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Composition and classification of clasts in the St. Mesmin LL chondrite breccia

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Seven samples of the unique St. Mesmin meteorite have been analyzed by instrumental and radiochemical neutron activation analysis for Na, Ca, Sc, Cr, Mn, Fe, Co, Ni, Zn, Ga, Ge, Se, In, Sm, Yb, Ir and Au. St. Mesmin is unique in being the only ordinary chondrite known to contain an unmelted xenolith of another ordinary chondrite. Data for two host matrix samples and three light clasts are consistent with their classification as LL chondrite material. The composition of the large dark xenolith confirms earlier evidence that it is an H chondrite; volatile abundances are consistent with it being highly shocked, petrologic type-4 material. In an olivine microporphyry, siderophile abundances are mostly about 0.13 times LL abundances, an apparent indication of metal loss during the shock melting which produced the clast. As in other regolithic chondrites, the dark host has higher contents of highly volatile elements than do the light clasts. We suggest that this results from a combination of differences in intensity of preexisting metamorphism as well as a redistribution of volatiles during regolith gardening.

The H-group xenolith in St. Mesmin is a relatively recent addition to the parent body (< 1.4 Ga ago), but it is argued that this does not require regolith activity at that time. Rather the view is supported that the regolith period occurred very early in the meteorite's history (≳4.0 Ga ago) and may have been related to the growth of the parent body. The H-group fragment may be part of the projectile whose impact excavated the St. Mesmin meteoroid from the LL parent body.

1. Introduction

Meteorites bearing fragments of a meteorite of a different class have attracted interest for several reasons:

(1) They provide evidence that objects belonging to different meteorite classes were at the same location at some point in time. Such polymict meteorites are rather rare; out of the 1000 or so chondrites whose interiors are exposed in the major meteorite collections, only 27 have been found to contain foreign xenoliths having dimensions larger than ~ 3–4 mm.

(2) Some xenoliths represent classes of meteorites that have not fallen to Earth as entire meteorites.

(3) Most xenolith-bearing meteorites have a regolith history, and their study offers insight into regolithic processes.

Of the 27 chondrites that contain foreign xenoliths, 10 contain xenoliths best interpreted as altered CM chondrite material and a further 9 are uncharacterized (but possibly CM-like) carbonaceous chondrite material (see Wasson and Wetherill [1, table 2] for details). Only one ordinary chondrite, St. Mesmin, contains an unmelted * xenolith which is not CM-like material [4]. Seven clasts from the St. Mesmin meteorite, including this large (4-cm) H-group xenolith, are the subject of the present study.

As discussed by Dodd [5], the assignment of a

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*A melted H xenolith has been reported in LL Ngawi [2] and a melted L xenolith in LL Paragould [3]; both are ≲3 mm across.

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petrologic type to St. Mesmin is difficult, since it contains numerous light and dark LL clasts that display a variety of petrologic types. These range from type 4 * to the partially melted material which Dodd terms type 7. It was not entirely clear to Dodd which type should be considered the "host", although the most common material seemed to be LL5. The breccia also contains a microporphyritic LL clast which is the product of complete melting.

Like many polymict breccias, St. Mesmin is gas-rich with solar-type gas and solar-flare tracks in the host material. It resembles Djermaia and Weston in containing at least one clast which has been irradiated prior to incorporation in the breccia. The remaining LL clasts have cosmic ray exposure ages of 10.3 ± 0.3 Ma. Eight clasts have mean K-Ar and U, Th-He ages of 4.40 ± 0.26 Ga and 3.84 ± 0.61 Ga, respectively; for the H-group xenolith the respective ages are 1.36 ± 0.08 Ga and 1.22 ± 0.26 Ga [6,7]. Rb-Sr data are consistent with these results [8].

Because of the unique nature of St. Mesmin, a consortium study was organized by P. Pellas and G. Poupeau of the Museum of Natural History, Paris. Mineralogical and petrological data were presented by Dodd [5], Dodd and Jarosewich [12] and Dodd et al. [9], track data by Ducatel and Poupeau [10], Rb-Sr data by Minster and Allègre [8], and noble gas data by Schultz and Signer [7]. In this paper, we present our radiochemical and instrumental neutron activation analyses for 17 major and trace elements.

