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The thermometry of enstatite chondrites: A brief review and update

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Abstract–Due to the discoveries in Antarctica, the number of known enstatite chondrites has doubled in the last few years, and many rare or previously unknown types have been collected, most notably many EL3 and EH3 chondrites. We have applied the five major enstatite chondrite thermometers to the new and previously known enstatite chondrites, the thermometers being: (1) kamacite-quartz-enstatite-oldhamite-troilite (KQEOT), (2) oldhamite, (3) alabandite-niningerite, (4) sphalerite, and (5) phosphide-metal. Measured temperatures based on the KQEOT and oldhamite systems are 800 °C–1000 °C with the type 3 enstatite chondrites having values similar to those of type 4–6. It seems likely that these temperatures relate to events prior to parent body metamorphism, such as nebula condensation or chondrule formation, and were not significantly reset by later events. Measured temperatures for alabandite-niningerite, metal-phosphide and sphalerite in EH chondrites increase from 300 °C–400 °C to 600 °C–800 °C with petrographic indications of increasing metamorphism. In contrast, measured temperatures for all EL chondrites, including the most heavily metamorphosed, are generally <400 °C. Apparently EL chondrites cooled more slowly than the EH chondrites regardless of metamorphism experienced. Measured temperatures for the alabandite-niningerite, metal-phosphide and sphalerite are actually closure temperatures for the last thermal event suffered by the meteorite, and the fast cooling rates indicated are most consistent with processes occurring in thick regoliths.

INTRODUCTION

Enstatite chondrites differ from other chondrite classes in that they contain mineral assemblages suggestive of extremely reducing conditions. Metal is abundant and Si-bearing, the enstatite is almost pure $MgSiO_3$, and these meteorites contain the cubic monosulfides niningerite, (Mg, Fe, Mn)S, alabandite, (Mn, Fe, Mg)S and sphalerite, (Zn, Fe)S, and the N-bearing sinoite (Si_2N_2O) and nierite (Si_3N_4) (Mason, 1966; Keil, 1968; Alexander *et al.*, 1994; Lee *et al.*, 1995). Early studies suggested that the EL chondrites were more heavily metamorphosed than the EH chondrites, but this suggestion was the result of inadequate sampling of these relatively rare meteorite groups. It now seems that EH chondrites display many textural and mineralogical trends that are widely associated with metamorphism, and in many respects similar to those of ordinary chondrites (Dodd, 1969), but this is not true of the EL chondrites (Zhang *et al.*, 1995).

The texture of metamorphosed EL chondrites indicates levels of metamorphism that are higher than those experienced by any known EH chondrite, but several thermometers suggest much lower closure temperatures for the EL chondrites than the EH chondrites (Skinner and Luce, 1971). For this reason, we recently proposed modification of Van Schmus and Wood's (1967) petrographic type scheme when applied to enstatite chondrites (Zhang *et al.*, 1995). We suggested that the single petrographic type be replaced with "textural type," reflecting peak metamorphic temperatures, and "mineralogical types" reflecting cooling history. The details are summarized in Table 5 of Zhang *et al.* (1995). Briefly summarized, chondrule delineation, pyroxene structure and composition, olivine composition and the presence of glass are used to define the textural types 3 to 7, while metal, phosphide and sulfide compositions are used to define the mineralogical types α to δ. While this provides a qualitative indication of the similarities and differences in the thermal histories of the individual EH and EL chondrites, quantitative estimates of the various temperatures are also helpful in understanding the origin and history of these meteorites.

Skinner and Luce (1971) showed that the FeS content of the niningerite and alabandite is strongly temperature-dependent and used their Fe-Mn-Mg phase diagram and Keil's (1968) analyses of these minerals to deduce closure temperatures of 700 °C–800 °C and <400 °C for EH and EL chondrites, respectively. Laboratory experiments also indicated that the cooling rate for the EH chondrites (~0.1 °C/min) was faster than that of the EL chondrites by several orders of magnitude. Skinner and Luce (1971) also pointed out that the composition of the oldhamite (CaS) and the CaS content of the niningerite and alabandite are temperature-dependent and could be used for thermometry.

Larimer and Buseck (1974) developed a thermometer for enstatite chondrites based on equilibria involving enstatite, oldhamite, quartz, troilite and metal and obtained measured temperatures for 15 meteorites. Values of ~700 °C were obtained for equilibrated EH chondrites, which is ~120 °C lower than those of the equilibrated EL chondrites. The most uncertain parameters in the Larimer and Buseck (1974) treatment were the activity coefficients for Ca in the enstatite and Si in the metal, and the method has been subsequently modified by Fogel *et al.* (1989) and Matsunami and Sato (1995) with special attention to these parameters.

The FeS content of the sphalerite also provides a means of thermometry, but since this quantity is both pressure and temperature dependent, either pressure or temperature must be assumed so that the other can be determined. Hutchison and Scott (1983) assumed a closure temperature of 600 °C and deduced pressures of –0.2 kbar and 0.7 kbar for Yilmia and Pillistfer, respectively. On the other hand, Kissin (1989) assumed zero pressure for seven enstatite chondrites and deduced temperatures of 270 °C to 650 °C that increased with petrographic type. Like Skinner and Luce (1971), Kissin (1989) pointed out that these were closure temperatures and therefore dependent on cooling rate. Kissin determined cooling rates of ~10^8 °C/Ma for four of his samples, and additionally ALHA77156 cooled relatively slowly (43 °C/Ma) while Indarch and Yilmia cooled especially rapidly (1.1×10^{13} °C/Ma and 6.8×10^{16} °C/Ma, respec-

TABLE 1. Composition of phases used for the geothermometry of enstatite chondrites (in wt%).

