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Chemical and physical studies of type 3 chondrites—III. Chondrules from the Dhajala H3.8 chondrite

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Abstract—Fifty-eight chondrules were separated from the Dhajala H3.8 chondrite and their thermoluminescence properties were measured. Chips from 30 of the chondrules were examined petrographically and with electron-microprobe techniques; the bulk compositions of 30 chondrules were determined by the fused bead technique. Porphyritic chondrules, especially 5 which have particularly high contents of mesostasis, tend to have higher TL (mass-normalized) than non-porphyritic chondrules. Significant correlations between log(TL) and the bulk CaO, Al_2O_3 and MnO content of the chondrules, and between log(TL) and the CaO, Al_2O_3, SiO_2 and normative anorthite content of the chondrule glass, indicate an association between TL and the abundance and composition of mesostasis. Unequilibrated chondrules (*i.e.* those whose olivine is compositionally heterogeneous and high in Ca) have low TL, whereas equilibrated chondrules have a wide range of TL, depending on their chemical and petrographic properties.

We suggest that the TL level in a given chondrule is governed by its bulk composition (which largely determined the abundance and composition of constituent glass) and by metamorphism (which devitrified the glass in those chondrules with high Ca glass to produce the TL phosphor). We also suggest that one reason why certain chondrules in type 3 ordinary chondrites are unequilibrated, while others are equilibrated, is that the mesostasis of the unequilibrated chondrules resisted the devitrification. This devitrification is necessary for the diffusive communication between chondrule grains and matrix that enables equilibration.

1. INTRODUCTION

THE TYPE 3 ordinary chondrites (or the unequilibrated ordinary chondrites) are thought to be almost unaltered material from the early solar system. These meteorites are compositionally heterogeneous and rich in volatiles relative to equilibrated chondrites. They contain numerous well-defined chondrules, abundant fine-grained opaque matrix and several unusual phases and phase assemblages, such as Si-bearing metal and graphite-magnetite aggregates. These features indicate that the type 3 chondrites have suffered less from parent-body metamorphism than their considerably more numerous counterparts of higher petrologic type (DODD *et al.*, 1967; WOOD, 1967; VAN SCHMUS and WOOD, 1967; LARIMER and ANDERS, 1967; ZÄHRINGER, 1968; TANDON and WASSON, 1968; RAMBALDI and WASSON, 1981; SCOTT *et al.*, 1981).

The amount of metamorphism experienced by type 3 chondrites varies considerably from meteorite to meteorite. Mineral heterogeneity and the abundance of volatile elements, including inert gases, decrease with increasing metamorphism; the fine-grained opaque matrix recrystallizes and changes in composition (DODD *et al.*, 1967; DODD, 1969; HUSS *et al.*, 1981; AFIATTALAB and WASSON, 1980). SEARS *et al.* (1980) showed that the thermoluminescence (TL) sensitivity also increases with degree of metamorphism, spanning a range of 10^5 over the ordinary chondrites as a whole, and a range of 10^3 within the type 3 chondrites. Apparently, TL is especially sensitive to the relatively low levels of metamorphism experienced by type 3 ordinary chondrites. In the first two papers in this series, we examined the relationship between metamorphism and the TL sensitivity of bulk powders (SEARS *et al.*, 1982; SEARS and WEEKS, 1983). We also observed systematic changes in the temperature of the TL peak and the peak width. These changes may give clues to the nature of the TL phosphor and how it changes with increasing metamorphism. We also found that TL differences between fragments of brecciated meteorites often reflect small differences in their metamorphic history.

In the present paper, we report our studies of 58 chondrules separated from the Dhajala H3.8 chondrite. We examined two related problems: first, the cause of the large spread in TL sensitivity throughout the ordinary chondrites, and, second, the cause of the TL variability among chondrules. Both have implications for meteorite history. The range of TL sensitivities displayed by type 3 chondrites is associated with metamorphism, but the mechanism behind this association is not known. We believe that it is probably associated with the formation of feldspar by the divitrification of glass, and thus, can potentially be used as a geothermometer (SEARS *et al.*, 1982). The large range of TL sensitivity displayed by individual chondrules could also be a result of each chondrule having experienced

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a different metamorphic history. DODD (1971, 1978a,b) and SCOTT (1983) have argued that certain chondrules experienced a stage of metamorphism prior to incorporation into the meteorite. This requires a fairly involved history including the formation and breakup of rather substantial parent bodies before or during the accretion of the present meteorite. We believe our data offer a plausible alternative to this scenario.

Previous reports based on this work were made by SPARKS and SEARS (1982) and SPARKS *et al.* (1983), who observed that the TL sensitivity of separated chondrules from Dhajala covered a very large range, and that some had an especially high TL. It was concluded that a small fraction of the chondrules were a major TL carrier.

2. EXPERIMENTAL

About 1.6 g of the Dhajala chondrite was broken into six fragments of approximately equal size and placed in a V-shaped trough made from a sheet of copper. This was placed between the jaws of a vice, which were slowly brought to within 2 mm of closure. Totally spherical grains were removed on the assumption that they were chondrules. They were individually inspected under the optical microscope or scanning electron microscope (SEM) and any adhering matrix chiselled off. After treatment, most chondrules had a shiny, clean surface. Their diameter and general appearance was noted.

Each chondrule was then broken in two. One half was further ground for TL measurement and the other was mounted in metallurgical resin, ground and polished for petrographic and microprobe examination. The means by which the TL was measured have been described previously (SPARKS and SEARS, 1982; SPARKS *et al.*, 1983). After TL measurement, the powder from 30 chondrules was placed on a molybdenum strip 5 cm × 5 mm × 10 μm and fused for a bulk composition determination. Although the methods of BROWN (1977) were followed, the chondrules dissolved small amounts of Mo and several may have lost Na and K. However, excellent homogeneity was obtained—the standard deviation displayed by 5 analyses at various locations on the bead was always less than 5% of the mean—and the data proved of value in looking for refractory element trends.

After petrographic examination and photography, the chondrule sections and the fused beads were carbon coated and analyzed with a Tracor Northern NS 880 energy dispersive X-ray spectrometer (EDS) attached to a Cambridge S600 scanning electron microscope (University of Arkansas) and with a wavelength dispersive crystal spectrometer (WDS) on an ARL electron-microprobe at the Smithsonian Institution. Silicon, Al, Mg, Fe, Mn and Ca were determined in beads and in minerals with both instruments. The EDS data for Al at concentrations below 5% Al_2O_3 are considerably inferior to those obtained by WDS and were ultimately rejected; there was good agreement between each instrument for the remaining elements. Additionally, Na, K, Mn and Cr were determined by WDS in the mafic silicates and all our chondrule glass analyses were made by WDS. A potential problem is secondary fluorescence, especially when analyzing Ca in olivine since it is usually surrounded by a calcic mesostasis. Therefore, analyses which showed detectable Al in olivine were rejected.

3. RESULTS

3.1 Thermoluminescence data

Our TL data are listed in Table 1 and plotted in Fig. 1. There have been a few minor revisions to our data since our earlier papers (SPARKS and SEARS, 1982; SPARKS *et al.*, 1983), but none of our previous trends or conclusions are affected. [Due to a drafting error, values on the horizontal axis of Fig. 3 of Sears *et al.* (1982) should be divided by 1.6.] Table 1 lists the TL of each chondrule normalized to that of a 4 mg sample of bulk Dhajala powder, the temperature at which th TL emission is a maximum and the full width of the peak at half its maximum intensity (FWHM) (see Fig. 1 of SEARS and WEEKS, 1983 for further explanation).

Table 1. Thermoluminescence and size data on separated Dhajala chondrules.

