THE TYPE THREE ORDINARY CHONDRITES: A Review

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Abstract. The ordinary chondrites are the largest group of meteorites, and the type 3 ordinary chondrites are those which experienced only very mild parent metamorphism; their study provides a unique means of studying the first solid material to from in the early solar system which is either free from the effects of mild metamorphism, or in which the effects of mild metamorphism can be distinguished from primary, nebular effects. In this paper we list all known type 3 ordinary chondrites and references to their study, their compositional data and data relating to the metamorphic history. We review current theories on their formation and the effects of metamorphism, with emphasis on quantitative considerations. Studies on the thermoluminescence properties of these meteorites, which have provided many new insights into their metamorphic history, are reviewed. Some of the least metamorphosed meteorites show evidence for aqueous alteration, which provides a link between the type 3 ordinary chondrites and objects containing water in various forms the carbonaceous chondrites, comets and planets with 'wet' mantles.

1. Introduction

1.1. THE IMPORTANCE OF METEORITES

The largest meteorite class, the chondrites, are widely heralded as essentially unaltered solid residues from the earliest days of the solar system. The basis for this conclusion are three types of observation which are deeply rooted in the history of meteorite studies. Firstly, chondritic meteorites are very similar to the solar photosphere in composition, and quite unlike the terrestrial surface or non-chondritic meteorites (Figure 1). Second, formation ages for chondrites (4.6 Ga) are greater than any other rock, terrestrial or lunar, and comparable with the best estimates for the age of the Moon, Earth and Sun. Third, they have a petrology clearly inconsistent with any known form of planetary processing. Chondritic meteorites consist of metal grains (Fe, Ni alloy), iron sulfide (FeS) and silicates in the form of matrix and chondrules: chondrules are millimeter-sized aggregates of silicates that had an independent existence prior to incorporation in the meteorite. This mixture of very different substances, and the fine structures within them, clearly precludes planetary processing; they are a form of 'cosmic sediment'. It is not surprising that the chondritic meteorites have been studied with a thoroughness exceeding even that afforded the expensive lunar samples. It will be many years before the other primitive objects in the solar system, comets and asteroids, receive anything approaching this degree of attention.

There are, however, two major problems facing students of meteorites. The first is that the formation location of the meteorites is unknown. The second is the diversity and complexity of the processes the meteorites have suffered. Most writers would argue that chondrites came from the asteroid belt, but the evidence is at best speculative. Despite the diversity and complexity of processes involved, it has been possible to identify several of the processes. We know, for instance, that after formation most
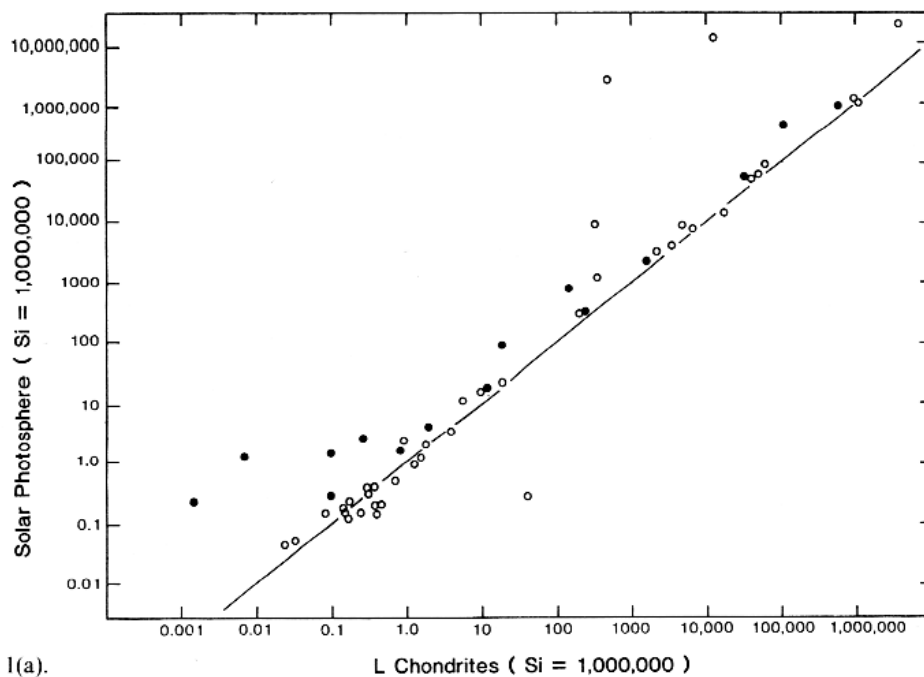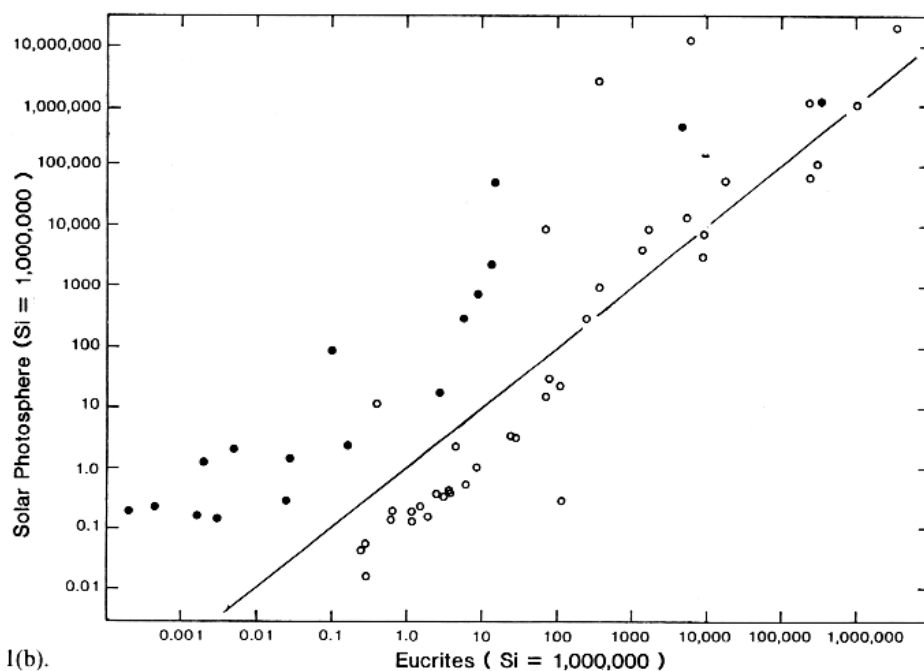
Fig. 1(a).   L Chondrites (Si = 1,000,000)

Fig. 1(b).   Eucrites (Si = 1,000,000)

Fig. 1. Plots of the elemental abundances (normalized to $Si = 10^6$) in the solar photosphere against elemental abundances in (a) L chondrites and (b) the eucrite meteorites. Siderophile and chalcophile elements are represented by filled symbols, others are represented by open symbols. Like all the chondrite classes the L chondrites closely resemble the sun in their proportions of all but a few of the most volatile elements (H, He, N, and the inert gases), whereas the eucrites, like lunar and terrestrial samples, are considerably depleted in siderophiles and chalcophiles and enriched in the others. Li is depleted in the sun as it is destroyed by nuclear reactions (from Sears, 1986).

meteorites underwent a period of metamorphism and a few suffered brecciation, while others experienced intense shock and yet others have suffered aqueous alteration. Fortunately, not all chondrites suffered all these processes, and there has been considerable effort spent in sorting them according to the degree of alteration suffered. It is now fairly clear, therefore, which meteorites most closely resemble the first solid materials to form in the nascent solar system, and may be considered 'most primitive'. The most primitive members of the largest chondrite group live, rather unpoetically, under the name of the type 3 ordinary chondrites.

In this paper we review the properties of the type 3 ordinary chondrites, beginning with their definition and classification. We then list some of the major questions they pose, review the available data, and end in addressing some of the questions.

1.2. CHEMICAL-PETROLOGIC CLASSIFICATION SCHEME FOR CHONDRITES

The classification scheme currently in common use for chondritic meteorites is that of Van Schmus and Wood (1967). It places the meteorites on a two-dimensional grid, with the chemical class as one dimension and the degree of metamorphic alteration as the other.

Although basically solar in composition, there are a number of fairly subtle variations in bulk composition and oxidation state (which is essentially bulk oxygen content) which enable the chondrites to be sorted into 9 classes: the EH and EL chondrites, collectively called the enstatite chondrites (Sears et al., 1982b); the H, L and LL chondrites, collectively termed the ordinary chondrites (Urey and Craig, 1953; Fredriksson et al., 1968); the CI, CM, CV and CO chondrites (Kallemeyn and Wasson. 1981), collectively termed the carbonaceous chondrites. Along the enstatite – ordinary – carbonaceous chondrite sequence, the degree of oxidation of the Fe and many other elements increases (Prior, 1920). Thus in the enstatite chondrites, Fe is entirely in the metallic state or as FeS (Mason, 1966; Keil, 1968); in the ordinary chondrites Fe is present in the metallic, sulfide and silicate forms (Keil, 1962); while in the carbonaceous chondrites Fe is present as silicates or oxides (McSween, 1979). Also along the enstatite – ordinary – carbonaceous sequence the ratio of several lithophile elements increases, for instance Mg/Si increases from 0.83 to 0.95 to 1.05 (Ahrens, 1965), and refractory lithophiles like Ca/Si and Al/Si go even higher in the CV chondrites (Van Schmus and Hayes, 1974). The third compositional trend is in the concentration of siderophile elements and it does not follow the enstatite – ordinary – carbonaceous sequence. Instead, it results in further subdivision of these groups; for instance, total Fe varies within the enstatite and ordinary groups, enabling the subdivision into the EH and EL and the H, L and LL classes, respectively (Sears et al., 1982b; Mason, 1965). The four carbonaceous classes can also be distinguished on the basis of these three compositional trends, but larger differences exist in their volatile element make up. As their name suggests, the ordinary chondrites are by far the largest chondrite class (87% of observed falls); the H, L, and LL chondrites constitute 32, 39 and 7% of the chondrites.

The chondrite groups can also be resolved using isotopic data. Carbonaceous,

TABLE I

Definition of petrologic types for ordinary chondrites.

Property	Petrologic Type							
	3.0-3.1	3.2-3.3	3.4-3.5	3.6-3.7	3.8-3.9	4	5	6
Homogeneity of Olivine[a]	→ 50 →	→	40-50	20-40	5-20	< 5	Uniform	Uniform
Structural state of low Ca pyroxene	Predominantly monoclinic					monoclinic > 20%	monoclinic < 20%	ortho-rhombic
Feldspar	Absent	→	Absent or rare →			< 2 μm grains	< 50 μm grains	< 50 μm grains
Primary glass	Clear isotropic	Turbid →		Turbid		Turbid if Present	Absent	Absent
Thermoluminescence sensitivity Dhajala = 1	< 0.01	.010-0.46	0.46-22	.22-1.0	1.0-4.6	1-10	> 5	> 5
Heterogeneity of metal[b]	> 17	10-17	6.0-10	2.5-6.0	< 2.5	Uniform	Uniform	Uniform
Average Ni content of sulfide minerals	> 0.5%	< 0.5% →						
Chondrule delineation	very sharply defined					well defined	readily defined	poorly defined
Matrix texture	≤ 20	10-20	~20-~50	> 60	> 60	100	matrix	matrix
	% transparent microcrystalline					Recrystalline		
Matrix $\left(\dfrac{FeO}{FeO + MgO}\right)$[c]	> 1.7	1.5-1.7	1.3-1.5	1.1-1.3	< 1.1	—	—	—

[a] Standard deviation of the mole % fayalite in the olivine divided by the mean fayalite expressed as a percentage.

[b] Standard deviation of the nickel content in the kamacite (wt%) divided by the mean nickel content expressed as a percentage.

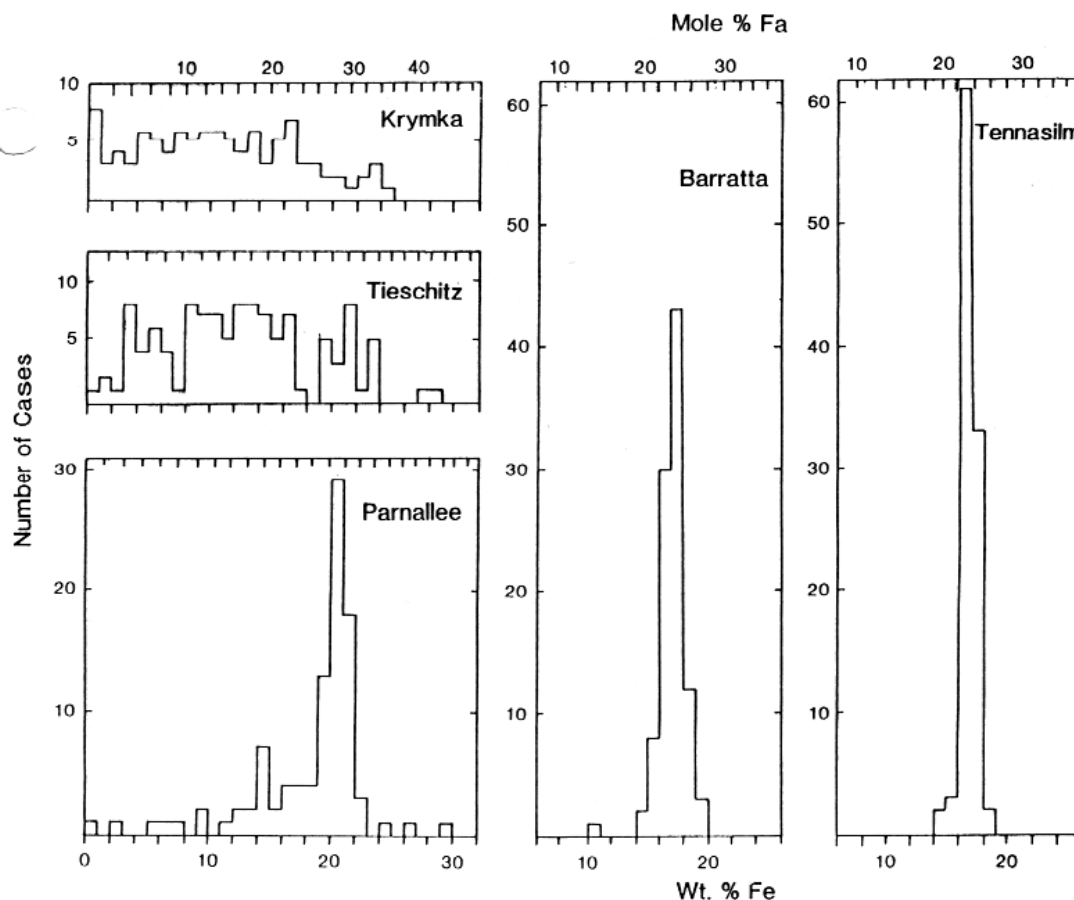[c] Divided by the same quantity for the bulk meteorite.

Fig. 2.   Histograms of olivine composition for 5 ordinary chondrites showing the decrease in heterogeneity with increasing petrologic type. Krymka is type 3.1, Tieschitz is type 3.4, Parnallee is type 3.6, Barratta is type ~ 3.8 and Tennasilm is type 5 (data from Dodd et al., 1967).

ordinary, and enstatite chondrites have lower, comparable and greater ^{17}O than terrestrial values, respectively, and on a plot of $\delta^{17}O*$ against $\delta^{18}O$ the H chondrites can readily be resolved from the L and LL chondrites, and the L and LL chondrites can be weakly resolved from each other (Clayton et al., 1976; R. N. Clayton, per. comm.).

The second dimension on the Van Schmus and Wood grid consists of six 'petrologic types' in which a higher types represent greater metamorphism. An updated version of their scheme is summarized in Table I. Some of the major changes occurring throughout the six types are (i) the homogenization of silicate compositions (Figure 2), (ii) disappearance of primary igneous glass, (iii) appearance of feldspar, (iv)

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* The δ notation is often used as a convenient means of comparing small differences in isotope ratios with a standard material. In this case, the ratios are with respect to ^{16}O, and the standard is 'standard mean ocean water' (SMOW).

$$\delta^{17}O = (\frac{(^{17}O/^{16}O)_{sample} - (^{17}O/^{16}O)_{SMOW}}{(^{17}O/^{16}O)_{SMOW}} \times 1000).$$
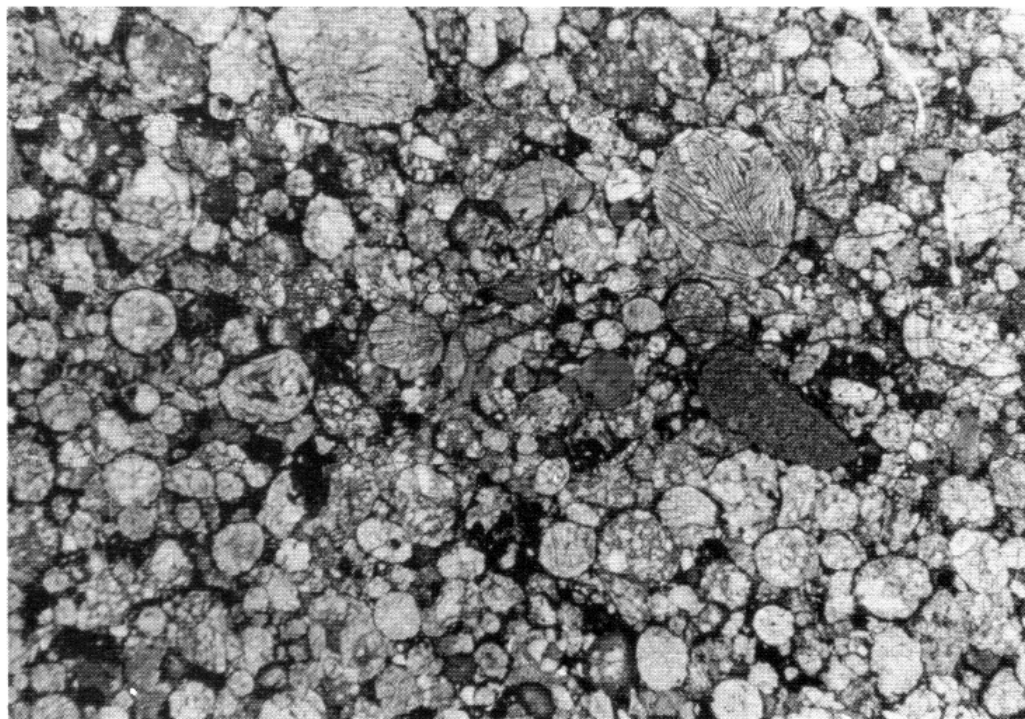
Fig. 3.   Photomicrograph of the Allan Hills A77011 type 3 ordinary chondrite in transmitted light showing the well-developed chondritic structure and opaque matrix. Horizontal field of view 17 mm (from McKinley *et al.*, 1981).

recrystallization and compositional changes in the matrix, and (v) change from clino to orthoproxene as the dominant form of pyroxene (Dodd *et al.*, 1967; Dodd, 1969). Dodd (1969) referred to these changes as a move towards equilibrium in response to metamorphism, and thus types 4-6 are sometimes referred to as the 'equilibrated' and type 3 as the 'unequilibrated' ordinary chondrites, although, strictly speaking, none of them have actually achieved true equilibrium. (vi) Chondrule textures also become obliterated (Figure 3), and (vii) volatile elements become less abundant with increasing petrologic type.

