±11.3	10.1 ± 6.5	4	5	6	a
					18.7 ± .32	16.7 ± 2.0			1	
79022	MWG (16)	L	3.7-4.0	A/B	23.6 ± 1.0	17.7 ± 5.1	9	3	1	
81024	MWG	L		B	19 ± 9	10 ± 9	4		18	
81025	MWG (7)	L		B	18 ±14	15 ±12	4		18	a
81030	MWG (8,10)	L		B/C	1-49	5-33	4		4	a
81031	MWG (11,13)	L		B/C	1-43	3-35	4		4	a
81032	MWG (6)	L		C	0-42	2-14	4		4	a
81251	MWG (8,9)	LL		B/C	14 ± 9.0	13 ± 9.0	4		18	c
Bremervörde	BM 33910	H	3.7-4.0	Fall	15.8 ± 2.4	12.5 ± 5.8	20	3	2	f
Dhajala	PRL (T67)	H	3.8	Fall			26	8		
Frenchman Bay	SI 5278 via UNM	H	3	Find			14	14		
Inman	UNM	L	3.4	Find			23	3	23	d
MezöMadaras	SI 4838		3.7	Fall	21.7 ± 7.2	14.1 ± 6.3		8	2	
Parnallee	BM (34792)		3.6	Fall	26.2 ± 7.3	15.7 ± 7.9		8	2	
Quinyambie	SI 6076	L	3.4	Find	21.9	15.8	16	5	16	
Ragland	UNM (C24)	L/LL	3	Find			14	14		
RKPA 79008	MWG (9,10)	L	3.7-3.8	B	22.6 ± 4.1	15.5 ± 6.0	4	3	1	
80207	MWG (6,7)	L	3.2	C	18.7 ± 4.1	15.3 ± 6.6	4	3	1	e
80256	MWG (8)	L	3.8	B	23.8 ± 1.1	15.6 ± 4.7	4	3	1	
Suwahib (Buwah)	BM(1983,428) via UNM(582)	L/H	3.6	Fall	13.5 ± 1.9	13.2 ± 7.8	15	3	15	h
Tieschitz	BM	H	3.6	Fall	19.9 ± 12	11.2 ± 7.8	20	2	2	
Willaroy	SI via UNM	H	3.5	Find	12.8 ± 3.4	11.8 ± 6.7	24	5	6,15	
					14.4 ± 0.8	13.3 ± 7.8				
Y 74191	NIPR (80)	L	3.6	A	21.4 ± 4.9	11.8 ± 7.0	12	5	1	
Types 4-6 ordinary chondrites										
AlHA 78084	MWG (35,91)	H	4	C	18.7 ± .32	16.7 ± 2.0	1	5,1	1	
82110	MWG (4,5)	H	4	B/C	1-24	4-27	11	11	11	
Alta Ameen	AR	LL		Fall						
Barwell	BM 1965,57	L	5	Fall						
Bruderheim	AML H7.45	L	6	Fall			20	20		
Butsura	BM 34795	H	6	Fall	18.4	16.7	20	20	22	
Crumlin	BM 86115	L	5				20	20		
Edmonson	JW	H		Fall						
Holbrook	AML57	L	6	Fall	24.6	20.8	20	20	22	
Jelica	BM 65605	LL		Fall	32.3	25.2	21	20	21	
Jilin(Kirin)	CAS	H		Fall						
Limerick	--	H	5	Fall						
Lunan	CAS	L		Fall						
Mangwendi	BM1934,839	LL	6	Fall	29.5	23.7	21	20	21	
RKPA 80213	MWG	H	6	B/C	19	17	4	4	4	i
Slovak	UA	H	5	Find	17.5 ± 0.3	15.5 ± 0.5	19	19	19	
Xingxang	CAS	H	5	Fall			25	25		

@ Errors quoted, where available, are ±1 standard deviation.

* ALHA, RKPA, and Y are abbreviations for Allan Hills, Reckling Peak, and Yamato, respectively.

\+ MWG - Meteorite Working Group of NASA/NSF (curatorial allocation number is given); UA - University of Arkansas Museum; BM - British Museum, Natural History; NIPR - National Institute of Polar Research, Tokyo (curatorial allocation number is given); UNM - Institute of Meteoritics, University of New Mexico, Albuquerque; SI - Smithsonian Institution, Washington; PRL - Physical Research Laboratory; CAS - Chinese Academy of Sciences, Guiyang, China; JW - Jim Westcott; AR - Y. Al-Rawi, College of Science, Bagdad, Iraq.

† 1. Scott (1984a); 2. Dodd et al. (1967); 3. Sears and Weeks (1983); 4. Anon (1984a); 5. Sears et al., (1982a); 6. B. Mason (unpublished); 7. J.N. Grossman (unpublished); 8. Sears et al. (1980); 9. C. Schwarz, per. comm., (August 20, 1982 letter); 10. Scott (1984b); 11. Anon (1984b); 12. Anon (1983b); 13. Yanai and Kojima (1984); 14. Scott, per. comm. (undated letter); 15. Scott et al.(1985); 16. Scott, per. comm. (July 12, 1982 letter); 17. McSween and Wilkening (1981); 18. Anon (1983a); 19. Scott, per. comm. (February 6, 1985 letter); 20. Van Schmus and Wood (1967); 21. Fredricksson et al. (1968b); 22. Keil and Fredricksson (1964); 23. Keil et al. (1978); 24. Chalmers and Mason (1977); 25. Bian (1981); 26. Das Gupta et al. (1978); 27. McKinley and Keil (1984).

\# a) Fragments of a single fall (dubbed Allan Hills A77011) according to Scott (1984b); b) paired with Allan Hills A77215 according to Scott (1984b); c) paired with Allan Hills A76004 according to Scott (1984b); d) Typographic error in ref. 3; e) Scott (1984a) found type H3.7 on the basis of silicate composition and heterogeneity, whereas Sears and Weeks found type 3.2 for the present samples based on TL. The present data for one fragment indicates an L classification while the other siderophile element abundance exceeds even H chondrite values and we assume is a metal-rich sample; f) the sample analyzed here is type 4, see Sears and Weeks (1983); g) samples for the present study provided by E. Jarosewich from a homogenized 20 g mass; h) oxygen isotope data suggest H group (see McSween and Wilkening (1981)); i) paired with Reckling Peak A80203 according to Scott (1984b).

phism alone converted type 3.0 to a type 6 chondrite (prograde metamorphism) or whether each meteorite is an assemblage of components which were metamorphosed to diverse degrees prior to, or during, aggregation of the meteorite parent bodies in the nebula (for example, hot accretion followed by autometamorphism) (DODD, 1969).

Bulk compositional studies of type 3 ordinary chondrites have been few and have tended to concentrate on the highly volatile elements such as In, Tl, Bi, Pb and inert gases (TANDON and WASSON, 1968; LAUL *et al.*, 1973; KEAYS *et al.*, 1971). These elements display a 10^3-fold variation in abundance and there has been considerable debate concerning whether this variation is metamorphism-related or whether it was accretionary (*e.g.* LARIMER and ANDERS, 1967; DODD, 1969). A recurring difficulty in the study of type 3 ordinary chondrites is identifying properties which resulted from nebular and accretionary processes and those which reflect their metamorphic history in the parent bodies.

DODD *et al.* (1967) compiled wet chemical bulk analyses of type 3 ordinary chondrites and DODD (1976) suggested that the type 3 chondrites contained lower abundances of siderophile elements than equilibrated ordinary chondrites, and therefore that the two meteorite groupings were not simply related through metamorphism. The details of this conclusion have subsequently been modified (DODD, 1981; JAROSEWICH and DODD, 1985). Recently MORGAN *et al.* (1985) found that two H chondrites of petrologic type 3 contain 10% lower abundances of siderophile elements than their equilibrated counterparts.

In the present paper, we report instrumental neutron activation analysis of 7 siderophile elements and magnesium in 38 type 3 ordinary chondrites (10 of which may be paired) and 15 equilibrated ordinary chondrites. We discuss the origin of type 3 ordinary chondrites with particular regard to the extent to which they can be classified into the groups defined on the basis of data for equilibrated chondrites, and the relationship between the type 3 and the equilibrated ordinary chondrites.

Table 2. Instrumental neutron activation analysis for eight siderophile elements and Mg in two samples of the Allende meteorite and literature data.

		Mg mg/g	Fe mg/g	Co µg/g	Ni mg/g	Ga µg/g	As[$] µg/g	Ir ng/g	Au ng/g
Allende (SI)[‡]	JA82	157	211	611	12.5	---	1.1	630	145
	DE82	162	243	698	13.9	8.2	1.9	777	126
	FE83	140	239	662	14.3	6.8	(87)	(963)	---
	JU83	140	236	662	13.8	6.4	(77)	772	151
	Mean	150	232	658	13.6	7.1	--	726	141
	% std dev	7.6	6.6	5.4	5.7	13.2	--	9.4	9.3
Allende (UA)[+]	FE83	143	285	783	15.7	---	--	818	138
	FE83	153	263	730	14.5	6.7	(45)	755	---
	FE83	151	265	752	16.6	8.2	(54)	794	169
	FE83	144	248	703	15.0	8.4	(53)	848	159
	JU83	138	230	652	13.1	5.6	(40)	664	112
	FE84	149	263	721	15.5	6.6	(48)	779	157
	OC84	149	234	666	16.5	5.8	(45)	852	160
	Mean	**147**	**255**	**715**	**15.3**	**6.9**	**(48)**	**787**	**149**
	% std dev	**3.6**	**5.2**	**6.4**	**8.0**	**17.1**	**11.1**	**8.2**	**13.9**
Literature[*]	Mean	148	237	662	13.3	6.0	1.55	785	145
	% std dev	---	3.5	4.1	5.9			9.8	28

[‡] Smithsonian Institution standard powder, split 3, position 18.

[+] Homogenized powder from a 2 g chip off NMNH (3636)

[*] References given in Weeks and Sears (1985); complete compilation available from the authors on request.

[$] Values in parenthesis may refer to contaminated samples which are used here as a secondary standard.