Chondrule	Diameter (mm)	TL sensitivity (Dhajala=1)	FWHM* (°C)	Peak Temperature (°C)
1	1.0	0.10	170	173
2	0.6	0.061	157	156
3	0.6	0.0073	167	173
4	0.4	0.0078	195	176
5	0.4	0.0069	190	193
6	0.5	0.011	217	183
7	0.5	0.017	190	170
8	0.5	0.0072	187	203
10	0.4	0.0039	187	210
11	0.8	0.021	197	190
12	0.7	0.029	173	163
14	0.5	0.012	190	213
15	0.4	0.027	173	146
16	0.5	0.12	103	113
17	0.4	0.027	170	173
18	0.4	0.0099	193	186
19	0.75	0.076	107	136
20	0.3	0.080	100	123
22	0.4	0.0021	240	180
23	0.6	0.017	183	196
24	0.4	0.0022	190	196
26	0.4	0.0048	187	190
28	0.2	0.0039	190	153
29	0.3	0.025	120	126
34	0.4	0.0060	217	183
35	0.7	0.0099	193	160
36	0.2	0.067	80	113
39	0.4	0.0052	210	206
40	1.0	0.0048	233	196
41	0.6	0.0034	190	236
42	0.6	0.0098	210	206
44	0.4	0.021	160	153
45	0.3	0.0027	147	203
48	0.6	0.0068	no data	206
50	0.6	0.0081	213	213
53	0.2	0.0033	183	103
54	0.5	0.0037	230	213
55	0.3	0.0020	200	190
58	0.8	0.041	190	180
61	0.3	0.0048	190	183
63	0.5	0.0069	203	183
69	0.4	0.076	103	130
70	0.5	0.0027	187	200
72	0.4	0.012	180	196
73	0.5	0.0082	157	196
75	0.5	0.0027	180	193
76	0.6	0.14	123	146
77	0.7	0.012	210	156
78	0.5	0.0027	200	170
79	0.3	0.0095	117	130
80	0.6	0.0026	207	183
83	0.3	0.0050	200	146
84	0.7	0.080	no data	120
86	0.7	0.14	163	170
89	0.7	0.14	no data	110
90	0.4	0.0084	187	193
92	0.3	0.0099	217	173
Dhajala bulk		1.03	167	163
Dhajala bulk		0.97	153	163

* Full width of peak at half its maximum intensity.

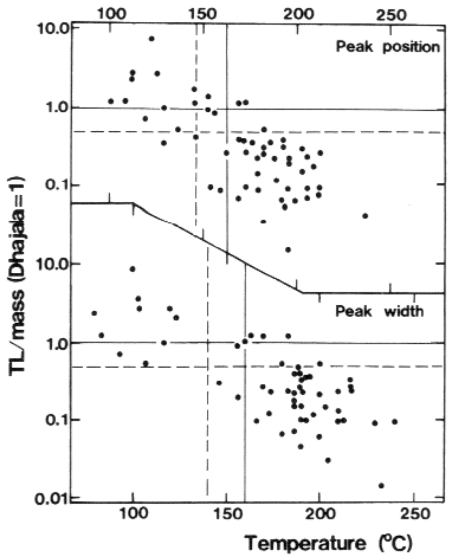

FIG. 1. Plot of the mass-normalized TL sensitivity of 58 separated Dhajala chondrules as a function of the temperature at which TL emission is a maximum (peak position) and the full-width of the TL peak at half its maximum intensity (peak width). The cross-hairs locate the position of bulk Dhajala powder (solid lines) and a glow curve made by summing, and then mass-normalizing, the glow curves of the individual chondrules (broken lines).

Because chondrule masses range over three orders of magnitude, we have attempted to remove the effect of mass by expressing the TL data as TL/mass, where

$$\mathrm{TL/mass} = \left(\frac{\mathrm{TL}}{\mathrm{mass}}\right)_{\mathrm{chondrule}} \Big/ \left(\frac{\mathrm{TL}}{\mathrm{mass}}\right)_{\mathrm{bulk\ sample}}.$$

Chondrule masses were calculated from their size assuming a density of 3.3 g cm^{-3}; errors range from 30% for the largest chondrules to a factor of 2 for the smallest chondrules.

As the TL sensitivity of individual chondrules decreases, the width of the peak gets greater and the peak moves to higher temperatures (Fig. 1). This would seem to reflect major changes in the nature of the TL phosphor; either a different phosphor with a narrower and lower temperature TL peak exists in the brighter chondrules, or crystallographic or compositional differences exist in the TL phosphor of chondrules with different TL. Trends similar to those observed here could conceivably be produced in a single unchanging phosphor by a fortuitous combination of circumstances associated with the TL mechanism. This would require that the kinetics of TL decay are second order (as is thought to be the case; SEARS and DURRANI, 1980) and that the extent to which a given radiation dose can be stored in the form of TL varies systematically with TL intensity. This combination of circumstances is highly contrived. In addition, the magnitude of the increase in peak width and temperature in the present case is much larger than is normally encountered in kinetic studies of TL (*e.g.* GARLICK, 1949, p. 38). The most important point about Fig. 1, however, is that the directions of these trends are opposite to those observed for bulk type >3.5 chondrites, where the TL peak broadens and moves to higher temperatures as the TL sensitivity *increases* (SEARS *et al.,* 1982). This is discussed below.

The data in Fig. 1 enable some comments on the source of the TL of bulk Dhajala TL powder, beyond those we have previously made (SPARKS *et al.,* 1983). The broken lines represent data for a synthetic glow curve produced by summing the individual curves for the 58 chondrules and performing the mass-normalization described above. We did not determine the precision of our TL sensitivity, peak position and FWHM values for individual chondrules, but if we take the SEARS and WEEKS (1983) values for Chainpur (whose TL sensitivity is ~0.1 times that of Dhajala) then the synthetic curve data lie near or within 2σ of the observed curve for bulk powder. The TL properties of the bulk sample appear therefore to be the composite of the properties of the individual chondrules. However, one cannot exclude entirely the possibility of an additional component, with high TL, minor mass and a wide high temperature TL peak, being present in the bulk powder, but absent from our chondrule suite. In any event, the bulk sample does not plot among the high TL chondrules, but instead plots at what appears to be a weighted average of the high and low TL chondrules. We conclude that although the low TL chondrules may not contribute significantly to the TL of the bulk sample (they affect it only by dilution), they do affect the width and temperature of the peak.

3.2 Petrographic data

Based on petrographic observations and mineral identifications made with the microprobe, we attempted to assign each of our chondrules to one of the types described by GOODING and KEIL (1981). Twenty of the 29 chondrules for which polished sections are made were porphyritic: 10 porphyritic olivine pyroxene (POP), 5 porphyritic pyroxene (PP), 3 porphyritic olivine (PO) and 2 of uncertain mineralogy. Six are non-porphyritic: 3 radiating pyroxene (RP), 2 granular olivine pyroxene (GOP) and 1 cryptocrystalline (C) (Table 2). Three did not belong to any of these types. These statistics are in reasonable agreement with those obtained by GOODING and KEIL (1981) who classified 139 Dhajala chondrules; in terms of percent abundances they found as follows: 46 POP, 14 PP, 15 PO, 8 RP, 6 GOP, 9 C and 2 BO (barred olivine). The three we were unable to classify are all very similar to each other in being fine-grained and rich in Ca and Al. However, they vary slightly in grain-size and considerably in Ca/Al. They apparently consist of crystallites of olivine and/or pyroxene in a glassy mesostasis; in one, the crystallites form a "herring bone" structure. They resemble certain of the Ca-Al rich chondrules described by BISCHOFF and KEIL