Types 1 and 2 were thought by Van Schmus and Wood (1967) to be less metamorphosed than type 3, the major reason being their higher abundances of volatile elements than the others which makes them more 'solar' in composition. However, it is now clear that the mineralogy and petrology of these two types were determined by extensive aqueous alteration on their parent bodies, some of them are 10-20% water, and they no longer resemble the solids which were once dispersed in space (DuFresne and Anders, 1962; Bunch and Kerridge, 1979; McSween, 1979). It therefore seems that it is the type 3 chondrites which best preserve the nebula record, and several type 3 ordinary chondrites appear to be 'little removed' from their unmetamorphosed state (Dodd *et al.*, 1967; Wood, 1967). Recent data suggest even a few of the type 3 chondrites

may also be aqueously altered (Bunch and Kerridge, 1979; Hutchison *et al.*, 1985; Guimon *et al.*, 1986; Keck and Sears, 1986).

It is also possible to devise classification schemes for the other secondary processes. Dodd and Jarosewich (1979) have suggested a means of sorting the chondrites according to the intensity of shock they have experienced, and Scott (1983) has suggested that chondrites which are breccias be identified in classification tables. Certainly both processes can confuse the picture, especially brecciation, and both may have played a particularly important part in the history of the type 3 chondrites.

1.3. SUBDIVISION OF TYPE 3 CHONDRITES INTO TYPES 3.0-3.9

While the type 3 ordinary chondrites have suffered less metamorphism than the higher types, many authors have concluded that there is considerable variation in the levels of metamorphism experienced within the type (Dodd *et al.*, 1967; Wood, 1967; Sears *et al.*,
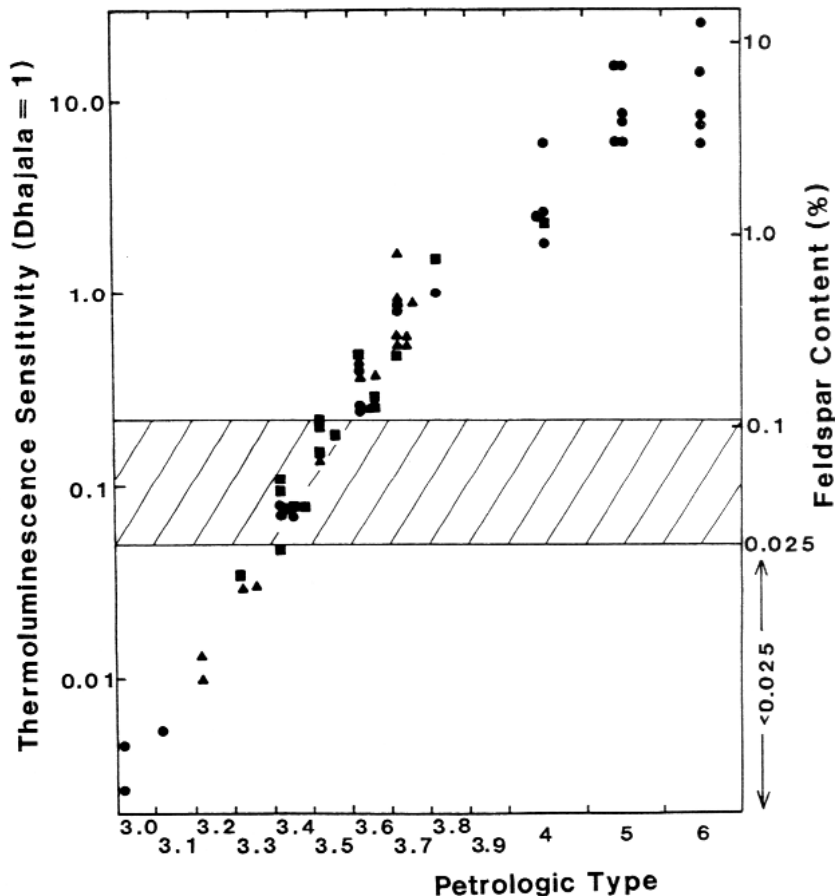

Fig. 4.   Thermoluminescence sensitivity against petrologic type. The symbols refer to the three sources of literature data used. Assuming the TL sensitivity is directly proportional to the amount of feldspar, the TL phosphor, and that type 6 ordinary chondrites typically contain 8% feldspar, it is possible to calculate the feldspar abundances indicated on the left-hand scale. The cross-hatching refers to meteorites in which the shape of the TL glow curve suggests that the feldspar is the low-temperature form (from Guimon *et al.*, 1986a).

TABLE II

Thermoluminescence data for type 3 ordinary chondrites[a].

Meteorite[d]		Pet. Type	TL Sensitivity (Dhajala = 1)	Peak Temp. (°C)	FWHM[c] (°C)	Ref.[f]
ALHA	76004	3.2	0.034	131	97	1
,,	77011[b]	3.5	0.22	130	100	2,3
,,			0.46 ± 0.09	131 ± 1	110 ± 2	5
,,	77013	3.5	0.14	165	162	1
,,	77015[b]	3.5	0.15	158	112	2,3
			0.18 ± 0.04	118 ± 6	88 ± 3	5
,,	77050[b]	3.5	0.18	160	105	2,3
		3.	0.3 ± 0.05	128 ± 2	90 ± 2	5
,,	77167[b]	3.5	0.075	152	110	2,3
			0.064 ± 0.01	120 ± 5	81 ± 2	5
,,	77176	3.2	0.010	131	114	1
,,	77197	3.6	0.032	187	–	1
,,	77214[b]	3.4	0.078	148	100	2,3
			0.041 ± 0.007	123 ± 11	84 ± 4	5
,,	77216[c]	3.7	1.6	191	154	1
,,	77249[b]	3.4	0.095	152	105	2,3
			0.043 ± 0.009	120 ± 1	90 ± 5	5
,,	77260[b]	3.5	0.11	155	105	2,3
			0.014 ± 0.03	105 ± 2	56 ± 2	5
,,	77278	3.6	0.25	200	162	2,3
,,	77299	3.7	0.47	120	162	2,3
,,	77304	3.8	0.60	195	192	1
,,	78038[b]	3.4	0.078	150	122	2,3
,,	78041	3.5	0.065 ± 0.009	107 ± 6	75 ± 8	5
,,	78119	3.5	0.0964	123 ± 4	97 ± 6	5
,,	78133	3.5	0.091 ± 0.02	142 ± 21	132 ± 70	5
,,	78138	3.6	0.11 ± 0.04	127 ± 17	107 ± 19	5
,,	78162	3.5	0.06 ± 0.02	125 ± 4	98 ± 9	5
,,	78176	3.4	0.04 ± 0.01	119 ± 2	91 ± 3	5
,,	78180	3.5	0.06 ± 0.01	122 ± 6	101 ± 15	5
,,	78235	3.4	0.05 ± 0.01	113 ± 1	85 ± 2	5
,,	78239	3.5	0.05 ± 0.01	117 ± 4	83 ± 7	5
,,	79022	3.7	0.96	189	157	1
,,	81024	3.3	0.20 ± 0.03	160 ± 4	139 ± 6	5
,,	81025[b]	3.7	0.4 ± 0.2	182 ± 8	143 ± 27	5
,,	81030[b]	3.5	0.081 ± 0.006	119 ± 1	72 ± 6	5
,,	81031[b]	3.4	0.042 ± 0.006	118 ± 7	82 ± 7	5
,,	81032[b]	3.5	0.06 ± 0.01	123 ± 8	89 ± 3	5
,,	81251	3.3	0.013 ± 0.006	127 ± 4	80 ± 6	5
,,	82110	3.7	0.35 ± 0.02	139 ± 2	128 ± 2	5
,,	83010	3.4	0.022 ± 0.002	135 ± 19	128 ± 29	5

TABLE II (continued)

Meteorite[d]	Pet. Type	TL Sensitivity (Dhajala = 1)	Peak Temp. (°C)	FWHM[c] (°C)	Ref.[f]
Bishunpur	3.1	0.0054	–	–	4
Bremervorde	3.7	0.60	–	–	1
,,	3.9	2.6	–	–	4
Brownfield	3.6	0.48	195	138	2,3
Chainpur	3.4	0.078	–	–	1
,,	–	0.083 ± 0.006	132 ± 28	91 ± 6	1
,,	–	–	120	77	3
Clovis	3.6	0.29	168 ± 4	160 ± 1	2,3
Dhajala	–	1	165 ± 8	160 ± 7	1
,,	3.8	1	165	165	3,4
EETA 82601	3.8	0.51	178 ± 1	138 ± 33	5
EETA 83213	3.5	0.57 ± 0.05	167 ± 8	156 ± 1	5
Frenchman Bay	3.5	0.08 ± 0.02	180 ± 6	135 ± 2	5
Hedjaz	3.7	0.82	200	157	2,3
Inman	3.4	0.031	177	150	1
Khobar	3.6	0.44	200	162	2,3
Krymka	3.0	0.0029 ± 0.0003	165	194	1,2
Manych	3.4	0.070	–	–	4
Mezo-Madaras	3.7	0.90	190	155	4,3
Moorabie	3.6	0.16 ± 0.01	174 ± 5	159 ± 3	5
,,	3.6	0.21 ± 0.06	168 ± 3	160 ± 1	5
Ngawi	3.6	0.25	–	–	4
OTTA 80301	3.8	0.52	179	173	1
Parnallee	3.6	0.042	–	–	4
,,	–	0.37	136	184	1
,,	–	–	135	130	3
Prairie Dog Creek	3.8	0.55	170	150	2,3
PCA 82520	3.7	0.36 ± 0.14	180 ± 5	152 ± 3	5
Quinyambie	3.4	0.047	–	–	2
,,	3.5	0.09 ± 0.02	206 ± 5	178 ± 8	5
,,	3.5	0.067 ± 0.008	214 ± 15	197 ± 4	5
,,	3.4	0.038 ± 0.006	189 ± 5	177 ± 7	5
Ragland	3.5	0.06 ± 0.02	126 ± 10	78 ± 12	5
RKPA 79008	3.7	0.089	194	150	1
,, 80205	3.7	0.55	185	171	1
,, 80207	3.2	0.013	168	111	1
,, 80256	3.8	0.38	199	174	1
Semarkona	3.0	0.0045	–	–	4
Sharps	3.4	0.071	–	–	4
,,	3.5	0.096	130	112	5
,,	–	–	122	120	3

TABEL II (continued)

Meteorite[d]	Pet. Type	TL Sensitivity (Dhajala = 1)	Peak Temp. (°C)	FWHM[e] (°C)	Ref.[f]
St. Mary's Co.	3.3	0.034	145	83	2,3
Starvation Lake	3.6	0.19 ± 0.02	188 ± 3	150 ± 8	5
Suwahib (Buwah)	3.6	0.25	182	164	1
Tieschitz	3.6	0.23	130	100	3,4
TIL 82408	3.4	0.040	190 ± 6	167 ± 2	5
Wilaroy	3.5	0.20	195	157	2,3
Y 74024	3.9	1.2 ± 0.27	174 ± 7	173 ± 6	5
Y 74032	3.5	0.08 ± 0.01	186 ± 3	137 ± 12	5
Y 74138	3.5	0.14 ± 0.03	195 ± 7	144 ± 2	5
Y 74191	3.6	0.41	168	142	2,3
Y 74417	3.7	0.27 ± 0.04	134 ± 3	102 ± 3	5
Y 74660	3.0	0.0019 ± 0.0002	197 ± 4	149 ± 8	5

[a] Errors quoted are 1 sigma on measurements for 3 aliquants from a single vial. For data without uncertainty estimates, a typical error of 5% can be assumed.

[b] The following meteorites (some are listed above) are paired with ALHA 77011 according to Scott (1984): ALHA 77031, 77033, 77034, 77036, 77043, 77047, 77049, 77050, 77052, 77115, 77140, 77160, 77163, 77164, 77165, 77166, 77167, 77170, 77175, 77178, 77185, 77211, 77214, 77241, 77244, 77249, 77260, 77303, 78013, 78015, 78038, 78038, 78186, 78188, 78236, 78238, 78243, 79001, 79045, 80133, 81025, 81030, 81031, 81032, 81053, 81060, 81061, 81065, 81066, 81069, 81085, 81087, 81121, 81145, 81156, 81162, 81190, 81191, 81214, 81243, 81272, 81280, 81292 and 81299.

[c] The following meteorites are paired with ALHA 77215 according to Scott (1984): ALHA 77216, 77217 and 77252.

[d] Abbreviations: ALHA, Allan Hills; EETA, Elephant Moraine; OTTA, Outpost Nunatak; PCA, Pecora Escarpment; RKPA, Reckling Peak; TIL, Thiel Mountains, and Y, Yamato.

[e] Full width of the TL peak at half the maximum intensity.

[f] References: 1. Sears and Weeks (1983); 2. Sears *et al.* (1982a); 3. Guimon *et al.* (1985); 4. Sears *et al.* (1980); 5. Unpublished.

1980; Afiattalab and Wasson, 1981; Huss *et al.*, 1981). Several have suggested subdivision; that used here is a decimal division into types 3.0 to 3.9 (Sears *et al.*, 1980). In addition to the petrographic changes displayed by the higher types, type 3 ordinary chondrites also display a 10^3-fold range in thermoluminescence (TL) sensitivity (Figure 4). This apparently reflects the formation of feldspar by crystallization of the glass and is particularly sensitive to the earliest phases of crystallization and the lowest levels of metamorphism. It is therefore an important measurement in the subdivision of type 3. In Table II we list all the available TL data for type 3 ordinary chondrites relevant to their petrologic type assignment. The intended implication of subdivision into types 3.0-3.9 is that metamorphism covered a spectrum of intensities and petrologic type is a semi-quantitative measure of this. There is no implication that metamorphism was 'quantized' (takes preferred values), as do the compositional data on which the classes are based. The subdivision of type 3 is also described in Table I, and the properties are described in greater detail below. It follows the same principles as the division into types

TABLE III

Known type 3 ordinary chondrites and some data (as of August 1986)

Meteorite[f]	Location of main mass	Mass (g)	Class.	Ref. to pet. descript.[e]	Ref. to bulk anal.[e]	Total Fe (mg g^{-1})	Mg/Si (a/a)	% Fa	% Fs	$\sigma(\mathrm{Fa})/\mathrm{mean}$ %	Co(α) %	Fe^0/Fe$_t$ (a/a)
Accalana[c]			L3	15								
ALHA 76004	MWG	305	L3.2-3.4[d]	21, 22, 9, 16	20	217		17.3	12.1	56		
ALHA 77011	see below											
ALHA 77013	MWG	23.0	LL3.5	22, 23	20	211		19,9-28	1-35	20		
ALHA 77176	MWG	55.4	LL3.2	22, 23	20	202		12	1-37	67		
ALHA 77197	MWG	20.3	L3.6	22, 23	20	218		24	4-21	12		
ALHA 77215	see below											
ALHA 77278	MWG	312.7	LL3.6	21, 22, 7	20	198		22.8	16.1		1.62	
ALHA 77299	MWG	260.7	H3.7	21, 22, 16	20	278		17.1	13.7	33		
ALHA 77304	MWG	650.4	L3.7	21, 22, 16	20	217		25.5	16.7	3.6		
ALHA 78037	MWG	0.5	L	24				7-38				
ALHA 77041	MWG	117.5	L3.5	21, 18				0-41				
ALHA 78046	MWG	70.0	L	25				8-25	8-20			
ALHA 78119	MWG	102.6	L3.5	24				0-28				
ALHA 78133	MWG	59.9	L3.5	25				1-34	1-16			
ALHA 78138	MWG	10.8	LL3.6	24				0-35				
ALHA 78149	MWG	23.2	L	24				18-31				
ALHA 78162	MWG	33.2	L3.5	24				2-30				
ALHA 78170	MWG	20.9	H	24				3-36				
ALHA 78176	MWG	8.2	L3.4	24				8-26				
ALHA 78180	MWG	7.9	L3.5	24				2-33				
ALHA 78235	MWG	19.2	L3.4	24				8-28				
ALHA 78239	MWG	16.0	L3.5	24				1-34				
ALHA 79003	MWG	5.1	LL34	6, 21, 18	6			25.6	13.4	11	1.4	
ALHA 79022	MWG	31.4	L3.7-4[d]	21, 18, 16	20	259		23.6	17.7	4.3		
ALHA 81024	MWG	797.7	L3.3	26, 27	20	242		3-28	2-24			
ALHA 81251	MWG	158.0	LL3.3	26, 27	20	222		1-29	2-28			

TABLE III (Continued)

Meteorite[f]	Location of main mass	Mass (g)	Class.	Ref. to pet. descript.[c]	Ref. to bulk anal.[c]	Total Fe (mg g^{-1})	Mg/Si (a/a)	% Fa	% Fs	$\frac{\sigma(Fa)}{mean}$ %	Co(α) %	Fe^0/Fe$_t$ (a/a)
ALHA 82110	MWG	39.3	H3.7	25				1-24	4-27			
ALHA 83010	MWG	395.2	L3.4	28				4-31	2-28			
ALHA 84086	MWG	234.0	LL3	31				25-29	17-26			
ALHA 84126	MWG	41.2	LL3	31				7-31	3-24			
Barratta	AM	~200000	L3 ~ 3.8	13	13	210.7	0.93		17			0.23
Bishunpur	GSI	1039	LL3.1	13, 37	13	199.8	0.92	16.6	13.0		7.0	0.33
Bremervorde	GU	7250	H3.7-4.0[a]	13	20, 13	265.2,260	0.94	15.8	12.5			0.48
Brownfield	BM	325	3.6									
Carraweena	SAM	28000	L3.9	13	13	198.3	0.96	24.9	19.9			0.23
Chainpur	GSI	8000	LL3.5	13, 37	13	197.8	0.94	20.6	14.5		11.4	
Clovis No. 1	SI	238000	H3.6	13	13	(229.1)	0.94	18.3	12.5			0.22
Dhajala	GSI	>60000	H3.8		20	289	0.92					0.15
EETA 82601	MWG	149.3	L3.8	25				2-39	1-35			
EETA 83213	MWG	2727.0	L3.5	28				13-20	3-26			
EETA 83248	MWG	39.2	H3	29				3-24	3-23			
EETA 83267	MWG	27.7	H3	30				13-23	12-20			
EETA 83260	MWG	15.4	L3	30				7-19	5-25			
EETA 83274	MWG	82.7	L3	30				5-28	5-15			
EETA 83399	MWG	203.3	L3	29				3-26	6-25			
Frenchman Bay	WAM	8800	L3.5	38	20	250						
FRO 8403	MPI		H3									
Geidan	GSN	725		13	13	272	0.98	18.1	15.7			0.58
Goodland	BM	1600		13	13	214.9	0.93	25.1	19.1			0.28
Hallingeberg		1456		13, 37	13	219.8	0.91	19.8	10.6		9.0	0.31
Hedjaz	MHN	4863	3.7	1	1	221	0.92	23-24	10-23			
Inman	UNM	7250	L3.4	4	4,20	195,218	0.92	21	15			0.35
Ioka				13	13	207.7	0.93	24.5	17.3			0.18
Khohar	GSI	9700	L3.6	13, 37	13	215.6	0.93	24	15.4		9.6	0.31
Krymka	UAS	50000	LL3.1	8, 13	10, 11	188.4	0.92/	15.5	12.5			0.02.
						196.7	0.93		13-21			0.24
Laundry East	WAM	43	H3									

TABLE III (Continued)