2. Samples and techniques

Masses, olivine compositions and brief descriptions of our 7 samples are listed in Table 1. Two stones are represented, 368 and 369 (slice III; we have followed the practice of Schultz and Signer and not included the III in our symbolic designations) [7]; the sample locations (C3, D3,..., etc.) are indexed on sketches lodged in the Museum of Natural History, Paris. Sketches showing the locations of all our samples except 368C3 were published by Schultz and Signer [7]. A photograph of 369 slice III, showing the 4 cm × 2 cm H-group clast (which we will initially designate the Fa20 clast or xenolith) was published by Pellas [4]. The genomict structure typical of most regions of St. Mesmin is shown on the photo on p. 194 of Wasson [11]. All but two of our clasts were described petrographically by Dodd [5] and Dodd and Jarosewich [12], and our descriptions, in Table 1 and below, are based on their work. Our samples include: (1) two which were thought to be host material by Pellas and Poupeau and designated matrix by Dodd and others; (2) three light clasts, one of which is typical LL6 material, one is described by Dodd as LL7 material and the third lacks petrographic description; (3) a dark microporphyrytic clast; (4) the Fa20 xenolith.

The samples arrived as small chips having masses of 200–300 mg; they were ground and 2 replicates analyzed. These were irradiated with standards in the UCLA reactor for 3 hours at a neutron flux of 2×10^{12} cm^{-2} s^{-1} and counted on a Ge(Li) detector with 11% efficiency. This instrumental neutron activation analysis (INAA) yielded data for 14 elements (Table 2). An additional four elements (and redundant data for Au, Ir and Ni) were determined by radiochemical neutron activation analysis (RNAA) with counting on well-type NaI detectors (Table 1).

3. Results

Our INAA and RNAA procedures and the precision of the results have previously been described [13,14]. Based on replicate analyses of USGS standard rocks BCR-1 and DTS-1, 95% confidence limits on the mean of two RNAA determinations are: Ni, ±6%; Zn, ±3%; Ga, ±3%; Ge, ±8%; In, ±9%; Ir, ±10% and Au, ±15%. Means of two INAA determinations have approximately the following analytical uncertainties at the 95% confidence level: approximately ±25% for Yb and Lu; ±15% for Ca and Se; ±6% for the remaining elements.

Possible systematic biases in our data appear to

*Dodd also mentions type 3, but the percent mean deviations of olivine and pyroxene he reports never reach the type 3 range.

TABLE 1

Petrographic information and replicate and mass-weighted mean RNAA concentration data on St. Mesmin samples. Because of the gross difference in replicate siderophile contents, no mean is calculated for 368D4. Mean LL values based on our unpublished data and Mason [15]

Sample	Ni (mg/g)	Zn (μg/g)	Ga (μg/g)	Ge (μg/g)	In (ng/g)	Ir (ng/g)	Au (ng/g)	Mass (mg)	Petrographic remarks
Host									
368D7	14.3	59.3	6.4	16.9	2.3	430	168	117	LL5, Fa27.3
	12.1	53.0	5.9	16.0	1.9	400	134	168	
Mean	13.0	55.6	6.1	16.4	2.1	412	148		
368D4	66.7	44.2	7.6	54.9	2.9	460	700	58	metal-rich
	13.6	55.8	6.6	13.1	2.8	430	160	134	
Light clasts									
368L1	13.7	65.0	5.5	12.3	0.2	540	230	89	LL6, Fa30.2
	7.7	56.4	4.9	10.7	0.1	380	151	145	some areas metal-rich
Mean	9.8	59.5	5.1	11.3	0.1	440	179		
368L6	10.4	54.1	5.8	~6.6	0.3	300	155	68	–
	16.9	58.1	6.4	16.4	0.4	450	167	116	
Mean	14.7	56.7	6.2	13.1	0.4	400	163		
368C3	11.6	47.7	6.7	~7.1	0.7 *	170	123	66	LL7, Fa30.0
	7.2	46.8	5.3	5.3	0.5	140	66	223	
Mean	8.2	47.0	5.6	5.7	0.5	147	79		
Dark clast									
368D3	3.1	31.6	5.4	2.2	1.0	65	33.0	58	Fa29.9 olivine
	0.6	28.3	5.3	1.4	2.0	59	15.6	205	microporphyry
Mean	1.2	29.0	5.3	1.6	1.8	60	19.4		
H clast									
369D1	21.2	18.7	6.8	16.3	0.6	570	263	86	H4?, Fa19.8
	21.9	18.6	7.0	17.5	≤2.5 *	860	242	172	intensely shocked
Mean	21.7	18.6	6.9	17.1	0.6	780	250		
Mean LL	11.0	58	5.6	11	–	360	150	–	–

* Not included in the mean.