EXPERIMENTAL

The samples analyzed for the present study are listed in Table 1 with certain literature data. The data reported here were gathered in six irradiations over a period of three years during which there was continual improvement in our methods; the irradiations are therefore identified. A brief report based on the results of the first irradiation was made by SEARS (1982). Whenever possible, duplicate chips taken from different lithologies were analyzed, and the Allende meteorite was also analyzed as a check for systematic errors in our methods. The samples were coarsely ground and 100–200 mg samples placed in cleaned high-density polyethylene vials. (The vials were obtained from Vrije Universiteit Biologish Laboratorium, Amsterdam.) Although small, these sample masses appeared to be reasonably representative of the meteorites as, with one exception, agreement between duplicates or replicates is very good. Standards were prepared by dissolving 99.9–99.999 percent pure elements or oxides in the appropriate acids, and pipetted onto ground, high purity silica glass and allowed to dry at 100°C. After the vials were labelled and heat-sealed they were twice irradiated using the pneumatic transfer tubes at the University of Missouri research reactor, Columbia, Missouri (10^{14} n/cm^2 sec). A five second irradiation was followed by two 2-minute counts, 4 and 8 minutes after irradiation, and a 15–30 minute irradiation was followed by 6–8 counts of 15 minutes to 12 hours duration performed over a period of 8 weeks. Thus elements which activated to produce nuclides of 1 minute to 5 year half-lives were determined. High-purity germanium detectors and Nuclear Data 66 analyzers were used for gamma counting, the sample-detector distance being adjusted to reduce dead-time correction to acceptable levels. The data were reduced using the SPECTRA program (BAEDECKER, 1976) and scrutinized for internal inconsistencies. The peaks for Ga and As were plotted using the EZGRAF program, the baseline inserted by eye and SPECTRA's value adjusted accordingly.

RESULTS

Our analysis of the Allende meteorite powder, type 3 ordinary chondrites, and equilibrated ordinary chondrites are presented in Tables 2, 3 and 4, respectively. Two samples of the Allende meteorite were used. The first was produced from a large homogenized mass and widely distributed by the Smithsonian Institution to be used as a standard (referred to as SI sample), the other from 2 g of homogenized powder from piece NMNH 3636 which was used by SEARS and MILLS (1974) for a thermoluminescence study (referred to as UA sample). Most of the literature data used to compile the values indicated in the table are for other splits from the Smithsonian standard and they agree very well with our SI data. The UA sample agrees well for Mg and Ir, but is about 10% enriched in Fe, Co, Ni and Au, presumably reflecting a slight metal enrichment in this sample. The precision of our procedures was calculated as follows. Our siderophile element concentrations were multiplied by 0.9, to correct for the metal difference in our sample, and the data pooled with that for our SI data. The standard deviation for the combined data was then divided by $\sqrt{2}$ to give the error on a duplicate sample. The results, as percentages of the means, were as follows: Mg 3.7, As 10, Ga 11, Fe 4.8, Ni 4.9, Co 4.1, Ir 6.1, and Au 8.5. Our Allende data for As agreed well with literature for the first two irradiations, after which our stock samples became contaminated, however, they continued to serve as a useful secondary standard.

Table 3. Instrumental neutron activation analysis for seven siderophile elements and magnesium in 38 type 3 ordinary chondrites.*

sample	irr.$^{+}$	weight mg	Mg mg/g	Fe mg/g	Co µg/g	Ni mg/g	Ga µg/g	As µg/g	Ir ng/g	Au ng/g
ALHA 76004	FE83	125.9†	146	217	536	11.4	6.4	1.0	369	(495)
ALHA 81251	OC84	166.7	135	222	786	17.1	2.7	1.5	860	178
ALHA 77013	DE82	146.5	147	214	574	11.2	---	1.5	372	230
	FE83	122.1	144	208	454	9.6	3.7	1.1	425	
	Mean		**146**	**211**	**514**	**10.4**	**3.7**	**1.3**	**398**	**230**
ALHA 77015	NO81	162.7	--	195	493	11.9			394	144
	JA82	137.7	159	189	485	10.5			431	163
	Mean		**--**	**182**	**489**	**11.2**			**413**	**154**
ALHA 77167	NO81	137.6	--	213	478	10.6			483	172
	JA82	153.4	148	178	442	9.4			362	119
	FE84	187.6	142	219	619	12.5	6.6	1.3	491	146
	Mean		**145**	**205**	**513**	**10.8**			**445**	**146**
ALHA 77214	NO81	173.0	--	198	575	13.7			388	154
	JA82	149.4	142	215	653	13.6			452	200
	FE84	177.1	149	233	644	13.4	6.8	1.3	465	174
	Mean		**146**	**215**	**624**	**13.6**			**435**	**176**
ALHA 77249	JU83	125.6	144	238	603	12.1	5.3	.98	460	177
	FE84	177.1	141	220	520	11.3	6.0	1.4	480	138
	Mean		**143**	**229**	**562**	**11.7**	**5.7**	**1.1**	**470**	**158**
ALHA 77260	JU83	137.2	149	222	475	10.7	3.4	1.3	442	107
	FE84	163.4	152	202	523	11.0			410	107
	Mean		**151**	**217**	**499**	**10.9**			**426**	**107**
ALHA 78038	JU83	150.7	142	214	564		5.4	1.1	474	163
	FE84	178.1	142	203	498	10.4	4.0	1.5	457	114
	Mean		**142**	**109**	**531**	**10.4**	**4.7**	**1.3**	**466**	**139**
ALHA 81025	OC84	175.0	137	225	508	10.7	3.6	1.3	451	182
ALHA 81030	OC84	137.0	140	208	632	11.0	5.6	1.5	449	161
ALHA 81031	OC84	131.0	137	213	591	11.2	3.8	1.5	417	153
ALHA 81032	OC84	196.9	132	198	365	6.76	5.5	1.2	420	201
ALHA 77176	DE82	131.7	156	202	502	10.4	---	1.3	349	90.5
	FE83	127.8	152	201	449	9.7	3.5	1.3	325	114
	Mean		**154**	**202**	**475**	**10.1**	**3.5**	**1.3**	**337**	**102**
ALHA 77197	DE82	150.9	145	226	586	13.4	---	1.6	481	156
	FE83	147.8	133	211	638	13.9	4.2	1.9	512	180
	Mean		**139**	**218**	**612**	**13.6**	**4.2**	**1.7**	**496**	**168**
ALHA 77216	DE82	141.6	134	262	(1024)	14.1	--	(3.2)	564	94.7
	FE83	150.5	138	236	694	14.4	3.1	2.0	545	
	Mean		**136**	**244**		**14.2**			**554**	**94.7**
ALHA 77278	NO81	171.4	--	199	466	12.0			576	146
	JA82	151.2	155	196	372	8.8			340	117
	Mean		**155**	**198**	**419**	**10.4**			**458**	**132**
ALHA 77299	JA82	150.0	141	261	786	16.2			689	235
	FE84	184.5	137	295	915	18.9	7.4	2.1	818	225
	Mean		**139**	**278**	**850**	**17.6**			**754**	**230**
ALHA 77304	FE83	145.9	140	217	602	11.4	--	2.1	328	168
ALHA 79022	JU83	153.9	--	259	810	15.9	5.8	1.7	629	159
ALHA 81024	OC84	158.5	124	242	732	13.8	5.2	1.6	680	220
Bremervörde	DE82	137.7	137	260	866	15.7	--	3.0	605	247
Dhajala	DE82	149.1	142	289	969	19.9	17.2	2.4	913	139
	FE83						8.1	2.6		
Frenchman Bay	OC84	202.1	--	250	717	13.2	4.8	1.9	708	254
Inman	DE82	126.3	142	218	410	9.14	--	3.0	398	125
MezöMadaras	NO81	130.0	--	240	640	15.7			490	199
	JA82	149.9	154	197	491	10.6			379	344
	Mean			**219**	**566**	**13.2**			**434**	
Parnallee	DE82	143.9	158	194	439	9.6	--	.81	322	165
	FE83	158.9	145	190	385	9.1	4.3	1.0	348	128
	Mean		**151**	**192**	**412**	**9.4**	**4.3**	**0.91**	**335**	**147**
Quinyambie	JA82	42.6	149	190	632	13.0			319	211
Ragland	OC84	203.2	133	200	359	8.7	3.8	1.1	377	135
RKPA 79008	DE82	150.1	142	210	478	11.8	--	1.9	504	92.5
RKPA 80207	DE82	135.4	146	223	658	13.9	5.4	1.7	618	158
	FE83$	125.0	120	308	1108	20.9	8.1	3.5	830	214
	Mean		**146**	**223**	**658**	**13.9**	**5.4**	**1.7**	**618**	**158**
RKPA 80256	DE82	157.1	147	218	556	13.0	---	0.85	491	103
	FE83	147.9	134	237	644	13.6	5.9	1.7	559	211
	Mean		**140**	**228**	**600**	**13.3**	**5.9**	**1.3**	**525**	**157**
Suwahib (Buwah)	DE82	145.0	152	228	658	12.5	---	2.1	499	(97)
	FE83	84.5	133	225	643	14.2	7.7	2.0	512	202
	Mean		**143**	**227**	**651**	**13.3**	**7.7**	**2.1**	**506**	**202**
Tieschitz	DE82	126.9	145	219	684	13.3	---	2.2	559	105
Willaroy	OC84	119.9	115	277	668	12.1	5.3	2.6	788	219
Yamato 74191	JA82	151.6	156	187	382	9.8	---	---	324	120
	FE84	194.5	150	190	417	9.0	5.6	1.4	335	99
	Mean		**153**	**188**	**400**	**9.4**	**5.6**	**1.4**	**330**	**110**

* Values in parenthesis are considered unreliable.

+ Irradiation identification.

† From a homogenized 20 g powder sample prepared by E. Jarosewich, Smithsonian Institution.

\$ Metal-rich, not included in the mean and plots.

Of our 15 equilibrated chondrites, 8 were analyzed in duplicate and 1 in triplicate. Agreement between duplicates was assumed to be satisfactory if the data were within 10%. Uniform differences in siderophile elements clearly indicate variation in the silicate-metal proportions in our samples. In one instance (Edmonson) a low Mg value accompanies low siderophile values and probably reflects a large component of weathered material in this badly weathered find. Gold seems to be particularly heterogeneously distributed and often shows poor agreement between duplicates; we doubt problems with our methods as an explanation for the scatter, since Allende data and equilibrated group means seem satisfactory.

We have also evaluated our data by comparing our results for the equilibrated chondrites by comparison with literature data (Fig. 1). Mason (1979) has compiled compositional data for the chondritic meteorites, although he made no attempt to discriminate between petrologic types. In Fig. 1 we plot selected literature data for the types 4–6 and types 3, and we discriminate between authors responsible for the data where it is helpful (see Table A2 for references). The extent to which the H, L and LL classes can be recognized on the basis of bulk composition can be assessed using Fig. 1.