Table 2. Petrographic and microprobe data on Dhajala chondrules.*

Chondrule	Type	Olivine					Pyroxene		
		N⁺	Mean Fa	σ(Fa)	Mean CaO	σ(CaO)	N⁺	Mean Fs	σ(Fs)
1	POP	14	18.9	0.70	0.09	0.09	13	18.9	0.68
2	POP	3	17.9	0.20	<0.20	----	4	7.97	1.76
6	PO	9	17.9	0.66	0.10	0.11	0	----	----
8	PP	0	----	----	----	----	16	6.79	2.37
10	POP	6	21.0	0.69	0.04	0.01	11	32.1	1.79
11	C	1	23.5	----	----	----	15	24.6	2.22
12	RP	0	----	----	----	----	12	15.9	0.97
14	POP	6	16.7	4.29	0.16	0.13	4	5.50	1.92
15	POP	5	19.6	0.58	<0.04	0.01	13	9.64	1.56
18	RP	0	----	----	----	----	16	28.3	1.00
22	RP	0	----	----	----	----	16	10.4	0.37
35	PP	0	----	----	----	----	14	14.0	0.49
48	POP	2	16.6	----	0.06	----	3	8.34	1.43
51	PP	0	----	----	----	----	5	9.44	1.10
55	PO	14	17.9	0.66	0.05	0.01	0	----	----
67	PP	0	----	----	----	----	16	16.4	0.72
68	POP	9	15.2	0.48	0.16	0.08	4	10.9	1.00
70	POP	16	18.9	0.70	0.04	0.02	2	15.8	----
72	POP	6	18.6	0.43	0.05	0.03	11	10.9	1.10
75	GOP	16	21.5	0.97	<0.04	0.01	4	25.5	0.48
76	PP	0	----	----	----	----	10	10.2	1.00
80	GP	0	----	----	----	----	18	31.3	2.50
89	PO	12	17.9	0.31	0.12	0.05	0	----	----
93	POP	2	18.5	----	<0.20	----	10	9.56	1.10

* Five chondrules for which sections were made are not represented in this table. Chondrules 4 and 7, both porphyritic, were lost during a re-polishing stage and no microprobe data were obtained. Chondrules 27, 36 and 39 are Ca-Al-rich with unusual textures.

⁺ Number of analyzes.

(1983). GOODING (pers. commun.) has suggested that they be included with the C chondrules, but here we treat them separately.

The proportion of olivine, pyroxene and glass in these chondrule sections varies considerably. As indicated above, 3 contain no pyroxene, 9 contain no olivine and 5 are noteworthy in containing considerable glass (roughly 30–40 vol.%). Photomicrographs of representative sections appear in Fig. 2.

Figure 3 compares the chondrules' mass-normalized TL sensitivities and chondrule type. Porphyritic chondrules cover a TL/mass range of 0.06–1.6, with 11 of the 16 being over 0.2, whereas the non-porphyritic chondrules spread uniformly over the range 0.03–0.4. Student's *t* test indicates that the two populations are different at >99% confidence level. In general, therefore, porphyritic chondrules have higher TL/mass than non-porphyritic chondrules. It is particularly noteworthy that 4 of the 5 chondrules containing abundant mesostasis have the highest TL values among those observed in this study. There is apparently no systematic difference in TL sensitivity of the various types of porphyritic chondrules. Data for the non-porphyritic chondrules are really too meager for meaningful conclusions about the relative TL of the various types, but in the present data, the radiating pyroxene chondrules are somewhat higher in TL than the granular or cryptocrystalline chondrules. The two Ca,Al-rich chondrules for which we obtained TL data have fairly high TL, one being higher than any of the porphyritic chondrules.

3.3 Electron microprobe data–mafic silicates

SCOTT (1983) found that several type ≥3.6 ordinary chondrites contain chondrules whose olivine is homogeneous and low in Ca. These chondrules can be considered "equilibrated" despite the relatively mild metamorphism experienced by the bulk meteorites. In terms of olivine composition, our chondrules vary considerably in the degree of equilibration. Most were equilibrated, particularly chondrules 15, 70 or 72. The standard deviation of their Fa content is less than a few percent of the mean Fa; the mean Fa is in the range characteristic of H4-6 chondrites (GOMES and KEIL, 1980) and the olivine CaO content is in the range <0.04–0.06 wt%. Other chondrules have slightly lower mean Fa, but otherwise appeared fairly equilibrated. However three out of eleven are extremely heterogeneous in composition, with high levels of CaO (>0.1 wt%) and mean Fa being slightly, but significantly lower than the mean for H chondrites. This variation in equilibration and mean composition is very similar to that observed in unpublished data for the Dhajala meteorite by E. R. D. Scott; the present data and those of Scott are compared in Fig. 4. Also indicated in the figure, are the TL sensitivity/mass for the present chondrules.

Our data do not display a simple correlation between TL and equilibration although there is an interesting pattern. The most highly unequilibrated chondrules have TL/mass of ~0.2, while the three chondrules with the highest TL/mass (0.47, 1.11 and 1.05) are all equilibrated. However, among the equilibrated chondrules are several with TL/mass at the low end of the total range observed in this study (*e.g.,* 0.058). Apparently, unequilibrated chondrules have low TL/mass, but equilibrated chondrules display a wide range of TL/mass values. Chondrule type does not appear to affect the TL/mass because, with one exception, all the olivine-bearing chondrules for which we have TL data are porphyritic.

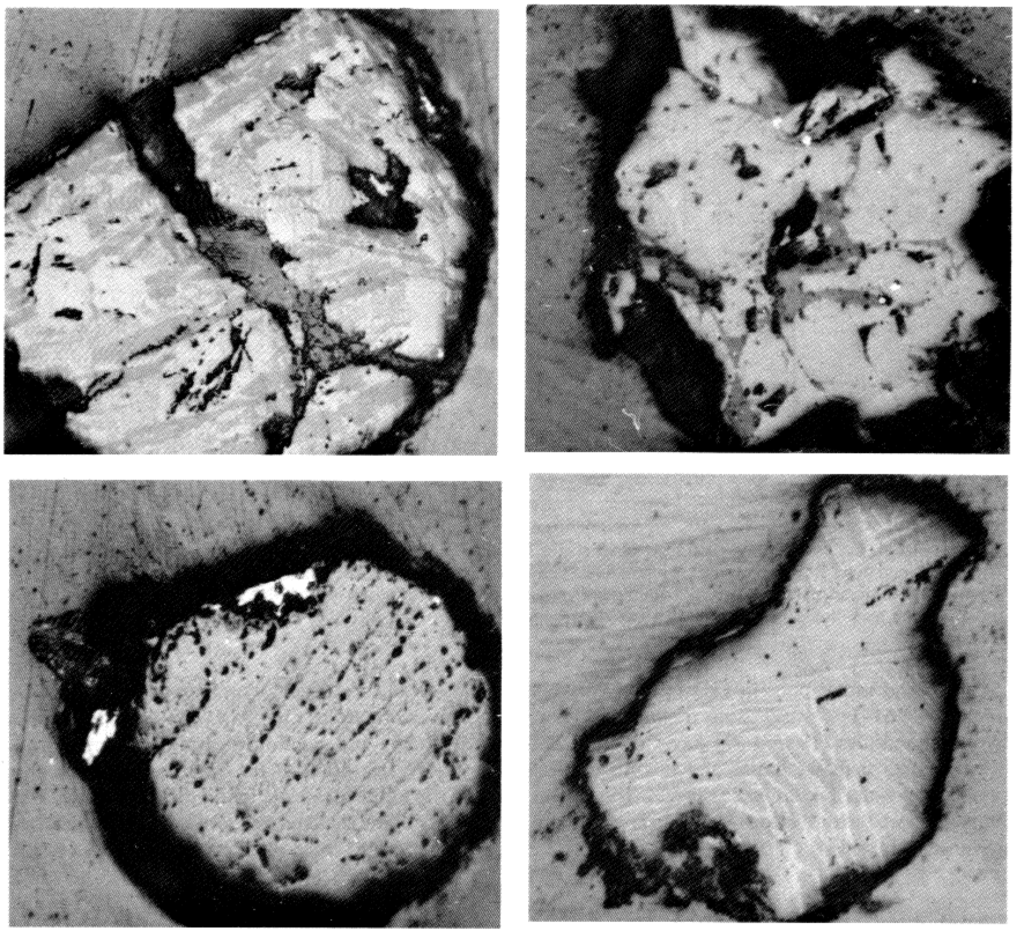

FIG. 2. Reflected light photomicrographs indicating some examples of the textures observed. Top left, chondrule 85, a glass-rich porphyritic olivine chondrule; top right, chondrule 35, porphyritic pyroxene chondrule; bottom left, chondrule 18, radiating pyroxene chondrule; bottom right, chondrule 36, calcium-aluminum rich chondrule. The horizontal field of view is 100 μm except for chondrule 85, for which the field of view is 150 μm.