be minor or negligible. Using wet-chemical methods, Dodd and Jarosewich analyzed two olivine microporphyry clasts that they inferred to be part of the same mass; one was 168D3 [12]. Data on Cr and Fe from the two groups are in excellent agreement, but our Ca and Mn data, while near mean LL values (Table 2), are 20% and 40%, respectively, lower than those of Dodd and Jarosewich. Laul et al. [43] determined the abundance of 9 volatile elements in a sample of St. Mesmin which they termed "light" and which they described as LL6; presumably it is comparable with the light xenoliths 368L1, 368L6, 368C3 in the present study. Three elements are common to both studies, Se, Zn, and In. Our value (~ 55 μg/g) is closer to the mean Zn concentration of 58 μg/g found by us in other studies of ordinary chondrites; their Zn value (70 μg/g) is somewhat higher and outside our quoted precision. Their Se value (5.8 μg/g) is outside the precision limits on our value (9 μg/g), which is 10% lower than the LL value given in Pelly and Lipschutz [44]. Our Co, Zn and Ga data agree with those of Bart and Lipschutz to within about ±5% [16]. The spread in In values is too great to allow a meaningful comparison with previous work.

TABLE 2

Replicate and mass-weighted mean INAA concentration data on St. Mesmin samples. Because of gross differences in siderophile replicates, no mean is calculated for 368D4. Mean LL values based on our unpublished data [15]

Sample	Na (mg/g)	Ca (mg/g)	Sc (μg/g)	Cr (μg/g)	Mn (mg/g)	Fe (mg/g)	Co (μg/g)	Ni (mg/g)	Se (μg/g)	Sm (μg/g)	Yb (μg/g)	Lu (μg/g)	Ir (ng/g)	Au (ng/g)
Host														
368D7	6.28	–	7.6	3.78	2.38	207	967 *	10.9	8.8	0.20	–	–	410	136
	7.40	14.4	10.0	3.98	2.51	210	447	12.9	9.9	0.23	0.31	0.04	400	146
Mean	6.94	14.4	9.0	3.89	2.46	209	447	12.1	9.4	0.22	0.31	0.04	404	142
368D4	5.86	–	6.8	3.84	2.05	307	2204	51.1	11.2	0.21	–	–	540	604
	7.62	13.3	9.6	4.11	2.59	219	459	14.2	11.4	0.25	0.32	0.03	424	166
Light clasts														
368L1	7.00	–	8.4	3.99	2.43	203	521	11.4	8.2	0.23	–	–	443	178
	7.17	14.2	10.2	3.79	2.44	206	357	11.8	11.9	0.27	0.20	0.03	392	173
Mean	7.11	14.2	9.5	3.87	2.44	205	419	11.6	10.5	0.25	0.20	0.03	411	175
368L6	7.11	–	9.3	3.87	2.62	186	400	10.6	6.7	0.18	–	–	400	143
	8.03	13.5	11.1	3.93	2.69	205	396	17.0	7.6	0.19	0.32	0.04	456	181
Mean	7.71	13.5	10.5	3.91	2.67	198	397	14.8	7.3	0.19	0.32	0.04	437	164
368C3	8.45	–	10.8	3.09	2.44	185	377	7.6	6.2	0.17	0.35	–	197	107
	8.86	14.3	11.9	3.05	–	217	354	8.3	8.2	0.19	0.36	0.04	144	89
Mean	8.77	14.3	11.6	30.6	2.44	210	359	8.1	7.7	0.19	0.36	0.04	156	93
Dark clast														
368D3	7.70	–	8.8	4.01	2.70	162	180	2.3	3.3	0.22	–	0.03	81	33
	7.60	12.2	10.9	3.98	2.68	172	131	1.7	3.0	0.26	–	0.04	45	16
Mean	7.67	12.2	10.4	3.99	2.68	170	142	1.8	3.1	0.25	–	0.04	53	20
H Clast														
369D1	5.87	–	7.8	3.55	2.14	286	940	17.2	8.7	0.13	–	–	720	234
	6.60	–	9.3	3.55	2.23	295	898	22.3	9.4	0.18	0.22	0.03	840	240
Mean	6.36	–	8.8	3.55	2.20	295	912	20.6	9.2	0.16	0.22	0.03	800	238
Mean LL	6.90	12.5	9.0	3.64	2.50	200	450	11.0	8.9	0.21	–	–	560	150

* Value discarded (see text for details).