The presence of a good hiatus between the equilibrated H and L chondrites in Fe and Ni is well known and is displayed well by the data of Wiik and Jarosewich in various publications (see Table A2). However, the LL chondrites do not form a well separated group, but instead grade into the L chondrites. For this reason Mason (1965) considered the LL chondrites a sub-class of the L chondrites. Although the hiatus is less well-defined, Co shows a very similar distribution to Fe and Ni in both the Wiik and Jarosewich wet-chemical data and Schmitt *et al.*'s (1972) INAA data. The distribution of Ir determined by Müller *et al.* (1971) and Ehmann *et al.* (1970) is very similar to that of Fe and Ni, there is a good resolution of H and L chondrites. The LL chondrites lie at the lower end of the L range and grade into them.

Literature data for Au, Ga, and As are slightly more equivocal. The Keays *et al.* (1971) data for Au in L chondrites agrees well with those of the other authors, but while the Fouché and Smales (1967) data resolve the H and L chondrites, despite some overlap, the Ehmann and Gillum (1972) data do not. The data of Keays *et al.* (1971) and Chou *et al.* (1973) agree in indicating that the H and L classes show a narrow, and totally overlapping range of Ga values and the Purdue group (Binz *et al.*, 1976; Case *et al.*, 1973) data also indicates overlapping range although the data scatter more. Arsenic shows non-overlapping ranges for the H and L chondrites according to the data of Fouché and Smales (1967), but the older data do not clearly resolve the groups. The data of CASE *et al.* (1973) and BINZ *et al.* (1976) also indicate higher As values for the H than the L chondrites, but their values seem to be systematically lower than the other authors.

Table 4. Instrumental neutron activation analysis for eight siderophile elements and magnesium in 15 equilibrated ordinary chondrites.*

sample	irr.[+]	weight mg	Mg mg/g	Fe mg/g	Co µg/g	Ni mg/g	Ga µg/g	As µg/g	Ir ng/g	Au ng/g
ALHA 78084	N081	186.6	--	243	698	17.9			741	190
	JA82	149.4	141	257	782	16.5			817	219
	Mean		**141**	**250**	**740**	**17.2**			**779**	**204**
Alta Ameen	JU83	151.1		189	476	9.4	4.8	0.97	416	--
	FE84	204.4	148	222	582	10.9	5.9	1.5	445	126
	Mean		**148**	**206**	**529**	**10.1**	**5.4**	**1.2**	**431**	**126**
Barwell	JU83	150.5		207	607	10.2	6.0	1.1	447	(247)
	FE84	199.8	160	205	415	11.5	4.5	1.0	461	143
	Mean		**160**	**206**	**511**	**10.9**	**5.3**	**1.1**	**454**	**143**
Bruderheim	JU83	149.8	143	221	486	13.9	6.0	1.0	517	164
	FE84	201.2	147	209	399	12.0	5.3	1.2	495	129
	Mean		**145**	**215**	**442**	**13.0**	**5.7**	**1.1**	**506**	**146**
Butsura	JU83	149.6	134	274	838	17.8	6.9	1.8	786	299
	FE84	152.7	143	286	841	18.4	4.7	1.8	759	201
	Mean		**138**	**280**	**840**	**18.1**	**5.8**	**1.8**	**772**	**250**
Crumlin	0C84	205.7	140	220	499	12.6	4.6	1.3	499	172
Edmonson	JU83	151.6	126	252	771	16.7	5.3	1.3	759	131
	FE84	204.1	144	289	828	18.2	5.2	1.9	849	196
	Mean		**135**	**271**	**799**	**17.5**	**5.3**	**1.6**	**804**	**164**
Holbrook	JU83	149.7	144	252	962	15.3	5.8	--	538	107
	FE84	192.7	146	253	875	15.4	3.0	2.0	546	175
	Mean		**145**	**252**	**919**	**15.4**	**4.4**	**2.0**	**542**	**141**
Jelica	JU83	155.5	150	197	462	10.1	4.6	0.70	346	75.2
	FE84	201.6	150	196	434	9.1	6.1	0.64	347	110
	Mean		**150**	**197**	**448**	**9.6**			**346**	**92.5**
Jilin	JA82	149.9	146	255	754	17.7			825	241
Limerick	0C84	207.1	136	296	956	18.1	3.7	2.2	767	262
Lunan	N081	165.5	--	234	635	13.6	--	--	428	181
	JA82	149.6	154	203	615	13.3	--	--	484	162
	0C84[$]	191.4	134	269	850	20.5	4.2	2.1	877	241
	Mean		**154**	**219**	**625**	**13.5**	**4.2**	**2.1**	**456**	**172**
Mangwendi	0C84	200.1	143	225	628	13.9	6.7	1.5	483	190
RKPA 80213	0C84	163.8	131	271	889	16.6	4.9	2.0	736	232
Slovak	FE84	167.2	140	231	694	18.9	7.3	1.9	781	211
Xingyang	N081	176.2	145	270	877	18.9			781	204
	JA82	148.2	145	290	962	18.8			722	255
	Mean		**145**	**280**	**920**	**18.8**			**752**	**229**

* Values in parentheses are considered unreliable.

[+] Irradiation identification.

[$] This sample is metal-rich, not included in the mean.

DISCUSSION

We are mainly interested in the relationship between the type 3 chondrites and the equilibrated chondrites. However, it is also necessary to discuss the related question, which is of considerable relevance to their origin, of how (and whether) the type 3 chondrites can be assigned to the H, L and LL classes.

Classification

Bulk composition. In Fig. 2 we plot the Mg and CI normalized compositional data for type 3 ordinary chondrites. An analogous plot for types 4–6 has been used to define boundaries for the H, L and LL classes. For these elements a Mg- and CI-normalized ratio of about 0.9 seems to serve well to separate the H and L classes. The LL chondrites tend to have lower siderophiles than the L chondrites, but since they are not separated from the L group by a distinct hiatus an almost arbitrary choice of parameters is required. Additionally, because there appears to have been a siderophile element fractionation as well as a metal-silicate fractionation, the element/Mg ratio which separates the L and LL chondrites will vary from element to element. On the basis of type 4–6 chondrites, the following element/Mg ratios (CI normalized) represent our best attempt to define L and LL chondrites compositionally: iridium, 0.56; Co, 0.63; Ni, 0.67; Fe, 0.71; and Au, 0.63. Using these ratios, the type 3 chondrites can be assigned to the classes indicated in Table 5. An attempt has also been made to indicate the degree of certainty; the classification of L and LL chondrites is never better than "probable".

Thus defined, of the 40 type 3 ordinary chondrites for which there exists compositional data, there are 8 H chondrites, 16 L chondrites, 16 LL chondrites. The distribution is unlike that of the type 4–6 chondrites (38.5% H, 53.7% L and 7.8% LL; VAN SCHMUS and WOOD, 1967), even when the H class is compared with L + LL to remove the uncertainty over using bulk composition to separate L and LL chondrites.

The distribution of type 3 chondrites over the petrologic types 3.0–3.9 is not the same in the three classes. Assuming the class assignments in Table 5 and the petrologic types listed in Table 1, the distributions over the petrologic type are shown in Fig. 3. The LL chondrites are the only class which covers the whole spectrum of petrologic types, but there are relatively few at the upper end. In contrast, the H chondrites appear to be predominantly at the upper end of the scale and there are no known H chondrites of petrologic type < 3.4. The L chondrites seem to occupy the middle part of the distribution. In short, on the basis of existing data it seems that the metamorphic intensity experienced increases in the order LL, L and H.

Oxidation state. KEIL and FREDRIKSSON (1964) and FREDRIKSSON *et al.* (1968b) showed that equilibrated chondrites could be readily separated into the H, L and LL classes on a plot of the fayalite content of the olivine against the ferrosilite content of the pyroxene. Figure 4 is such a plot for the type 3 ordinary chondrites with the fields occupied by the equilibrated ordinary chondrites superimposed. The meteorites which are identified as H chondrites in Table 5 lie at the lower end of the Fa and Fs distributions, while the majority of the L chondrites plot at the upper part of the distribution. However those meteorites assigned to the LL class scatter widely, being spread almost uniformly over the Fa and Fs values displayed by the unequilibrated members of all three classes. The H, L and LL classes cannot clearly be resolved in Fig. 4. The heterogeneity causes considerable uncertainty in each point, and much of the scatter reflects this, but despite this uncertainty the chondrites plot below the fields