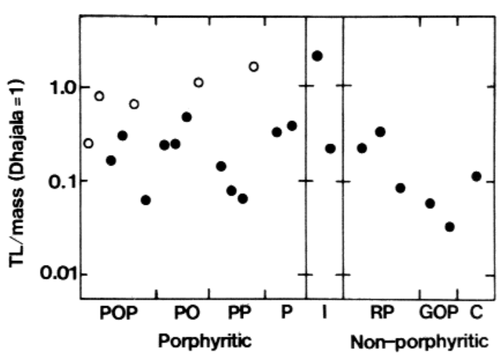

FIG. 3. Mass-normalized TL sensitivity of 30 chondrules as a function of the petrographic description of the chondrules: POP, porphyritic olivine pyroxene; PO, porphyritic olivine; PP, porphyritic pyroxene; P, porphyritic (mineralogy uncertain); RP, radiating pyroxene; GOP, granular olivine pyroxene; C, cryptocrystalline; I, fine-grained "igneous" textures. The open symbols refer to chondrules noteworthy for their high glass content.

The pyroxenes show greater compositional heterogeneity both within individual chondrules and from chondrule to chondrule. This is the normal situation for meteorites of comparable petrologic type to Dhajala and is usually attributed to differences in diffusion rates between the two minerals (*e.g.* Allan Hills A77278, Hedjaz and Parnallee; MCSWEEN and WILKENING, 1980; DODD *et al.,* 1967). In general, meteorites more heavily metamorphosed than Dhajala have both phases homogeneous, while meteorites less metamorphosed have both phases heterogeneous.

3.4 Electron microprobe data—mesostasis

Fourteen chondrule sections contain mesostasis which we could analyze with the electron microprobe; all but 3 of the chondrules are porphyritic. The number of analyses which could be made ranged from 1 to 9 (Table 3). In general, the mesostases are rich in CaO (1.1–15.0 wt%), Al_2O_3 (4.5–26.5 wt%) and Na_2O (1.4–

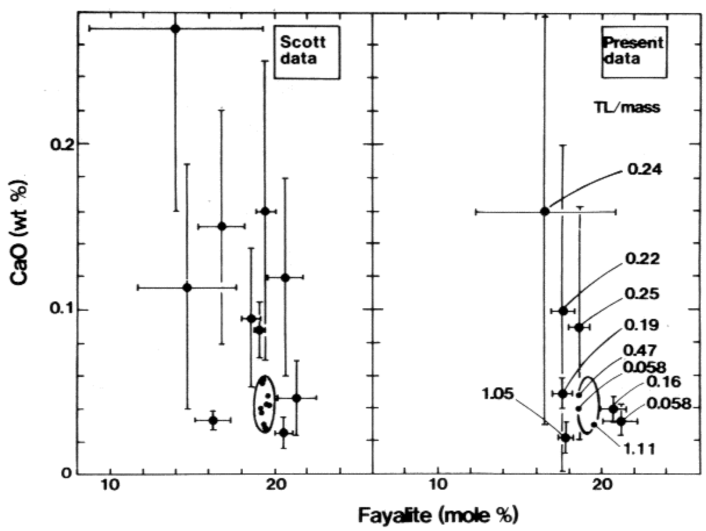

FIG. 4. CaO content of chondrule olivine as a function of its fayalite content; left, unpublished data obtained by E. R. D. Scott, right, present data. The error bar indicates ±one standard deviation. The ellipse refers to homogeneous, low Ca "equilibrated" chondrules. Superimposed on the plot for the present data are the mass-normalized TL sensitivity values.

8.54 wt%) and rather poor in FeO (1.13–4.96 wt%) and MgO (1.61–11.7 wt%). Two of three non-porphyritic chondrules (18 and 22) have much higher FeO and MgO than the others and this may reflect beam overlap with adjacent mafic silicates. The present results agree well with the data for Dhajala chondrule mesostasis obtained by GOODING (1979).

Statistically significant correlations with log(TL/mass) are displayed by CaO, Al_2O_3 and SiO_2. Excluding the texturally anomalous chondrule 36, these correlations are significant at the 95% level; with it, the level rises to the 99% level for all three elements. The similarity of the sign and magnitude of the correlation coefficient for the three elements suggests that a single

Table 3. Composition (wt %) of mesostasis in separated Dhajala chondrules.†

Chondrule	N+	SiO_2	Al_2O_3	FeO	MgO	CaO	K_2O	Na_2O	MnO	Cr_2O_3	Sum
1	9	64.1	15.1	2.71	4.36	3.21	0.28	7.6	0.12	0.66	98.2
6	4	54.6	18.2	2.98	7.55	3.83	0.40	6.6	0.14	0.68	95.0
8	6	60.4	14.4	2.20	5.70	2.20	2.2	6.8	0.13	0.34	94.4
10	4	71.7	11.3	4.96	2.95	4.00	1.9	3.9	0.17	0.24	101.2
12	2	63.2	17.3	2.40	5.50	1.10	0.17	6.6	0.16	0.55	96.9
14	4	58.8	20.4	2.17	4.05	1.29	0.24	8.5	0.08	0.26	95.8
15	3	59.6	20.8	1.57	3.17	5.69	0.25	7.1	0.16	0.18	98.5
18	1	58.8	4.50	9.00	16.3	2.27	0.09	2.2	0.51	0.66	94.8
22	1	60.0	5.00	4.20	22.4	1.70	2.4	1.4	0.49	1.0	98.6
35	5	62.0	17.1	2.30	3.50	3.60	0.62	6.3	0.12	0.14	95.7
36	6	44.9	26.5	2.29	6.24	15.0	0.05	1.4	0.10	0.16	96.8
51	7	59.4	11.7	2.80	11.7	2.80	3.8	3.4	0.15	0.65	96.3
55	4	61.3	11.8	3.80	5.80	8.30	0.80	5.1	0.15	0.57	97.7
67	2	68.3	13.8	1.39	4.22	1.08	0.06	6.6	0.14	0.41	96.0
68	5	53.6	21.5	1.81	7.48	12.5	0.13	3.2	0.13	0.35	100.7
70	5	62.0	14.3	3.32	6.50	4.00	0.23	6.2	0.22	0.73	97.5
72	5	59.1	21.6	1.13	1.61	6.00	0.19	7.6	0.15	0.24	97.6
76	4	54.1	19.2	2.24	4.73	8.44	0.21	5.3	0.22	0.44	94.8
89	5	49.5	24.6	1.44	5.20	13.7	0.12	2.8	0.06	0.17	97.5
93	1	55.3	21.0	3.80	8.40	3.00	0.71	5.0	0.13	0.40	97.7
r(n=16)*		-.69	.63	-.28	-.26	.72	-.50	-.20	-.25	-.50	
r(n=15)#		-.56	.53	-.26	-.29	.61	-.47	.02	-.18	-.43	

† The high MgO of chondrules 22, 51 and 18, and in two cases low Al_2O_3, suggest that there may be beam overlap with mafic silicates for these fine-grained chondrules.