As is clear from Tables 1 and 2, our samples proved to have variable contents of metal as indicated by the scatter in the siderophile data. The most striking case is the host sample 368D4, in which concentrations of Ni, Ge and Au are 4 × higher in the first portion than in the second. This in part reflects the small size of the first portion, but also reflects the difficulty of sampling breccias in general and LL breccias in particular. Noteworthy is the fact that Ir concentrations are similar in the two portions. Lithophile concentrations show only minor variations between replicates.

Our data are presented graphically in Fig. 1. Since the RNAA and INAA data for Ir, Ni and Au are in satisfactory agreement, a simple average has been taken. All means are mass-weighted. The elements were Si-normalized and then expressed as ratios to LL chondrites (LL means listed in Tables 1 and 2). Also shown for the siderophiles are typical H chondrite values based on our unpublished results. Silicon values for clasts 368D3 (209.1 mg/g) and 368L1 (199.2 mg/g) are unpublished data supplied by E. Jarosewich. For the LL

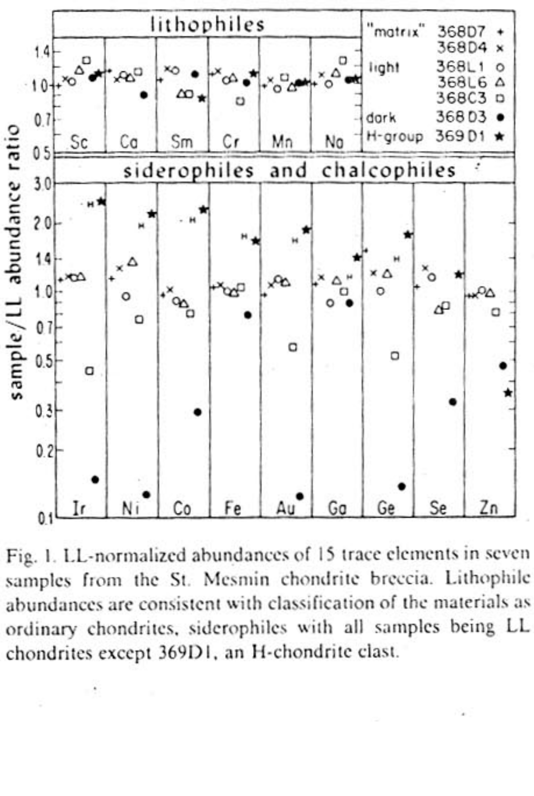

Fig. 1. LL-normalized abundances of 15 trace elements in seven samples from the St. Mesmin chondrite breccia. Lithophile abundances are consistent with classification of the materials as ordinary chondrites, siderophiles with all samples being LL chondrites except 369D1, an H-chondrite clast.

mean and for other samples from stone 368 we have assumed a value of 195 mg/g, slightly higher than the LL mean given by Moore [42]. For clast 368D1 we used a value of 171 mg/g, the mean H group value given by Moore. In Fig. 1 we have divided the elements according to their geochemical affinities; within each division they are ordered approximately in terms of decreasing nebular condensation temperature.

4. Classification of St. Mesmin samples

Refractory lithophile abundances are quantized within each clan * of chondrites, thus these elements (e.g., Ca, Sc, rare earths) can be used to search for evidence of an exotic nature in the St. Mesmin materials. Another compositional parameter that is relatively specific to ordinary chondrites is Zn concentration; our data show that 95% of ordinary chondrite Zn values are in the range 45–75 μg/g, much lower than those in other chondrite groups with the exception of EL and EH chondrites (i.e., low-Fe and high-Fe enstatite chondrites [45]).

The separation of the 3 ordinary chondrite groups is best made in terms of siderophile abundances (high in H, intermediate in L, low in LL), and in terms of the degree of oxidation, as measured by the distribution of Fe between oxidized silicates and reduced Fe-Ni metal. The latter is generally measured by the Fe/(Fe + Mg) ratio in ferromagnesian silicates, providing these are essentially equilibrated, as they are in St. Mesmin samples.

Our LL-chondrite-normalized lithophile data for the 7 St. Mesmin samples are shown in the upper portion of Fig. 1. With the exception of 368C3, refractory lithophile abundances are within ± 20% of mean LL values, and extreme refractory abundances are not correlated (e.g., the 20% high Sm in 368D4 is accompanied by Sc and Ca values that are within 7% of the mean). Thus all data,

* A clan is defined to be one or more groups having similar properties, and thus probably originating within a small range of heliocentric distances. The 3 groups of ordinary chondrites comprise a clan.

including those on the Fa20 clast 369D1, are consistent with the samples being ordinary chondrites.