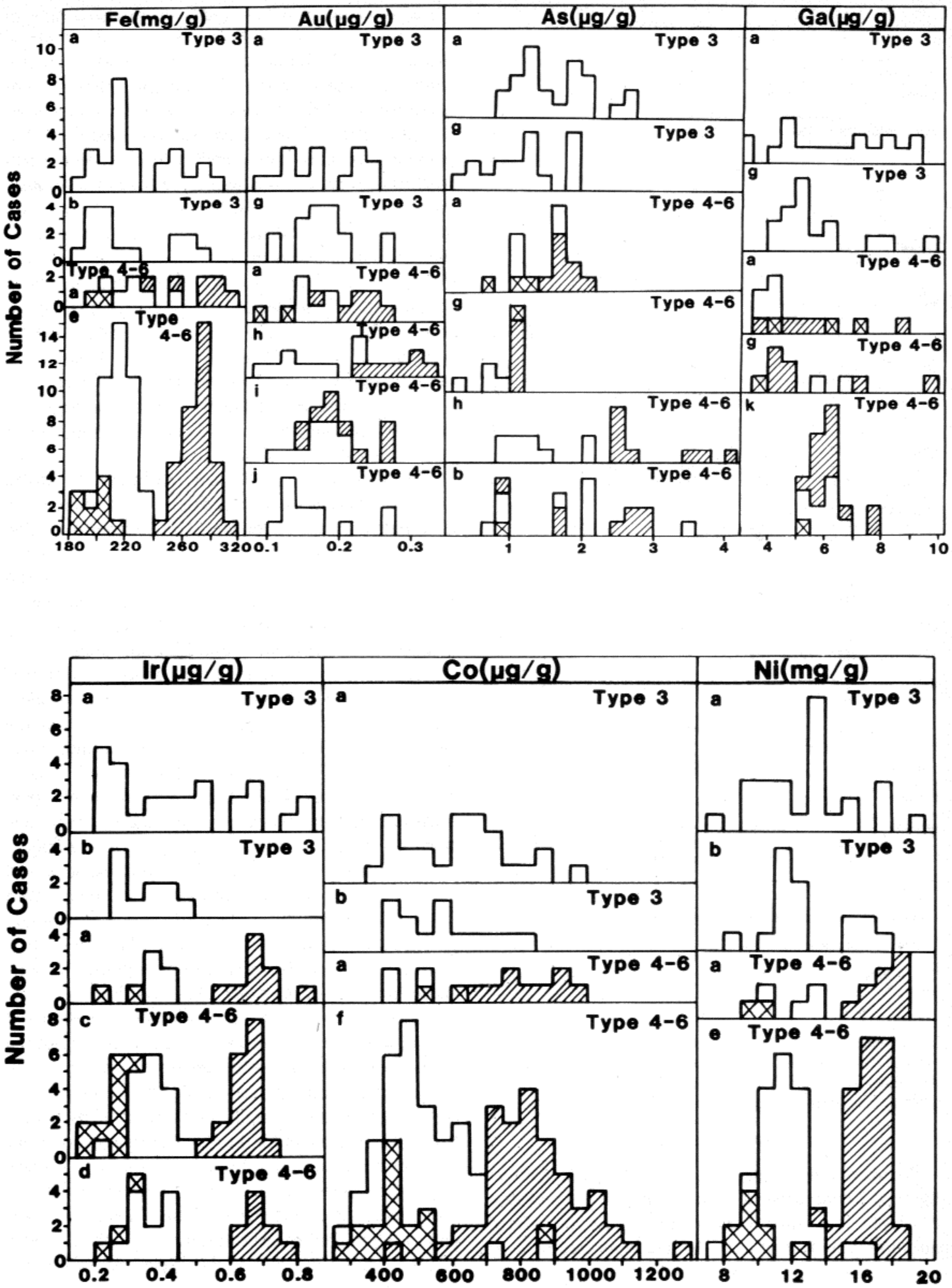

FIG. 1. Histograms of concentrations of Ir, Co, Ni, Fe, Au, As and Ga in equilibrated and type 3 ordinary chondrites according to the present work and literature data. For the equilibrated meteorites, the classification is indicated; diagonal shading H chondrites, cross-hatching LL chondrites, no shading L chondrites. The letters in the upper left for each histogram indicate data source: a) present data; b) literature data (see Table A2); c) MÜLLER *et al.* (1971); d) EHMANN *et al.* (1970); e) wet-chemical analyses by Wiik and Jarosewich (see Table A2); f) SCHMITT *et al.* (1972); g) CASE *et al.* (1973); h) FOUCHÉ and SMALES (1967); i) EHMANN and GILLUM (1972); j) KEAYS *et al.* (1971); k) CHOU *et al.* (1973).

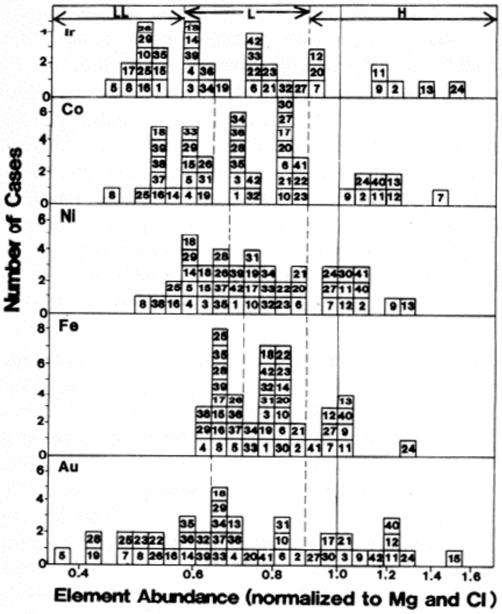

FIG. 2. Histograms of Mg and CI normalized element abundances in unequilibrated ordinary chondrites using both literature and the present data. The vertical broken lines indicate boundaries between the H, L and LL classes as inferred from data for equilibrated chondrites. Key to meteorite identification: Data from Table 3—1. ALHA 76004; 2. ALHA 81251; 3. ALHA 77013; 4. ALHA 77015 (ALHA 77167, 77214, 77249, 77260, 78038, 81025, 81030, 81031, 81032 not plotted on the assumption they are paired with ALHA 77015); 5. ALHA 77176; 6. ALHA 77197; 7. ALHA 77216; 8. ALHA 77278; 9. ALHA 77299; 10. ALHA 77304; 11. ALHA 81024; 12. Bremervörde; 13. Dhajala; 14. Inman; 15. Mezö Madaras; 16. Parnallee; 17. Quinyambie; 18. Ragland; 19. RKPA 79008; 20. RKPA 80207; 21. RKPA 80256; 22. Suwahib (Buwah); 23. Tieschitz; 24. Willaroy; 25. Yamato 74191. Data from the literature (Table A2); 26. Bishunpur; 27. Bremervörde; 28. Carraweena; 29. Chainpur; 30. Clovis; 31. Goodland; 32. Hallingberg; 33. Ioka; 34. Khohar; 35. Krymka; 36. Manych; 37. Ngawi; 38. Parnallee; 39. Semarkona; 40. Sharps; 41. Tieschitz; 42. Mezö Madaras.

occupied by the equilibrated meteorites with remarkably few exceptions. DODD *et al.* (1967) also observed that the Fa content of olivine tended to decrease with increasing silicate heterogeneity, and that the effect was particularly marked for the LL and L chondrites. The olivines and pyroxenes, or at least those which are normally used for classification purposes, in the type 3 ordinary chondrites are apparently more reduced than their supposed equilibrated counterparts. The difference is particularly marked for the pyroxenes; this may be related to the diffusion of cations through pyroxene being more sluggish than diffusion through olivine. We return to this point below.

Similar trends may be present in the Co content of the kamacite (Fig. 5), another parameter which reflects the oxidation state of the iron (SEARS and AXON, 1975, 1976). The H and L classes have narrow ranges and discretely different amounts of Co in the kamacite (4–6 and 8–10 mg/g, respectively), while LL chondrites

Table 5. An attempted classification of type 3 ordinary chondrites on the basis of bulk composition.#

Meteorite	No$	Ir	Co	Ni	Fe	Au	Selected Class	Conf@	Lit. Classif.*
ALHA 76004	1	LL	L	Lm	L	ND	L	2	LL(2)
ALHA 77013	3	Lm	L	LL	L	H	LL	3	L(27)
ALHA 77015	4	Lm	LL	LL	LL	L	LL	2	LL(2)
ALHA 77176	5	LL	LL	LL	LLm	LL	LL	2	L(5)
ALHA 77197	6	L	L	Lm	L	L	L	2	L/H(5)
ALHA 77216	7	Hm	H	H	L/H	LL	H	1	L(4)
ALHA 77278	8	LL	LL	LL	LL	LL	LL	2	LL(17)
ALHA 77299	9	H	H	H	H/L	LL	H	1	H(4)
ALHA 77304	10	LL	L	L	L	L	L	2	L(4)
ALHA 81024	11	H	H	H	H	H	H	1	L(4)
ALHA 81251	2	H	H	H	Lm	Lm	H	1	LL(4)
ALHA 79022							L		L(9)
Bishunpur	26	LL	LLm	LL	LL	LL	LL	2	L/LL(2)
Bremervorde	27	HmLm	L	H	H	Hm	H	1	H(2)
Carraweena	28	ND	ND	LL	LL	LL	LL	2	L(2)
Chainpur	29	LL	LL	LL	LL	Lm	LL	2	L/LL(2)
Clovis #1	30	ND	L	H	ND	H	H	1	H(2)
Dhajala	13	H	H	H	H	L	H	1	H(26)
Frenchman Bay							L		L(5)
Goodland	31	ND	ND	ND	L	L	L	2	L(2)
Hallingberg	32	L	L	L	L	LLm	L	2	L/LL(2)
Inman	3	?	?	LL	L	LL	L	2	L(23)
Ioka	33	L	ND	L	Lm	Lm	L	2	L(2)
Khohar	34	L	L	L	Lm	Lm	L	2	L/LL(2)
Krymka	35	LL	L	LLm	LL	LL	LL	2	LL(2)
Manych	36	L	L	LL	LLm	LL	LL	2	L/LL(2)
Mezo Madaras Lit†	42	L	L	Lm	L	H	L	2	L/LL(2)
Mezo Madaras Pres†	15	LL	LL	LL	LL	H	LL	2	--
Ngawi	37	ND	ND	LLm	LLm	Lm	LL	2	LL(2)
Parnallee	38	LL	LL	LL	LL	LL/L	LL	2	LL(20)
Quinyambie	17	LL	L	L	LL	LL	LL	2	L(16)
Ragland	18	Lm	LL	LL	L	Lm	LL	3	L/LL(14)
RKPA 79008	19	L	LLm	L	L	LL	L	2	L(4)
RKPA 80207	20	Hm	L	Lm	L	L	L	2	L(4)
RKPA 80256	21	L	L	Lm	Lm	H	L	2	L(4)
Semarkona	39	Lm	LL	Lm	LL	LLm	LL	2	LL(2)
Sharps	41	ND	H	H	H	H	H	1	H(2)
Suwahib	22	L	Lm	L	ND	ND	L	2	L/H(15)
Tieschitz	23	L	Lm	L	L/H	L/LL	L	3	H(2)
Willaroy	24	H	H	H	H	H	H	1	H(24)
Y 74191	25	LL	LL	LL	LL	LL	LL	2	

 # Lower case "m" indicates "marginal", ND indicates "no data". (No Mg data for ALHA 79022 and Frenchman Bay.)

$ Number in Fig. 2.

@ A subjective evaluation of the level of confidence we have in the present classification; 1 high, 3 low.

* See Table 1 for references.

† Literature data indicate L classification, while the present data indicate LL.

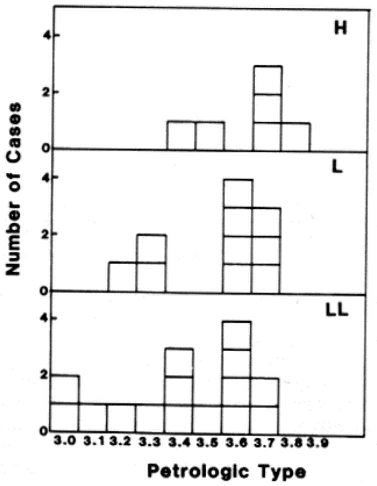

FIG. 3. Distribution of type 3 ordinary chondrites over the petrologic types.