Meteorite[f]	Location of main mass	Mass (g)	Class.	Ref. to pet. descript.[e]	Ref. to bulk anal.[e]	Total Fe (mg g^{-1})	Mg/Si (a/a)	% Fa	% Fs	$\frac{\sigma(\text{Fa})\%}{\text{mean}}$[f]	Co(α) %	Fe°/Fe$_t$ (a/a)
Manych	MAS	3555	LL3.4	13	10, 12	207.5, 204.3	0.92/, 0.95	24.9	14.3			0.20, 0.29
Mezo Madaras	NHMV	22700	L/LL3.7	13, 37	13, 20	219.216	0.93	21.7	14.1		9.3	0.30
Monte Colina			L3	15								
Moorabie	LR	14000	3.6									
Ngawi	NHMC	1393	LL3.6	13, 37	13	185.7	0.94	21.6	15.3		4-140	0.032
OTTA 80301	MWG	35.5	H3.8	16, 22, 32				18.2	11.0	6.1		
Parnallee	BM	77564	LL3.6	13, 37	20.13	192, 182.9	0.96	26.2	15.7		11.4	0.14
Prairie Dog Creek	AMNH	2900	3.8	13				19.6	14.5			
PCA 82520	MWG	22.7	H3.7	25	20	190		15-22	2-19			
Quinyambie	SAM	1600	LL3.4									
Ragland	UNM	57.7	LL3.5	2	2	200, 212[a]	0.86	18.3	14.6	10		
RKPA 79008	MWG	73.0	L3.7-4[d]	16, 21, 18	20	210		22.6	15.5	18.1		
RKPA 80205	MWG		3.7	16, 27, 32				16.0	13.0	19.6		
RKPA 80207	MWG	17.7	L3.2	16, 27, 32	20	223		18.7	15.3	22.1		
RKPA 80256	MWG	153.2	L3.6	16, 27, 32	20	228		23.8	15.6	4.7		
Rose Co. 001[b]	UNM	462	H3	3								
Rose Co. 031[b]	UNM	397.1	H3	3								
Semarkona	GSI	691	LL3.0	13, 37	13	190.9	0.92	16.3	12.2		4.7	0.11
Sharps	SI	1265	H3.4	13, 37	13	262.6	0.94	19.2	13.9		6.1	0.46
St. Mary's Co.	SI		3.3									
Starvation Lake	SAM	12000	3.6	5	5	~310	0.97	1-26	1-16			
Study Butte	SI	417	H3		20	227					0.4	
Suwahib (Buwah)	BM	465	L3.6									
Tieschitz	NHMV	28000	L3.6	13	20,13	219, 251.3	0.96	19.9	11.3			0.32
TIL 82408	MWG	80.1	LL3.4					1-29	2-21			
Willaroy	AM	4050	H3.5	14	14,20	253, 277	0.92	14.6	14.5			
Yamato 74024	NIPR	50.0	L3.9	36				22.8	10.5			
Yamato 74138	NIPR	41.6	H3.5	36				17.1	14.5			

TABLE III (Continued)

Meteorite[f]	Location of main mass	Mass (g)	Class.	Ref. to pet. descript.[e]	Ref. to bulk anal.[e]	Total Fe (mg g^{-1})	Mg/Si (a/a)	% Fa	% Fs	$\frac{\sigma(\text{Fa})}{\text{mean}}$ %	Co(α) %	Fe°/Fe$_t$ (a/a)
Yamato 74191	NIPR	1091.6	LL3.6	16, 36	20	188		21.4	11.8	23		
Yamato 74417	NIPR	44.5	H3.7	36				13.1	10.9			
Yamato 74660	NIPR	27.2	LL3.0	36				10.5	8.9			
Yamato 74441	NIPR	27.4	L3	36				15.1	11.6			

a Second figure has been corrected for weathering.

b Rose Co. 001 & 031 may be paired (Scott et al., 1986).

c Accalana and Monte Colina are probaly paired (Mason, 1974).

d Breccias.

e References: 1. Fredriksson et al. (1986); 2. Recca et al. (1986); 3. Scott et al. (1986); 4. Keil et al. (1978; 5. Fredriksson et al. (1984); 6. Scott et al. (1982); 7. McScween and Wilkening (1980); 8. Semenko et al. (1978); 9. Olsen et al. (1978); 10. Jarosewich and Dodd (1981); 11. D'yakonova and Kharitonova (1961); 12. D'yakonova (1964); 13. Dodd et al. (1967); 14. Chalmers and Mason (1977); 15. Mason (1974); 16. Scott (1984); 17. McKinley et al. (1981); 18. Score et al. (1982b); 19. Score (1980); 20. Sears and Weeks (1986); 21. Score et al. (1981); 22. King et al. (1980); 23. McKinley and Keil (1984); 24. Anon (1985b); 25. Anon (1984b); 26. Anon (1983a); 27. Score et al. (1984); 28. Anon (1985a); 29. Anon (1986a); 30. Anon (1986b); 31. Anon (1986c); 32. Score et al. (1982a); 33. Anon (1983b); 34. Anon (1984a); 35. Yanai and Kojima (1984); 36. Anon (1983c); 37. Afiattalab and Wasson (1980); 38. Delisle et al. (1986).

f Abbreviations: ALHA, Allan Hills A; AM, Australian Museum; AMNH, American Museum of Natural History, New York; BM, British Museum (Natural History), London; EETA, Elephant Hills A; GSI, Geological Survey, India; GSN, Geological Survey of Nigeria; GU, Gottingen University; LR, L. Russell (1.5 kg in Adelaide University); MAS, Academy of Science, Moscow; MHN, Museum d'Histoire Naturelle, Paris; MWG, Meteorite Working Group of NASA/NSF; NHMC, Natural History Museum, Chicago; NHMV, Naturhis. Mus., Vienna; NIPR, National Institute of Polar Research, Tokyo; PCA, Pensacore Escarpment A; SAM, South Australian Museum; SI, Smithsonian Institution, Washington; UAS, Ukraine Academy of Science; UNM, University of New Mexico, Albuquerque; WAM, West Australian Museum.

TABLE IV

Antarctic type 3 chondrites paired with ALHA 77011 and 77215.

Meteorite (ALHA)	Mass (g)	Class.	Ref. to Pet. Description[a]	Ref. to Anal.[a]	Total Fe (mg g⁻¹)	% Fa	% Fs	σ(Fa)	²⁶Al[b] (dpm kg⁻¹)	TL Sens.[c] (Dhajala = 1)
77011	291.5	L3.5	21, 23			4-36	1-33		39 ± 4	0.34
77015	411.1	LL3.5	21, 22	20	182	1-21	4-24		36 ± 4	0.17
77031	0.5	L3	23, 33			–	–			
77033	9.3	L3	21, 22			8-28	8-9			
77034	1.8	L3	23, 33			–	–			
77036	8.5	L3	23, 33			–	–			
77043	11.4	L3	23, 33, 17			16.9	11.9			
77047	20.5	L3	23, 33			–	–			
77049	8.3	L3	23, 33			–	–			
77050	84.2	L3.5	23, 33			–	–			0.24
77052	112.2	L3	23, 33			–	–			
77115	154.4	L3	23, 33			–	–		48 ± 3	
77140	78.6	L3	21, 22			8-44	2-17		40 ± 4	
77160	70.4	L3	21, 22			3-46	6-40			
77163	24.3	L3	23, 33			–	–			
77164	38.1	L3	21, 22			6-39	3-41		44 ± 5	
77165	30.5	L3	21, 22			8-33	6-35			
77166	138.8	L3	23, 33			–	–			
77167	611.2	L3.4	21, 22	20	205	2-41	3-17		37 ± 2	0.070
77170	12.2	L3	23, 33			–	–			
77175	23.3	L3	23, 33			–	–			
77178	5.7	L3	23, 33, 17			16.9	11.9			
77185	28.0	L3	23, 33			–	–			
77211	26.7	L3	23, 33			–	–			
77214	2111.0	L3.4	21, 22	20	215	1-49	4-23		56 ± 6	0.060
77241	144.1	L3	23, 33			–	–			
77244	39.5	L3	23, 33			–	–			
77249	503.6	L3.4	21, 22	20	229	7-35	2-25		37 ± 2	0.069

TABLE IV (continued)

Meteorite (ALHA)	Mass (g)	Class.	Ref. to Pet. Description[a]	Ref. to Anal.[a]	Total Fe (mg g⁻¹)	% Fa	% Fs	σ(Fa)	26Al[b] (dpm kg⁻¹)	TL Sens.[c] (Dhajala = 1)
77260	744.3	L3.4	21, 22	20	217	7-23	1-28		37 ± 2	0.13
77303	78.6	L3	23, 33			—	—			
78013	4.1	L3	25			11-45	1-31			
78015	34.9	LL(?L)3	22, 23			8-35				
78038	363.0	L3.4	21, 24	20	209	4-42	2-19		36 ± 3	0.078
78186	3.1	L3	25			3-36	3-24			
78188	0.9	L3	21, 24			1-34	5-29			
78236	14.4	L3	25			2-37	3-26			
78238	9.8	L3	25			2-34	3-21			
78243	1.9	L3	25			1-36	3-30			
79001	32.3	L3	21, 24			6-39	2-31			
79045	115.4	L3	21, 24			2-38	2-29			
80133	3.6	L3	32, 27			1-35	5-30			
81025	379.0	L3.7	26, 27	20	225	1-41	3-40			0.4
81030	1851.6	L3.5	26, 27	20	208	1-49	5-33			0.081
81031	1594.9	L3.4	26, 27	20	213	1-43	3-35			0.042
81032	726.8	L3.5	26, 27	20	198	0-42	2-14			0.06
81053	2.5	L3	33			1-29	1-42			
81060	28.3	L3	33			2-28	5-27			
81061	23.7	L3	33			3-33	5-27			
81065	13.1	L3	33			10-41	5-24			
81066	8.7	L3	33			1-44	1-25			
81069	7.2	L3	33			4-38	1-31			
81085	16.2	L3	33			1-39	2-25			
81087	8.4	L3	33			2-29	3-31			
81121	88.4	L3	33			8-40	1-24			
81145	21.1	L3	34			5-40	3-23			
81156	19.7	L3	34			4-42	1-30			
81162	59.4	L3	34			1-40	4-20			
81190	48.3	L3	25			0.3-32	4-28			
81191	30.4	L3	25			2-29	1-30			
81214	4.4	L3	25			0.2-38	0.1-45			

TABLE IV (continued)

Meteorite (ALHA)	Mass (g)	Class.	Ref. to Pet. Description[a]	Ref. to Anal.[a]	Total Fe (mg g⁻¹)	% Fa	% Fs	σ(Fa)	²⁶Al[b] (dpmkg⁻¹)	TL Sens.[c] (Dhajala = 1)
81243	15.0	L3	28			5-44	6-31			
81272	22.9	L3	28			2-36	3-22			
81280	54.9	L3	28			1-32	2-24			
81292	12.9	L3	28			11-34	2-31			
81299	0.5	L3	28			1-37	2-16			
77215	819.6	L3	19, 21, 22			22-26	9-21			
77216	1470.0	L3.4-3.9	19, 21, 22			15-35	14-23			1.6
77217	413.2	L3	19, 21			17-25	9-26			
77252	343.1	L3	19, 21, 22			22-28	2-22			

[a] See Table III footnotes for key to references.
[b] Data from Evans et al. (1982) and Anon (1983a).
[c] Data from Table II (averaging where duplicates are available).
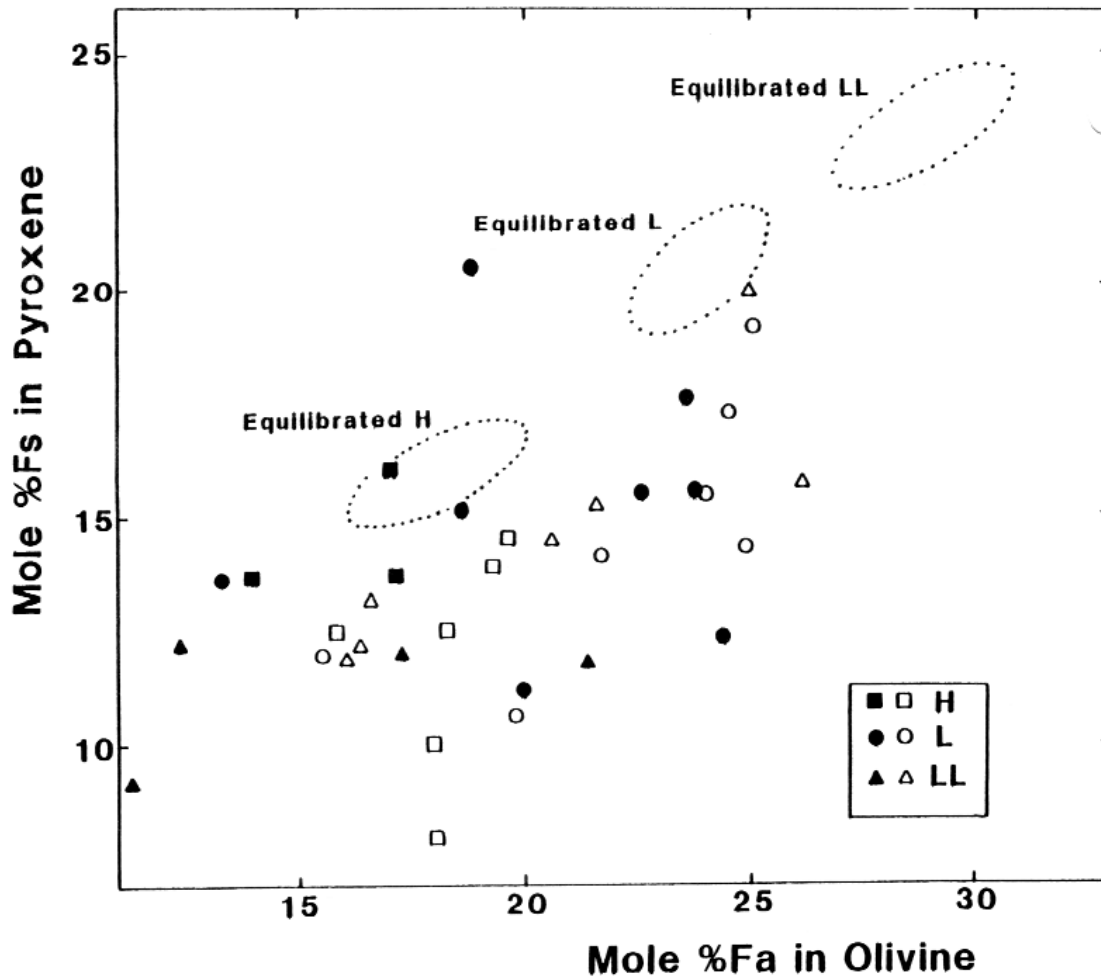
Fig. 5. Plot of the amount of ferrosilite in the pyroxene against the amount of fayalite in the olivine for type 3 chondrites compared with the fields occupied by the equilibrated chondrites. The open symbols refer to samples in the Sears and Weeks (1986) study. Type 3 chondrites contain more reduced silicates; this is especially true of the pyroxene which has smaller diffusion coefficients for Fe transport (from Sears and Weeks, 1986).

3, 4, 5 and 6, although some parameters are better suited to subdivision of the low metamorphic levels than others.

1.4. TYPE 3 ORDINARY CHONDRITES AND THEIR CLASSIFICATION

Table III lists all the known type 3 ordinary chondrites, and some data potentially relevant to their classification. 161 type 3 ordinary chondrites are known, but 71 are probably separate fragments of 3 meteorite finds which became dispersed during fall through the atmosphere or on Earth, so the number of genuinely different type 3 ordinary chondrites is probably only 90 (Scott, 1984; Mason, 1974). Table IV lists the 65 meteorite fragments which Scott (1984) has suggested are all fragments of the Antarctic meteorite Allan Hills A77011.
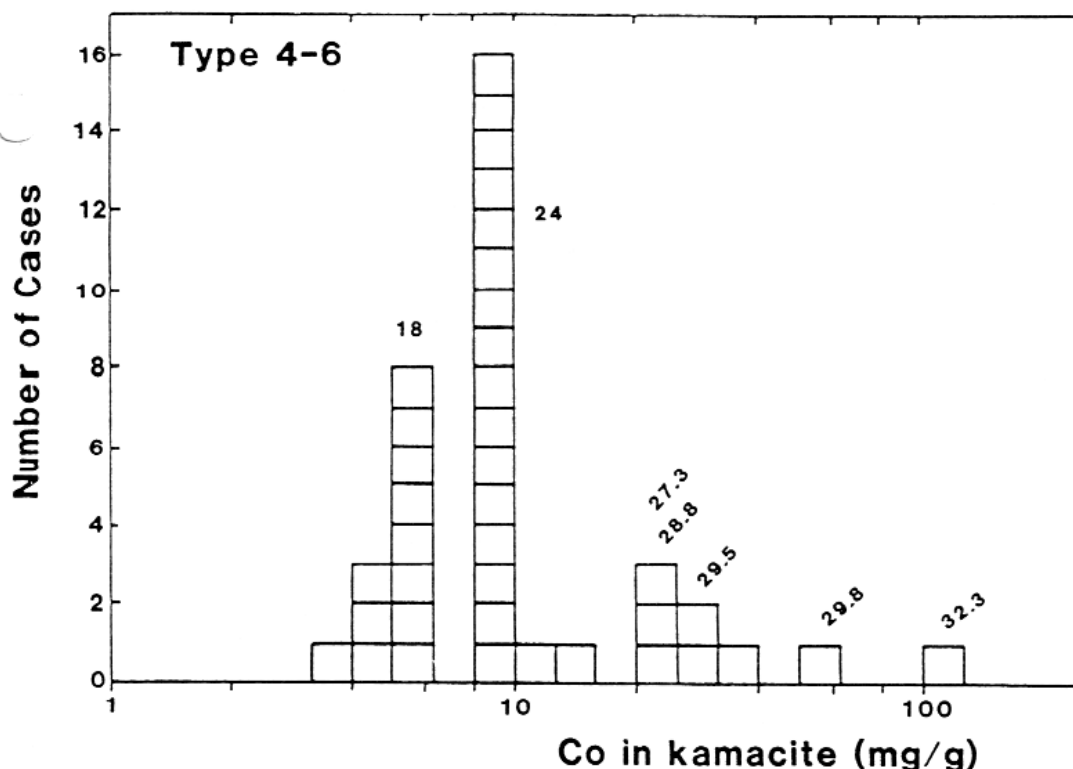
Fig. 6.   Histograms showing the Co content of the kamacite in type 3 ordinary chondrites. Like the FeO content of olivine and pyroxene, this parameter is governed by the oxidation state of the Fe, modified by the kamacite-taenite phase relationships (Sears and Weeks, 1986).

The classification of the type 3 chondrites into the H, L, and LL classes is difficult because one of the parameters well-suited for the classification of equilibrated chondrites – oxidation state – is difficult to apply to type 3 ordinary chondrites; this is also true of oxygen isotope data. Figure 5 compares the Fayalite content of the olivine with the Ferrosilite content of the pyroxene in ordinary chondrites. The equilibrated chondrites plot in three tight clusers, reflecting the differences in oxidation state of the Fe in the H, L and LL classes. However, the unequilibrated chondrites scatter widely due to their mineral heterogeneity, and fall below the equilibrated fields; apparently the Fe in the type 3 chondrites tends to be more reduced compared to that in the equilibrated chondrites. The Co content of the kamacite is also a function of the amount of Fe which has been oxidized out of the metal, and type 3 chondrites have lower Co contents than equilibrated chondrites of the same class (Figure 6). Figure 7 shows the three isotope plot for oxygen. Again the equilibrated chondrites plot in three tight clusters, but the type 3 chondrites scatter widely, and they contain heavier oxygen.