Meteorite*	Class†	$MgSiO_3$	Fe,Ni				CaS		(Mg,Mn,Fe)S			ZnS	$(Fe,Ni)_3P$			Ref.‡
		Ca	Fe	Ni	Si	P	Mg	Mn	Fe	Mn	Mg	Fe	Fe	Ni	P	
Abee	EH4γ	0.04	87.2	8.2	3.3	0.54	1.70	0.36	37.1	10.1	4.02	–	76.1	7.1	15.5	6
Adhi-Kot	EH4γ	0.07	89.2	6.5	3.5	0.28	1.33	0.39	34.2	4.3	7.1	–	77.4	7.3	15.5	6
ALHA77156	EH3α	–	–	–	–	–	–	–	13.0	24.7	15.2	27.1	–	–	–	2,10§
ALH 81021	EL6β	0.57	89.9	6.0	1.2	0.08	–	–	–	–	–	–	–	–	–	5
ALH 81189	EH3α	–	–	–	–	–	–	–	11.0	27.0	12.0	26.1	–	–	–	3
ALH 84170	EH3α	–	92.8	2.9	2.2	0.07	–	–	11.9	27.1	11.7	–	68.5	17.8	14.2	4,5
ALH 84206	EH3α	–	95.7	2.3	1.9	0.003	–	–	11.8	26.1	14.6	–	68.7	16.2	15.4	4,5
ALH 85119	EL3α	0.37	93.6	5.6	0.5	0.02	–	–	8.7	3.0	48.9	–	42.6	41.5	16.1	4,5
Atlanta	EL6β	0.53	91.9	6.1	1.2	0.13	–	–	16.4	2.3	42.5	–	52.2	31.8	15.4	6
Blithfield	EL6β	0.58	91.0	6.8	1.6	0.09	–	–	13.8	6.3	40.3	–	59.0	24.9	15.3	6
Daniel's Kuil	EL6β	0.55	90.7	6.5	1.2	0.14	0.59	1.20	19.2	4.6	35.5	–	60.7	23.7	15.4	6
Eagle	EL6β	0.70	90.5	8.5	1.0	–	–	–	–	–	–	–	–	–	–	13
EET 87746	EH4α,β	0.10	93.3	5.8	2.0	0.04	–	–	20.6	26.3	5.6	–	70.4	18.1	14.8	4,5
EET 90299	EL3α	0.14	92.9	6.6	0.4	0.05	–	–	–	–	–	–	53.8	32.1	14.2	4,5
Hvittis	EL6β	0.58	92.3	6.1	1.1	0.13	0.44	1.11	15.4	2.49	43.4	–	58.7	25.7	15.5	6
Indarch	EH4β,γ	0.22	89.3	7.1	3.5	0.09	1.17	0.22	27.0	18.3	6.5	35.8	71.2	13.6	15.5	6,10,15
Jajh der Kot Lalu	EL6β	0.51	92.0	6.2	1.3	0.13	–	–	11.7	2.15	45.8	–	62.4	22.4	15.4	6
Khairpur	EL6β	0.54	91.7	6.8	1.2	0.12	0.57	0.11	16.2	3.34	39.4	–	57.3	27.5	15.2	6
Kota-Kota	EH3α	0.23	93.1	3.3	2.6	0.04	0.90	0.17	15.6	23.5	11.6	–	68.5	15.1	15.4	7
LEW 87119	EL6γ	0.70	89.2	8.8	1.5	–	–	–	32.9	8.2	15.5	–	–	–	–	4
LEW 87223	EL-an	0.30	92.9	6.2	0.5	0.40	–	–	27.8	2.0	28.8	–	74.3	10.4	15.6	4,5
LEW 88135	EL6β,γ	0.68	89.6	7.3	1.1	0.13	–	–	–	–	–	29.8	71.3	15.6	13.1	4
LEW 88180	EH6δ	0.30	88.4	9.0	2.6	0.21	–	–	39.5	10.6	5.3	–	77.0	7.4	16.1	4,5
LEW 88714	EL6γ	0.68	90.2	7.1	1.5	0.4	–	–	33.3	9.1	14.5	–	74.2	12.9	12.7	4
MAC 88136	EL3α	0.22	93.4	5.0	0.5	0.02	–	–	8.8	1.7	50.4	–	38.7	44.4	17.0	4,5
MAC 88180	EL3α	0.20	92.3	5.2	0.3	0.02	–	–	10.6	1.5	50.6	28.6	49.0	34.8	16.8	4,5
MAC 88184	EL3α	0.49	92.4	5.7	0.5	0.05	–	–	9.4	0.8	51.0	31.4	41.6	40.6	15.4	4,5
Parsa	EH3α	–	–	2.4	2.3	–	0.65	0.17	12.3	26.0	11.7	–	–	10.8	13.4	1,7
PCA 82518	EH4α,β	0.10	93.9	4.3	2.9	0.01	–	–	–	–	–	–	67.2	18.1	14.8	4,5
PCA 91020	EL3β	0.70	91.9	7.5	0.5	–	–	–	28.2	3.45	26.2	–	58.1	28.3	14.3	4,5
Pillistfer	EL6β	0.51	91.3	6.3	1.4	0.13	0.55	1.31	15.5	42.0	4.0	30.2	63.5	19.3	15.4	6
Qingzhen	EH3α	0.27	94.0	3.1	2.5	0.06	0.51	0.26	14.6	24.0	12.1	27.9	70.0	15.0	15.0	1,8-10,15,19-21
RKPA80259	EL5γ	0.49	90.3	7.0	1.8	0.49	–	–	33.7	9.4	12.8	–	–	–	–	4,5,14
St. Marks	EH5β	0.05	90.4	6.0	3.6	0.05	0.70	0.25	16.6	22.7	11.8	–	62.5	21.7	15.4	6
Saint-Sauveur	EH5γ	0.05	89.5	7.5	2.9	0.36	1.51	0.39	35.2	13.2	3.93	–	77.2	6.3	15.5	6
TIL 91714	EL5β	0.72	92.6	6.0	0.9	0.09	–	–	15.9	2.7	43.4	–	53.6	33.2	13.1	4,5
Ufana	EL6β	0.43	90.7	6.3	1.7	0.13	0.46	0.99	14.6	3.15	41.6	–	58.6	26.0	15.3	6
Y 69001	EH3α	0.76	94.9	2.9	2.0	0.01	0.38	0.11	13.8	32.4	3.8	29.4	69.4	15.0	14.4	9,15-18
Y 74370	EH3α	–	–	–	–	–	–	–	11.0	29.0	10.0	–	–	–	–	11
Yilmia	EL6β	0.45	92.8	5.68	0.92	0.09	0.50	1.88	14.6	4.4	42.5	33.5	63.2	20.8	14.0	10,12