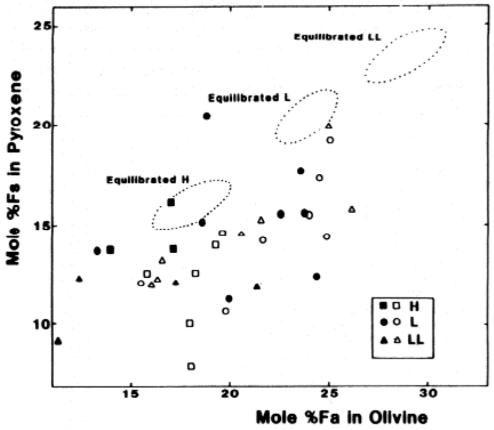

FIG. 4. Plot of the ferrosilite content of the pyroxene against the fayalite content of the olivine for type 3 ordinary chondrites. Data from sources in Table 1 and classifications from Table 5. Samples analyzed in the present study are indicated by filled symbols. The dotted ellipsoids indicate the well-defined fields of the equilibrated chondrites and are taken from KEIL and FREDRIKSSON (1964) and FREDRIKSSON *et al.* (1968b).

have a large range and high amounts of Co in the kamacite (20–100 mg/g). Data for the type 3 chondrites is rather meager. Many have L group values of Co in the kamacite, however, Bishunpur and Semarkona, for which bulk composition indicates an LL chondrite classification, have H group values of Co in the kamacite. Bishunpur and Semarkona are petrologic type 3.1 and 3.0, respectively, so again there is an indication that the lower petrologic types are more reduced.

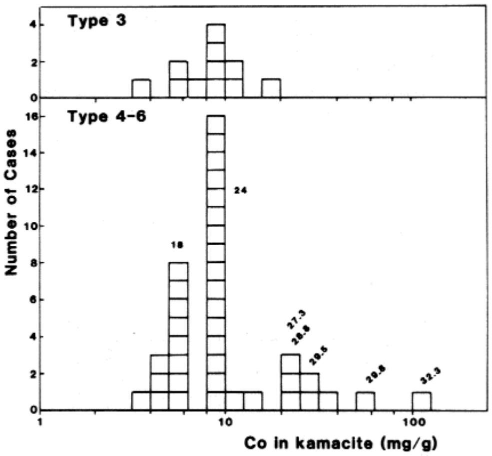

FIG. 5. Histograms showing the Co content of the kamacite in type 3 and type 4–6 ordinary chondrites. The values refer to typical fayalite contents of the olivine (mole %). Data sources for type 4–6 are AFIATALLAB and WASSON (1980) and Appendix A3. From left to right the type 3 chondrites are as follows (data from AFIATTALAB and WASSON, 1980, see Appendix A3, except as indicated): 1. Semarkona; 2. Sharps; 3. Bishunpur; 4. ALHA 77011 (MCKINLEY *et al.*, 1981); 5. ALHA 79003 (SCOTT *et al.*, 1982); 6. Mezö Madaras; 7. Khohar; 8. Hallingeberg; 9. Parnallee mean of AFIATTALAB and WASSON's (1980) value and Appendix A3 value; 10. Chainpur; 11. ALHA 77278 (MCSWEEN and WILKENING, 1981).

Oxygen isotopes. The oxygen isotope data are summarized in Fig. 6. The situation is somewhat similar to bulk composition, the equilibrated H chondrites are well resolved from the equilibrated L and LL chondrites, but resolution of the L and LL chondrites is, at best, weak. Most significantly, the type 3 chondrites contain heavier oxygen than the others and can, in principle, be related to the equilibrated chondrites by mass-fractionation as they lie along a line with a slope of 1/2. However, it is difficult to understand how this could have been physically achieved if the most obvious mechanism is involved, namely the loss of O as CO(g) (SEARS and WEEKS, 1983). The extent of heavy isotope enrichment is related to petrologic type with Semarkona, Krymka, and Bishunpur having the greatest enrichment. The amount of scatter above and below the mass fractionation line probably reflects heterogeneity in the distribution of an ^{16}O-rich component, such as that known to be present in Allan Hills A76004 (MAYEDA *et al.*, 1980). Despite this scatter, there is some indication that LL, L and H type 3 chondrites can be resolved and lie on mass fractionation lines connecting them to the equilibrated classes.

Siderophile elements in type 3 ordinary chondrites

Siderophile elements and petrologic type. The present data indicate that type 3 chondrites are systematically lower in siderophile elements than the equilibrated meteorites. The group means for siderophile elements in type 3 and for equilibrated chondrites based on the present data are plotted in Fig. 7. The amount of depletion varies from about 5 to 15 percent, which is comparable with the uncertainty of the analyses, but is probably present in the LL, L and H classes for all the elements considered except Ga.

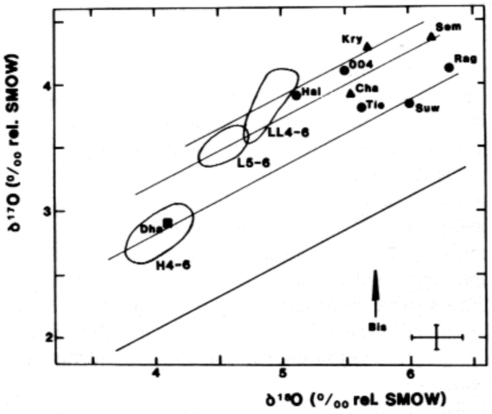

FIG. 6. Three isotope diagram for oxygen in ordinary chondrites. The fields of the equilibrated chondrites and certain individual type 3 chondrites are indicated. One sigma error bars are shown. Squares, circles and triangles refer to H, L and LL chondrites, respectively (CLAYTON *et al.*, 1981; SCOTT *et al.*, 1985).

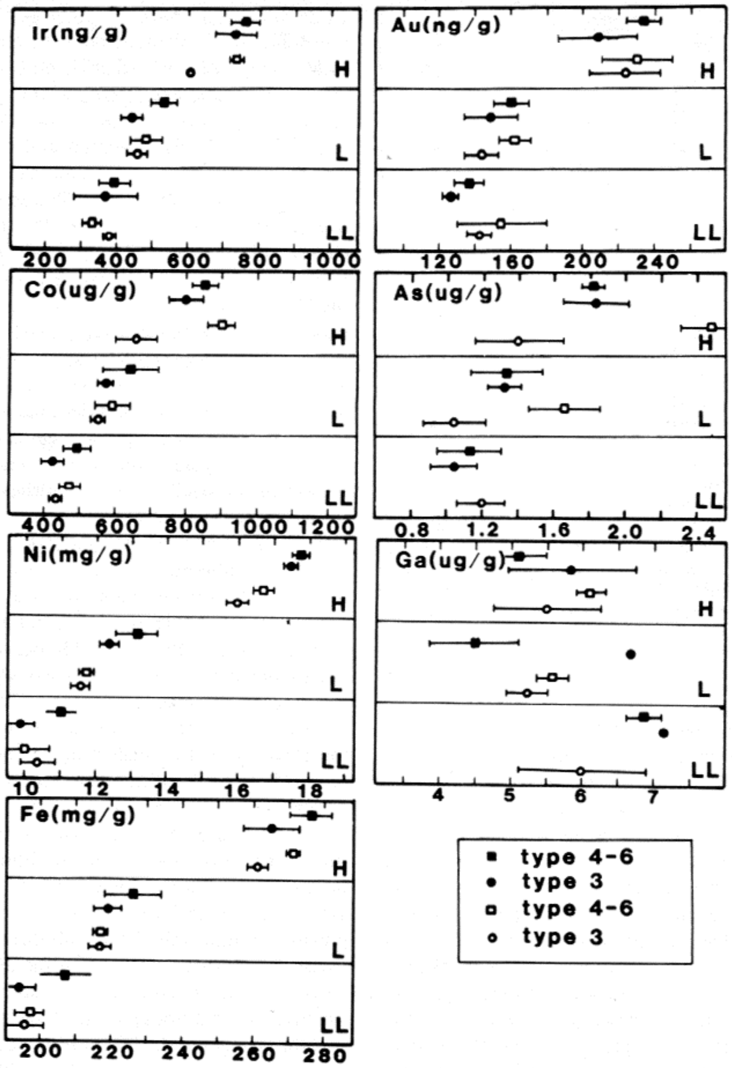

FIG. 7. Mean concentrations of siderophile elements (error bars ± 1 sigma) in equilibrated and type 3 ordinary chondrites as indicated by literature data (filled symbols) and the present data (open symbols).

Since a large proportion of the present type 3 samples are Antarctic finds, we have considered the question of whether the depletion could reflect loss of siderophile elements by terrestrial weathering. FULTON and RHODES (1984) analyzed a considerable number of Antarctic and non-Antarctic meteorites and did not detect any compositional differences. Figure 8 is a histogram of their data for Fe and Ni; there appears to be no indication for a 5–15 percent depletion in the Antarctic meteorites. Fulton and Rhodes found the same to be true of all the major elements and Ga. We have also used literature data to compare siderophile element abundances in type 3 chondrites with type 4–6 chondrites and the results are also shown in Fig. 7. In 16 instances out of 19, the literature data also indicate small depletions of siderophile elements in the type 3 chondrites. We conclude that the type 3 chondrites are systematically depleted in siderophile elements and that it is not due to a weathering effect in our samples.

The next question is whether the depletion occurs gradationally throughout the petrologic types 3–6 or whether the type 3 chondrites are unusual in this respect. Figure 9 is a compilation of literature data and the present data. It compares the siderophile element contents in each class with petrologic type. A systematic increase in siderophile element content with increasing petrologic type is displayed by Co, Ni, Fe and possibly, Au in H chondrites, and there is some indication that there may also be such a trend in Ir, Ga and As. For the L chondrites Ir, Co, Au, and As display an increase with increasing petrologic type but the trend is weak

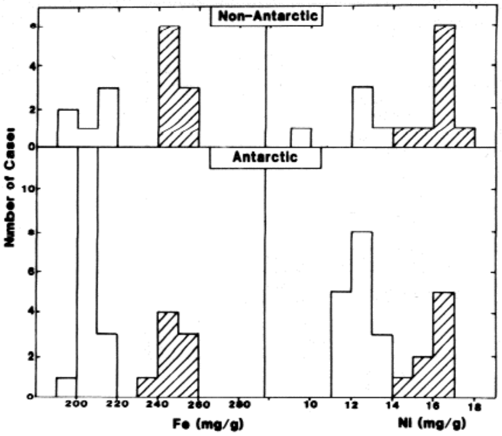

FIG. 8. Histograms of the Ni and Fe content in Antarctic finds and non-Antarctic observed falls. H chondrites are crosshatched, L chondrites are unshaded. (The data are from FULTON and RHODES (1984) whose Fe data for 5 H chondrite falls and 5 L chondrite falls are lower by factors of 1.06 and 1.10 than the Wiik-Jarosewich group means calculated from the references in Table A2; all their data have been multiplied by 1.1 for the purposes of the above figure, but this correction in no way affects the comparison of Antarctic and non-Antarctic meteorites.)

or absent in Ga, Fe and Ni. There is little or no evidence for systematic trends in the siderophile elements abundances in LL chondrites, but the data base is weak.