For the classification of type 3 chondrites, it is therefore necessary to rely heavily on bulk compositional data (Figure 8). This is satisfactory for the H chondrites, which are compositionally well-resolved, but not for the L and LL chondrites and it is necessary to use concentration ratios based on equilibrated chondrites to define class boundaries.
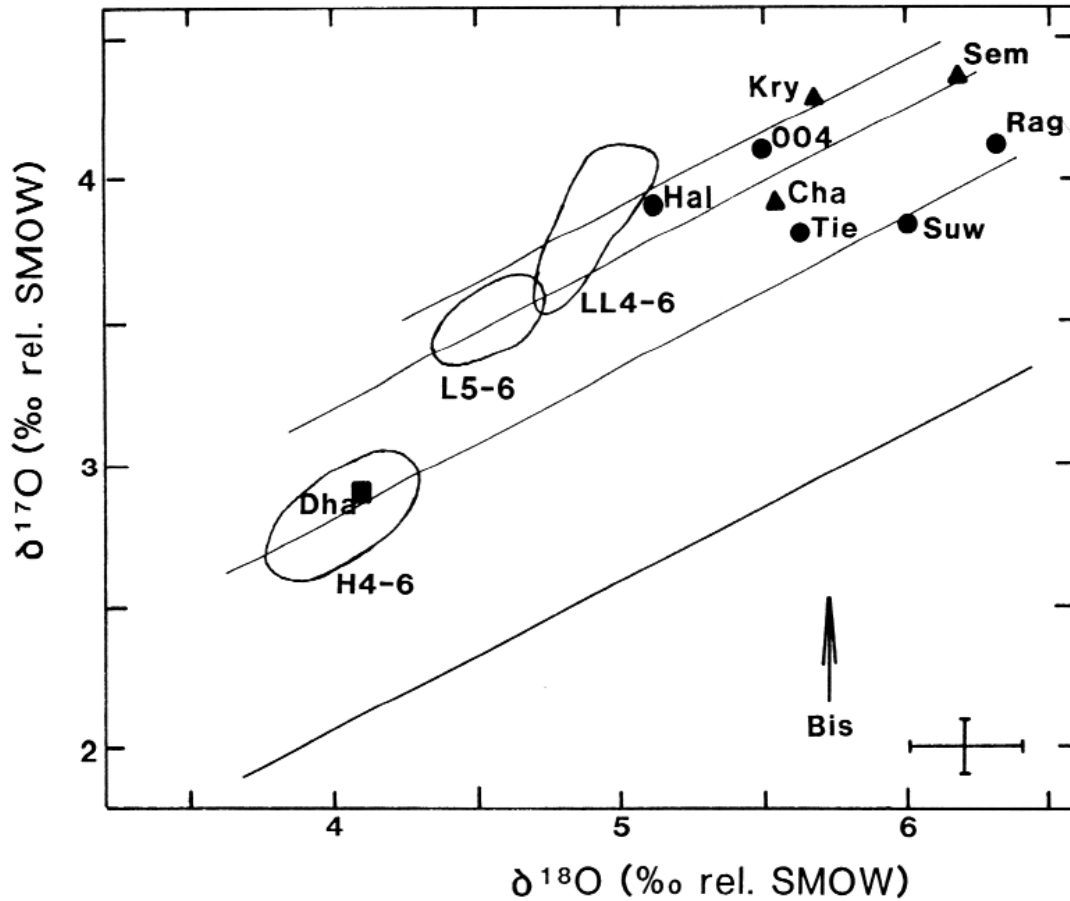
Fig. 7. Three isotope plot for oxygen in which type 3 ordinary chondrites are compared with the fields displayed by the equilibrated chondrites (types 4-6). The diagonal lines have slope 0.5 and provide an indication of the trends expected for mass-fractionation, the heavier line is that produced by terrestrial and lunar samples. Type 3 chondrites contain heavier oxygen but lie, approximately, on mass-fractionation lines with respect to the equilibrated chondrites. In principle, type 3 chondrites may be related to the equilibrated chondrites by chemical processes, such as the preferential loss of heavy oxygen as CO during open-system metamorphism. However, the magnitude of the difference makes this seem unlikely. Typical experimental uncertainties are shown in the bottom right-hand corner (from Sears and Weeks, 1986).

Based on bulk composition data for 40 type 3 ordinary chondrites, Sears and Weeks (1986) found that the distribution of meteorites over the H, L and LL classes were 20%, 40% and 40%, respectively. This is significantly different from the distribution of types 4-6 over the classes (38%H, 54%L, 8%LL).

Another difference between type 3 and the higher types is the distribution over petrologic types. Most type 3 H chondrites are petrologic type > 3.4, while L chondrites show a preference for types 3.3-3.7 (Sears and Weeks, 1986). Type 4-6 H chondrites tend to show a preference for type 5, while L and LL chondrites show a preference towards type 6.
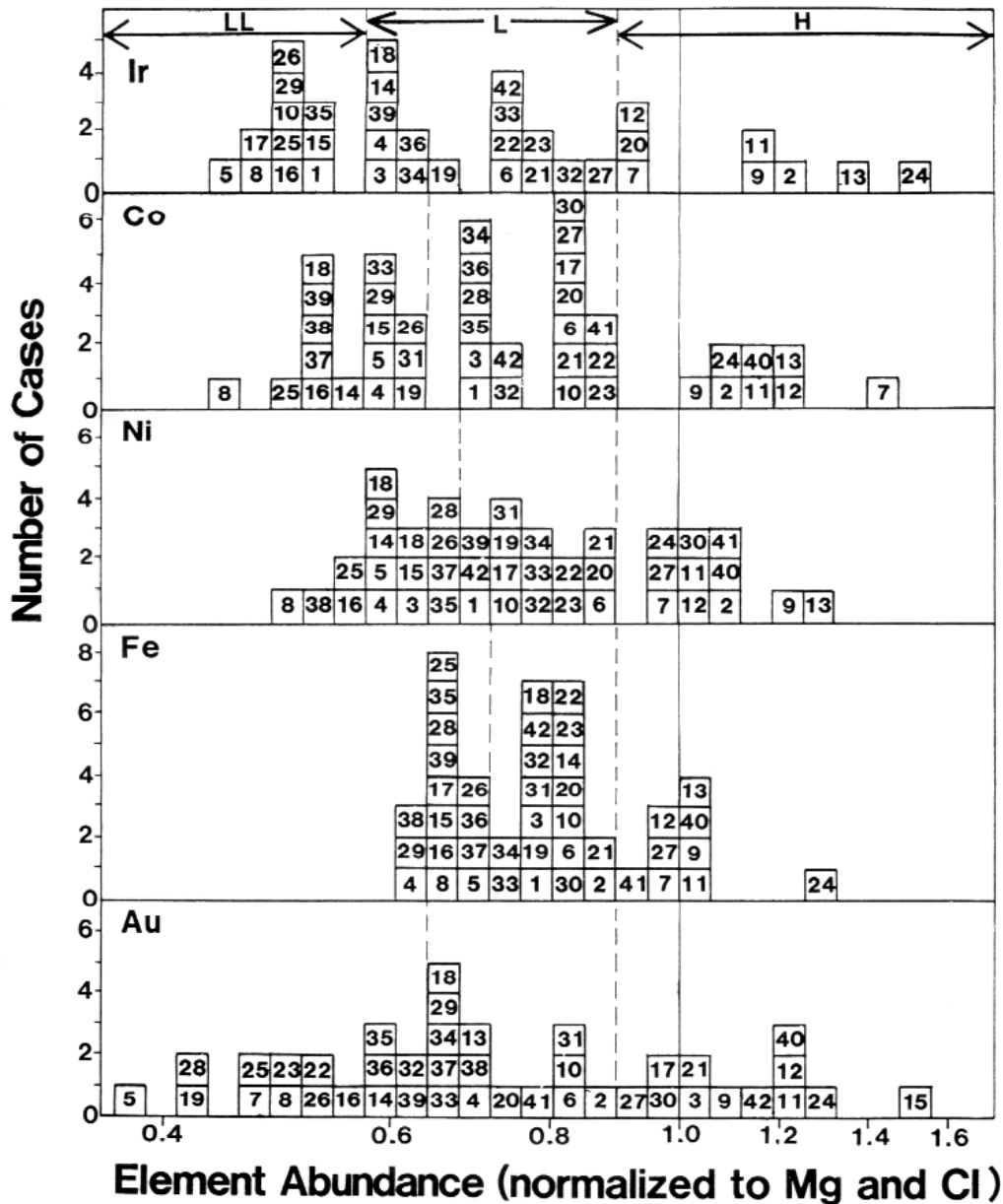
Fig. 8. Histograms showing the elemental abundances (normalized to Mg and CI chondrites) for sidero-phile elements in type 3 ordinary chondrites. The vertical broken lines indicate the ranges observed for equilibrated ordinary chondrites. The numbers identify the individual meteorites (see Sears and Weeks, 1986, from which the figure is taken, for details).

1.5. SOME MAJOR QUESTIONS CONCERNING THE TYPE 3 CHONDRITES

The broadest questions one can ask about any chondrite class is how and where did they form, and what does this tell us about conditions in the primordial solar system. To bring these questions into sharper focus we will address the following specific questions.

(1) What is the relationship between the type 3 ordinary chondrites and the higher petrologic types? It seems very likely that the compositional trends, upon which the chondrite classes are defined, reflect nebular processes. Did the type 3 ordinary chondrites suffer the same processes, and if the details are different, does this shed any light on the process that affected the equilibrated classes?

(2) What was the nature of the metamorphism suffered by the type 3 ordinary chondrite? What can we say quantitatively about the metamorphism suffered by the type 3 ordinary chondrites that might enable an estimation of the size of the parent body and the source of heat that caused the metamorphism? In particular, can we estimate metamorphic temperatures and post-metamorphic cooling rates. Can we determine whether the object accreted hot and metamorphism occurred during the subsequent cooling period ('autometamorphism'), or was there a separate subsequent heating period ('retrograde metamorphism')? Associated with this question is whether the separate components in the meteorite were metamorphosed to any degree prior to incorporation into the meteorite.

(3) Are all the chemical and physical trends observed throughout the type 3 ordinary chondrites due to metamorphism, or is there any evidence that some are due to accretionary (nebular) processes, shock, brecciation, or aqueous alteration?

(4) Can we identify any components in the type 3 ordinary chondrites which still retain a major part of their pre-accretionary, or nebular, properties?
The ultimate challenge is to see if, in attempting to answer any of these questions, we can offer any new insights into the broader questions above.

2. The Data

2.0. COMPOSITIONAL TRENDS IN TYPE 3 ORDINARY CHONDRITES

2.0.0. *Volatile Elements*

A characteristic feature of the type 3 ordinary chondrites is that the highly volatile elements (In, Tl, Bi, Pb, the inert gases and carbon, which is not volatile itself but forms the stable volatile compounds CO and CH_4) are more abundant by factors of 100-1000 than in types 5 and 6, with type 4 chondrites being intermediate (Tandon and Wasson, 1967; 1968; Laul *et al.*, 1970a, b; Case *et al.*, 1973; Keays *et al.*, 1971; Laul *et al.*, 1973; Zahringer, 1968; Heymann and Mazor, 1968; Marti, 1967; Moore and Lewis, 1967).

The apparent correlation with petrologic type is most often interpreted in terms of metamorphism – induced loss of volatiles (Dodd, 1969; Wood, 1967; Wasson, 1972). This pre-supposes that volatiles can move large distances in the meteorite parent body; that the system is essentially open. This supposition is not universally accepted, and, based on an idea of Urey (1951; 1966), the Anders' group have suggested that both trace element abundance and petrologic type reflect burial depth on the meteorite parent body, the highest petrologic types being at greatest depths (Larimer and Anders, 1967; Alaerts *et al.*, 1979). This idea also contains several assumptions: (1) accretion of the
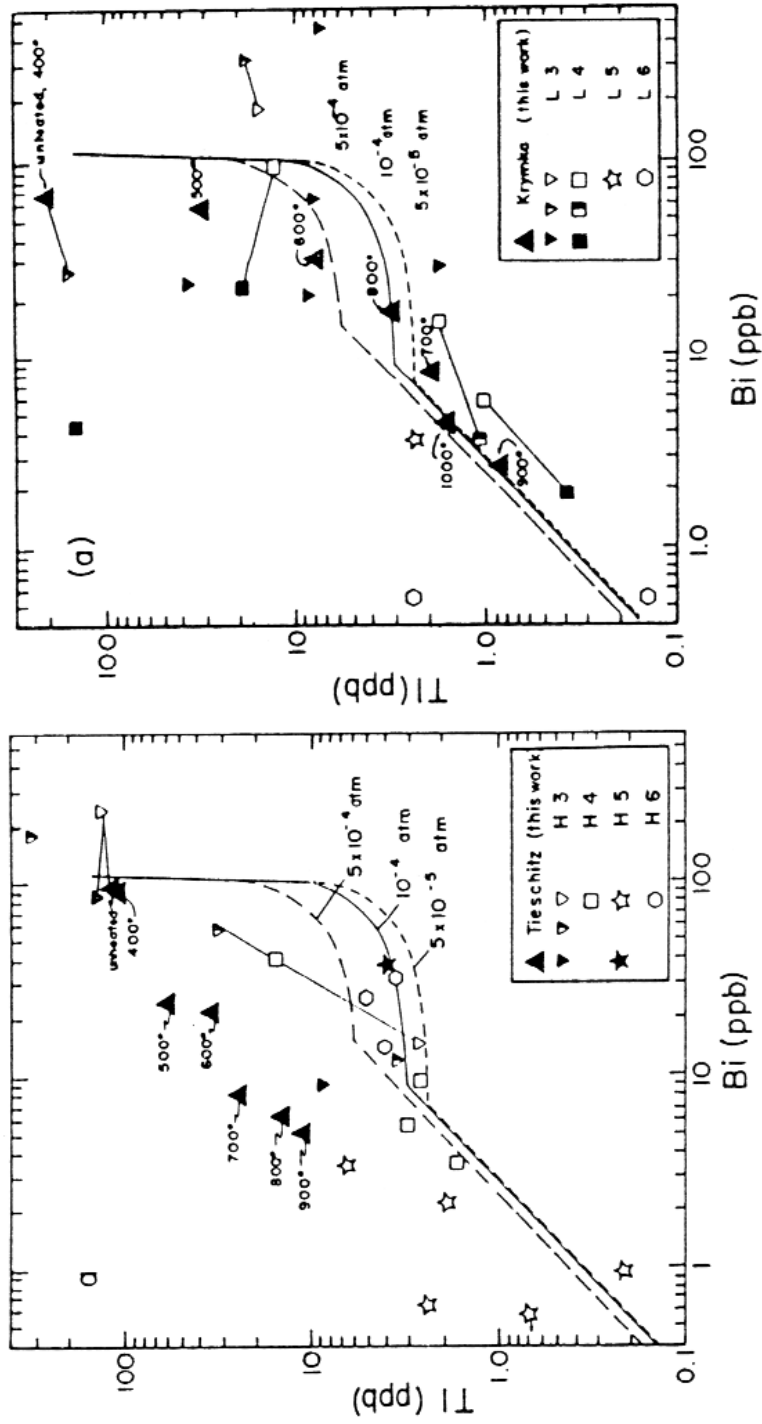
Fig. 9. Plots of indium concentration against bismuth concentration in two type 3 ordinary chondrites (Tieschitz and Krymka). Filled symbols refer to samples which have been annealed at the temperatures indicated for 1 week in a hydrogen atmosphere (pressure 10^{-5} atm), and the open symbols refer to various ordinary chondrites. The curves are the theoretical predictions assuming chemical equilibrium between gas and solids in an open system with overall cosmic abundances (from Ikramuddin *et al.*, 1977a, b).
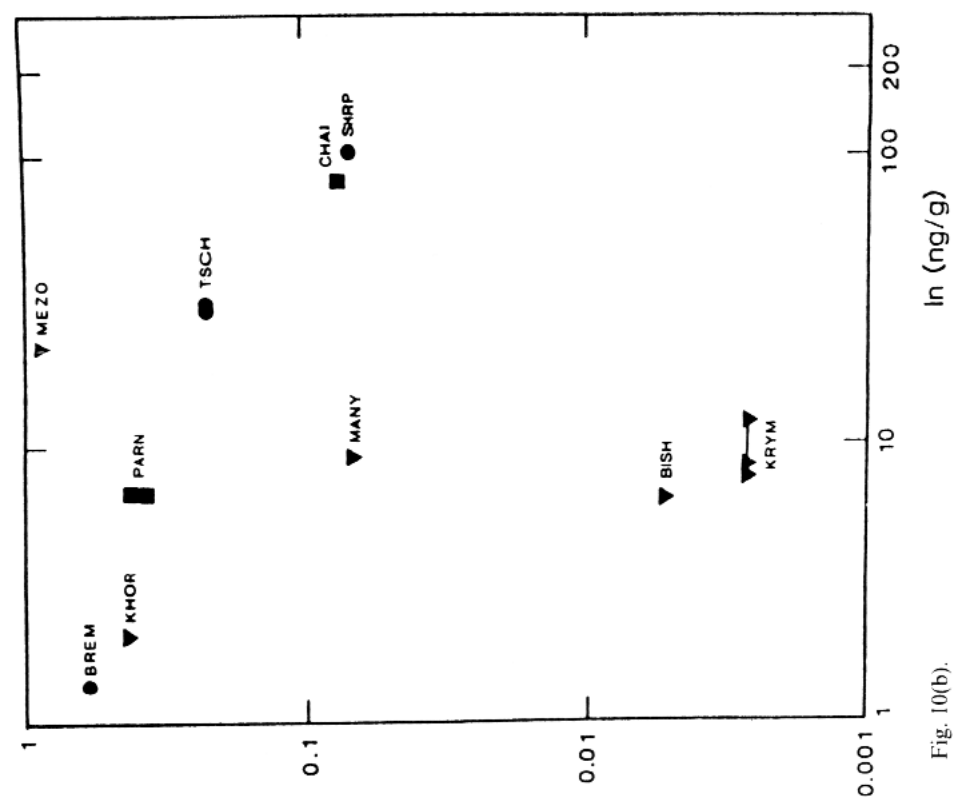
Fig. 10(b).
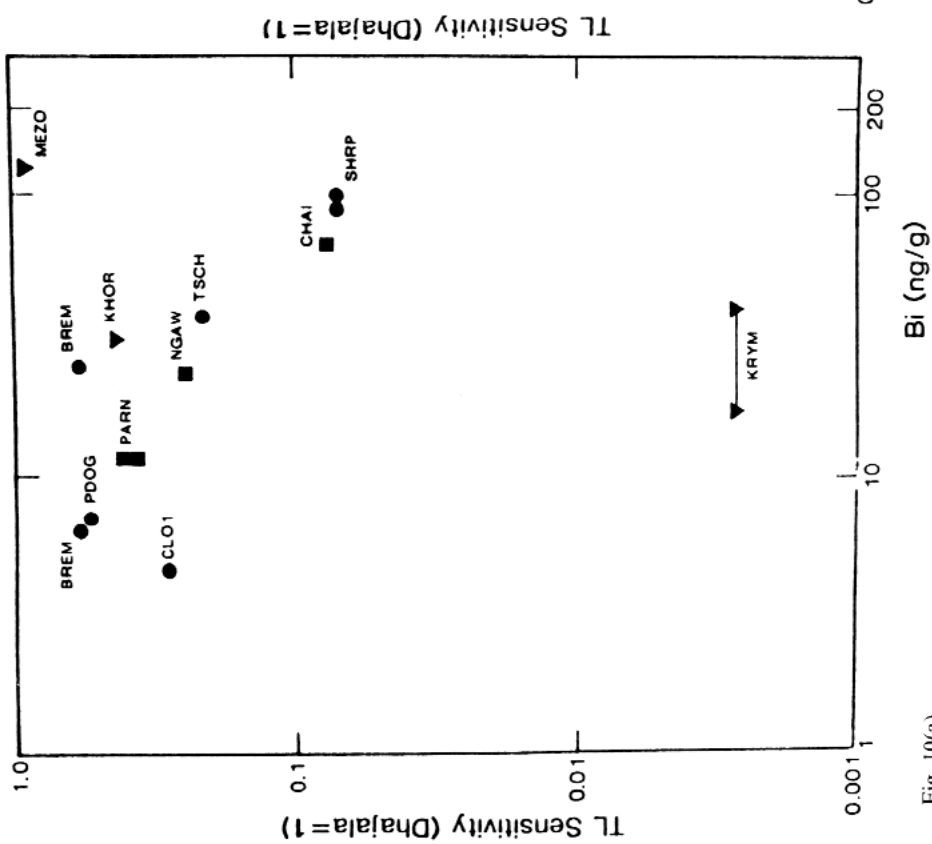
Fig. 10(a).
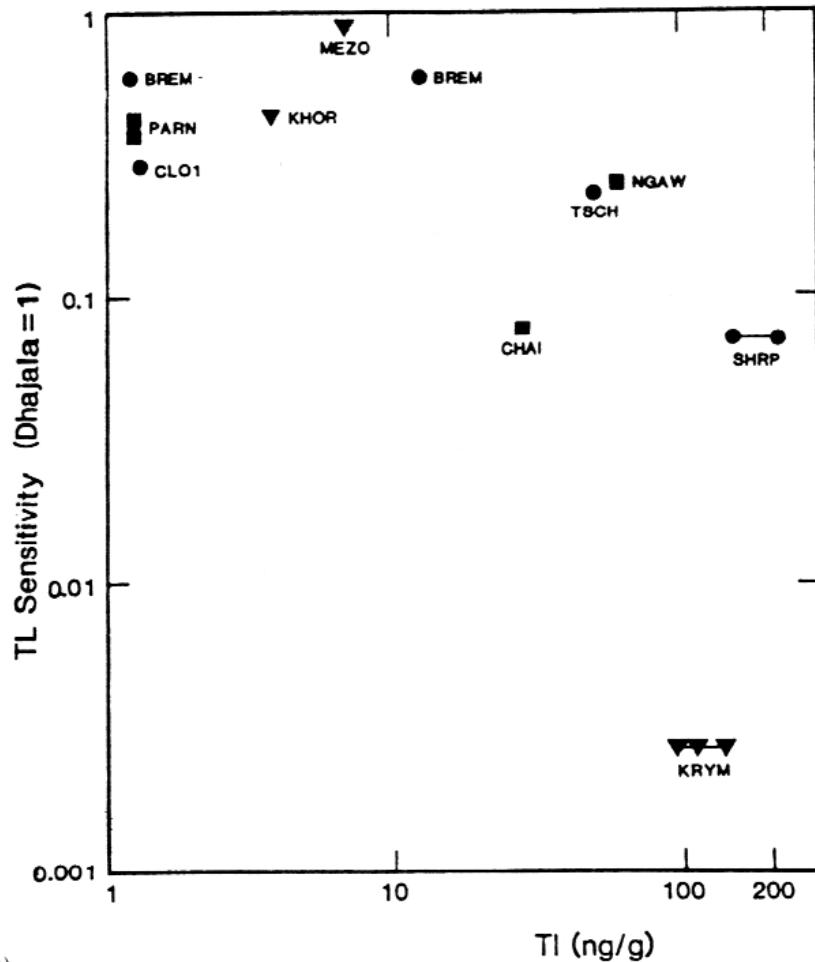
Fig. 10(c).