* r is the correlation coefficient for log(TL/mass) vs. element oxide. There are no TL data for chondrules 51, 67, 68 and 93.

+ Number of analyses.

Without chondrule 36.

Table 4. CIPW norms for Dhajala chondrule glass.†

Chondrule	Q#	Or	Ab	An	Ne	Di	Hy	Ol	Cr	C
1	5.11	1.65	64.59	6.13	----	7.92	12.03	----	0.97	----
6	----	2.36	55.26	18.99	0.18	0.01	----	17.14	1.00	----
8	----	12.94	57.54	2.30	----	6.84	12.49	1.73	0.50	----
10	27.20	11.23	33.00	7.73	----	10.11	11.50	----	0.35	----
12	11.99	1.00	55.43	5.41	----	----	17.93	----	0.80	4.36
14	----	1.42	72.27	6.40	----	----	5.50	6.11	0.38	3.75
15	----	1.48	60.08	24.15	----	3.28	9.08	0.19	0.27	----
18	10.68	0.53	18.79	2.05	----	7.42	53.92	----	0.97	----
22	3.88	14.18	11.85	0.27	----	6.44	60.49	----	1.50	----
35	8.40	3.60	53.31	16.55	----	1.06	12.53	----	0.21	----
36	----	0.30	11.12	65.70	0.58	6.96	----	11.80	0.24	----
51	1.25	22.46	28.77	5.44	----	6.69	30.84	----	0.96	----
55	6.47	4.73	43.16	6.94	----	27.63	7.85	----	0.84	----
67	20.01	0.35	55.77	5.36	----	----	12.97	----	0.60	0.93
68	----	0.77	27.33	43.78	----	14.43	11.01	2.88	0.52	----
70	6.14	1.36	52.46	10.51	----	7.50	18.46	----	1.08	----
72	----	1.12	64.40	24.22	----	4.50	0.58	2.46	0.35	----
76	----	1.24	44.43	28.20	----	10.97	5.95	3.41	0.59	----
89	----	0.71	23.69	54.20	----	10.92	1.43	6.38	0.25	----
93	1.42	4.20	42.31	14.88	----	----	27.79	----	0.59	6.55
r(n=16)*		-.50	-.21	.76		.04		-.07	-.07	
r(n=15)#	.21	-.46	.02	.67		.07	-.38	-.35	-.31	

* Correlation coefficient for log(TL/mass) vs. normative mineral abundance. There are no TL data for chondrules 51, 67, 68 and 93.

\# Without chondrule 36.

† Q = quartz, Or = orthoclase, Ab = albite, An = anorthite, Ne = nepheline, Di = diopside, Hy = hypersthene, Ol = olivine, Cr = chromite, C = corundum.

mineral component is responsible for the considerable variation in these elements. This is confirmed by the CIPW norms (Table 4), since the only normative phase to correlate with TL is anorthite (significant at the 99% level). Plots of log(TL/mass) *vs.* CaO and normative anorthite appear in Fig. 5. The norm also indicates that the mesostasis is essentially albitic. Even when there is no possibility of overlap with mafic silicates, pyroxene always appears in the norm, sometimes accompanied by small amounts of olivine. This was observed petrographically by GOODING (1979, p. 63). Quartz also appears in the norms of most of the chondrules. This phase was neither sought nor observed in the present study, although SiO_2 occurs in some chondrules in other type 3 ordinary chondrites (BRIGHAM *et al.*, 1982; GOODING, 1979, p. 90).

The composition of the mesostasis varies in the extent of homogeneity. Several chondrules are fairly uniform and have standard deviations for SiO_2, Al_2O_3 and CaO that are less than 10% of the mean chondrule value. However, ten of the fourteen have heterogeneity in at least one of these oxides, usually CaO, in excess of 10%, and in 5 cases the standard deviation for CaO exceeds 20% of the mean. None of these heterogeneity data correlates significantly with log(TL/mass) (*i.e.* none exceeds a 95% confidence level), although the CaO figure approaches this value.

3.5 Fused glass bead analysis

Our data for the fused beads are listed in Table 5. The data resemble those of previous workers in terms of the variability of chondrule composition (OSBORN

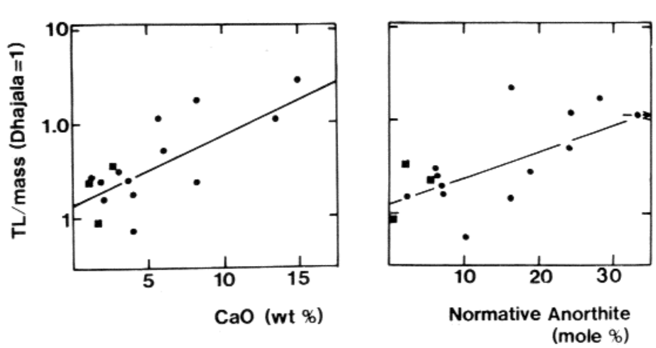

FIG. 5. Mass-normalized TL sensitivity as a function of CaO content of the glass (left) and normative anorthite content of the glass (right). The lines are regression lines with correlations significant at >95% level (see Tables 3 and 4). Non-porphyritic chondrules represented by squares.

Table 5. Bulk composition (wt %) of separated Dhajala chondrules determined from fused glass bead analysis.

Chondrule	SiO_2	Al_2O_3	FeO	MgO	CaO	K_2O	Na_2O	MnO	Cr_2O_3
1	46.1	3.66	17.8	24.8	3.00	0.12	1.08	0.49	0.91
4	46.4	2.36	8.90	40.9	0.73	0.06	0.05	0.23	0.34
5	48.5	3.22	9.72	34.8	2.45	0	0	0.31	0.71
8	59.9	2.58	6.52	30.0	2.10	0	0.03	0.31	0.63
10	50.4	1.76	9.99	34.2	2.64	0	0.06	0.47	0.52
12	57.4	2.70	9.16	27.5	1.79	0	0.08	0.52	0.79
14	50.1	3.32	9.48	34.3	1.91	0	0.04	0.35	0.58
17	53.4	3.22	9.27	32.1	2.35	0	0	0.36	0.61
18	48.2	3.73	9.20	38.5	2.23	0	0.04	0.18	0.65
19	46.8	1.99	10.7	38.1	1.42	0	0.06	0.35	0.55
20	47.5	9.74	9.66	26.6	5.75	0.05	0.05	0.33	0.23
23	51.7	3.72	10.3	33.6	1.55	0	0	0.30	0.70
26	53.0	4.90	11.1	29.1	2.97	0	0.05	0.30	0.27
28	59.6	4.26	6.30	28.2	2.96	0	0	0.27	0.47
35	56.9	2.99	9.92	26.2	1.89	0	0.99	0.46	0.65
36	48.6	26.2	2.38	7.19	15.1	0	0.09	0.16	0.22
42	54.9	3.34	7.33	32.3	2.74	0	0	0.47	0.60
51	45.9	6.21	1.73	43.8	4.94	0.12	0.18	0.29	0.37
54	50.2	3.57	11.3	32.1	1.28	0	0	0.29	0.21
58	48.1	3.74	9.05	36.4	3.51	0	0	0.33	0.69
72	50.6	1.87	10.1	33.7	2.59	0	0.06	0.51	0.54
76	46.8	4.66	6.56	37.0	4.19	0	0	0.27	0.77
78	51.8	2.69	6.48	34.6	3.15	0	0.10	0.58	0.45
80	58.1	1.36	15.2	21.6	1.72	0.17	0.59	0.63	0.61
84	51.8	19.5	3.17	12.8	14.9	0	0	0.17	0.23
86	61.7	19.6	2.88	7.11	6.52	0.07	1.69	0.12	0.29
89	51.9	17.1	5.12	13.9	12.6	0.05	0.11	0.21	0.23
92	48.9	3.20	13.9	29.8	2.29	0	0.33	0.37	0.51
r(n=26)*	-.19	.49	-.36	-.31	.43	----	----	-.55	-.26
r(n=24)	-.19	.50	-.31	-.26	.60	----	----	-.52	-.18

* r is the correlation coefficient for log (TL/mass) vs. element oxide. (r was not calculated for K_2O and Na_2O because these elements are frequently below detection limits). There are no TL data for chondrule 51. Without chondrule 36.