Abundances of Zn are shown at the lower right portion of Fig. 1. Five samples fall within 20% of the mean LL chondrite value, consistent with classification as ordinary chondrites. The microporphyry sample and the Fa20 clast have Zn abundances 0.5 and 0.4 × mean LL values. Such low values are rare, but have been found within a few ordinary chondrites (e.g., in H4 Beaver Creek and H5 Hessle based on our unpublished data). As will be discussed below, we infer that the missing Zn was lost by shock-related processes.

Abundances of siderophiles in the host matrix and in the light clasts 368L1 and 368L6 are in the LL range. Occasional extreme values (such as the high Ni in 368L6 and the high Ge in 368D7) seem to reflect experimental or sampling (e.g., in the taenite content) error, since they are not correlated with extreme values of the other siderophiles. Particularly striking is the high Co value in the first sample of host 368D7; such a high fractionation of Co from all other siderophiles is unprecedented in our bulk analyses of chondrites, and we have discarded this value.

The Fa20 clast 369D1 has siderophile abundances very similar to those in H chondrites; for reference an H in the siderophile columns shows typical H/LL abundance ratios. If the siderophile-rich first replicate of host 368D4 is combined with the plotted second replicate in a mass-weighted mean, the resulting siderophile abundance ratios are similar to H group. We suspect this is fortuitous, but ferromagnesian mineral compositions should be determined on this material to confirm that it is metal-rich LL rather than H.

As previously found by Dodd and Jarosewich [12], siderophile abundances are very low in the olivine microporphyry 368D3; Ir, Ni, Au and Ge abundances are all near 0.13 × mean LL values. These almost certainly reflect the separation of immiscible Fe-Ni from the silicate melt before it migrated to its present position. Note that the "siderophiles" having the strongest lithophilic tendencies have higher abundances: Co is 0.3 × LL, Fe is 0.8 × LL and Ga is about 0.9 × LL, within the normal LL range. The Se content is 0.3 × LL suggesting that about 70% of the FeS remained behind with the Fe-Ni metal. This is confirmed by the FeS data of Dodd and Jarosewich; they report 15.6 mg/g FeS compared to an LL mean of ~ 58 mg/g.

The LL7 clast 368C3 also has low siderophile abundances; Ir, Ni, Au and Ge again have the lowest abundance ratios, averaging about 0.6 × LL values. Thus this material has not only suffered a high grade of metamorphic reheating, it seems to have lost metal as well. Dodd [5] on the basis of analogy with Shaw, speculated that later study might show that this material had lost metal and sulfide by anatexis (partial melting). Recently metal-rich areas have been discovered in Shaw, and it now appears that the whole rock is not metal deficient [17], but that metal was mobilized and redistributed as a result of shock-induced shear and melting. This suggests the possibility that the St. Mesmin LL7 materials have had a similar history, and that the presently observed metamorphic grade chiefly reflects impact heating rather than an internal (e.g., ^{26}Al) or external (a hyperactive Sun) heat source.

To summarize this section, host clast 368D7, the large second replicate on 368D4, and the light clasts 368L1 and 368L6 appear to be normal LL materials. The highly metamorphosed clast 368C3 and the remelted microporphyry sample 368D3 appear to be LL materials that have lost metal and, from the latter sample, sulfide. The Fa20 clast 369D1 appears to be normal H material; only for Zn does it show deviant behaviour.

5. Volatile elements, light-dark structure and petrologic type

The elements Cr, Mn, Na, Ga, Ge, Se and Zn are moderately volatile elements [18]. The extent of their depletion in ordinary chondrite whole-rock increases as their nebular volatility increases, but they show no variation as a function of petrologic type. Not surprisingly, our clasts show the same general trend. Most moderately volatile elements have similar abundance in H, L and LL chondrites. As noted above, abundances of these elements are similar to mean LL values with the exception of the H chondrite clast 369D1, and the olivine microporphyry 368D3.

TABLE 3

Indium in the dark and light portions of gas-rich meteorites

	In(ng/g)		In (dark)/In (light)	Reference *
	dark	light		
Cangas de Onis	2.38	0.05	47.6	c
Fayetteville	9.1	1.1	8.3	b
Krähenberg	24.0	13.0	1.8	a
Leighton	151	15.7	9.6	b
	170	0.89	191	c
Pantar	36	2.4	15.0	b
Tysnes Island	17.8	1.4	12.7	b
	19.6	46.2	0.42	c
Weston	13.4	1.1	12.2	b
	7.99	0.99	8.07	c
St. Mesmin	1.6	8.18	0.20	c
St. Mesmin 368D7	2.1	0.3	7.0	d
St. Mesmin 368D4	2.8	0.3	9.3	d

* Data from (a) Kempe and Müller [49], (b) Rieder and Wänke [19], (c) Bart and Lipschutz [16] and (d) present work. Replicates have been averaged where available. Our data for St. Mesmin (light) are averages for clasts 368L1, 369L6 and 368L3.