*The usual abbreviations have been used for Antarctic meteorites: ALH, Allan Hills; EET, Elephant Moraine; LEW, Lewis Cliff; MAC, MacAlpine Hills; PCA, Pecora Escarpment; RKP, Reckling Peak; TIL, Thiel Mountains; Y, Yamato.
†Chemical class, EH or EL; textural type, 3–6; mineralogical type, α–δ.
‡References: 1, Prinz *et al.* (1984); 2, McKinley *et al.* (1984); 3, Prinz *et al.* (1985); 4, Present work; 5, Zhang *et al.* (1995); 6, Keil (1968); 7, Nehru *et al.* (1984); 8, Wang and Xie (1981); 9, El Goresy *et al.* (1988); 10, Kissin (1989); 11, Nagahara and El Goresy (1984); 12, Buseck and Holdsworth (1972); 13, Olsen *et al.* (1988); 14, Sears *et al.* (1984); 15, El Goresy and Ehlers, 1989; 16, El Goresy *et al.* (1986); 17, Ikeda (1989a); 18, Ikeda (1989b); 19, Hou *et al.* (1989); 20, Rambaldi *et al.* (1983a); 21, Rambaldi *et al.* (1983b).
§Data refer to ALHA77295 that is paired with ALHA77156.

tively). El Goresy and Ehlers (1989) determined values of 366–728 °C for Qingzhen and 377–459 °C for Yamato 691, and they interpreted zoning in the sphalerite in terms of subsequent re-equilibration at 0.18 kbar and 0.77–0.91 kbar for Qingzhen and Yamato 691, respectively.

Except for Rubin's (1984) application to Blithfield and preliminary reports of this work (Zhang *et al.*, 1992), the phosphide-metal equilibria have not previously been used for thermometry, although the necessary laboratory data have been available for some time (Buchwald, 1966; Doan and Goldstein, 1970). Using phosphide-metal equilibria, Rubin (1984) found a value of 550 ± 55 °C for Blithfield.

Two methods for thermometry of enstatite chondrites, the CaS content of the alabandite and niningerite (Skinner and Luce, 1971) and the partitioning of Fe between metal and enstatite (Wasson *et al.*, 1994), have been discussed in the literature but will not be considered here. The CaS content of the alabandite and niningerite is a poorly calibrated thermometer as it relies on data that are outside the range observed for the meteorites and does not yield linear arrays. As pointed out by Wasson *et al.* (1994), partitioning of Fe between metal and enstatite, which yields values ~1470 °C, is a highly uncertain thermometer because it involves measuring the very low FeO of the enstatite under the most unfavorable circumstances.

The measured temperatures are invariably closure temperatures and therefore depend on cooling rate, the rate of diffusion of the various ions through the relevant minerals, the dimensions of the grains involved, the presence of fluids that might catalyze the processes and other factors. Often it is assumed that mineral equilibria reflect peak metamorphic temperatures on the assumption that considerable time was spent at peak temperature and that cooling was sufficiently fast to leave the equilibria unaffected. This is often the case with silicates but is rarely the case with metal and sulfides. To avoid confusion, or biasing our observations with interpretative terms, we will use the noncommittal term "measured temperature" when reporting our results and "closure" or "peak metamorphic" temperature when discussing specific interpretations. Another complication is that when a rock experiences several thermal events, some systems might be reset by the later events while others were either not affected or were only partially affected. Texture (*i.e.*, the ease of chondrule delineation, recrystallization of fine-grained material or crystallization of glasses) provide independent information that primarily (but not entirely) reflects conditions at peak metamorphism. We suggest that all these considerations are relevant to the thermal history of the enstatite chondrites. It is also conceivable that some enstatite chondrites may have experienced multistep cooling, as was recently proposed for the unusual aubrite Shallowater (Keil *et al.*, 1989).

Over the last decade or so, a large number of meteorites have been found in Antarctica, and these have included a great many enstatite chondrites. Most significantly, many of the new enstatite chondrites have combinations of chemical class and petrographic type that were previously very rare or unknown. Of special interest are the great many type 3α enstatite chondrites, two EL5 chondrites, a new EH5 chondrite and three EL6 chondrites that are mineralogical type γ instead of the more usual type β. New insights into the thermal history of these highly unusual meteorite classes now seem possible. We recently completed a study of many of these meteorites, determining compositions for many of the mineral phases of significance in thermometry. Some of these data were reported by Zhang *et al.* (1995). In the present paper, we apply the available thermometers to these new data, as well as literature data, compare the results, explore the relationship between measured temperature and textural and mineralogical type, and comment on some of the implications.

THE ANALYTICAL DATA

The analytical data we used are given in Table 1. Many of the data were taken from the literature but about half were determined by the present authors and were reported in Zhang *et al.* (1995) or are reported here for the first time. We have included the literature data fairly uncritically. Our data were gathered by the senior author using the Johnson Space Center Cameca electron microprobe, avoiding weathering effects and averaging the data for 5–10 grains for each mineral in each meteorite. Kaersutite was used as the standard for Ca, Ti, Fe, Si and Mg; garnet for Mn; troilite for S; apatite for P; and NBS steel 479A for Ni and Cr. The microprobe accelerating voltage was 15 kV with a 1 μm beam diameter and 17.2 nA beam current. The three-sigma detection limits on the data were 0.02% (absolute) for all element oxides except SiO_2 (0.03%), TiO_2 (0.03%), FeO (0.04%), MnO (0.04%), and Cr_2O_3 (0.04%).

THE THERMOMETERS

The Niningerite-Alabandite Thermometer

The data of Skinner and Luce (1971) yield the empirical equations:

$$T = (12.2 \pm 0.2)\, x_{FeS} + (446.6 \pm 5.9) \qquad \text{Eq. (1)}$$

for FeS in the niningerite and:

$$T = (19.8 \pm 0.6)\, x_{FeS} - (192.3 \pm 8.8) \qquad \text{Eq. (2)}$$

for FeS in the alabandite, where x_{FeS} is the concentration of FeS in mol% and T is the measured temperature in K. The correlation coefficients are 0.999 for Eq. (1) and 0.997 for Eq. (2).