Without chondrules 36, 84 and 89.

et al., 1973; GROSSMAN and WASSON, 1982; GOODING *et al.*, 1980; WALTER and DODD, 1972; DODD and WALTER, 1972). Most variable are Al_2O_3 and CaO, whose standard deviations are comparable in size to the mean; least variable is SiO_2, whose standard deviation is <10% of the mean. Al_2O_3 and CaO show significant correlations with log(TL/mass), again implying a relationship between TL and the glass/feldspar content of the chondrule since both elements concentrate in this phase. (However, Ca also goes into pyroxene.) A surprise is that there is a significant correlation (>99% confidence level) between log(TL/mass) and MnO. This oxide shows only moderate variability (σ = 30% of mean) and is normally thought to concentrate in olivine and pyroxene.

4. DISCUSSION

4.1 *Mechanism for TL variation in type 3 ordinary chondrites*

In the equilibrated Saint Séverin meteorite, LALOU *et al.* (1970) found that the TL carrier was located in the low-density, feldspar-rich fraction. Microscopically visible feldspar is virtually absent from the type 3 chondrites, but forms in chondrites of higher petrologic types through the metamorphism-induced devitrification of glass. A plausible interpretation of the TL range in type 3 chondrites is that the TL phosphor is feldspar and the range of TL reflects progressive formation of this phase. This mechanism may explain the tendency for the TL peak in bulk meteorites to broaden and move to higher temperatures with increasing metamorphism; similar TL behavior is observed in terrestrial albite where it is associated with the transformation from the low to the high temperature form (PASTERNAK *et al.*, 1976; PASTERNAK, 1978; SEARS *et al.*, 1982).

We have previously observed that a few of the chondrules in Dhajala are very significant TL carriers and suggested that this is consistent with the devitrification of glass mechanism because glass is present to varying extents inside chondrules. In the present study, certain of the chondrules that are especially rich in glass are amongst those with the highest TL. In fact there is a general tendency for porphyritic chondrules to contain a higher volume percent of mesostasis than non-porphyritic chondrules (GOODING, 1979) and this may be responsible for their difference in TL.

Another line of evidence perhaps consistent with an association between glass and TL are the weak correlations between TL and CaO and Al_2O_3 in our fused beads (Table 5). Calcium is distributed between pyroxene and mesostasis, but occurs predominantly in the latter, and Al occurs almost entirely in the mesostasis. Thus, chondrules rich in Ca and Al should also contain abundant mesostasis. The correlation between log(TL/mass) and MnO content does not have such a straight-forward interpretation. However, in the factor analysis of chondrule compositions performed by GROSSMAN and WASSON (1982), Mn generally loaded near glass (Fig. 2 of Grossman and Wasson), suggesting that this correlation may also reflect a relationship between TL and glass. GOODING (1979) found that Dhajala mesostasis contains more than 60% as much MnO by weight as olivine and pyroxene in this meteorite. Thus, porphyritic chondrules with abundant glass would contain most of their bulk Mn in the glass phase.

Of high statistical significance is the relationship between TL and CaO, Al_2O_3 and SiO_2 or modal anorthite content of the glass. The normative anorthite increases from 0.27 mole % (in chondrule 22) to 28.2 mole % (in chondrule 76) or even 54.2 mole % (in chondrule 89), a factor of over 100, while the TL increases by a factor of about 40. It is possible that the glass in all the chondrules we studied was equally devitrified and that it is the amount of anorthite which determines the TL level of a chondrule. However, SEARS (1974) examined the TL of terrestrial feldspars from various sources and with compositions ranging from albite to anorthite and found no systematic variation in their TL properties. Such measurements on feldspars from various sources and with various histories and trace element chemistries are by no means definitive. An alternative possibility exists. Perhaps the bulk Ca content of the glass determined the extent of devitrification, which in turn determined the TL level. SCHAIRER and BOWEN (1956) observed that calcic glasses devitrify more readily than sodic glasses, and GIBSON *et al.* (1977) observed that the chondrule mesostasis in the Kramer Creek L4 chondrite had higher CaO when devitrified (14.1–17.6 wt%) than when glassy (1.16–5.8 wt%).

All the available evidence suggests that, for Dhajala at least, the TL phosphor is associated with chondrule glass and the mechanism behind the relationship between TL and metamorphism involves the composition of the glass.

4.2 Mechanism for the variation of TL from chondrule to chondrule

Both the abundance and composition of mesostasis in a chondrule are functions of the bulk composition of the chondrule (although chondrule cooling history also affects both parameters). The diversity in chondrule bulk compositions has been used by many authors to argue that chondrules were formed by the melting of fairly coarse-grained pre-existing solid material (see GROSSMAN and WASSON, 1983, for a review), so that to some extent, the TL variation may be said to be a primary property. The *extent* to which this is true is not clear, however. If the relationship between TL and CaO in the mesostasis reflects the facility with which glasses devitrify, then the variation in TL from chondrule to chondrule may be considered entirely a primary property.

If this is correct, the situation from chondrule to chondrule is very different than the situation from chondrite to chondrite where the metamorphic history of a meteorite determines its TL sensitivity. The TL trends displayed in Fig. 1 may also be evidence that the mechanism behind the range of TL displayed by chondrules differs from that responsible for the range of TL displayed by bulk chondrites. The trends in TL sensitivity with peak width and peak temperature for chondrules are the opposite to those present in such plots for bulk chondrites, at least for those meteorites with bulk TL > 0.05 (SEARS and WEEKS, 1983). Although the interpretation of these trends is unclear at the moment, they do signal that different processes may be involved in the chondrule and chondrite cases.

It is pertinent to ask, at this point, to what extent the TL data suggest that individual chondrules have experienced different metamorphic histories. When our TL data are compared with the olivine composition data, we see no simple direct relationship. Similarly, there is no correlation between the heterogeneity of the glass and log(TL/mass). To a first approximation, there appears to be no evidence that the level of TL displayed by a chondrule reflects its individual metamorphic history, but there may be a more complex relationship between TL and the metamorphism experienced by individual chondrules. It appears from the present data that while low TL chondrules are unequilibrated, equilibrated chondrules may have either high or low TL. As we have seen, chondrule TL is apparently governed by the amount and composition of constituent glass. This is consistent with (a) our observation that the major fraction of the TL in Dhajala is carried by a few of the larger chondrules and (b) with the observed strong dependence of the TL of the bulk sample on metamorphism. The TL of the bulk sample is thus governed by the few most equilibrated chondrules with compositions which result in calcic mesostasis.

If this interpretation is correct, then it is fortunate that we chose Dhajala to make this study of chondrule TL. It may be that the chondrule-to-chondrule variability in TL is greater for Dhajala and meteorites of comparable metamorphic history (*i.e.* petrologic type ~3.8) than any other. Less metamorphosed meteorites have not experienced sufficient recrystallization to produce any high TL chondrules, whereas more heavily metamorphosed meteorites may have been metamorphosed sufficiently to devitrify even the most sodic chondrule glasses. Meteorites that have been considerably more heavily metamorphosed than Dhajala will show a range in TL reflecting only their range of feldspar content, since their chondrule mesostasis will be fully devitrified.