The range in abundances of the highly volatile element, In, is $\gtrsim 10$ among the various clasts. In Table 3 we compare our data on highly volatile In in light and dark portions of regolithic ordinary chondrites with literature data, primarily from reference 19. St. Mesmin samples 368D7 and 368D4 appear to be dark materials in the sense usually meant in the term light-dark structure, since Schultz and Signer [7] found them to be rich in solar gas. We find higher In concentrations in these matrix samples compared with the three light clasts but, in agreement with Rieder and Wänke [19], no enrichment for Na, Mn, Ga, Ge and Au.

Müller and Zähringer [20] reported higher C and Bi concentrations in the dark matrix than in the clasts of gas-rich meteorites and suggested that the volatile enrichments were due to the presence of a carbonaceous chondrite component; Mazor and Anders [21] invoked the same explanation for the inert gases. In a similar vein, Wilkening [22] suggested that, in terms of the sources of their volatile elements, type 3 and gas-rich dark chondritic materials are equivalent.

Bart and Lipschutz [16] and Rieder and Wänke [19] determined 8 highly volatile elements (He, B, C, Cs, Cd, In, Tl, Bi) in the dark and light portions of gas-rich meteorites. Although, with the exception of St. Mesmin, the dark portions had higher volatile concentrations than the light, Bart and Lipschutz noted that the elemental patterns are highly variable and thus "do not support prior suggestions of the presence of significant proportions of C1, C2 or indeed any known sort of primitive material in the dark...portions". They hypothesize that "each part represents parent material compositionally more variable than in the 'normal' chondrites of the same chemical groups".

Our assessment of the source of the volatile element patterns differs. To some degree the fine-grained host probably has higher volatile contents than the more recrystallized clasts for the same reason that type 3 chondrites have more volatiles than type 5 or 6; i.e., differing degrees of metamorphic loss. However, the patterns in the gas-rich hosts seem to be more erratic than in type 3 chondrites, and in some cases (e.g., In in Leighton) the concentrations of soe elements exceed those found in type 3 chondrites. Thus an additional source of volatiles is required, and the following seem the most likely:

(1) As Wilkening notes [22], carbonaceous clasts *are* present, and finer carbonaceous material must also be present; by analogy with the howardites which show similar numbers of carbonaceous clasts, this CM(?) component probably accounts for only 2–3% of the whole rock [23], too little to

account for the bulk of the volatiles.

(2) The solar wind has deposited large amounts of rare gases, and must also have contributed a portion of the highly volatile elements; however, the volatile metal/rare gas ratios should be solar, and a simple calculation shows that the solar windcomponent is $< 0.1\%$ of the whole rock.

(3) Dreibus and Wänke [24] suggested outgassing of the interior of the parent body as a result of metamorphism produced by an internal heat source.

(4) We propose a simpler metamorphic model, viz. that impact metamorphism during regolith gardening both removed volatiles from clasts and redeposited these in the matrix. In support of the latter, we note that the petrologic grade of the typical precursor LL material prior to the impact-induced metamorphism was probably at least as low as 4, and possibly lower [25,4]. Thus, impact metamorphism of clasts could easily have provided a portion of the volatiles now found in the dark (host matrix) samples. The variable elemental patterns probably reflect differences in the response of the various highly volatile elements to the brief and highly localized impact heating events. Whether an element was lost from a hot sample (e.g., the olivine microporphyry) would have depended not only on thermodynamically controlled volatility but also on kinetic effects, i.e., the ability of the element to migrate out of the hot material before it chilled. Thus we find no requirement for "more variable" compositions of the precursor materials as proposed by Bart and Lipschutz [16], nor for the internal heat source implied in the model of Dreibus and Wänke [24].

The relationship between highly volatile element content and petrologic type is well established [25–27], and our data show variations in In consistent with the range of petrologic types petrographically observed in our clasts. in Fig. 2 we compare our In data with the primordial ^{36}Ar data of Schultz and Signer [7]. We have also indicated the In and ^{36}Ar observed in the petrologic types. As conveniently illustrated by Heymann [28, fig. 13], gas-rich meteorites do not conform to the $^{36}Ar_p$ vs. petrologic-type relationship because an appreciable fraction of the ^{36}Ar is from solar gases that were subsequently added to the dark host.