The compositions of the niningerite in EH chondrites and alabandites in EL chondrites are listed in Table 1, and measured temperatures estimated from these equations are listed in Table 2 and shown in Fig. 1. The uncertainties in the temperatures are ±20 °C or better, with average measured temperatures of ~350 °C for EH3α chondrites and 700 °C–900 °C for EH4γ and EH5δ chondrites. The temperatures increase with mineralogical type and, to a lesser degree, textural type (Fig. 1). Measured temperatures for most EL chondrites cannot be derived by this method because the FeS content in alabandite in most EL chondrites is below that of the experimental data (Skinner and Luce, 1971). We will assume upper limits of 400 °C for the fairly arbitrary reason that this is the cut-off of Skinner and Luce's graphs (Larimer and Buseck, 1974, used a figure

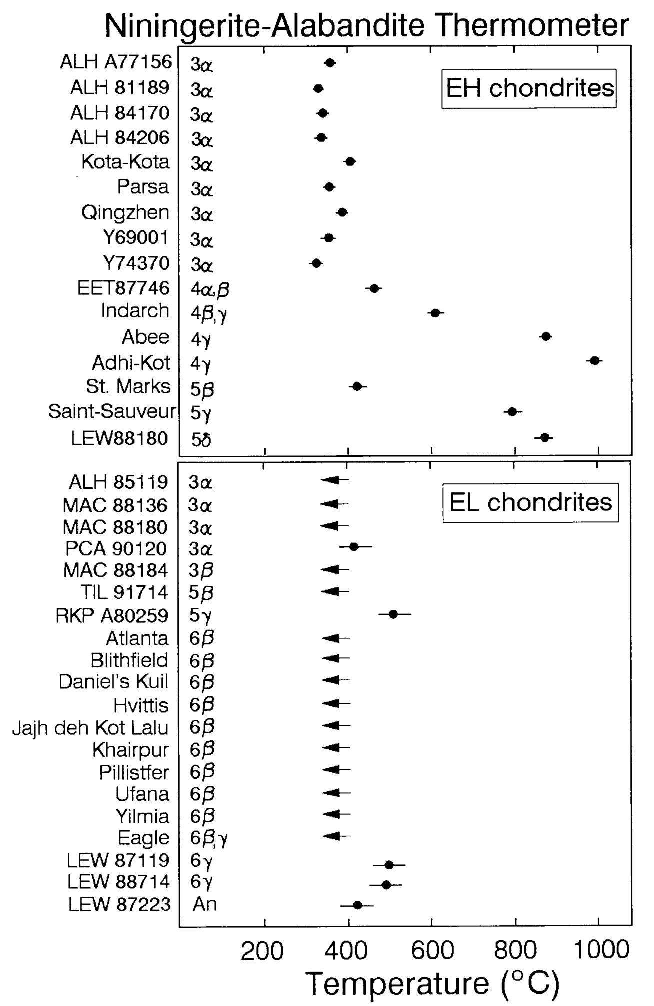

FIG. 1. Measured temperatures for enstatite chondrites determined from the composition of alabandite in EL chondrites and niningerite in EH chondrites using Eqs. (1) and (2) and the compositional data in Table 1. The arrows indicate upper limits. On this and subsequent figures, the numbers and Greek letters alongside the meteorite name refer to textural and mineralogical types, respectively. The EH3α chondrites have measured temperatures similar to the limits or values shown by the EL chondrites including the relatively metamorphosed EL6β-γ chondrites (~400 °C), whereas the more metamorphosed EH chondrites have temperatures that are generally considerably higher (~800 °C).

TABLE 2. Measured temperatures (°C) for enstatite chondrites*†.

Meteorite‡	Class§	FeS in (Mg,Mn)S			FeS in ZnS			Fe-Ni-P	(Mg,Mn)S in CaS		KQEOT			
		S & L	S & L	Present	E & E	Kissin	Present	Present	S & L	Present	L & B	Fogel	M & S	Present
Abee	EH4γ	870	780	877	–	–	–	614	830	845	640	833	820	813
Adhi-Kot	EH4γ	770	690	987	–	–	–	538	810	815	680	908	881	880
ALH A77156	EH3α	–	–	360	–	271	315	–	–	–	–	–	–	–
ALH 81021	EL6β	–	–	–	–	–	–	–	–	–	–	–	–	1015
ALH 81189	EH3α	–	–	331	–	274	274	–	–	–	–	–	–	–
ALH 84170	EH3α	–	–	342	–	–	–	435	–	–	–	–	–	–
ALH 84206	EH3α	–	–	340	–	–	–	237	–	–	–	–	–	–
ALH 85119	EL3α	–	–	<400	–	–	–	372	–	–	–	–	–	879
Atlanta	EL6β	<400	<300	<400	–	–	–	515	820	–	820	1024	1014	1004
Blithfield	EL6β	<400	<300	<400	–	–	–	461	840	–	840	1070	1067	1042
Daniel's Kuil	EL6β	–	<300	<400	–	–	–	507	820	786	820	1029	1023	1010
Eagle	EL6β,γ	–	–	–	–	–	–	–	–	–	–	–	1006	1024
EET 87746	EH4α,β	–	–	464	–	–	–	382	–	–	–	–	–	845
EET 90299	EL3α	–	–	–	–	–	–	426	–	–	–	–	–	751
Indarch	EH4β,γ	700	650	610	–	1859	1060	432	800	800	780	1055	1029	1016
Hvittis	EL6β	<400	<300	<400	–	–	–	504	820	775	820	1025	1019	1007
Jajh der Kot Lalu	EL6β	–	<300	<400	–	–	–	496	820	–	820	1028	1019	1007
Khairpur	EL6β	–	<300	<400	–	–	–	495	820	530	820	1027	1020	1007
Kota-Kota	EH3α	<600	<300	408	–	–	–	383	–	770	780	1015	983	982
LEW 87119	EL6γ	–	–	500	–	–	–	–	–	–	–	–	–	1061
LEW 87223	EL-an	–	–	427	–	–	–	615	–	–	–	–	–	854
LEW 88135	EL6β,γ	–	–	–	–	–	454	485	–	–	–	–	–	1029
LEW 88180	EH5δ	–	–	870	–	–	505	485	–	–	–	–	–	1017
LEW 88714	EL6γ	–	–	491	–	–	–	606	–	–	–	–	–	1056
MAC 88136	EL3α	–	–	<400	–	–	–	380	–	–	–	–	–	814
MAC 88180	EL3α	–	–	<400	–	–	387	365	–	–	–	–	–	770
MAC 88184	EL3α	–	–	<400	–	–	563	447	–	–	–	–	–	918
Parsa	EH3α	–	–	353	–	–	–	–	–	736	–	–	–	–
PCA 82518	EH4α,β	–	–	–	–	–	–	292	–	–	–	–	–	889
PCA 90120	EL3α	–	–	425	–	–	–	–	–	–	–	–	–	971
Pillistfer	EL6β	<400	<300	<400	–	450	479	491	820	799	820	1038	1025	1014
Qingzhen	EH3α	–	–	391	366-455	397, 463	352	416	–	712	–	–	–	994
RKP A80259	EL5γ	–	–	512	–	–	–	–	–	–	–	–	–	1034
St. Marks	EH5β	<600	<300	425	–	–	–	395	650	743	650	845	828	844
Saint-Sauveur	EH5γ	820	700	792	–	–	–	567	650	830	650	830	819	817
TIL 91714	EL5β	–	–	<400	–	–	–	480	–	–	–	–	–	1016
Ufana	EL6β	<400	<300	<400	–	–	–	499	810	759	810	1040	1025	1012
Y 69001	EH3α	–	–	357	377-459	443	431	296	–	684	–	–	–	1091
Y 74370	EH3α	–	–	327	–	–	–	–	–	–	–	–	–	–
Yilmia	EL6β	<400	<300	<400	–	646	752	462	790	853	790	980	–	964