4.3 The metamorphic history of individual chondrules

On the basis of our mineralogical and petrological data for separated Dhajala chondrules we have concluded that the range of TL sensitivity observed from chondrule to chondrule primarily reflects the range in glass content and composition. This in turn was determined by the bulk composition of the chondrules. The level of TL in the bulk samples reflects the metamorphism experienced by the bulk meteorite because this metamorphism enabled certain chondrules to acquire extremely high TL sensitivity. We see two processes at work; a primary one which determined how the chondrite would respond to metamorphism, and a second process which was metamorphism itself.

The number of equilibrated chondrules present in the type 3 ordinary chondrites seems to vary with petrologic type. None of the 10 chondrules examined by SCOTT (1983) in the Allan Hills A76004 type 3.3 chondrite were found to be equilibrated, and only 5/100 of the chondrules examined by DODD (1968, 1971) in the Sharps type 3.4 chondrite were equilibrated. On the other hand, four meteorites of petrologic type 3.6–3.7 (Yamato 74191, Allan Hills A77299 and Reckling Peak A80205 and A79008) typically contain ~10/20 equilibrated chondrules, while all of the chondrules in Bjurbole (L4) and Richardton (H5) are equilibrated (SCOTT, 1983).

One of three situations could explain these data: 1) Meteoritic chondrules were metamorphosed to varying degrees prior to incorporation in the meteorite. 2) The chondrules cooled at differing rates prior to incorporation in the meteorite; the heterogeneous chondrules cooled most rapidly. 3) The chondrules have experienced only *in situ* metamorphism but individual chondrules display a variety of susceptibilities to metamorphism.

If meteoritic chondrules were metamorphosed prior to incorporation into the meteorite, the bulk TL of the sample, and the overall petrologic type of the chondrite, reflect the proportion of equilibrated chondrules. The spectrum of metamorphism throughout the type 3 chondrites, and presumably other types, is therefore the result of accretionary forces rather than progressive metamorphism of similar starting materials. This explanation runs into the difficulty that it fails to explain why, in general, chondrules and the other components in type 3 ordinary chondrites (the metal and fine-grained matrix) seem to have experienced similar levels of metamorphism. For example, the extent of recrystallization in the matrix varies with the proportion of equilibrated chondrules. Meteorites of types > 3.5 have ~50% recrystallized chondrules and >60% recrystallized matrix, while types < 3.5 have, apparently, 0–5% recrystallized matrix (SCOTT, 1983; HUSS *et al.*, 1981). Meteorites of petrologic type > 4 have all of their chondrules recrystallized and 100% recrystallization in their matrix. Similarly, the heterogeneity of the metal, and its morphology, seem to suggest the same metamorphic sequence as chondrule-based properties. We think the data suggest an *in situ* mechanism for producing variable chondrule homogeneity. The same objections can be made against the idea that a range of chondrule heterogeneity reflects a range of cooling rates of independent, free-floating chondrules.

The mechanism we find most plausible is that all the chondrules experienced a similar pre-accretionary history, but somehow responded differently to metamorphism after they had accreted into the meteorite. It is hard to dispute that meteorites suffered post-accretionary metamorphism; matrix recrystallization and changes in metal petrology must have occurred *in situ* (HUSS *et al.*, 1981; WOOD, 1967; AFIATTALAB and WASSON, 1981). There must have been a mechanism that could make some chondrules more highly susceptible to recrystallization than others, and that could recrystallize ~5% of the chondrules while only recrystallizing 20% of the fine-grained matrix, as in Sharps. The mechanism should also explain why the rims, which are sometimes observed around chondrules (2 out of 6 meteorites examined by SCOTT, 1983), tend to occur around unequilibrated chondrules.

SCOTT (1983) discussed two related means whereby some chondrules could withstand *in situ* metamorphism and remain inhomogeneous, and their olivines Ca-rich, while others did not. First, large chondrules and grains would tend to lag behind small chondrules and grains because of diffusion limitations. This process was not thought to be the answer because of the lack of an inverse correlation between size and equilibration. However, pending a detailed quantitative study the possibility cannot be dismissed. Second, olivines which were enclosed and isolated by pyroxene, with its lower diffusion rates, would have equilibrated more slowly than exposed olivines. This idea was also dismissed since unequilibrated chondrules do not tend to consist predominantly of olivine crystals enclosed in pyroxene. Scott made an additional observation which, together with the TL data in this paper, may suggest a third alternative. He observed that the mesostasis was "generally, but not always" more crystalline in the equilibrated chondrules. GOODING (1979) made the same observation.

The third alternative is that it is the amount, or more importantly, the composition, of the chondrule mesostasis which determines a chondrule's ability to respond to metamorphism. To a good approximation, the mesostasis encloses the olivine and pyroxene. Diffusion through a glass requires volume diffusion, with possibly even a need to break Si-O bonds. It is therefore going to be a much slower process than grain-boundary diffusion. Thus, glassy mesostasis would constitute a significant barrier to diffusion both between grains within the chondrule and between the chondrules and matrix. When devitrified, the mesostasis would no longer constitute a barrier to diffusion because the small size of the crystallites and their large number would provide efficient pathways for grain-boundary diffusion.

A possible explanation for the tendency for rims of opaque matrix to occur around unequilibrated chondrules is provided by a consideration of recrystallization of the mesostasis. During the time a particular chondrule with devitrified mesostasis was equilibrating with the rest of the meteorite, various cations were diffusing in and out of the chondrule. All of these cations had to diffuse through the chondrule's opaque matrix rim. A second chondrule with abundant glass would have retarded cation diffusion through its opaque matrix rim. Cations would only pass in and out of the chondrule sluggishly. Although both chondrules may have experienced the same degree of mild metamorphic heating, rim recrystallization would occur preferentially around the first chondrule simply because more cations would have been available in this rim for incorporation into suitable crystallographic sites at crystal surfaces. The incorporation of these cations would have decreased the free energy of the crystals and caused grain growth.

This is essentially what one would predict from the data presented in this paper. The TL sensitivity of a given chondrule is governed by the amount and composition of the mesostasis, so that high TL chondrules are associated with calcic glasses (Fig. 5), which tend to devitrify more readily than other glasses. These chondrules were found to be equilibrated (Fig. 4). On the other hand, our unequilibrated chondrules are associated with low TL and low CaO glass. We emphasize, however, that we do not expect, or observe, a simple correlation between TL and equilibration, because TL is governed by the amount as well as the composition of glass. We observed several glass-poor chondrules in Dhajala where little or no devitrification would be required to enable communication between the chondrule grains and chondrite matrix.

It thus seems that a detailed study should be made of the chondrule mesostases and their composition. It might be that chondrules which retain their primitive mineral chemistries despite the meteorite-wide metamorphism may have been protected by a mesostasis which is resistive to devitrification. If this is correct, then there would be no need to involve a complicated phase of burial in a parent body, metamorphism, excavation and removal of individual chondrules, and subsequent reaccretion into the same or a new parent body, followed by a second phase of metamorphism.

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REFERENCES

AFIATTALAB F. and WASSON J. T. (1980) Composition of the metal phases in ordinary chondrites: Implications regarding classification and metamorphism. *Geochim. Cosmochim. Acta* **44,** 431–446.

BISCHOFF A. and KEIL K. (1983) Ca-Al rich chondrules and inclusions in ordinary chondrites. *Nature* **303,** 588–592.

BRIGHAM C., MURRELL M. T. and BURNETT D. S. (1982) SiO_2-rich chondrules in ordinary chondrites. *Meteoritics* **17,** 187–188.

BROWN R. W. (1977) A sample fusion technique for whole rock analysis with the electron microprobe. *Geochim. Cosmochim. Acta* **41,** 435–438.