The type 3 chondrites have experienced a range of metamorphic intensities in many senses comparable to the range experienced by the other petrologic types, so it is instructive to see if there is any indication of a metamorphism-related variation in petrologic type within type 3. The current data base provides little or no evidence for a variation in the siderophile element content of type 3 chondrites with petrologic type, but it could be that it is being obscured by the metal-silicate heterogeneity of the samples, since the INAA data, which constitute the major source of data for most of these elements, are based on sub-gram samples.

Siderophile element fractionations in type 3 ordinary chondrites. The equilibrated ordinary chondrites experienced a process which caused their relative proportions of siderophile elements to be changed. MÜLLER *et al.* (1971) observed the Ir/Ni ratio in L chondrites to be different from that of the H chondrites, and EHMANN *et al.* (1970) observed that the same was true of Ir/Au. The type 3 chondrites suffered a similar siderophile element fractionation, as can be seen in Fig. 2. The 'hourglass' shape of the element distributions, Ir and Au showing the greatest spread and Fe showing the least, indicates that the type 3 chondrites also experienced the siderophile element fractionation.

We can examine this process more closely by comparing the ratio of Ir/Mg to those of Ni/Mg and Au/Mg; if the data are obtained from the same samples, any scatter caused by metal-silicate heterogeneity during sampling will cause the data to move up and down a line of constant Ni/Ir or Au/Ir and not change the ratios. Figure 10a demonstrates the observation made by MÜLLER *et al.* (1971) that H and L + LL chondrites differ in Ni/Ir and can be separated by a diagonal with an Ni/Ir atom ratio of 5.6×10^4. The present data display the same fractionation and our H chondrite data form a tight cluster in the middle of that produced by the literature data. Figure 10b also shows the same plot for the type 3 chondrites. The H and L + LL classes still display differing Ni/Ir ratios, but the boundary is at 4.8×10^4, rather than 5.6×10^4, and the H chondrites no longer cluster but are widely dispersed. All three classes have moved to smaller Ni/Ir values, but the increase is greatest for the H class and least for the LL class. The type 3 chondrites are therefore not just lower in bulk siderophiles, for this would just move the data down the diagonals, but also have experienced a siderophile element fractionation with respect to the equilibrated chondrites by an amount which depends on the class.

The situation for Au/Mg and Ir/Mg is different (Fig. 11). The equilibrated H and L + LL ordinary chondrites can be readily resolved on a plot of Au/Mg against Ir/Mg; unlike the Ir/Mg ratio, there is not a well-developed hiatus in Au/Mg between the groups, but a value of 0.15×10^{-6} for the Au/Mg ratio separates the groups. As noted above, the LL chondrites lie at the lower end on the L + LL range. Significantly, both the H and L + LL clusters lie on the cosmic Au/Ir ratio. The type 3 ordinary chondrites produce a very similar plot, with the H and L + LL groups resolved and with the LL chondrites lying at the lower end of the L + LL range. As with the equilibrated chondrites, the two clusters lie on the cosmic Au/Ir line. The 5–10% depletion in bulk siderophiles discussed in the previous section, will, like metal-silicate heterogeneity, cause the points to move down the diagonal and not away from it. Apparently, the siderophile element fractionation did not upset the Au/Ir ratio, suggesting that the changes in the Ni/Ir ratio discussed above and by MÜLLER *et al.* (1971) are attributable to anomalous behavior on the part of Ni.

Genetic implications

The metal-silicate fractionation, oxidation state and metamorphism of ordinary chondrites. The data presented and reviewed in this paper have considerable implications for understanding the origin and history of ordinary chondrites (MÜLLER *et al.*, 1971; EHMANN *et al.*, 1970; WASSON, 1972; DODD, 1976, 1981; LARIMER and ANDERS, 1967; ANDERS, 1971; JAROSEWICH and DODD, 1985). UREY (1961) pointed out that the Fe/Si ratio of a meteorite cannot be changed by metamorphism alone without invoking melting, which chondrites have not experienced. We now know of a few exceptions to this. The Shaw L chondrite appears to have undergone melting which has caused siderophile element changes (RAMBALDI and LARIMER, 1976), probably caused by impact melting (SCOTT and

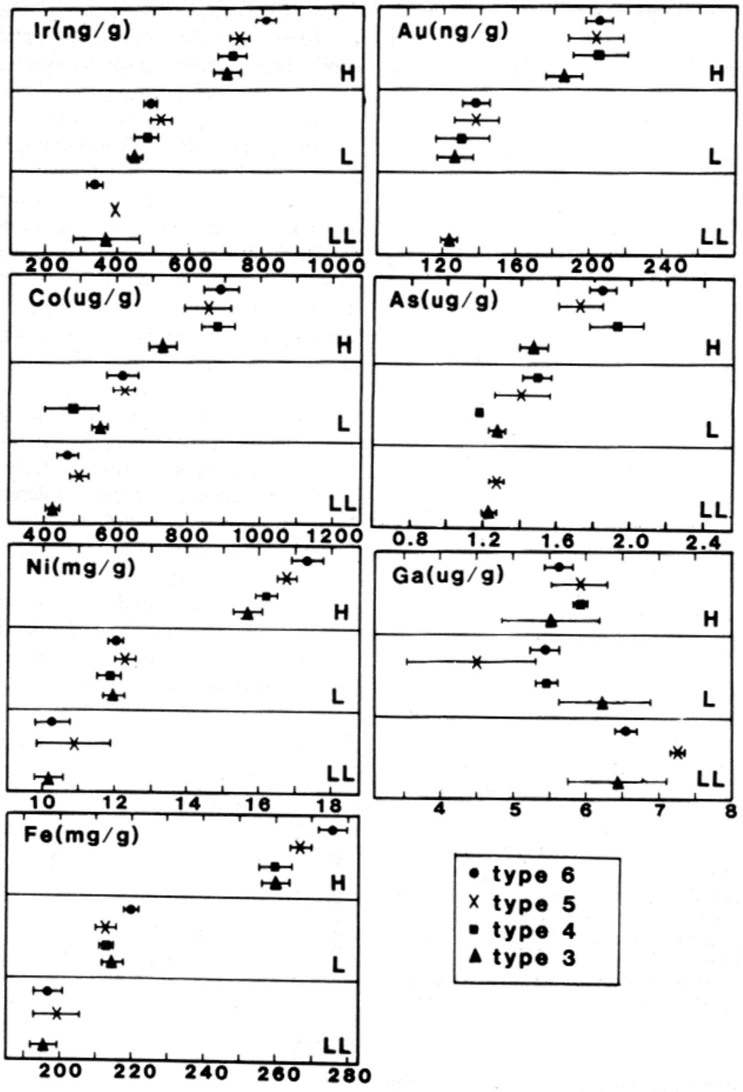

FIG. 9. Mean concentrations of siderophile elements (error bars ± 1 sigma) in ordinary chondrites of each petrologic type. Data are a composite of the present data and literature data.

RAJAN, 1979; TAYLOR *et al.*, 1979), and heavily shocked chondrites have suffered redistribution, and perhaps loss, of siderophile (and chalcophile) elements which is probably associated with formation of sulphurous veins (WALSH and LIPSCHUTZ, 1982; JAROSEWICH and DODD, 1985). Such heavily shocked chondrites are rare, only a dozen or so out of several hundred are known, and probably do not seriously affect the statistics. Nevertheless, the possibility of premetamorphic, shock-related siderophile element loss has to be borne in mind (LINGNER *et al.*, 1984). However, most authors have assumed that changes in the siderophile elements, such as those producing the H, L and LL classes, occurred prior to accretion as the components of the chondrites were being brought together. The questions which have been asked in the past with respect to the equilibrated chondrites might also be posed in connection with the type 3 chondrites. The details appear to be different, and a discussion of such questions here might shed some light on the origin of both the type 3 chondrites and the equilibrated chondrites, and on the relationship between the various petrologic types.

The questions we discuss are the following: 1) what was the mechanism causing the difference in siderophile elements between the H, L and LL classes; 2) at what temperature did it occur; 3) how does it relate to the oxidation state difference between the H, L and LL chondrites; 4) how does it relate to metamorphism and parent-body structure; 5) how does it relate to the

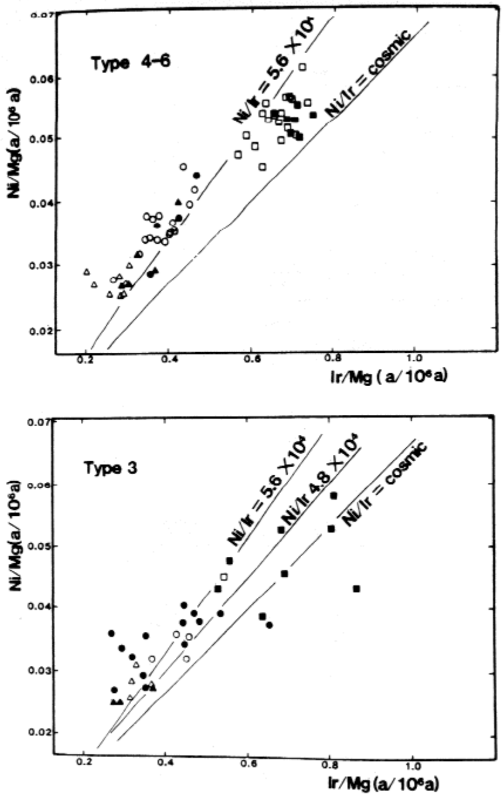

FIG. 10. Ni/Mg against Ir/Mg for equilibrated ordinary chondrites (upper figure) and type 3 ordinary chondrites (lower figure). H, L and LL chondrites are indicated as squares, circles and triangles, respectively (classifications for equilibrated chondrites from Table 1 and for type 3 chondrites from Table 5). The present data are indicated with filled symbols and literature data (Appendix A3) with open symbols. The diagonal lines are lines of constant Ni/Ir value (5.0×10^4 is the value which distinguishes H and L + LL chondrites, MÜLLER *et al.*, 1971).

oxygen isotope differences between type 3 and the other chondrites. We will also discuss briefly the evidence for similar fractionations in the other chondrite classes.