*The following abbreviations have been used to describe the thermometers: CaS in (Mg,Mn)S, CaS in niningerite (EH chondrites) or alabandite (EL chondrites); FeS in (Mg,Mn)S, FeS in the niningerite (EH chondrites) or alabandite (EL chondrites); FeS in ZnS, FeS in sphalerite; Fe-Ni-P, the distribution of Ni and P between co-existing kamacite and schreibersite; (Mg,Mn)S in CaS, MgS (EH chondrites) or MnS (EL chondrites) in oldhamite; KQEOT, equilibria between kamacite, quartz, enstatite, oldhamite and troilite. References and details are given in the text. One-sigma experimental uncertainties are approximately ±50 °C, except for the KQEOT thermometer for which they are ±100 °C.

†References for thermometers: S & L, Skinner and Luce (1971) as quoted in Larimer and Buseck (1974); Kissin, Kissin (1989); E & E, El Goresy and Ehlers (1989); L & B, Larimer and Buseck (1974); Fogel, Fogel *et al.* (1989); M & S, Matsunami and Sato (1995); Present, present work.

‡Abbreviations for Antarctic meteorites: ALH, Allan Hills; EET, Elephant Moraine; LEW, Lewis Cliff; MAC, MacAlpine Hills; PCA, Pecora Escarpment; RKP, Reckling Peak; TIL, Thiel Mountains; Y, Yamato.

§Chemical class, EH or EL; textural type, 3–6; mineralogical type, α–δ.

of 300 °C which they did not justify). Exceptions are RKPA80259 (EL5γ), LEW 87119 (EL6γ) and LEW 88714 (EL6γ), which have measured temperatures of ~500 °C.

The Oldhamite Thermometer

Although Skinner and Luce (1971) reported only three measurements for the MnS and MgS content of oldhamite in contact with FeS, the data produce linear arrays with compositions overlapping those of the meteorite data. The equations we determine from their data are:

$$T = \frac{(4329 \pm 376)}{[(4.577 \pm 0.047) - \log(\text{mol\% MgS})]} \quad \text{Eq. (3)}$$

$$T = \frac{(3443 \pm 152)}{[(3.449 \pm 0.019) - \log(\text{mol\% MnS})]} \quad \text{Eq. (4)}$$

with correlation coefficients of 0.996 and 0.999, respectively. The compositions of the oldhamite in enstatite chondrites are listed in Table 1, and the calculated temperatures are listed in Table 2 and shown in Fig. 2. The uncertainties in the temperatures determined by this method are 60–100 °C.

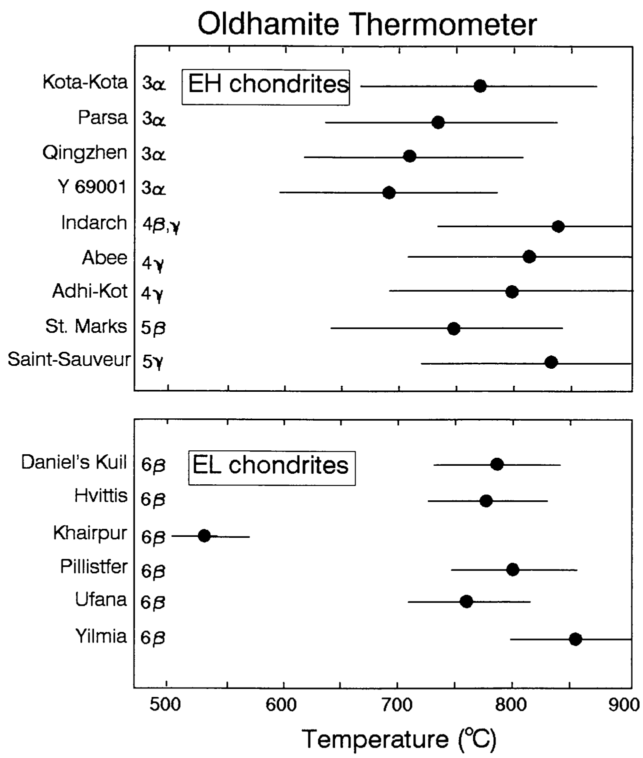

FIG. 2. Measured temperatures for enstatite chondrites determined from the MgS content of the oldhamite (CaS) in EH chondrites and the MnS content of the oldhamite in EL chondrites using Eqs. (3) and (4) and the compositional data in Table 1. With the exception of the EL6β chondrite Khairpur, measured temperatures for all enstatite chondrites are ~800 °C regardless of textural and mineralogical type.

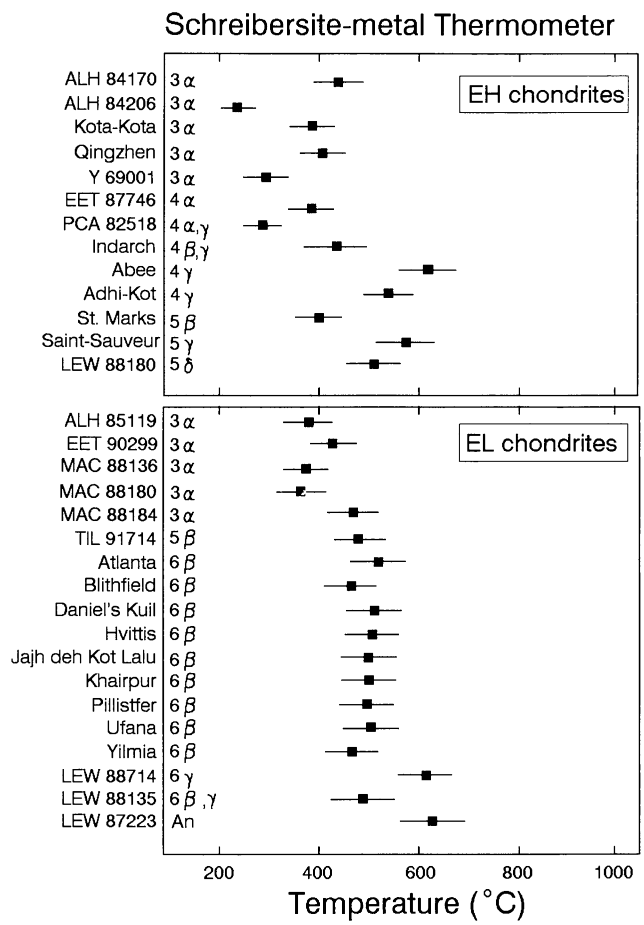

FIG. 3. Measured temperatures based on the composition of co-existing schreibersite and metal in enstatite chondrites calculated from Eq. (5) and the compositional data in Table 1. Measured temperatures for unmetamorphosed EH and EL chondrites are ~400 °C, while for metamorphosed meteorites of both classes they are ~600 °C.