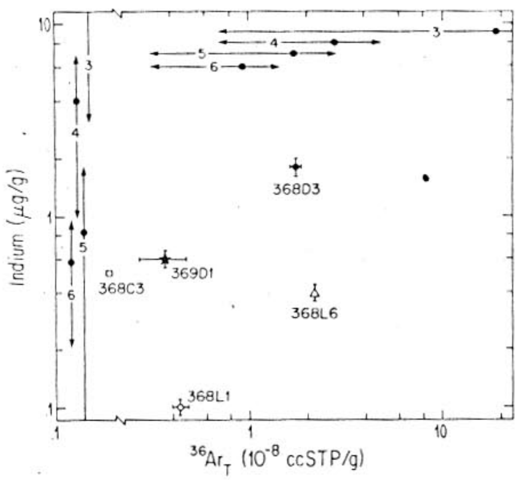

Fig. 2. Relationship between our In data for six St. Mesmin clasts with the primordial ^{36}Ar contents calculated from the data of Schultz and Signer [7]. No argon data are available for clast 368C3. The ranges and dots indicate the mean $\pm 1\sigma$ for In and ^{36}Ar contents observed in the different petrologic types (circled numbers) of L chondrites. (Data from the sources in references 40 and 41.)

The host samples studied here (368D4 and 368D7) have therefore been omitted from Fig. 2.

The two light clasts, 368L6 and 368L1, have volatile element abundances consistent with type 5 or 6 (indistinguishable in terms of $^{36}Ar_p$ and In), which, for 368L1 is in agreement with its assigned petrological type. Surprisingly, the In contents in the type-7 clast 368C3 are near the upper limit of the observed range in type 5 and 6. (No rare-gas data are available for this clast.) Even more important are the observed high $^{36}Ar_p$ and In contents in the microporphyritic clast 368D3, which, despite having been melted, contains type-4 abundances of these volatiles. This surely indicates that (1) the precursor material was volatile rich, and (2) that the melt migrated to its present location and solidified within seconds of its genesis, too quickly to lose a very large fraction of the volatiles, although the Zn data suggest that as much as 50% of some volatiles were lost. However, chalcophile Zn may have been lost together with a metal-sulfide liquid rather than by volatilization.

It is interesting to examine the volatile element abundances in the H chondrite clast because of the ambiguity over its petrologic type in the petrologic and mineralogical data. The silicate inhomogeneity and distinct chondrule outlines suggested to Dodd [5] that it was type 4 or lower, whilst the presence of augitic pyroxene suggested it was equilibrated, i.e., type 4 or higher. Schultz and Signer [7] observed that their ^{36}Ar data were more consistent with type 5 or 6, and this is also true of the In data. Interpretation of the metamorphic history of this clast is complicated by evidence of intense shock. The feldspar is in the form of maskelynite, the stone is black in the hand specimen, almost opaque in this section and has mosaicked olivine and numerous metal and sulfide veins. The concentration of Zn, the most volatile of the moderately volatile elements, is about 2 × lower than expected, suggesting volatilization loss. The possibility exists, therefore, that the meteorite originally contained type-3 or -4 quantities of highly volatile elements, but that these were driven off by the reheating associated with the shock event.

Heymann [29] observed that the black chondrites, which display a variety of metallographic evidence for intense shock, almost invariably had K-Ar ages much lower than the 4500 Myr age expected. The highly shocked H-group clast in St. Mesmin also has a low K-Ar age of 1.4 Ga [7], and some loss of $^{36}Ar_p$ must also have occurred, although planetary Ar is more resistant to shock-induced loss than radiogenic. Whether In is generally lost during the shock processes that lead to blackening is not known, but it seems plausible that some loss could occur. Thus the compositional data are probably not in conflict with petrologic type 4.

6. History and origin of St. Mesmin and similar xenolithic meteorites

The St. Mesmin breccia is important because it is the only ordinary chondrite that contains a large unmelted, clast of another ordinary chondrite group. Binns [25] and Fodor and Keil [3,30] reported surveys of 169 brecciated meteorites all of which were genomict, i.e., consisted of clasts which were the same group as the host, differing only in petrologic type. Two of these meteorites contained small melted clasts that were assigned to a group different from the host. According to Binns' survey, 62% of the LL, 10% of the L and 25% of the H chondrites are genomict. Several authors have therefore concluded that the ordinary chondrite classes evolved in different and isolated regions of the solar nebula [25,4,31,3]. These regions only remained isolated as long as the orbits remained essentially circular. As soon as the eccentricities increased enough to cause orbits to overlap, breccias consisting of clasts from several groups should have formed.