Fig. 10. Thermoluminescence sensitivity against the concentration of (a) bismuth, (b) indium and (c) thallium in type 3 ordinary chondrites. To a good approximation, TL sensitivity decreases systematically with the amount of these highly volatile elements in the type 3 ordinary chondrites, but the meteorites with lowest TL sensitivity have lower concentrations of these highly volatile elements than expected.

parent body occurred in a cooling gas during the condensation of the volatile elements, (2) that the heat source for metamorphism was internal radioactivity from longlived nuclei. This early accretion meant lower abundances of volatile elements, greater burial depth, and higher metamorphic temperatures. The calculated curves for concentration against temperature, and resulting predictions for plots of one volatile element versus another, have been compared with the observed abundances of volatile elements (Figure 9) to determine accretion temperatures (Keays *et al.*, 1971; Laul *et al.*, 1973). However, this procedure has been criticized because of uncertainty over the thermodynamic data and phases involved (Blander, 1975; see defense by Anders and Larimer, 1975). Nevertheless, it is possible for the Anders theory to be qualitatively correct, but quantitatively weak, and Ikramuddin *et al.* (1977a, b) have observed that the data resemble the theoretical curves more closely than they do samples of Krymka

and Tieschitz annealed at metamorphic temperatures in the laboratory (see below).

The discovery that ^{26}Al was present when certain chondritic components accreted (Lee *et al.*, 1976; Gray and Compston, 1974) has suggested alternative possibilities, since objects as small as 5 km could have become heated significantly. The petrologic type could therefore reflect small differences in accretion time, earlier-formed solids containing greater amounts of the rapidly decaying ^{26}Al and therefore destined to become the higher petrologic types. A great many smaller objects, metamorphosed to varying extents, might be more compatible with the existence of breccias in which materials of various petrologic types are mixed (Scott and Rajan, 1981).

Within the type 3 ordinary chondrites, the highly volatile elements show considerable variation. Figure 10 compares TL sensitivity with In, Tl, and Bi. There is a general tendency for lower levels of TL sensitivity to be accomplished by higher volatile element contents, but the trend is broken by type 3.0-3.1 which have lower abundances of these elements than several types 3.3-3.4. Anders and Zadnik (1985) suggested that the abundance of the highly volatile elements was a measure of 'primitiveness' in the sense of 'closer to solar' and suggested a decimal classification scheme based on volatile elements. Recent TL and other data indicate that the type 3.0-3.1 may have been subjected to aqueous alteration (Hutchison *et al.*, 1985; Guimon *et al.*, 1986b; see below), which account for the discrepant behavior of these meteorites on TL sensitivity vs. highly volatile element plots.

2.0.1. *Non-Volatile Elements*

The major question concerning the non-volatile elements in type 3 ordinary chondrites concerns their siderophile elements and a possible systematic depletion with respect to the equilibrated chondrites. Dodd (1976) first reported that type 3 chondrites were depleted in iron with respect to the higher types, a conclusion that has been confirmed by more recent wet-chemical analyses (Jarosewich and Dodd, 1985). Morgan *et al.* (1985) found that Os, Re, Ir, Ni, Pd, Au and Ge were also about 10% depleted in two type 3 ordinary chondrites, and Sears and Weeks (1986) found Fe, Ni, Ir, Co, Au and As to be depleted 10-15% in 30 type 3 ordinary chondrites compared to the higher types. They also found that the depletion appeared to increase systematically as petrologic type decreases and was not unique to type 3 (Figure 11).

Such depletions demonstrate that the petrologic type 6 meteorites were not produced from the type 3 chondrites by simple closed-system metamorphism. Rather, like the differences in bulk siderophiles that are the basis for the definition of the H, L and LL classes, they must have occurred in the nebula when the material was a diffuse dust. Jarosewich and Dodd (1985) argued that the meteorite parent body for each class must have been compositionally stratified, consistent with the onion skin structure described above, rather than ^{26}Al-heated planetesimals.

The equilibrated H, L and LL classes differ from each other not only in their bulk siderophiles, but also in the ratio of one siderophile to another. Ni/Ir is $> 5.6 \times 10^4$ in the H, but less than this value in the L chondrites (Müller *et al.*, 1971), while on the other hand, the distribution of Au and Ir in the type 3 ordinary chondrites appears fairly
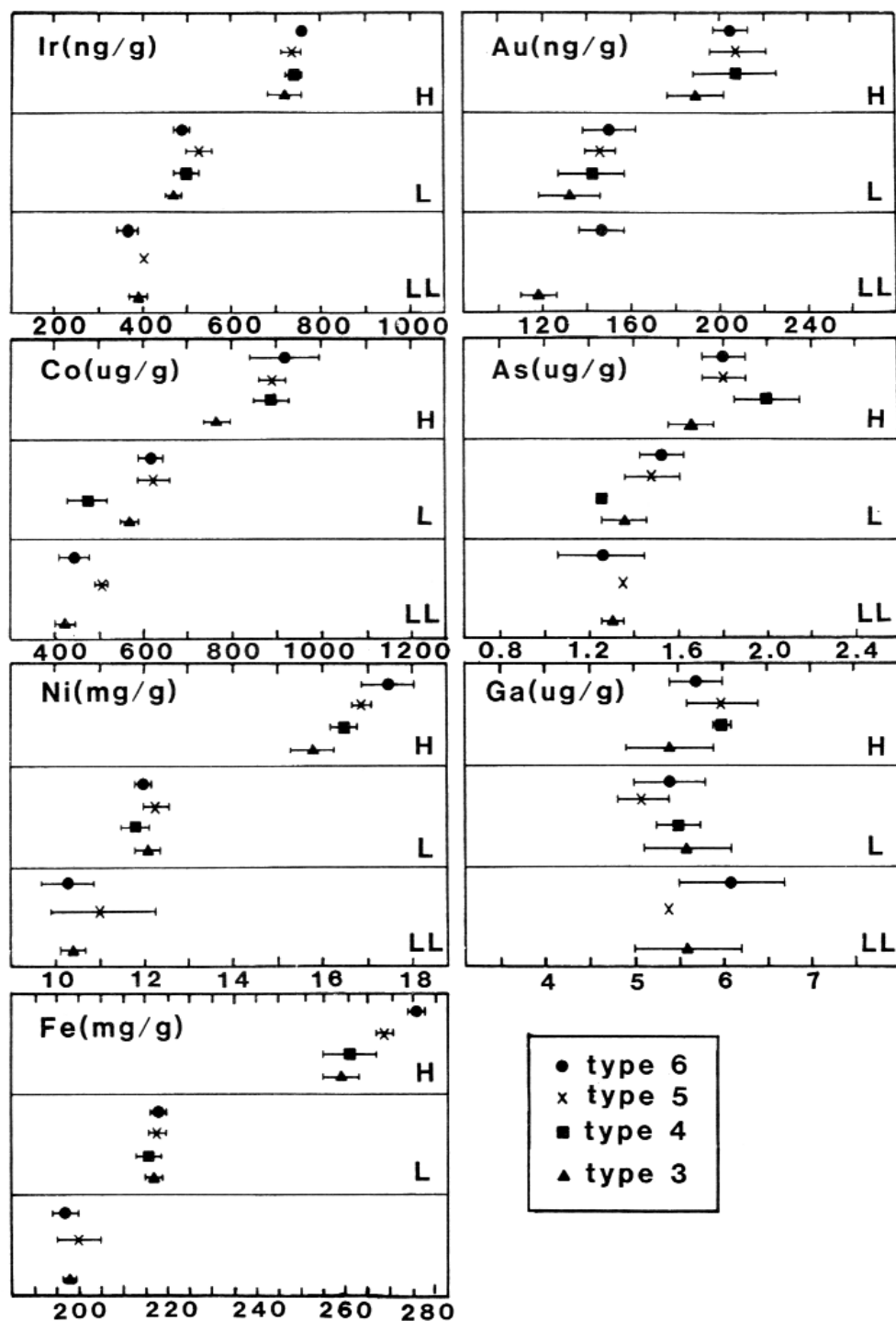
Fig. 11.   The concentration of 6 siderophile elements in ordinary chondrites as function of petrologic type and chemical class. Within each class, the abundance of all elements but Ga decreases systematically with decreasing petrologic type (from Sears and Weeks, 1986).
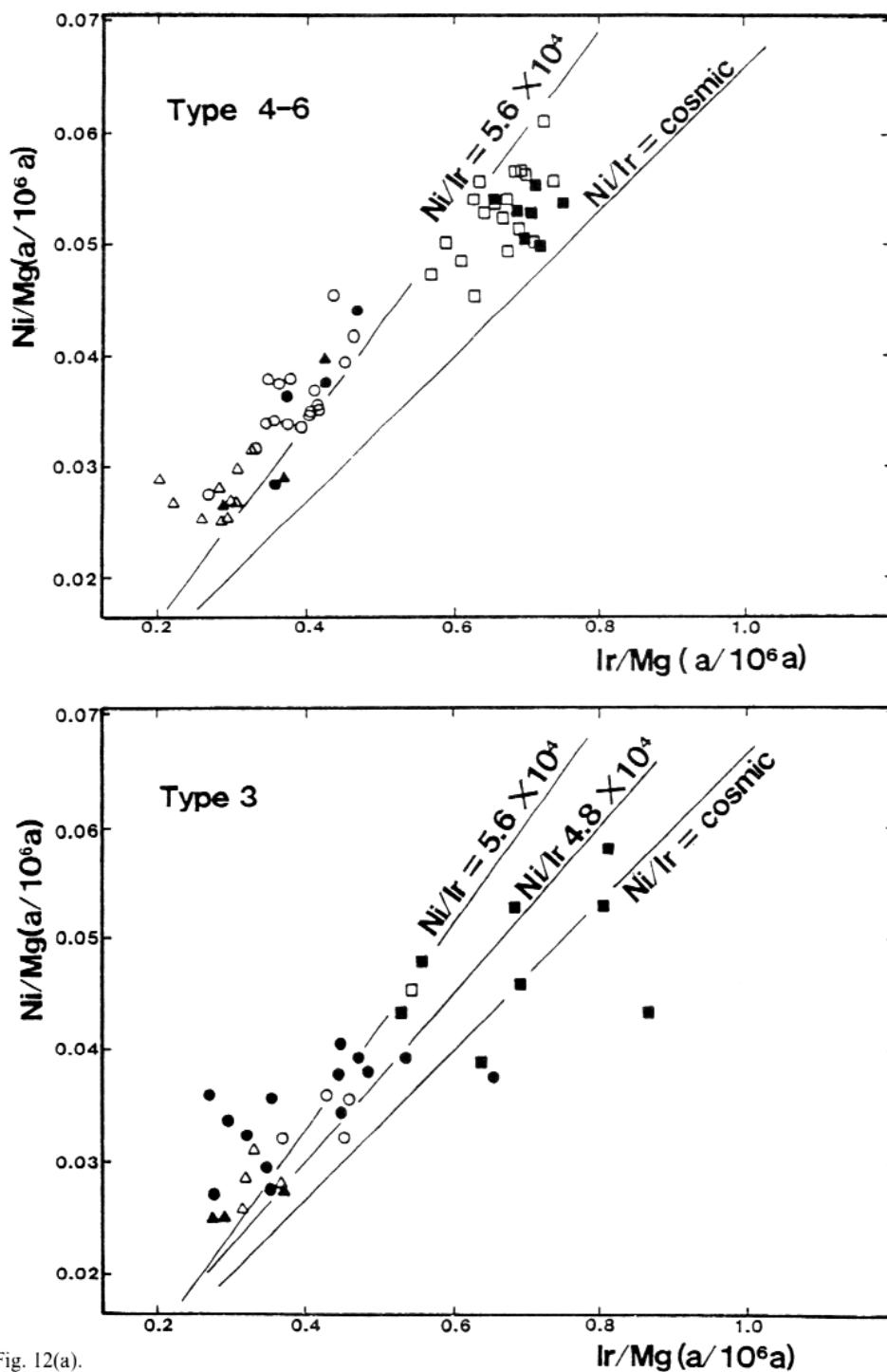
Fig. 12(a).

Fig. 12. Plots of (a) Ni/Mg and (b) Au/Mg against Ir/Mg for the type 3 and type 4-6 ordinary chondrites. In addition to suffering the smaller loss of siderophiles relative to the L chondrites, the H chondrites have smaller Ni/Ir ratio than the L chondrites. The type 3 chondrites show this effect to a greater degree than types 4-6. On the other hand, the Au and Ir distributions for type 3 and type 4-6 are similar (from Sears and Weeks, 1986).
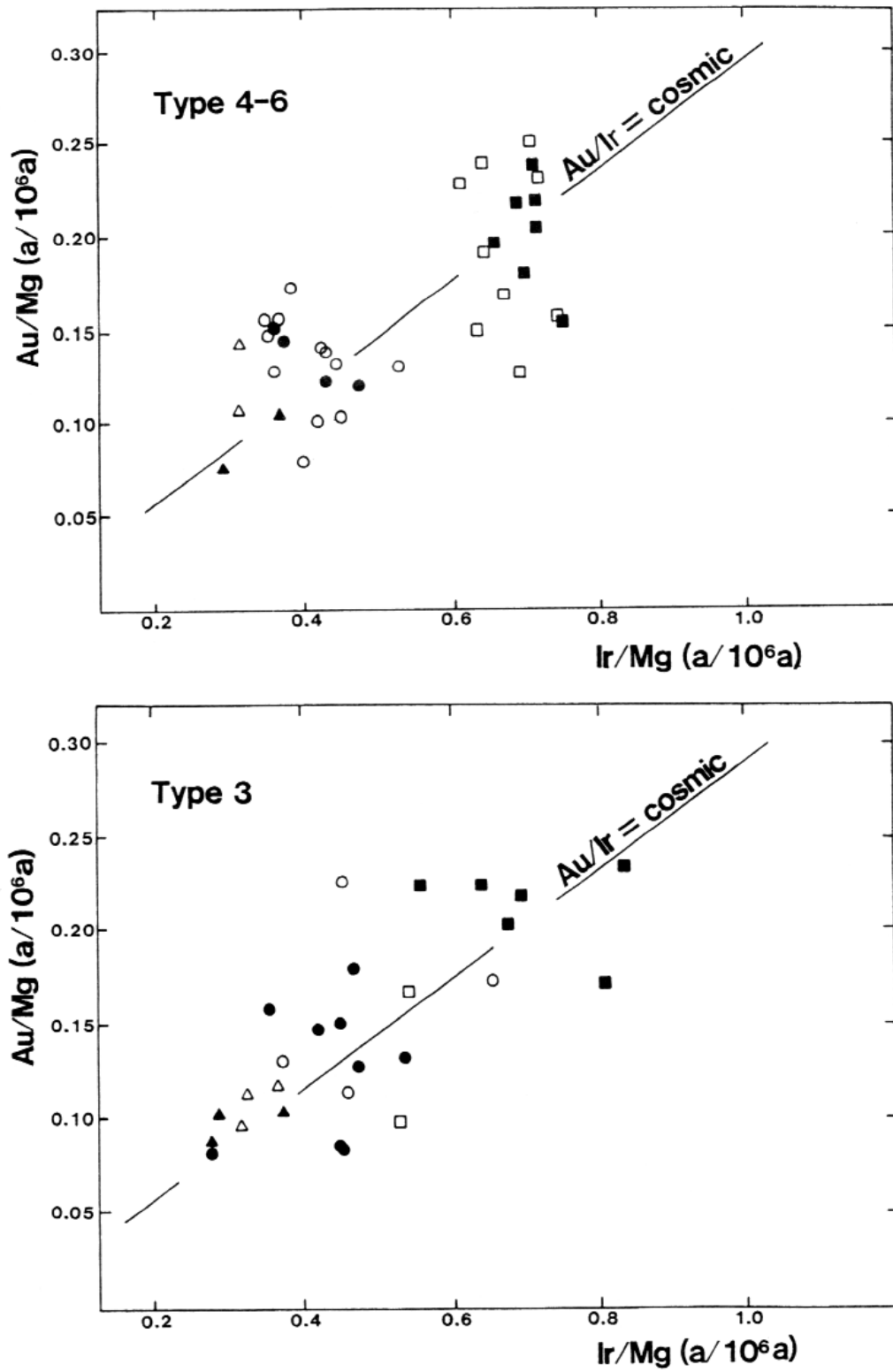
Fig. 12(b).

similar to their equilibrated counterparts. It could be that during separation of the metal from the silicates, a process was operative that removed one siderophile from another: perhaps Ni was being removed into another phase. Sears and Weeks (1986) have shown that the type 3 ordinary chondrites also underwent a fractionation of their siderophile elements, but to a different degree (figure 12; Ni/Ir of 4.8×10^4 separates the two classes). In other words, certain nebular processes which affected the equilibrated ordinary chondrites, also affected the type 3 ordinary chondrites but to a greater degree.