DODD R. T. (1968) Recrystallized chondrules in the Sharps (H-3) chondrite. *Geochim. Cosmochim. Acta* **32,** 1111–1120.

DODD R. T. (1969) Metamorphism of ordinary chondrites. *Geochim. Cosmochim. Acta* **33,** 161–203.

DODD R. T. (1971) The petrology of chondrules in the Sharps meteorite. *Contrib. Mineral Petrol.* **31,** 201–297.

DODD R. T. (1978a) Compositions of droplet chondrules in the Manych (H-3) chondrite and the origin of chondrules. *Earth Planet Sci. Lett.* **40,** 71–82.

DODD R. T. (1978b) The composition and origin of large microporphyritic chondrules in the Manych (L-3) chondrite. *Earth Planet Sci. Lett.* **39,** 52–66.

DODD R. T. and WALTER L. S. (1972) Chemical constraints on the origin of chondrules in ordinary chondrites. In *L'Origine du Systeine Sulaire* (ed. H. REEVES) (C.N.R.S., Paris) 293–297.

DODD R. T., VAN SCHMUS W. R. and KOFFMAN D. M. (1967) A survey of the unequilibrated ordinary chondrites. *Geochim. Cosmochim. Acta* **31,** 921–951.

GARLICK G. E. J. (1949) *Luminescent Materials.* Clarendon Press, Oxford.

GIBSON E. K., LANGE D. E., KEIL K., SCHMIDT T. E. and RHODES J. M. (1977) The Kramer Creek, Colorado Meteorite. A new L4 chondrite. *Meteoritics* **12,** 95–107.

GOMES C. B. and KEIL K. (1980) *Brazilian Stone Meteorites,* University of New Mexico Press, Albuquerque, 161 pp.

GOODING J. L. (1979) Petrogenetic properties of chondrules in unequilibrated H-, L-, and LL-group chondritic meteorites. Ph.D. Thesis, Univ. New Mexico, Albuquerque.

GOODING J. L. and KEIL K. (1981) Relative abundances of chondrule primary textural types in ordinary chondrite and their bearings on conditions of chondrule formation. *Meteoritics* **16,** 17–43.

GOODING J. L., KEIL K., FUKUOKA T. and SCHMIDT R. A. (1980) Elemental abundances in chondrules from unequilibrated chondrites: Evidence for chondrule origin by melting of pre-existing materials. *Earth Planet Sci. Lett.* **50,** 171–180.

GROSSMAN J. N. and WASSON J. T. (1982) Evidence for primitive nebula components in chondrules from the Chainpur chondrite. *Geochim. Cosmochim. Acta* **46,** 1081–1099.

GROSSMAN J. N. and WASSON J. T. (1983) The composition of chondrules in unequilibrated chondrites: an evaluation of models for the formation of chondrules and their precursor materials. In *Chondrules and Their Origins* (ed. E. A. KING), Lunar and Planetary Institute, Houston, TX, 88–121.

HUSS G. R., KEIL K. and TAYLOR G. J. (1981) The matrices of unequilibrated ordinary chondrites: Implications for the origin and history of chondrites. *Geochim. Cosmochim. Acta.* **45,** 33–51.

LALOU C., NORDEMANN D. and LABYRIE J. (1970) Etude preliminaire de la thermoluminescence de la meteorite Saint Severin. *Cr. hebd. Seanc. Acad. Sci. (Paris) Serie D* **270,** 2104–2401.

LARIMER J. W. and ANDERS E. (1967) Chemical fractionations in meteorites—II. Abundance patterns and their interpretation. *Geochim. Cosmochim. Acta* **31,** 1239–2170.

MCSWEEN H. Y. and WILKENING L. L. (1980) A note on the Allan Hills A77278 unequilibrated ordinary chondrite. *Meteoritics* **15**, 193–199.

OSBORN T. W., SMITH R. H. and SCHMITT R. A. (1973) Elemental composition of individual chondrules from ordinary chondrites. *Geochim. Cosmochim. Acta* **37**, 1909–1942.

PASTERNAK E. S., Thermoluminescence of ordered and thermally disordered albite. Ph.D. Thesis, University of Pennsylvania, Philadelphia, 1978.

PASTERNAK E. S., GAINES A. M. and LEVY P. W. (1976) Thermoluminescence of ordered and disordered albites. *Geol. Soc. Amer. Abstracts with Program* **8**, 1044.

RAMBALDI E. R. and WASSON J. T. (1981) Metal and associated phases in Bishunpur, a high unequilibrated ordinary chondrite. *Geochim. Cosmochim. Acta* **45**, 1001–1015.

SCHAIRER J. F. and BOWEN N. L. (1956) The system Na_2O-Al_2O_3-SiO_2. *Amer. J. Sci.* **254**, 129–195.

SCOTT E. R. D. (1983) Type 3 chondrites from Antarctica—classification, metamorphism and brecciation. *Smithsonian Contrib. Earth Sci.* (submitted).

SCOTT E. R. D., TAYLOR G. T., RUBIN A. E., OKADA A. and KEIL K. (1981) Graphite-magnetite aggregates in ordinary chondritic meteorites. *Nature* **291**, 544–546.

SEARS D. W. (1974) Thermoluminescence and fusion crust studies of meteorites. Ph.D. Thesis, University of Leicester.

SEARS D. W. and DURRANI S. A. (1980) Thermoluminescence and the terrestrial age of meteorites. *Earth Planet. Sci. Lett.* **46**, 159–166.

SEARS D. W. G. and WEEKS K. S. (1983) Chemical and physical studies of type 3 chondrites—II: Thermoluminescence of sixteen type 3 ordinary chondrites and relationships with oxygen isotopes. *Proc. Lunar Planet Sci. Conf. 14th, Part 1, J. Geophys. Res.* **88**, B301–B311.

SEARS D. W., GROSSMAN J. N., MELCHER C. L., ROSS L. M. and MILLS A. A. (1980) Measuring the metamorphic history of unequilibrated ordinary chondrites. *Nature* **287**, 791–795.

SEARS D. W., GROSSMAN J. N. and MELCHER C. L. (1982) Chemical and physical studies of type 3 ordinary chondrites—I: Metamorphism related studies of Antarctic and other type 3 ordinary chondrites. *Geochim. Cosmochim. Acta* **46**, 2471–2481.

SPARKS M. H. and SEARS D. W. G. (1982) Mechanism for metamorphism-induced TL changes in UOC: Evidence from Dhajala chondrules. In *Lunar and Planetary Science XIII*, 754–755. Lunar and Planetary Inst., Houston.

SPARKS M. H., MCKIMMEY P. M. and SEARS D. W. G. (1983) The thermoluminescence carrier in the Dhajala chondrite. *Proc. Lunar Planet Sci. Conf. 13th, Part 2, J. Geophys. Res.* **88**, A773–A778.

TANDON S. N. and WASSON J. T. (1968) Gallium, germanium, indium and iridium variations in a suite of L-group chondrites. *Geochim. Cosmochim. Acta* **32**, 1087–1109.

VAN SCHMUS W. R. (1969) The mineralogy and petrology of chondritic meteorites. *Earth Sci. Rev.* **5**, 145–184.

VAN SCHMUS W. R. and WOOD J. A. (1967) A chemical-petrologic classification for the chondritic meteorites. *Geochim. Cosmochim. Acta* **31**, 747–765.

WALTER L. S. and DODD R. T. (1972) Evidence for vapor fractionation in the origin of chondrules. *Meteoritics* **7**, 341.

WOOD J. A. (1967) Chondrites: their metallic minerals, thermal histories, and parent planets. *Icarus* **6**, 1–49.

ZÄHRINGER J. (1968) Rare gases in stony meteorites. *Geochim. Cosmochim. Acta* **32**, 209–237.