1) *Mechanism.* It was originally thought that all siderophiles were uniformly depleted in a given ordinary chondrite class and that the mechanism involved simple separation of metal and silicate. Mechanisms which have been proposed to achieve this separation have involved magnetism (LARIMER and ANDERS, 1967), nucleation and growth processes (DONN and SEARS, 1963) and other effects leading to selective accretion, such as aerodynamic sorting (DODD, 1976). However, the siderophile element fractionation indicates that the process was more complicated than that; it was as if during metal-silicate separation there was a continual separation of gas and dust so that the amount of element lost from the solid depended on its condensation temperature (MÜLLER *et al.*, 1971). RAMBALDI (1976, 1977) has shown that the refractory siderophile elements (Ir, Rn, Pt, Os and Re) are enriched in the finest sieve-fraction of magnetic material, consistent with the physical separation of different condensates in the meteorite. The present data indicate that both the metal-silicate separation and the siderophile element fractionation experienced by the type 3 ordinary chondrites differed quantitatively from that experienced by the equilibrated chondrites; the type 3 chondrites experienced slightly greater loss of metal and they also lost more Ni, relative to the other siderophiles, than the equilibrated chondrites. It is commonly assumed that the type 3 chondrites accreted at a lower temperature than the higher types, in which case it appears that with the advance of time the nebular temperature decreased while the extent of metal-silicate separation increased. Also consistent with such a process are differences in the siderophile element fractionations displayed by the type 3 and other chondrites, since the relative proportions of each siderophile element in the accreting metal will depend on its distribution over the phases and their relative accretion efficiencies. At the low temperatures of accretion experienced by the type 3 chondrites the siderophile elements are all fully condensed, but several important reactions are probably occurring in the nebula. One which may affect Ni is sulfuration, since at very low temperatures some Ni will form NiS and go into solid

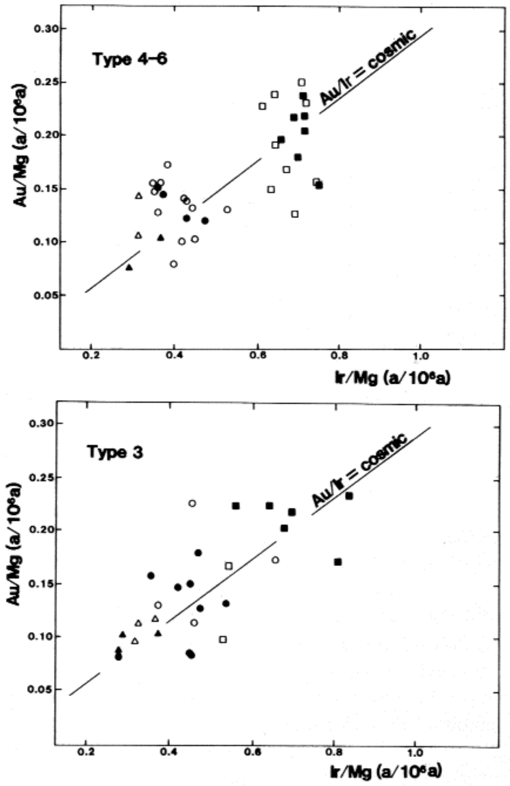

FIG. 11. Au/Mg against Ir/Mg for equilibrated ordinary chondrites (upper figure) and type 3 ordinary chondrites (lower figure). Symbols as in Fig. 10.

solution to form various Fe-Ni sulphides. Pentlandite has been found to be fairly abundant in the Semarkona type 3.0 chondrite (J. GROSSMAN, pers. commun., 1985). Other possibilities are the formation of carbides and phosphides, both of which have been observed in certain type 3 ordinary chondrites. Whatever the details, the fact that both the metal-silicate and siderophile element fractionations are similar in kind but different in degree (in the type 3 chondrites) is consistent with the idea that they are nebula effects which do not occur at a single temperature, such as magnetic separation upon cooling through the Curie point, or loss of a high temperature, refractory-rich phase.

2) *Temperature.* The extent of metal-silicate separation and the relative proportions of the siderophile elements were varying with time and temperature in the nebula, and each petrologic type provides a snapshot view of the situation at the time when it accreted. If enough were known about the temperature-dependencies of the processes occurring, the refractory and moderately volatile elements could be used for the determination of the temperatures of accretion. The chondrite classes (H, L and LL) have also experienced differing degrees of metal-silicate separation and siderophile element fractionation and provide some further clues as to the temperature of the processes. The H chondrites have experienced very little of either process, while the L chondrites have lost about 25% of their siderophile elements and suffered a significant siderophile element fractionation. The LL chondrites have lost more metal and suffered greater fractionation of their siderophile element than the L chondrites. Gallium is a particularly important element in this connection, because it did not participate in the metal-silicate separation; it has the same abundance in the three chondrite classes. LARIMER and ANDERS (1970) argued that the metal-silicate separation must have occurred just before Ga condensed, which the prevailing condensation calculations put at about 1000 K; this was consistent with their suggestion that the separation involved magnetism, since the Curie point for iron is about 1000 K. The condensation details for Ga have been refined several times since 1967, the latest calculations being those of SEARS (1978); these indicate that Ga condenses from the nebular gas at about 600–700 K.

3) *Oxidation state.* The proportion of oxidized iron in the ordinary chondrites increases along the sequence H-L-LL and if, on the basis of siderophile element patterns discussed above, we assume the oxidation state was fixed by the temperature at which the solids ceased to be able to equilibrate with the nebula gases, we have an independent clue to accretion temperatures. The oxidation of Fe occurs between 500 and 600 K in a gas of solar composition (pressure independent) implying that the ordinary chondrites formed in this temperature range in the order of decreasing temperature H, L and LL. The type 3 ordinary chondrites contain silicates which, while highly heterogeneous, are on average considerably lower in Fe than the equilibrated chondrites (Fig. 4). This could indicate that the type 3 chondrites accreted at higher temperatures than the equilibrated chondrites, or in a region of the nebula with lower oxygen fugacity, however this is contrary to the arguments for lower accretion temperatures based on volatiles and with the composition of the olivine and the pyroxene in the fine-grained opaque matrix which have FeO contents more-or-less normal for the class of meteorite (HUSS *et al.*, 1981; NAGAHARA, 1984). Alternatively, the oxidized iron is present in phases other than the chondrule olivines and pyroxenes usually measured for classification purposes, or metamorphism was accompanied by oxidation of the Fe and its migration into the chondrules. Many type 3 chondrites contain magnetite, Semarkona especially so, and it is possible that H_2O in the matrix of type 3 chondrites may have been the oxidizing agent (MCNAUGHTON *et al.*, 1983; HUTCHISON *et al.*, 1985). The Co in the kamacite of two low petrologic type 3 chondrites (Semarkona, 3.0, and Bishunpur, 3.1) is in the H group range, implying that more Fe is in the reduced state than is normal for the LL class (to which these meteorites belong on the basis of bulk composition).

The most oxidized class of ordinary chondrites (LL) is also expected to be the class with the greatest range of oxidation state. This is because the proportion of oxidized Fe increases exponentially as the temperature falls (see Fig. 1 in SEARS, 1978). We see this effect in both the Fa content of the olivine and the Co content of the kamacite (Fig. 5). HEYSE (1978) found that the Fa content of the olivine increased with petrologic type in the LL4–6 chondrites.

4) *Metamorphism and parent-body structure.* JAROSEWICH and DODD (1985) pointed out that the relationship between bulk siderophile elements and petrologic type was consistent with an onion-skin model for the meteorite parent bodies, that is with the most highly metamorphosed samples lying at its center and with petrologic type increasing towards the center of the body. This is the structure to be expected if the members of a given class formed in a single body with an internal heat source. The most plausible internal heat source is internal radioactivity, probably ^{26}Al since it requires only small parent objects.

5) *Oxygen isotopes.* SEARS and WEEKS (1983) argued that the presence of heavy oxygen in type 3 ordinary chondrites, compared with the equilibrated chondrites, was difficult to reconcile with a relationship between type 3 chondrites and the others involving only the preferential loss of heavy O as CO during metamorphism. The siderophile element differences between the type 3 chondrites and the others suggests that there is no reason to believe type 3 and the equilibrated chondrites should have identical O isotope proportions. The type 3 chondrites presumably equilibrated with a nebula gas which was isotopically different from that with which the other ordinary chondrites equilibrated. There appear to have been several isotopically distinct gases with which various early solar

system solids equilibrated. Those recognized so far are those associated with the Allende meteorite, the equilibrated ordinary chondrites and the type 3 ordinary chondrites. The mixing line between the ^{16}O-rich solid and the type 3 heavy oxygen-rich gas was identified by MAYEDA *et al.* (1980) using separates from the Allan Hills A76004. It is possible that mass fractionation, such as that caused by the loss of O as CO, could change the oxygen isotopes of a type 3.0 chondrite to those of a type 3.9, so that only one reservoir of gaseous oxygen is necessary for the type 3 chondrites. The gaseous oxygen reservoir with which the ^{16}O rich solid reacted to form the equilibrated chondrites lies at the end of the slope 1 line defined by the H, L and LL chondrites (Fig. 6).

6) *The fractionation of moderately volatile elements (Ga and As) and the metal-silicate fractionation.* As mentioned in the Introduction, the cause of the fractionation of the moderately volatile elements is uncertain. Two possibilities are that: (1) volatiles were partially or totally lost during chondrule formation and that the present abundance of the affected elements reflects the chondrule to metal proportions. Siderophile elements may have not been associated with the chondrules at the time of the chondrule-forming event, but it is presumed that metal will also have suffered from the event (ANDERS, 1971); (2) dust and gas became continually separated throughout the condensation process, so that the amount of depletion is related to the volatility of the element involved (WASSON, 1977).

Assuming that bulk oxidation state was fixed in the nebula, and that metal-silicate fractionation occurred before Ga condensation, we argued above that metal-silicate fractionation occurred when temperatures were 600–700 K. If the moderately volatile element proportions were determined by mechanism 2 above, then metal-silicate fractionation was occurring simultaneously with the latter stages of gas-dust fractionation. If the moderately volatile element fractionation occurred by mechanism 1, then it is impossible to determine the relative timing of the two processes. If Ga was lost during chondrule formation, then the event must have occurred before metal-silicate fractionation in order for Ga to have been present in the chondrules; however, the proposed mechanism is equally viable if Ga had not yet condensed when the event occurred.