2.1. CHRONOLOGICAL DATA

Radioactive nuclides enable a variety of episodes in the history of meteorites to be dated. Some of these are the fragmentation which led to intense shock (using loss of radiogenic ^{49}Ar) or exposure to cosmic rays (using cosmogenic nuclides such as ^3He and ^{21}Ne), formation of the meteorites (using long-lived nuclides, ^{235}U ^{232}Th, ^{40}K, ^{87}Sr), and relative formation times (using extinct ^{244}Pu and ^{129}I) (Bogard, 1979). Other chronologies (e.g. time interval between the end of nucleasynthesis and meteorite formation), involve the use of sometimes poorly-understood models. A number of type 3 chondrites have been included in these studies, but no detailed systematic comparison of chronological data for type 3 chondrites and the others has been made. Turner (1969) observed that the L3 chondrite, Barratta, like may L chondrites, experienced a major shock event about 500 Ma ago. In view of the unique isotopic, compositional and petrologic properties of type 3 chondrites, such a comparative study is overdue.

2.2. ISOTOPIC DATA

Type 3 ordinary chondrites are noteworthy, not only for their enrichment in heavy oxygen mentioned above (Figure 7), but also for extreme deuterium enrichments (Mc Naughton et al., 1982, Figure 13). The enrichment is greatest for the lowest petrologic types, especially Semarkona and Krymka, and step-wise heating experiments released the deuterium mainly as water. δD values as high as $+5740‰$ were found in Semarkona. If the water really was indigenous, and not formed during the experiment, such δD values would clearly confirm extraterrestrial origin for the water.

Grady et al. (1982) found that certain type 3 ordinary chondrites contained heavier carbon than the others ($\delta^{13}C$ of -18 to -10 per mil, compared with more normal values of -20 to -30 per mil), but the relevant meteorites were all finds and the enrichments were attributed, in large part, to weathering.

The oxygen data provide an additional indication that the type 3 ordinary chondrites are not simply related to the equilibrated chondrites by closed system metamorphism. The type 3 chondrites approximately lie on a mass fractionation line about 1 per mil from the equilibrated chondrites so that it is possible, in principle, to convert type 3 $\delta^{18}O$ values into types 4-6 values by chemical means. Since the type 3 chondrites are enriched in C relative to type 4-6, loss of ^{18}O as CO during metamorphism is an obvious possibility. Laboratory experiments show that at low temperatures ^{18}O goes preferentially into the CO, when in contact with olivine or pyroxene. However there is
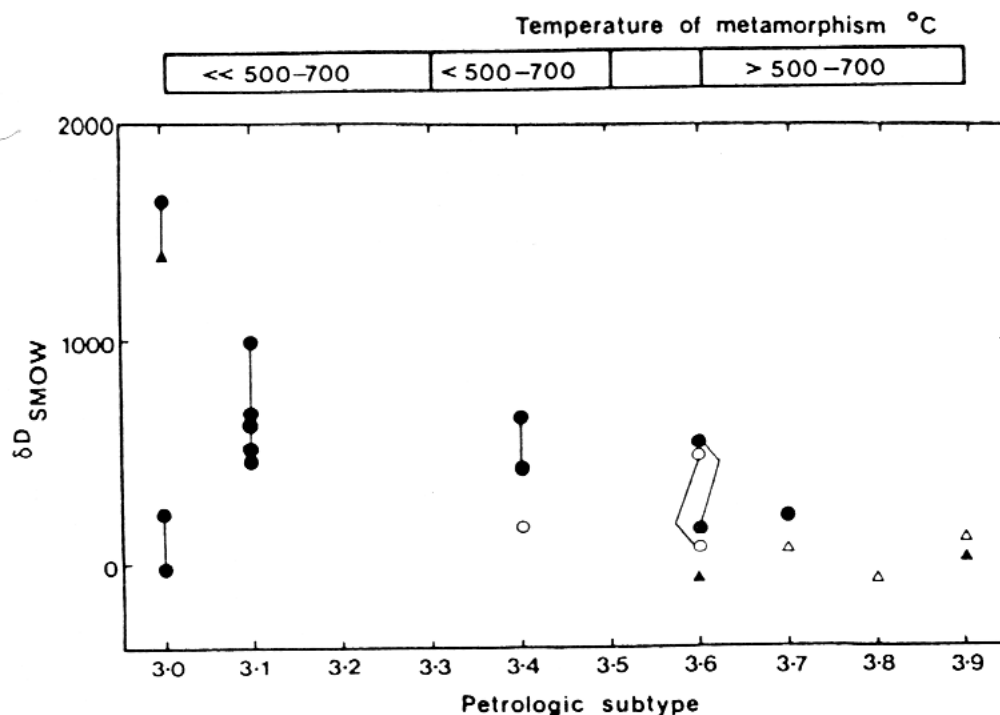
Fig. 13.   Deuterium enrichments in type 3 ordinary chondrites as a function of petrologic type. The lowest types show the greatest enrichments and this heavy hydrogen is released during stepwise heating in the form of water (from McNaughton *et al.*, 1982).

insufficient C available to convert type 3.0 values of $\delta^{18}O$ to those of the equilibrated chondrites (Sears and Weeks, 1983).

The type 3 ordinary chondrites scatter above and below the slope 1/2 line produced by mass fractionation, indicating that a component of unusual ^{16}O is present in the meteorite. Components from the Allan Hills A76004 meteorite were found to plot on a line with slope 1.0, indicating that they were a mixture of a component of almost pure ^{16}O and another, probably a gas, enriched in heavy oxygen (Mayeda *et al.*, 1980). In fact, there seems to have been several gaseous reservoirs in the early solar system equilibrating with a single heavily ^{16}O-enriched solid (this is discussed below).

The inert gases, which are abundant in type 3 ordinary chondrites, also show complex isotopic structure suggestive of several components, some of which may be non-solar in origin. Bishunpur, Krymka and Chainpur contain a curious V-shaped pattern for the 9 stable isotopes of Xe. Both heavy and light isotopes are enriched (Alaerts *et al.*, 1979). The same pattern is observed in carbonaceous chondrites, and theories for its origin are essentially two fold: (1) the xenon suffered mass fractionation and the addition of a component produced by fission of a superheavy element (Anders *et al.*, 1975) and (2) this xenon is of an unusual nucleosynthetic (i.e. extrasolar system) origin (Manuel *et al.*, 1972; Clayton, 1977).

2.3. Mineralogic and Petrologic Data

2.3.1. *Chondrules*

Chondrules are unique to meteorites and, by volume, constitute the bulk of the meteorite. Because their properties are highly sensitive to metamorphism, most of the volumous literature on chondrules concerns those of type 3 ordinary chondrites. They were the subject of a recent book which includes several reviews (King, 1983).

Chondrules in type 3 ordinary chondrites are 90-1700 μm in diameter, with a mode around 0.5-1.0 mm (Martin and Mills, 1976; Hughes, 1978; King and King, 1981; Gooding, 1979; Sparks *et al.*, 1983; Rubin and Keil, 1984). The Piancaldoli meteorite contains an unusual clast with 0.2-64 μm chondrules (Rubin *et al.*, 1982). The petrology of the chondrules is well-summarized in Gooding and Keil's (1981) classification scheme in which they are divided broadly into porphyritic and non-porphyritic, and then into finer divisions (Figure 14). The porphyritic chondrules consist of large grains of olivine and/or pyroxene located in a glass of essentially feldspathic composition. They are subdivided into porphyritic olivine, porphyritic pyroxene, porphyritic olivine-pyroxene and barred olivine types. The non-porphyritic chondrules have much finer textures, but also consist essentially of olivine and pyroxene located in a glass and are subdivided into radiating pyroxene, cryptocrystalline and granular olivine pyroxene types.

Certain chondrules have been found to contain 'relic grains', grains which retain evidence for not being melted during the chondrule forming process (Rambaldi, 1981; Nagahara, 1981; Rambaldi and Wasson, 1981; Kracher *et al.*, 1984).

There is no difference in the size distribution of porphyritic and non-porphyritic chondrules, but the proportion of the two chondrule types and their size distribution differs from meteorite to meteorite (Rubin and Keil, 1984). The last observation implies that the chondrules experienced a size-sorting process, perhaps aerodynamic sorting occured (Dodd, 1976). Microcraters on the surfaces of some chondrules, and compound chondrules – where one chondrule has impacted another and adhered (Tschermak, 1964) – clearly show that the chondrules were independent entities in space prior to incorporation in the meteorite and were formed in regions of fairly high chondrule densities. However, charged particle tracks have not been observed on the surfaces of chondrules, which indicates that exposure to cosmic rays was of very limited duration (Allen *et al.*, 1980).

The extent to which metamorphism has affected individual chondrules seems to vary from chondrule to chondrule in many type 3 ordinary chondrites. Some chondrules may contain compositionally heterogeneous, high-Ca olivine and glassy mesostasis ('unequilibrated chondrules') while others contain homogeneous, low-Ca olivines and recrystallized mesostatis ('equilibrated chondrules'). This has led Dodd (1968; 1971) and Scott (1984) to suggest that individual chondrules had separate metamorphic histories prior to incorporation in the meteorite. Variations in TL sensitivity, TL peak temperature and width, and their relationships with the amount and composition of chondrule mesostasis, led Sears *et al.* (1984) to suggest that these differences in
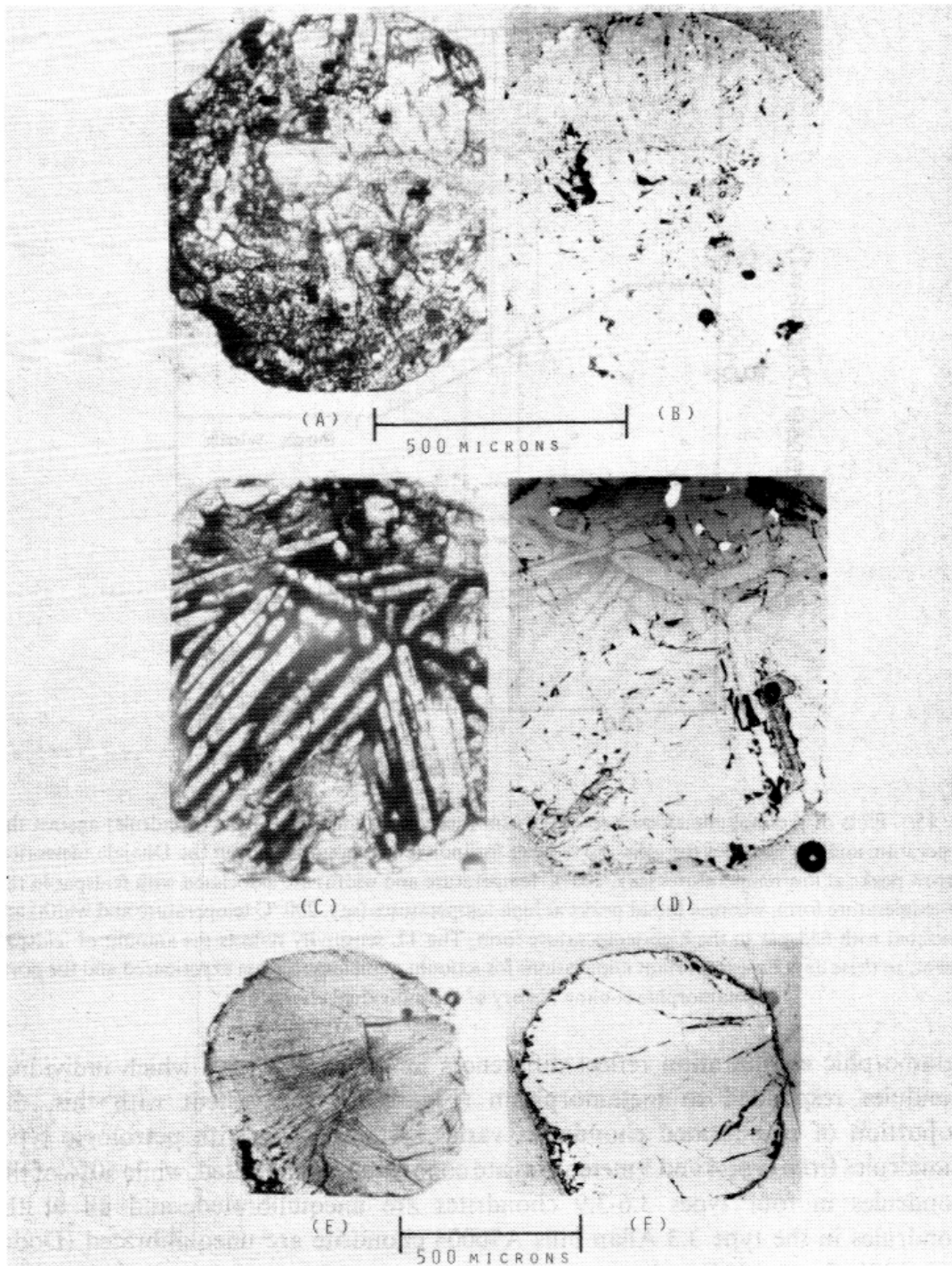
Fig. 14. Photomicrographs of several varieties of chondrules in ordinary chondrites, transmitted light images on the left and reflected light on the right. A-B, prophyritic olivine, pyroxene chondrule in Semarkona; C-D, barred olivine chondrule in Weston; E-F, radiating pyroxene chondrule in Weston (from Gooding and Keil, 1981).
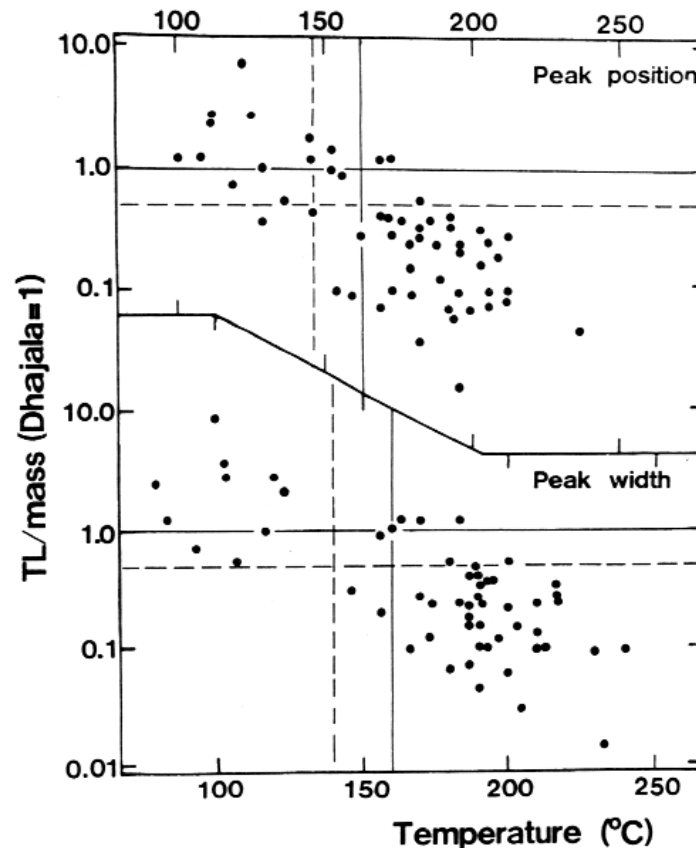
Fig. 15.   Plots of thermoluminescence sensitivity (normalized to the mass of the chondrule) against the temperature and the width of the glow curve peak for individual chondrules from the Dhajala meteorite. Narrow peaks at low temperatures (say, 100 °C temperature and width) are associated with feldspar in the low-temperature form, whereas broad peaks at high temperatures (say, 200 °C temperature and width) are associated with feldspar in the high-temperature form. The TL sensitivity reflects the amount of feldspar present, so these data have important implications for amount of metamorphism experienced and the post-metamorphic cooling history of the individual chondrules.

metamorphic equilibration reflect differences in the facility with which individual chondules responded to metamorphism (Figure 15). Consistent with this, the proportion of equilibrated chondrules varies systematically with petrologic type: Chondrules from type 4 and 5 meteorites are completely equilibrated, while 50% of the chondrules in four types 3.6-3.9 chondrites are unequilibrated, and all of the chondrules in the type 3.3 Allan hills A76004 chondrite are unequilibrated (Dodd, 1968; 1971; Scott, 1984).

Evidence for the pre-accretionary history for certain chondrules is provided by rims of fine-grained, matrix-like material that surrounds many chondrules (Allen *et al.*, 1980; Rambaldi and Wasson, 1981; Rubin, 1984). It seems that the rims formed by the accretion of clumps of dusty material onto the chondrule while it was still hot and in free space. Rims of sulfide and sulfide-rich silicates are also observed, and are assumed
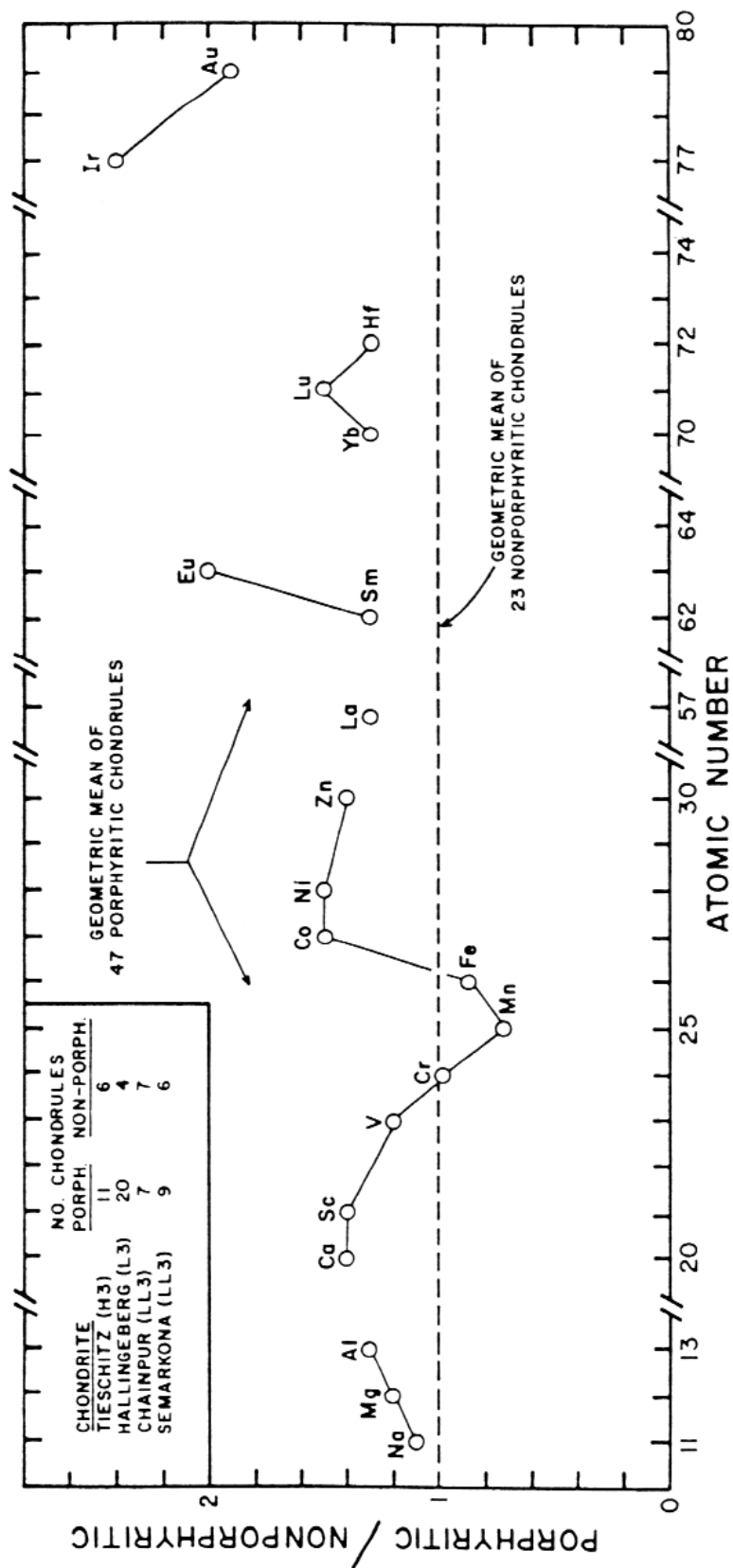
Fig. 16. Composition of individual chondrules from 4 type 3 ordinary chondrites. The mean composition of porphyritic chondrules has been divided by the mean composition of non-porphyritic chondrules. Porphyritic chondrules are enriched in most lithophile elements as well as Ir and Au (from Gooding et al., 1980).

to have a similar origin. Chemical analysis of separated chondrules from type 3 ordinary chondrites has shown that the chondrules are depleted in siderophile elements by factors of 5-10, presumably reflecting the loss of metal before or during chondrule formation. There are also small compositional differences between porphyritic and non-porphyritic chondrules, the porphyritic chondrules being about 40% enriched in refractory and siderophile elements relative to non-porphyritic chondrules (Figure 16; Osborne *et al.*, 1973; Gooding *et al.*, 1980). This could reflect either different source materials, or different degrees of vapor fractionation during chondrule formation (Dodd and Walter, 1972). Grossman and Wasson (1982; 1983) have used factor analysis to show that chondrules are mixtures of several compositional groups of material – metal and sulfide, Ir-rich metal, refractory – rich silicates, non-refractory – rich silicates, volatile rich silicates – and argued from this that chondrules were formed from pre-existing grains.