The Schreibersite-Metal Thermometer

Assuming equilibrium between schreibersite $(Fe,Ni)_3P$ and kamacite, we can write:

$$Fe_3P_{ph} = P_{ka} + 3Fe_{ka}$$

for which the equilibrium constant, K, is:

$$K = \frac{(a_P a_{Fe}{}^3)}{a_{Fe_3P}}$$

$$\log (K) = \log (a_P) + 3\log (a_{Fe}) - \log(a_{Fe_3P})$$

and where the a terms refer to activities. In terms of mole fractions, X, this expression may be written:

$$\log (K) = \log (X_P\gamma_P) + 3 \log (X_{Fe}\gamma_{Fe}) - \log (X_{Fe_3P}\gamma_{Fe_3P})$$

where the γ terms refer to activity coefficients. Writing:

$$\log (K') = \log (K) - \log\left(\frac{\chi_P \chi_{Fe}}{\chi_{Fe_3P}}\right)$$

so that:

$$\log (K') = \log (X_P) + 3 \log (X_{Fe}) - \log (X_{Fe_3P})$$

we can obtain an empirical relationship between log (K') and temperature using the phase diagrams of Doan and Goldstein (1970):

$$\log (K') = \frac{-(2480 \pm 147)}{T + (0.601 \pm 0.029)} \qquad \text{Eq. (5)}$$

The relationship is linear with a correlation coefficient of 0.989. Application of this thermometer, using the compositions in Table 1, gives the measured temperatures listed in Table 2. The uncertainties in the measured temperatures are ~±50 °C.

The average measured temperatures determined for this system are ~360 °C, ~440 °C and ~490 °C for EH3α, EH4β,γ and EH5γ,δ chondrites, respectively (Fig. 3), which is very similar to those obtained from the alabandite-niningerite thermometer. We obtain ~400 °C and ~500 °C for EL3α and EL6β chondrites, respectively.

The Sphalerite Thermometer

Hutchison and Scott (1983) showed that the FeS content of sphalerite was related to pressure and temperature by the relationship:

$$P\ (\text{kbar}) = -(3.576 \pm 0.180) + (0.0551)\,T - 0.0296\,T \log (\text{mol\% FeS}) \qquad \text{Eq. (6)}$$

We will follow Kissin (1989) and assume that the measured temperature occurred at low pressures (<1 bar) so that:

$$T = \frac{3.576 \pm 0.18}{(0.0551) - 0.0296 \log (\text{mol\% FeS})} \qquad \text{Eq. (7)}$$

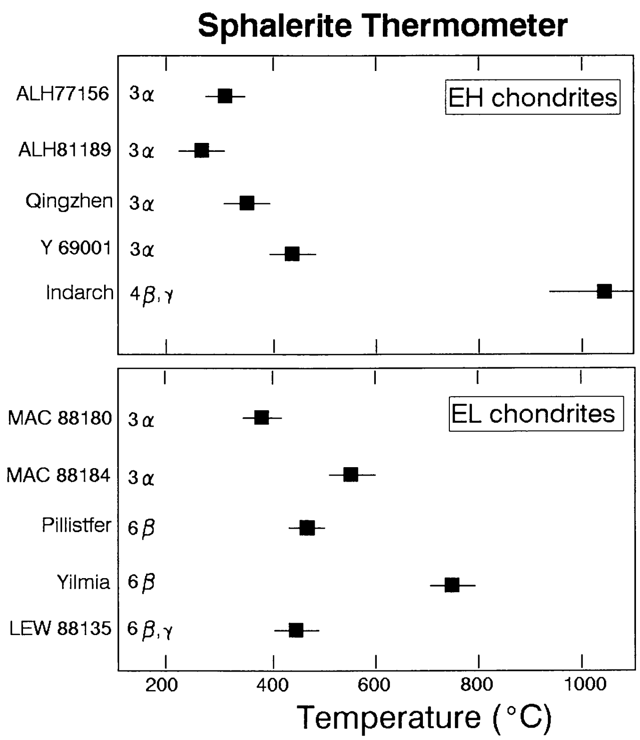

FIG. 4. Measured temperatures based on the FeS content of the sphalerite (ZnS) calculated from Eq. (7) and using the compositional data in Table 1. Data are relatively few because of the scarcity of sphalerite. Measured temperatures are ~400 °C with a suggestion of an increase to 600 °C for the metamorphosed meteorites.

Application of this thermometer to the compositions in Table 1 yields the temperatures in Table 2 and Fig. 4. Again, the uncertainty of this thermometer is <±50 °C. Unfortunately, sphalerite is a rare mineral in enstatite chondrites, but available data yield values of 300 °C–400 °C for EH3α chondrites, ~400 °C for EL3α chondrites and 500 °C–600 °C for EL6β chondrites.

The Kamacite-Quartz-Enstatite-Oldhamite-Troilite Thermometer

This is probably the most intensely studied thermometer for enstatite chondrites (Larimer, 1968; Larimer and Buseck, 1974; Fogel *et al.*, 1989; Matsunami and Sato, 1995). It involves the equilibria:

$$Si + O_2 = SiO_2$$
$$2\,CaMgSi_2O_6 + S_2 = 2\,CaS + 2\,MgSiO_3 + 2\,SiO_2 + O_2$$
$$2\,Fe + S_2 = 2\,FeS$$