7) *Other classes.* Much of what has been learned about the type 3 ordinary chondrites may apply to type 3 chondrites in the enstatite and carbonaceous classes. The EH3 chondrites, for example, have siderophile element abundances which plot at the lower end of the ranges displayed by the EH4–5 chondrites, although they do not display any hiatus and are clearly EH chondrites (WEEKS and SEARS, 1985).

CONCLUSIONS

Because of their heterogeneity and higher state of reduction, it is difficult to impossible to assign type 3 ordinary chondrites to the H, L, and LL classes using parameters which reflect oxidation state, or oxygen isotopes. The type 3 ordinary chondrites show bulk compositional properties similar to the equilibrated chondrites. The H3 chondrites are compositionally distinct from the L3 + LL3 classes, with a good hiatus separating it from the others, but the L and LL chondrites grade into each other. When bulk composition is used to assign the type 3 chondrites to classes, using the equilibrated chondrites to define the L/LL boundary, the proportion of LL to L to H type 3 chondrites is 1.4:2:1, compared to 5:7:1 for the equilibrated chondrites.

The siderophile element contents of the type 3 ordinary chondrites are 5 to 15 percent lower than those of the equilibrated chondrites, and there is some indication that the siderophile elements vary systematically with petrologic type. The type 3 chondrites also experienced a fractionation of their siderophile elements, but the details are quantitatively different from that experienced by the equilibrated chondrites; in relation to Au and Ir, Ni was more heavily depleted in the type 3 chondrites.

These siderophile element differences indicate that the type 3 ordinary chondrites are not related to the equilibrated chondrites by simple closed system metamorphism. The differences in the extent of metal-silicate fractionation and the details of the siderophile element fractionations between the type 3 and the other ordinary chondrites are consistent with each petrologic type representing a different sampling of nebula solids which were continually changing in composition during the condensational accretion process. The co-variation in siderophile element patterns and petrologic type would seem to be consistent with an onion-shell structure for the meteorite parent bodies of the ordinary chondrites.

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APPENDIX

Table A1. Means, standard deviations and numbers of samples used to compile Figs. 7 and 9.

		H			L			LL		
		Mean	σ	n	Mean	σ	n	Mean	σ	n
LITERATURE DATA										
Type 3	Ir	616	--	1	505	48	4	403	39	4
	Co	678	81	5	577	32	3	445	52	7
	Ni	16.3	0.5	6	12.2	0.8	4	10.8	1.0	7
	Fe	259	8.0	7	216	4	4	197	8	9
	Au	223	34	5	150	10	3	145	25	7
	As	1.4	0.5	4	0.57	0.31	3	1.2	0.4	8
	Ga	5.5	1.7	5	5.4	0.7	4	6.0	2.2	7
Type 4-6	Ir	739	55	20	498	80	28	335	68	9
	Co	909	151	33	580	136	37	456	86	9
	Ni	16.7	1.1	35	12.1	1.0	40	10.6	2.0	9
	Fe	268	14	38	218	9	50	197	9	10
	Au	222	41	12	165	40	26	155	35	2
	As	2.60	.39	9	1.61	0.73	15			
	Ga	6.1	.82	14	5.6	0.7	9			
PRESENT DATA										
Type 3	Ir	734	120	8	452	94	10	379	69	3
	Co	827	125	8	569	66	10	410	10	3
	Ni	15.4	2.6	8	12.2	1.4	10	9.70	0.60	3
	Fe	259	22	8	217	8	10	193	5.0	3
	Au	200	52	8	153	47	10	123	12	3
	As	2.2	.5	8	1.6	.4	9	1.1	0.3	3
	Ga	5.4	1.8	7	5.6	1.9	6	4.6	0.9	3
Type 4-6	Ir	777	30	7	541	75	5	420	69	3
	Co	842	83	7	599	190	5	535	90	3
	Ni	17.7	0.7	7	13.2	1.6	5	11.2	2.4	3
	Fe	271	15	7	223	18	5	209	14	3
	Au	226	33	7	165	22	5	136	49	3
	As	1.9	0.2	7	1.5	0.5	5	1.2	0.4	3
	Ga	4.9	0.9	4	4.8	0.6	5	5.8	0.8	3
LITERATURE PLUS PRESENT DATA										
Type 3	Ir	721	119	9	467	85	14	391	48	7
	Co	764	130	13	571	59	13	435	46	10
	Ni	76	2	14	12.2	1.2	14	10.4	1.0	10
	Fe	259	16	15	217	7	14	196	7	12
	Au	209	46	17	152	40	13	139	24	10
	As	1.9	0.6	12	1.3	0.6	12	1.2	0.5	10
	Ga	5.4	1.8	12	5.6	1.6	11	5.6	2.0	10
Type 4	Ir	742	36	6	507	86	7			
	Co	894	35	11	475	128	8			
	Ni	16.5	0.9	11	11.8	.8	8			
	Fe	261	20	12	216	8	9			
	Au	227	40	5	162	39	7			
	As	2.9	0.7	4	1.1	--	1			
	Ga	6.0	0.1	4	5.5	0.5	5			
Type 5	Ir	742	63	12	529	104	11	406	--	2
	Co	894	138	21	624	156	11	510	17	3
	Ni	16.9	1.0	22	12.3	1.1	12	11.1	2.1	3
	Fe	269	11	25	218	9	13	200	9	3
	Au	228	36	8	163	36	10			
	As	2.2	0.5	4	1.5	0.8	10	1.3	--	1
	Ga	6.0	0.9	5	5.1	0.4	3	5.4	--	1
Type 6	Ir	755	50	7	475	49	14	365	23	8
	Co	921	200	6	567	112	16	443	98	10
	Ni	17.1	1.6	7	12.0	1.0	18	10.3	1.7	9
	Fe	276	4.3	6	2.8	8.3	26	197	9	10
	Au	218	30	4	170	40	12	167	32	3
	As	2.2	0.5	6	1.6	0.5	8	1.1	0.6	2
	Ga	5.7	0.6	5	5.4	0.9	5	6.1	0.9	2

Table A2. Sources of literature data used in the present paper.*

	Equilibrated	Type 3
As	18, 22, 27, 28	3, 18, 19, 22
Ga	3, 19, 24, 29	3, 19, 24, 29
Fe	8, 9, 15, 33, 34, 35, 36, 39, 40, 41, 43, 44, 45, 46	5, 8, 9, 10, 11, 12, 13, 14, 15, 20, 21, 26, 31, 47
Co	8, 9, 15, 33, 34, 35, 36, 39, 40, 41, 43, 44, 45, 46	3, 5, 6, 7, 8, 9, 11, 12, 13, 14, 15, 16, 19, 19, 31, 47
Ni	8, 9, 15, 33, 34, 35, 36, 39, 40, 41, 43, 44, 45, 46	1, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 20, 31, 47
Ir	1, 2, 23	1, 2, 17, 21
Au	2, 3, 4, 18, 18, 24	2, 3, 4, 17, 18, 19, 24

* 1. Calculated from Chou *et al.* (1973), used where no other data are available; 2. Ehmann *et al.* (1970); 3. Case *et al.* (1973); 4. Ehmann and Gillum (1972); 5. Schmitt *et al.* (1972); 6. Ikramuddin *et al.* (1977a); 7. Ikramuddin *et al.* (1977b); 8. Wiik (1969); 9. Jarosewich (1966); 10. Dyakonova (1964); 11. Noonan *et al.* (1976); 12. Fredriksson *et al.* (1968a); 13. Binns (1968); 14. Noonan *et al.* (1973); 15. Jarosewich (1967); 16. Greenland and Lovering (1967); 17. Lewis *et al.* (1979); 18. Fouche and Smales (1967); 19. Binz *et al.* (1976); 20. Fulton and Rhodes (1984); 21. Tandon and Wasson (1968); 22. Hamaguchi *et al.* (1969); 23. Müller *et al.* (1971); 24. Keays *et al.* (1971); 26. Dyakonova and Kharitonova (1961); 27. Kiesl (1967); 28. Onishi and Sandell (1955); 29. calculated from Chou and Cohen (1973), used where no other data are available; 31. Jarosewich and Dodd (1981); 32. Von Michaelis *et al.* (1969); 33. Jarosewich and Mason (1969); 34. Clarke *et al.* (1971); 35. Fredriksson *et al.* (1975); 36. Fodor *et al.* (1972); 39. Fodor *et al.* (1971); 40. Mason (1973); 41. Levi-Donati and Jarosewich (1974); 43. Fodor *et al.* (1976); 44. Levi-Donati and Jarosewich (1971); 45. Levi-Donati and Jarosewich (1972); 46. Clarke *et al.* (1972); 47. Noonan *et al.* (1973).

Table A3. Unpublished data for Ni and Co in the kamacite of type 4-6 chondrites from the study of Sears and Axon (1975).

Meteorite	No grains	No analyses	Ni (mg/g)	Co* (mg/g)
Limerick	5	36	55.1	6.3
Estacado	7	38	57.1	5.2
Butsura	7	33	59.0	5.7
Ogi	8	31	61.7	4.9
Mean H group			**58.2**	**5.2**
Saratov	9	48	56.1	8.5
Tennasiln	8	33	55.4	7.2
Crumlin	9	31	53.3	8.5
Barwell	3	17	56.2	11.0
Bruderheim	6	41	57.3	9.6
Durala	6	20	49.2	8.8
Gambat	3	3	62.6	7.3
Holbrook	10	61	63.6	14.7
Mauerkirchen	5	16	53.2	7.5
Wold Cottage	7	43	59.2	8.5
Mean L group			**56.6**	**10.6**
Soko Banja	6	34	46.1	20.6
Aldsworth	2	10	57.6	22.5
Dhurmsala	6	29	52.3	23.1
Mangwendi	5	21	51.0	25.3
Mean main LL group			**51.8**	**22.9**
Olivenza	2	6	43.5	44.5
Khanpur	3	8	45.6	38.3
Jelica	1	10	45.0	110.0

* Afiattalab and Wasson (1980) find group means for Co in the kamacite as follows: H, 4.2; L, 7.6; LL ("main group", i.e. Beeler and Dhurmsala), 20.6 mg/g. There is apparently a systematic difference in the data for the two laboratories and to remove this effect from Fig. 5 we have multiplied the Afiattalab and Wasson (1980) Co in the kamacite data by 1.2. We think the Sears/Axon data are correct since they used pure Co as a standard whereas Afiattalab and Wasson used an iron meteorite as a standard.