Much of the available data on the oxygen isotope abundances in chondrules from type 3 ordinary chondrites is presented in Figure 17. Interpretation of these data is difficult because of fine structure caused by chemical class and petrolic type differences and the data base is too small to disentangle the effects. It is clear that more than just mass fractionation from a single starting material is involved, however; some mixing of ^{16}O-rich and ^{16}O-poor components is necessary and this probably required a nebular environment (Gooding *et al.*, 1982; Clayton *et al.*, 1983). Components, mainly
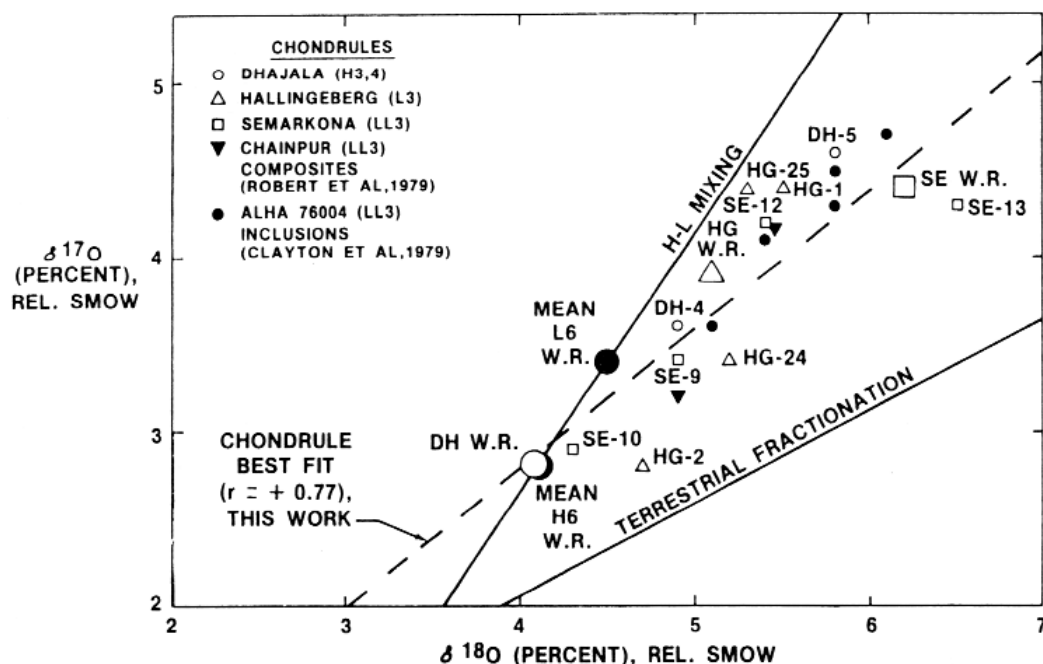
Fig. 17.   The isotope plot for oxygen showing data for individual chondrules. The 'H-L mixing' line passes through the fields for the equilibrated ordinary chondrites, the 'terrestrial fractionation' line refers to the mass-fractionation line produced by lunar and terrestrial samples. The individual chondrules neither plot on a mixing line with slope 1, nor a mass fractionation line with slope 0.5, and it is thought that both processes have been involved (from Gooding *et al.*, 1982).

chondrules, from the type 3.4 ordinary chondrite Allan Hills A76004 yielded a slope 1 line, indicating that the individual components are the result of mixing two components of differing ^{16}O (Mayeda *et al.*, 1980).

Separated chondrules from ordinary chondrites, including many type 3, have been dated by the U-Pb, Rb-Sr, ^{40}Ar-^{39}Ar and I-Xe methods and the results recently summarized by Swindle et al. (1983). According to the U-Pb and Rb-Sr methods chondrules are the same age as each other and the host meteorite to within 20 m.y. (the precision of the methods), while the more precise I-Xe method indicates a 5-10 m.y. spread in ages. Some of the spread in I-Xe ages could reflect ^{129}I heterogeneities in the nebula.

Rb-Sr isochrons yield ages which vary with petrologic type, suggesting that the ages are referring to post-metamorphic equilibration: Parnallee (LL3.6), 4.53 ± 0.02 (Hamilton *et al.*, 1979); Soko Banja (LL4), 4.452 ± 0.02 (Minster and Allegre, 1981); Richardton (H5), 4.39 ± 0.03 (Evensen et al., 1979). The ^{40}Ar-^{39}Ar method is difficult to apply to type 3 ordinary chondrites because they fail to produce a plateau; this is attributed to redistribution of the ^{39}Ar by recoil during neutron irradiation. However, age estimates based on total Ar spread over 200 m.y., probably also referring to the end of metamorphism; however, there is no correlation between petrologic type and age bases on total Ar. Ages based on total Ar for chondrules from type 3 and 4 ordinary chondrites indicate that barred olivine chondrules are 200 m.y. older than nonporphyritic chondrules (Swindle *et al.*, 1983).

Most authors have concluded that chondrules formed by the flash melting of pre-existing coarse-grained dust. Evidence cited for this conclusion is the elemental and isotopic heterogeneity of the chondrules, and the presence of relict grains (Gooding *et al.*, 1982; Grossman and Wasson, 1983; Rambaldi, 1981; Nagahara, 1981). One chondrule exists which contains relic material resembling the matrix (Scott *et al.*, 1984), consistent with an origin of the chondrule from matrix. Taylor *et al.*, (1983) recently reviewed the evidence concerning the siting of chondrule formation, favoring a nebula setting. They rejected impact on planetary bodies or during accretion on the grounds that chondrules are too numerous and melt glasses too scarce in chondrites, chondrules are uniformly dated to around 4.5 Ga while impacts occurred to much more recent times, and that accretion is insufficiently energetic to produce chondrules. Volcanic theories can be rejected for the same reasons. The presence of chondrule rims and the oxygen isotopic heterogeneity seem especially consistent with a nebula location for chondrule formation. However, while the Taylor *et al.* (1983) arguments have been well-received, the number of workers on record as favoring an impact origin is significant.

2.3.2. *Matrix*

There are considerable differences in the nature of the matrix of ordinary chondrites, and this is well-apparent in their cathodoluminescence properties. In the lowest petrologic types it is a uniform blood-red color, in type 3.1 it is a blotchy red with occassional small blue grains, in type 3.3-3.4 it is essentially non-luminescent and in
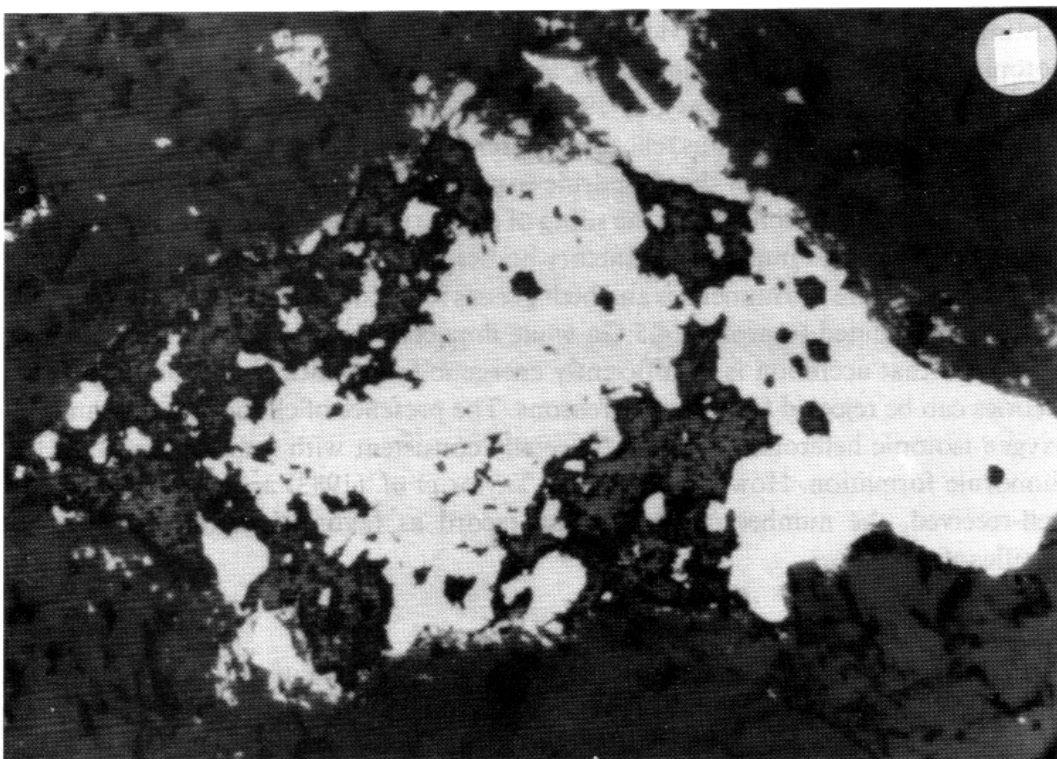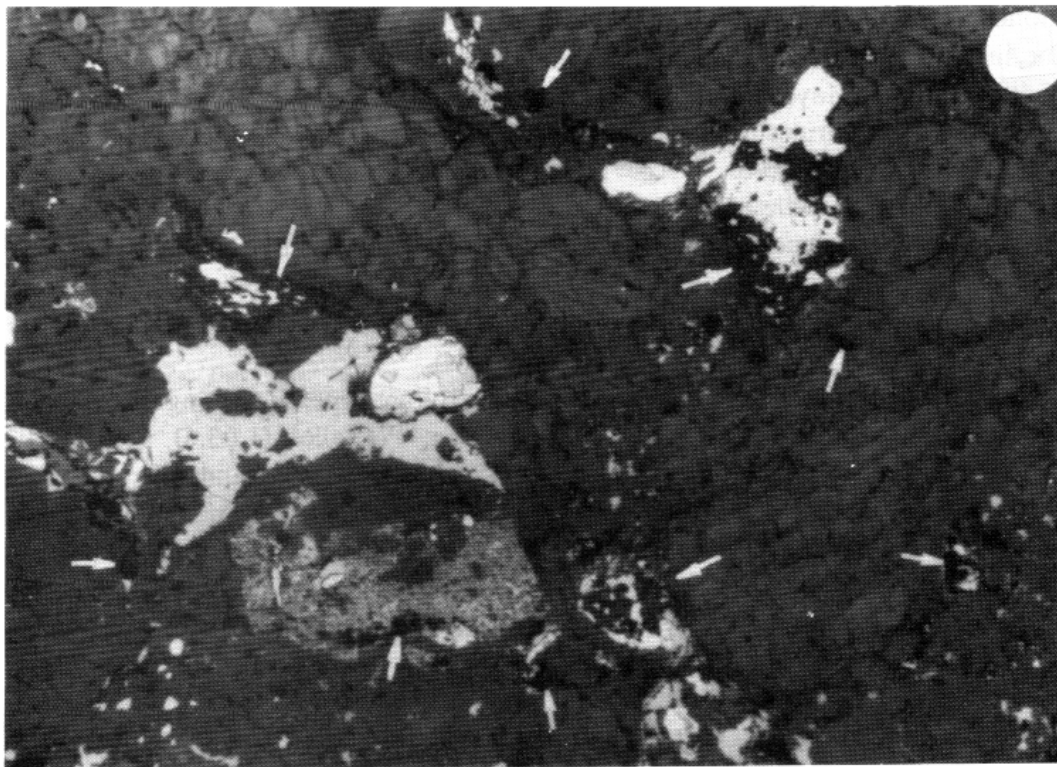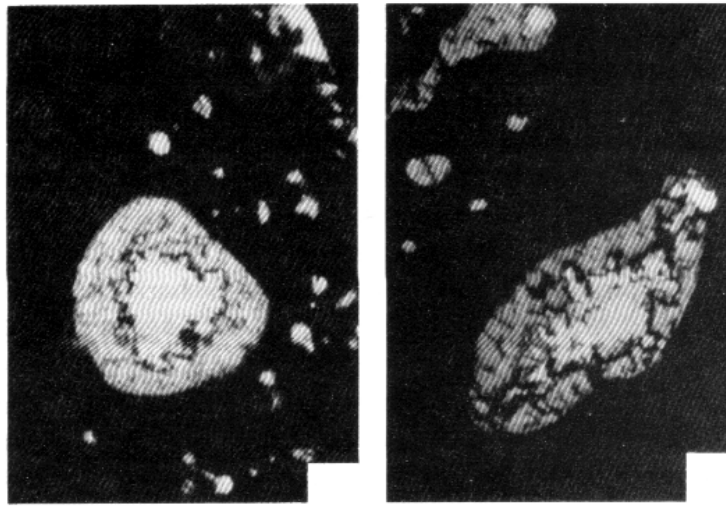
Fig. 18(a).

Fig. 18(b).

Fig. 18.   Photomicrograph showing (a) an inclusion of graphite-magnetite in Allan Hills A77011 (from McKinley *et al.*, 1981) and (b) Si-bearing metal grains encased in sulfide (from Rambaldi *et al.*, 1980).

higher types it is coarse-grained and blue. In the higher types, the matrix begins to resemble the chondrules in CL and texture and may be comminuted chondrules. Clearly there are major mineralogical changes occurring as petrologic type increases.

These conclusions are borne out by petrographic work (Huss *et al.*, 1981; Nagahara, 1984; Scott *et al.*, 1984). In the lowest petrologic types (< 3.3) the matrix is predominantly ($> 80\%$) opaque, while in types 3.3-3.4 it is 50-60% opaque and for type > 3.4 it is $<40\%$ opaque. The loss of opacity is caused by recrystallization (Ashworth, 1977; Ashworth and Barber, 1976), but is also associated with decreases in the Fe and Ni which may indicate the loss of very fine grained metal from the matrix. The $Feo/Feo + Mgo$) value for the matrix decreases from > 1.9 to < 1.0 (normalized to the whole rock value) through type 3 as metal grains migrate out of the matrix and coalesce (Huss *et al.*, 1981). The matrix is also enriched in Na and K, relative to whole-rock (Ikeda *et al.*, 1981; Ikeda, 1980; Fujimaki *et al.*, 1981; Grossman, 1985), which Grossman (1985) attributed to re-condensation of elements lost during chondrule formation.

Calcite has been observed in the matrix of the type 3.0 chondrite, Semarkona (Nagahara, 1984; Hutchison *et al.*, 1985), and most authors get low analytical sums when analyzing the matrix by electron microprobe. Huss *et al.* (1981) attribute the low sums to porosity or carbon, but water is another possibility and Hutchison *et al.* (1985)

find chondrules with alteration zones which also give low sums; these are more difficult to attribute to carbon or porosity. Hydrous silicates have recently been observed in Semarkona (Alexander *et al.*, 1986). Aqueous alteration of metal-sulfides, to produce magnetite and Ni-bearing sulphides were described by Huss et al. (in the preprint to their 1981 paper) in Semarkona, Krymka (3.0) and Ngawi (3.6 with 3.1 clasts; DeHart and Sears, 1985, 1986). It seems clear that the matrix in Semarkona, and probably Krymka (3.1), Bishunpur (3.1) and certain regions (3.1 clasts!) in Ngawi, have been exposed to liquid water, and McNaughton *et al.* (1982) found that water with non-terrestrial D/H was produced by step-wise heating of Semarkona and Bishunpur.

Sharps (H3.4) and Allan Hills A77011 (L3.5) contain aggregates of graphite and magnetite (Scott *et al.*, 1981; McKinley *et al.*, 1981), which Scott *et al.* (1981) suggested were nebular products because they contain pure Ne-22 (produced by decay of short-lived Na-22) and graphite is an abundant component in the interstellar medium (Figure 18a). It also seems possible that they were formed by aqueous alteration of ^{22}Ne-bearing metal-carbide assemblages common in the more primitive type 3 ordinary chondrites, however Taylor *et al.* (1981) argue against this as the magnetite does not occur in veins.

Most authors have concluded that the matrix is dust which formed in the nebula and accreted at fairly low temperatures; however, other possibilities that have been discussed are that it is comminuted chondrules or other material, perhaps even with an igneous phase to its history (Huss *et al.*, 1981; Ikeda, 1980; Fujimaki *et al.*, 1981; Housley and Cirlin, 1983; Hutchison and Bevan, 1983). The I-Xe method indicates that the matrix pre-dates the chondrules by 10 m.y. or less, while the Rb-Sr and Ar-Ar methods indicate that it is 500 m.y. younger; presumably the Rb-Sr and Ar-Ar methods are more easily disturbed than the I-Xe method which utilizes only the Xe trapped in highly stable sites (i.e. the gas released > 1000 °C). This being so, an origin entirely by the communition of chondrules seems unlikely.

2.3.3. *Metal and Sulphide*

Metal and sulphide occurs predominantly in the interstitial material between the chondrules, some times forming a rim around the chondrules, but smal amounts are also found in the chondrules. Matrix metal contains Ni and Co and is similar to that found in equilibrated ordinary chondrites except that it tends to have higher Fe, reflecting the greater reduction of Fe in type 3 chondrites (see above) and is very heterogeneous: type < 3.3 have standard deviations for Co in the kamacite in excess of 10%, while types >3.2 have values less than this (Afiattalab and Wasson, 1980; Rambaldi and Wasson, 1981; 1983).

Semarkona contains sulfide-coated metal grains which contain appreciable quantities of metallic silicon (Figure 18b). Rambaldi *et al.* (1980) argued that this metal formed at high temperatures in the nebula, before the major phase of silicate condensation occurred to compete for the Si in the nebula gas. Gooding *et al.* (1980) argued, instead, that the silicon entered the metal as the metal was melted during the condrule-forming event. This presupposes that the metal was also involved in the

chondrule-forming process and that post-melting cooling rates were slow enough to permit reduction of the silicates without complete loss of FeS, Na and other volatile constituents from the chondrule.

Some of the metal in chondrules is almost pure Fe, suggesting that it formed by reduction of the FeO in the silicates.

2.3.4. *Exotic Inclusions*

We shall consider two forms of 'exotic' inclusions in the type 3 ordinary chondrites, the calcium-aluminum-rich inclusions and inclusions ("CAI") of carbonaceous chondrites resembling the CM meteorites.