By solving the three equations using the relationship between measured constants, free energy and activity coefficients, Fogel *et al.* (1989) derived the following:

$$T = \frac{\dfrac{3221 + 18300X_{Si} + 2(X_{Mg_2Si_2O_6}{}^2\mathrm{Wg})}{2.3026R}}{1.60 + 2\log\left(\dfrac{a_{Fe}a_{Cas}a_{MgSiO_3}a_{SiO_2}{}^{3/2}}{a_{FeS}X_{CaMgSi_2O_6}X_{Si}{}^{1/2}}\right) + 6.30X_{Si}} \qquad \text{Eq. (8)}$$

where W_g is the Margules energy parameter (taken as 52 kJ/mol). It is assumed that $a_{Fe} = X_{Fe}, a_{CaS} = 1$, $a_{MgSiO_3} = 1$ and $a_{SiO_2} = 1$. Because of the solidification of the FeS-metal eutectic below 950 °C, $a_{FeS} = 1$ is replaced with $a_{FeS} = 0.6$, and above 950 °C, the constants 3221 and 1.60 are replaced with 6501 and 3.79, respectively. Instead of using diopside and the Margules solution approach to determining the activity coefficient for Ca in enstatite, Matsunami and Sato (1995) used literature data for triclinic $CaSiO_3$. However, their results were very similar to those of Fogel *et al.* (1989). Application of Eq. (8) to the mineral compositions in Table 2 yields the results in Table 2 and Fig. 5. The uncertainty for these temperatures is ±100 °C. The average measured temperatures for EH3α, EH4α-γ, EH5β-γ and EH5δ chondrites are ~1020 °C, ~890 °C, ~890 °C, and ~1000 °C, respectively. For the EL3α and the EL5 and 6 chondrites of all mineralogical types, these values are ~830 °C and ~1020 °C, respectively.

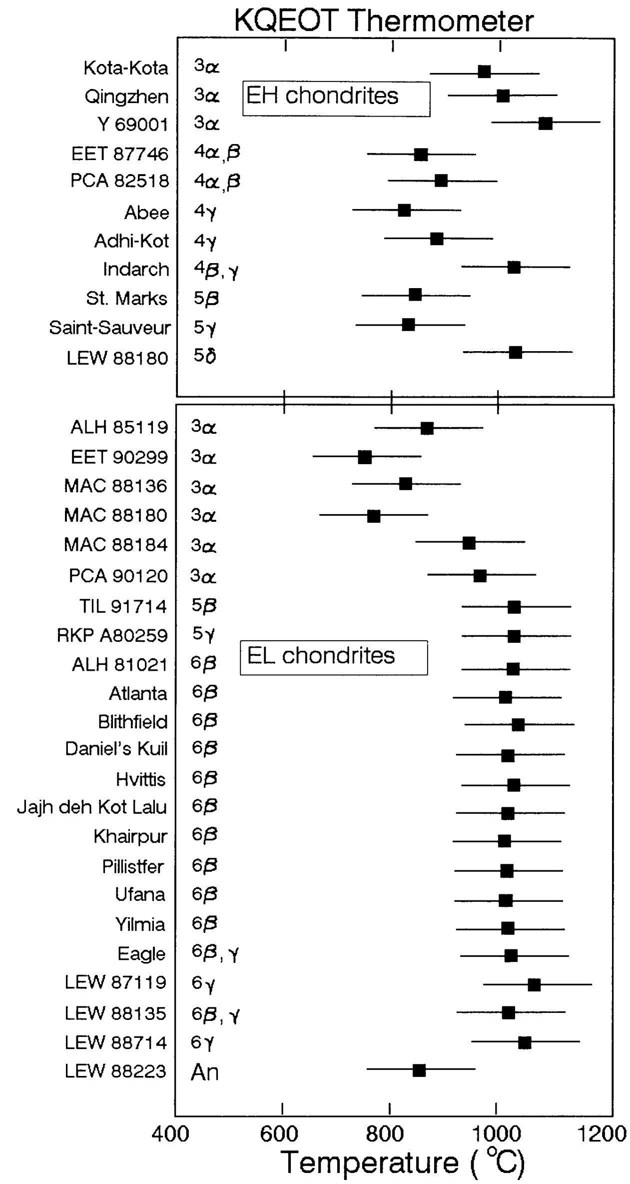

FIG. 5. Measured temperatures based on a complex set of chemical equilibria involving kamacite (Fe,Ni metal), quartz (SiO_2), enstatite ($MgSiO_3$), oldhamite (CaS) and troilite (FeS) using Eq. (8) and the compositional data in Table 1. Measured temperatures for the EH chondrites are 800 °C–1000 °C with little or no indication of a trend with metamorphism, while the EL chondrites have measured temperatures of 800 °C–1000 °C for the EL3α chondrites and 1100 °C for the other enstatite chondrites.

DISCUSSION

Figure 6 summarizes the temperatures obtained in this work and enables comparison of data for different classes and types. We first

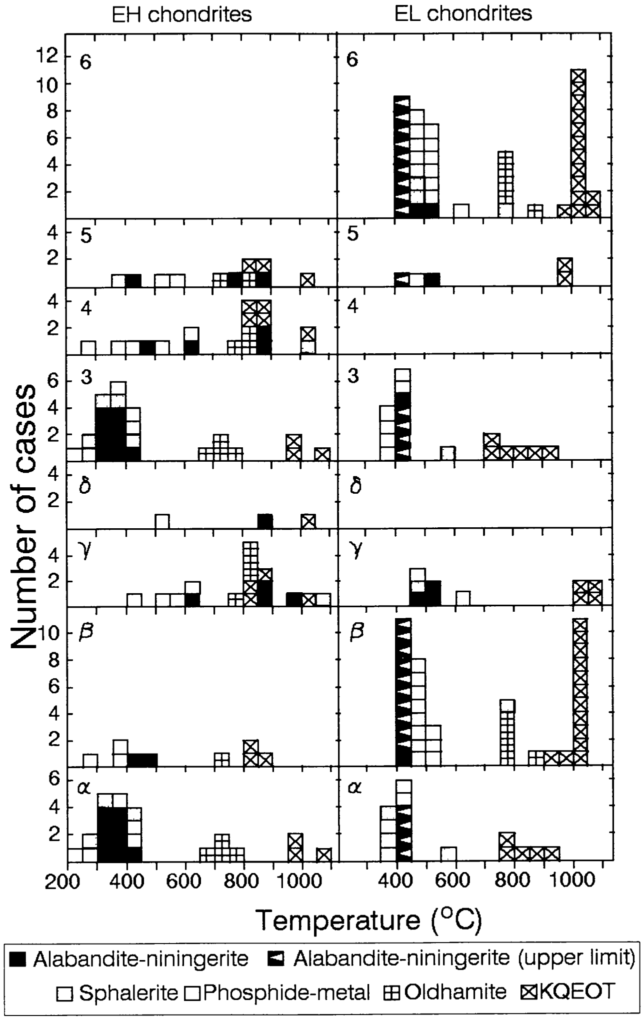

FIG. 6. Summary of measured temperatures determined from five thermometers in enstatite chondrites. The three "low-temperature" thermometers (the alabandite-niningerite, schreibersite-metal, and sphalerite) yield temperatures 300 °C–400 °C that increase with textural and, especially, mineralogical type, while the "high-temperature" thermometers (oldhamite and KQEOT) produce temperatures of ~800 °C–1000 °C with little or no dependence on textural and mineralogical type.