Our data and those of Dodd [5] show that with the exception of the H group clast, all the clasts and matrix samples studied are LL group material. Some of this material has been shock-melted and Fodor and Keil [3] observed that some clasts have been shock darkened. Despite this, the clasts have K-Ar and U, Th-He ages in excess of 4.0 Ga, even those that have been melted.

Such observations led Pellas [4] and Wasson and Wetherill [1] to argue that essentially all the regolith activity responsible for shock melting clasts, implanting solar winds, and producing solar flare tracks in gas-rich breccias occurred between 4.0 and 4.3 Ga ago. It seems that the dark matrix or host material rich in In and other volatiles has not been reheated since ~ 4.0 Ga. A recent study has shown that St. Mesmin LL clasts have retained charged particle tracks for ⩾ 4.0 Ga; this is noteworthy because tracks are more sensitive to metamorphic annealing than radiogenic gases are to loss [32]. Were it not for the H-group clast, it would seem appropriate to assume that regolith activity ceased ~ 4.0 Ga ago, since there are no young LL clasts.

A lower limit on the duration of regolith activity can be estimated from differences in the irradiation histories of breccia clasts [4]. Since one clast in St. Mesmin has a cosmic ray age 1.5 Ma greater that the remaining clasts (including the H-group clast), the St. Mesmin regolith was active for at least 1.5 Ma. A more detailed study of the Djermaia H chondrite indicates a minimum of 15 Ma regolithic activity at that location [33].

The existence of the H group clast with its young K-Ar age of 1.4 Ga has led to the generation of alternative models. This clast was probably a separate object at the time it was heavily shocked and outgassed 1.4 Ga ago, otherwise some of the LL clasts in St. Mesmin should have 1.4 Ga ages. There are no other examples of gas-rich meteorites containing clasts as young as the St. Mesmin H clast. The youngest are a clast in the Plainview H chondrite that was shock-melted 3.6 Ga ago [34], and a clast in the Kapoeta howardite dated at 3.5 Ga (most Kapoeta ages are > 4 Ga) [35–37]. Primarily on the basis of these age data several authors [7,8,34,38] have concluded that the regolith processes continued until very recently. This model offers a simpler cosmic-ray irradiation history than that in which regolith activity ceased $\gtrsim$4.0 Ga ago, since the irradiation in the regolith and in the meteoroid (during its travel time to Earth) could have been continuous.

It appears important at this point to define a regolith process. We suggest that the term regolith be restricted to the repeated mixing of a near-surface layer of a body with a gravitational field strong enough that negligible mass was lost under the bombardment conditions prevailing. Clearly, the St. Mesmin material was in a regolith at the time the solar-wind gases were incorporated. Furthermore, the absence of young ages in the LL material suggests that regolith activity ceased ~ 4.4 Ga ago; of particular note is the fact that microporphyries D3 and D5 plot directly on the 4.48-Ga reference isochron of Minster and Allègre [8]. How then is one to understand the presence of the 1.4-Ga H clast?

We agree with Schultz and Signer [7] that it seems unduly complex to assume that the LL regolith was active early, was then buried too deeply to be affected by cosmic rays until 1.4 Ga ago, was then augmented by the addition of an H-group object, and then quickly (within a few Ma) reburied again until the meteoroid was liberated. On the other hand, we also find it difficult to accept the Schultz and Signer proposal that the St. Mesmin regolith was active *only* during the last few million years before the meteoroid was ejected from the parent body, since the high ages of all LL clasts and especially the microporphyritic samples testify to regolithic activity ~ 4.4 Ga ago. We note that Schultz and Signer do not attempt to counter the general arguments against a late regolithic origin for the genomict chondrites, e.g., that the paucity of gas-rich L breccias is difficult to understand on the basis of such a model [4].

We suggest that the problem lies in the implicit assumption that emplacement of the H group clast occurred during a period when the regolith was active, though we agree with Pellas that the H clast was the last material added to the St. Mesmin breccia. A simple explanation of the cited facts is that the H clast was part of the projectile that excavated the St. Mesmin meteoroid from its parent body. We suggest that the H clast was incorporated by the same kind of impact-induced welding that was involved in the production of all breccias. There is no need to connect this incorporation with the regolithic activity that led to the introduction of the solar rare gases. Note that we are not introducing an ad hoc mechanism: the St. Mesmin meteoroid must have been liberated by an impact event and impact events must occasionally lead to the welding together of a small fragment of the projectile with the local material.

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