Noonan (1975) found 5 CAI in 80 type 3 and 4 ordinary chondrites, and Bischoff and Keil (1983) found 27 rare Ca-Al rich inclusions in 8 mainly type 3 ordinary chondrites. Most (21) of the CAI in Bischof and Keil's study had igneous origins and therefore are probably chondrules. They were 0.1-0.8 mm in size and made of fassaite and olivine in a plagioclase glass. The 6 irregular inclusions were 100-250 μm fine-grained aggregates of spinel and fassaite with onion-shell structures. In many respects, they closely resemble the CAI in the Allende meteorite which are the subject of a vast literature (Grossman, 1980).

About 30 ordinary chondrites are known to contain clasts of another chondrite class. Usually the host meteorites are gas-rich regolith breccias or type 3 ordinary chondrites, and the inclusions are CM or CM-like (Wilkening, 1976). Probably the best studied foreign inclusion in a type 3 ordinary chondrite is that found in Krymka (Higuchi et al., 1977; Leitch and Grossman, 1977; Davis et al., 1977; Lewis et al., 1979; Grossman et al., 1980).

2.4. PHYSICAL MEASUREMENTS

There have been a number of studies of the Mossbauer spectra of chondritic meteorites, the most thorough study of type 3 ordinary chondrites is that of Sprenkel-Segel (1969). The technique provides a novel means of studying the relative abundance of iron-bearing minerals, which is relevant to the apparent oxidation state differences between type 3 and equilibrated chondrites. While expected to be similar on the basis of bulk composition, type 3 chondrites contain olivine and pyroxene which is low in Fe (Fig. 5). One possibility is that magnetite is present in the fine-grained matrix (Wood, 1962; Sears and Marshall, 1980; Taylor et al., 1981). However, Sprenkel-Segel (1969) could find no evidence for magnetite in the Mossbauer spectra of Tieschitz, Bremervorde, Clovis (No. 1), Hallingeberg, Barratta, and Chainpur.

Magnetic studies of ordinary (and carbonaceous) chondrites are also numerous, but there appears to have been no systematic (or even partial) study of type 3 ordinary chondrites. The subject has been reviewed by Brecher (1973) and Herndon and Rowe (1974).

2.5. LABORATORY ANNEALING EXPERIMENTS

While most of the information on the history of the type 3 ordinary chondrites comes from a study of the natural properties of the rocks, a useful adjunct has been laboratory annealing experiments, sometimes in the presence of fluids. The studies have been of particular value in the interpretation of trace and minor element abundances and thermoluminescence, which show variations of two or more orders of magnitude throughout the type 3 ordinary chondrites.

Ikramuddin et al. (1977a, b) annealed samples of the Krymka (L3.1) and Tieschitz (H3.4) chondrites in a hydrogen atmosphere at 10^{-5} atm for 1 week at 400-1000 °C. They then measured the abundance of ten mainly volatile elements. McSween *et al.* (1978) also made a petrographic study of the annealed Krymka samples. The chemical results for the two meteorites were very similar, with over 100-fold decreases in abundance being observed for many of the elements with the degree of loss increasing in the order In, Tl, Bi, Zn and Te. Cs showed only a 2-fold decrease after annealing at 1000 °C and Se, Ga, Ag, and Co showed little or no loss. The pattern of loss was unlike the pattern of abundances observed in type 4-6 chondrites (see, for example, Figure 10)
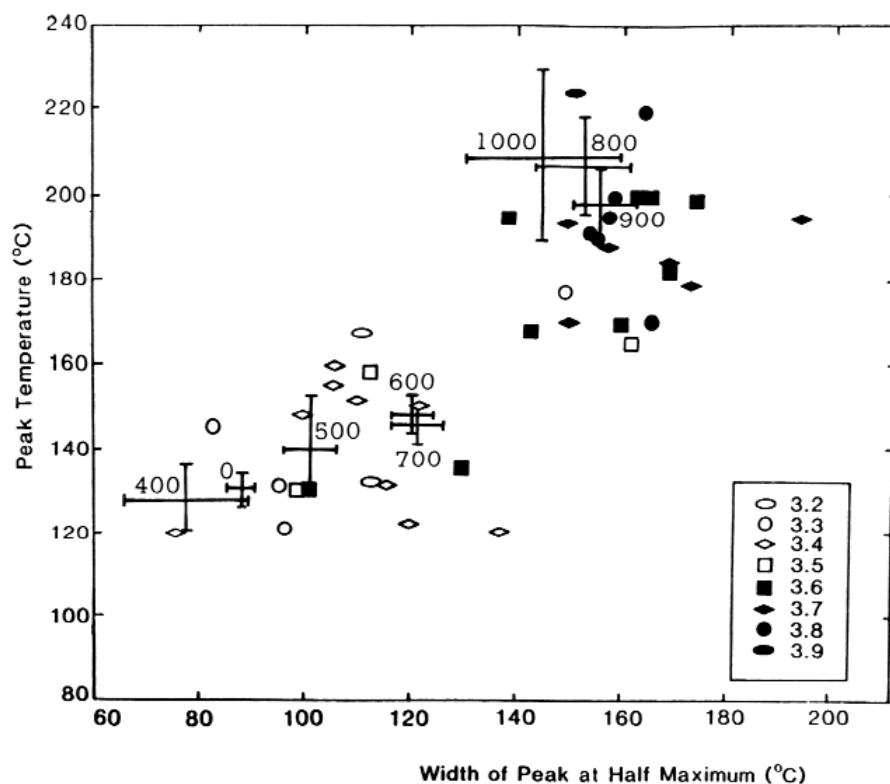
Fig. 19. Plot of TL peak temperature vs. peak width for type 3 ordinary chondrites and samples of Allan Hills A77214 annealed at the temperatures indicated (°C) for 100 h. These data provide an indication of post metamorphic equilibration temperatures. Annealing experiments on Amelia albite indicate that the TL-glow-curve shape is governed by Al, Si disordering and that the order/disorder transformation temperature (500-600 °C) corresponds to petrologic type 3.5-3.6 (data from Guimon et al., 1985).

and Ikramuddin *et al.* (1977a, b) concluded that open system metamorphism was not responsible for the range of highly volatile element abundances observed in ordinary chondrites. McSween *et al.*, (1978) found that the metal and sulfide in the annealed samples had undergone changes resembling those observed in type 3 chondrites which are commonly attributed to metamorphism, but that the silicate phases had not (e.g.) there had been no devitrification of chondrule glass). They attributed this to the short duration of the experiments. Most of the trace elements determined by Ikramuddin *et al* (1977a, b) are expected to be associated with the metal and sulfide.

There are three trends displayed by TL which laboratory annealing should reproduce if those trends are due to metamorphism and if metamorphic conditions can be reproduced in the laboratory. With increasing metamorphism through the type 3 chondrites, in addition to the TL sensitivity increasing 1000-fold, the peak temperature increases from 100 °C for type 3.3-3.5 to 210 °C for type 3.6-3.9, with a corresponding
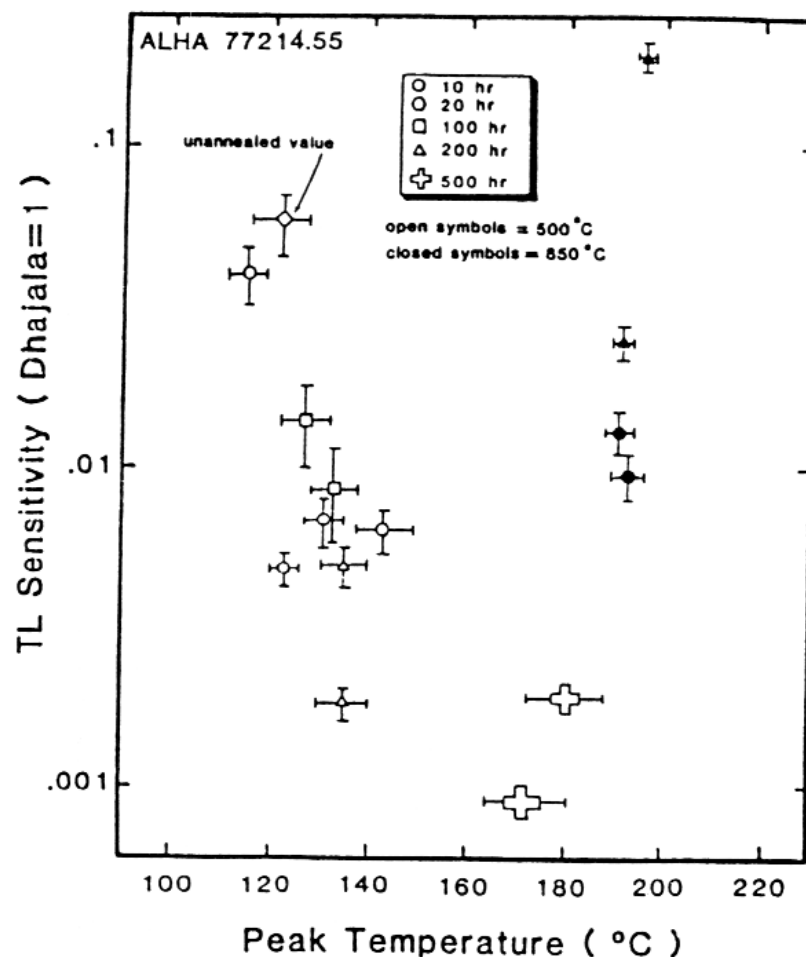
Fig. 20.   Plot of TL sensitivity vs. peak position for samples of Allan Hills A77214 annealed with 5% water at the times and temperatures indicated. Annealing at 500 °C causes a > 10-fold decrease in TL sensitivity and movement of the peak to higher temperatures, while annealing at 850 °C causes the peak to appear at ∼ 200 °C and return to, or exceed, its original value (from Lofgren *et al.*, 1986).

increase in width from 100 to 200 °C. Annealing Allan Hills A77011, type 3.4, at 400-1000 °C for up to 200 h in an inert atmosphere caused the peak temperature and width to increase to values similar to those of type 3.5-3.9 chondrites when the annealing temperature was above 700 °C (Figure 19, Guimon et al., 1984; 1985). Amelia albite behaved in the same way and X-ray diffraction data showed that it was associated with disordering of the Al, Si chain of feldspar (Figure 19). However, the annealing did not produce an increase in TL sensitivity, in fact, there was a factor of 2 decrease after annealing at 900 °C and a factor of 100 decrease was observed at higher temperatures; the behavior is very similar to that observed for Cs and Ar loss upon step-wise heating (Ikramuddin et al., 1977a, b; Bogard and Hirsch, 1980), and all probably reflect the behavior of feldspar.

As McSween et al. (1978) observed for annealed Krymka, annealing under the conditions used by Ikramuddin et al. (1977a, b) and Guimon et al. (1984), 1985) does not produce devitrification, and it was the crystallization of chondrule glass which Sears et al. (1980) suggested was responsible for the metamorphism-induced TL sensitivity changes in type 3 ordinary chondrites. Devitrification can be catalyzed by the addition of sodium disilicate and water, and annealing under such conditions does produce factors of up to 20 increase in TL sensitivity (Guimon et al., 1986a). However, the mechanism producing the increase is in competition with one which decreases the TL sensitivity, presumably the destruction of the feldspar. This is apparently favored by low temperatures and short annealing times (Figure 20; Lofgren et al., 1986; Guimon et al., 1986b).

3. Interpretations

3.1. RELATIONSHIP BETWEEN TYPE 3 CHONDRITES AND THE EQUILIBRATED CLASSES

On the basis of their petrologic properties, the type 3 chondrites look like less metamorphosed versions of the higher petrologic types. However, the siderophile element data (Figure 11) and the oxygen isotope data (Figure 7) show that this is not the case. No parent body process other than melting could change the abundance of non-volatile siderophile elements. Rather, processes involving the separation of silicates and metal, such as might occur during the aggregation of the silicates and metal to form the chondrites, seem to be required. The differences in siderophile element chemistry between the type 3 ordinary chondrites and equilibrated members of the same class are qualitatively similar to those distinguishing the H, L and LL classes from each other (Sears and Weeks, 1986).

The oxygen isotope differences between the type 3 chondrites and the higher types could in principle be accounted for by mass fractionation. The only plausible chemical process so far identified is the preferential loss of heavy oxygen as CO during open-system metamorphism. However, assuming CO-silicate distribution coefficients for ^{18}O from laboratory data (Onuma et al., 1972), and Moore and Lewis' (1967) data for the abundances of carbon in the lower petrologic types, this mechanism is quantitatively inadequate (Sears and Weeks, 1983).

The picture created, therefore, is that the siderophile element and oxygen isotope contents changed steadily during aggregation of the chondrites. If the heat source responsible for metamorphism was the radioactivity from long-lived nuclides (^{238}U, ^{232}Th, ^{40}K) then the parent body had an onion skin structure with siderophile element abundance and oxygen isotope composition varying throughout, and with the highest petrologic types located at the center and lowest on the surface. If the heat source was ^{26}Al, then smaller parent bodies are conceivable and the amount of heating is experienced by a particular body is controlled by the time of accretion (which determines the amount of ^{26}Al), rather than size. This removes the constraint of a single parent object, but there remains the point that the siderophile element chemistry and oxygen isotopes were probably varying steadily throughout accretion in a way that was ultimately coupled to petrologic type.

3.2. EQUILIBRATION TEMPERATURES, COOLING RATES, SIZE AND STRUCTURE OF THE METEORITE PARENT OBJECTS

For the equilibrated chondrites, there are estimates for equilibration temperatures based on Fe and Ca distribution between orthopyroxene and diopside (Olsen and Bunch, 1984), Mg and Fe distribution between olivine, spinel and Mg-ilmenite (Wlotzka, 1985), and the partitioning of O isotopes between olivine, pyroxene and plagioclase Onuma et al., 1972). The consensus seems to be that the following temperatures and petrologic types correspond: type 4, 600-700 °C; type 5, 700-750 °C; type 6, 750-900 °C (Dodd, 1981).

Palaeothermometry of type 3 chondrites is very difficult because of the lack of equilibrium between mineral pairs. In the case of the oxygen isotope thermometer, there is the additional difficulty that a component with anomalous ^{16}O is present. Wlotzka (1985) found that Clovis No. 1 (a type 3.9) equilibrated at 600-700 °C and Tieschitz and Sharps (type 3.5) were too unequilibrated to obtain a temperature. The lack of a relationship between the size of taenite grains and their central Ni content has caused several authors to suggest that Krymka and Bishunpur have not experienced temperatures above 400 °C (Wood, 1967; Rambaldi and Wasson, 1981).

The shape of the TL glow curve offers a further clue to the palaeotemperatures for the type 3 ordinary chondrites (Figure 19). The annealing treatments show that peak shape is related to thermal history, and experiments with terrestrial feldspars demonstrate that the relationship involves disordering of the Al, Si chain. This being so, the type 3.3-3.5 chondrites, with narrow low-temperature TL peaks, contain predominantly low temperature feldspar while type 3.6-3.9 contain predominantly high form; the two forms can be identified with different suites of chondrules in the Dhajala meteorite (Figure 15). Thus the feldspar in type 3.3-3.5 chondrites equilibrated below the order/disorder transformation temperature (500-600 °C), while types 3.6-3.9 equilibrated above the transformation temperature.

Post-metamorphic cooling rates for ordinary chondrites have been determined from compositional gradients in metal grains (Wood, 1967) and by the density of tracks in various minerals caused by the fission of ^{244}Pu (Pellas and Storzer, 1976). Until a few

years ago the two methods agreed very well, suggesting cooling rates on the order of 1 °C/Ma and that cooling rates decreased as the petrologic type increased. This relationship implies an onion shell parent body with the type 6 chondrites at the center and type 3 chondrites at the surface. However, in recent years it has been found that the calculated cooling rate is acutely sensitive to the geometry of the metal. For instance, assuming rods instead of infinite slabs increases the estimated cooling rate 1000-fold (Narayan and Goldstein, 1983). This may throw doubt on the metallographic method when applied to highly irregularly shaped chondritic metal.

From the cooling rate an estimate can be made of the size of the object, assuming a reasonable elemental and isotopic composition. If the object is chondritic in composition and heated by the long-lived rationuclides U, Th and K, then a cooling rate of 1 °C/Ma suggests burial at 400 km in the object (Wood, 1967). However, if ^{26}Al was present in the object in the proportions observed in certain CAI in Allende, then cooling rates of this order are consistent with objects as small as a few km (Lee et al., 1976).

3.3. METAMORPHISM, BRECCIATION, SHOCK AND AQUEOUS ALTERATION

The four major secondary processes which meteorites as a whole have experienced are represented in the type 3 ordinary chondrites. The role of metamorphism is well-documented and were described in section 1.2 above. Descriptions of shock effects are somewhat fewer. It is clear that metamorphism largely predated brecciation, since on occasion clasts of very low type exist in host of much higher type. Ngawi is a spectacular example of this, since type 3.7 material surrounds clasts of type 3.1 and impact melts (DeHart and Sears, 1986).

Huss et al. (1981) and Huss (1980) briefly reviewed shock effects in type 3 ordinary chondrites, commenting especially on its heterogeneity which may, in some part, be caused by the structural heterogeneity of the meteorites. Dodd (1971) discussed the possible role of shock in the history of individual chondrules and the characteristically high Ca content of olivine in type 3 ordinary chondrites. Dodd and Jarosewich (1979) pointed out that their classification into 6 'shock facies' on the basis of petrographic criteria and which works well for equilibrated chondrites, is difficult or impossible to apply to type 3 ordinary because of their unique petrology.

Observations of aqueous alteration have only recently been reported. Kurat (1968, 1970) and Christophe-Michel-Levy) (1976) suggested this as a possibility in the case of Tieschitz, and in the preprint of their 1981 paper, Huss et al. described magnetite and Ni-bearing iron sulfide assemblages in Semarkona, Krymka and Ngawi which they attributed to aqueous alteration effects. Hutchison et al. (1986) have found chondrules and regions within the fine-grained matrix which appear to have been attacked. The altered material produced sums less than 100% upon electron-microprobe analysis, suggesting the presence of significant amounts of a light substance not detectable by the technique (such as water). More recently the group have found direct transmitted electron microscope evidence for hydrous silicates in the altered material (Alexander et al., 1986). Hutchison et al. (1986) also point out that the non-terrestrial water released

on stepwise heating may be indigenous, and not produced from other H-bearing phases during the heating experiments, and Lofgren *et al.* (1986) and Guimon *et al.* (1986b) suggest that the low TL sensitivity of type 3.0-3.1 could be due to hydrothermal alteration. These observations were discussed above.

3.4. PRE-SOLAR COMPONENTS AND THE TYPE 3 ORDINARY CHONDRITES

The widely held view that the least metamorphosed ordinary chondrites most closely resemble nebula condensates has survived the scrutiny of years, albeit with some qualification. The secondary processes decreased above are superimposed on the original nebular properties, but despite this many of the feature are still best considered primordial. To date, there has been no petrographic observation of material purported to be extra-solar system in origin. However, the isotopic data discussed above may suggest that extra-solar system components are present in certain type 3 ordinary chondrites. Deuterium enrichments were attributed by Reeves and Geiss (1981) to the presence of interstellar molecules in the meteorites; radio frequency observations indicate the presence of enhanced D/H in ratios certain molecules in interstellar clouds. They discussed several modes of origin for the high D/H and favored kinetic isotope effects during ion-molecule reactions in the interstellar medium. The ^{16}O-rich component in Allan Hills A76004 described by Mayeda et al. (1980) is similar to that observed in the calcium-aluminum-rich inclusions in the Allende CV chondrite. This 'exotic' component has been the subject of considerable debate, most authors favoring an extra-solar system origin (e.g. Wasserburg and Papanastassiou, 1981; Clayton, 1977).

Acknowledgements

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