note that, despite the large number of new meteorites, the data for specific classes and types are still sometimes rather meager. There are no EH6, EL4 or ELδ chondrites, for instance. Nevertheless, among the new meteorites, there are some very important samples, most notably the EH3 and EL3 chondrites. A second point concerns the spread in the measured temperatures. Values range from <400 °C to >1000 °C, with the alabandite-niningerite, sphalerite and phosphide-metal thermometers giving results at the lower end of this range and the oldhamite and KQEOT thermometers giving results at the top of the range. We will discuss the thermometers yielding high temperatures first, then discuss the low-temperature thermometers, and finally make a few comments on plausible scenarios.

The High-temperature Thermometers

Probably the most significant results of the present study are the high measured temperatures observed for little-metamorphosed (type 3) EH and EL chondrites. Values are generally in the upper part of the range 700 °C to 1100 °C. This is much too high for the low levels of metamorphism thought to have been experienced by these meteorites. In their review of chondrite metamorphism, McSween *et al.* (1988) suggested that type 3 chondrites had experienced temperatures up to ~600 °C, and, by definition, their textures indicate that type 3 and type 6 have experienced very different degrees of metamorphism. We therefore suggest that the high-temperature equilibria were not established during metamorphism. Most probably they were established prior to metamorphism (Zhang *et al.*, 1995). Equilibria between gases and solids in the nebula, during condensation of solids in a gaseous nebula (Larimer and Bartholomay, 1979; Sears 1980) or during chondrule formation in the nebula or on the parent body (*e.g.*, Sears *et al.*, 1996) are processes that may have determined measured temperatures prior to final aggregation of the meteorites. The high rare-earth-element abundances of oldhamite and the high Si content of the metal have also been attributed to reactions in the nebula (Lodders and Fegley, 1993; Grossman *et al.*, 1979; Rambaldi *et al.*, 1980), but they could also be attributed to reactions accompanying chondrule formation.

While the temperatures based on the KQEOT and oldhamite thermometers may not reflect parent-body metamorphism, variable degrees of parent-body metamorphism did occur and are reflected in the variations in texture. However, they apparently left the high-temperature thermometers unaffected, presumably because subsequent thermal processing was either of low temperature or short duration, or maybe both.

The Low-temperature Thermometers

The low-temperature thermometers (*e.g.*, alabandite-niningerite, sphalerite, and phosphide-metal) produce temperatures in reasonable agreement with each other that increase with textural and, especially, mineralogical type. However the range of temperatures, 200 °C to 650 °C, is much less than the range of 400 °C to 900 °C thought to have been experienced by the chondrites as a whole (McSween *et al.*, 1988). This suggests that they are closure temperatures, rather than metamorphic temperatures, and can be used to estimate cooling rates (Skinner and Luce, 1971; Kissin, 1989). Skinner and Luce (1971) determined cooling rates of ~6 °C/h for the EH chondrites (mainly, St. Marks and Saint-Sauveur that have relatively high measured temperatures) and suggested that the EL chondrites cooled several orders of magnitude more rapidly. Kissin (1989) found an extremely large range of cooling rates, based on sphalerite compositions, from 43 °C/Ma for ALHA77156 to 2100 °C/s and 20 °C/min for Indarch and Yilmia, respectively, with four meteorites having cooling rates of 1×10^{-5} °C/s. Rubin (1984) estimated 10^3–10^4 °C/Ma for the Blithfield EL chondrite based on composition-dimension plots for the schreibersite. This cooling rate for Blithfield, while many orders of magnitude slower than EH chondrites, is still 10^2–10^3 °C times faster than cooling rates inferred from metal compositions in ordinary chondrites (1–10 °C/Ma; Wood, 1979). However, the highly model-dependent metallographic cooling rates may be too slow by several orders of magnitude (Narayan and Goldstein, 1983). These proposed cooling rates for enstatite chondrites range from values expected for millimeter-sized objects cooling in free space to values expected for objects buried ~100 km in compact chondritic objects. However, most are comparable with chondrule cooling rates and consistent with burial in a medium intermediate to the vacuum of space and the interior of an asteroid, say in various depths in a thick regolith.

An extended low-temperature period of metamorphism for the EL6β chondrites is probably suggested by pyroxene structures. Zhang *et al.* (1996) show that the series of cathodoluminescence colors displayed with increasing textural type were different for the

EH and EL chondrites. This difference was not dependent on composition, but x-ray diffraction measurements suggested that it might be related to differences in the stacking order of the pyroxenes and that while most enstatite chondrites contained fairly disordered clino- or orthopyroxene, the EL6β chondrites contain ordered orthopyroxene. The temperature limits of the orthopyroxene field are poorly known but are probably ~600 °C–800 °C (Brown and Smith, 1963), which is somewhat higher but in reasonable agreement with measured temperatures suggested by the schreibersite-metal and sphalerite thermometers. We would infer that the cooling rates indicated by the alabandite-niningerite system refer to an event postdating their heating in the orthopyroxene field.

Thermal History of the Enstatite Chondrites

Based on the discretely different thermal histories suggested by texture, the high-temperature thermometers and the low-temperature thermometers, Zhang *et al.* (1995) proposed that three temperature regimes had dominated the history of enstatite chondrites. Shock and cosmic-ray exposure events were considered a fourth, loosely defined regime. The first regime was condensation or chondrule formation, and this set the high-temperature thermometers. The second was the parent-body metamorphic event that produced the observed textures. The third was the low-temperature measured event that was associated with rapid cooling rates, especially for the EH chondrites. Zhang *et al.* (1995) speculated that the second regime occurred deep inside the parent bodies while the third thermal regime was inside the parent body regoliths, since these must be the last events suffered by the meteorites and such rapid cooling rates require isolated millimeter-sized grains. The lower measured temperatures displayed by the low-temperature thermometers in the EH3α and EL3α chondrites, compared with the more metamorphosed meteorites, suggests either that they cooled more rapidly or that there was a secondary metamorphic series at low temperatures reflecting, perhaps, differences in burial depth in the regolith.

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