N88-14888

S14-90
116677
20P.

THE DISTRIBUTION OF EVAPORITIC WEATHERING PRODUCTS ON ANTARCTIC METEORITES

MW 822115

Final Report

NASA/ASEE Summer Faculty Fellowship Program--1987

Johnson Space Center

Prepared by:	Michael A. Velbel, Ph.D.
Academic Rank:	Assistant Professor
University & Department:	Michigan State University Dept. of Geological Sciences East Lansing, MI 48824-1115

NASA/JSC

Directorate:	Space and Life Sciences
Division:	Solar System Exploration
Branch:	Planetary Materials
JSC Colleague:	James L. Gooding, Ph.D.
Date:	August 7, 1987
Contract:	NGT 44-001-800

ABSTRACT

White evaporite deposits of terrestrial origin occur on some 5% of Antarctic meteorites. The few previous studies, and new mineralogical analyses, indicate that the deposits are predominantly carbonates and/or sulfates of magnesium. The distribution of white evaporitic salt deposits differs among different meteorite compositional groups and weathering categories of Antarctic meteorites. Salts occur with unusual frequency on carbonaceous chondrites, and are especially common in carbonaceous chondrites of weathering categories A and B. Among achondrites, weathering categories A and A/B show the most examples of salt weathering. Unlike carbonaceous chondrites and achondrites, most salt-bearing ordinary (H and L) chondrites are from rustier meteorites of weathering categories B, and, to a lesser degree, B/C and C. LL chondrites are conspicuous by their complete lack of any salt-weathering product.

Almost two-thirds of all evaporite-bearing meteorites belong to weathering categories A, A/B, and B. Where chemical and/or mineralogical data are available, there is a persistent suggestion that evaporite formation is accompanied by elemental redistribution from meteorite interiors. Meteorites of weathering categories B, A/B, and even A may have experienced significant element redistribution and/or contamination as a result of terrestrial exposure. Evaporite formation during terrestrial weathering cannot be neglected in geochemical, cosmochemical, and mineralogical studies of Antarctic meteorites. A lower-case "e" should be added to the weathering classification of evaporite-bearing Antarctic meteorites, to inform meteorite scientists of the presence of evaporite deposits and their associated compositional effects.

INTRODUCTION

Terrestrial weathering interferes with the use of meteorite mineralogy and chemistry as windows into the pre-terrestrial history of the meteorites, their parent bodies, and the early solar system, because weathering transforms original minerals to alteration products and redistributes chemical elements. Nowhere is this phenomenon of greater concern to meteorite scientists than in Antarctica. More than 7000 samples, representing several thousand meteorites, have been collected in Antarctica in the past two decades (Lipschutz and Cassidy, 1986). However, none of these are fresh falls.

Although weathering most likely proceeds only slowly in the cold, dry Antarctic environment, Antarctic meteorites have been exposed to terrestrial conditions for tens of thousands to hundreds of thousands of years (e.g., Nishiizumi, 1986; Schultz, 1986a). Thus, ample opportunity exists for small increments of weathering to accumulate into measurable effects. Characterization of terrestrial weathering effects is therefore crucial to studies of Antarctic meteorites (e.g., Gooding, 1986a,b), in order to prevent terrestrial alterations from being misinterpreted as primary compositional attributes of the meteorites.

The present procedure for classifying the weathering of Antarctic meteorites is based on the amount of rust visible to the unaided eye; weathering categories "A", "B", and "C" indicate, respectively, "minor", "moderate", and "severe" rustiness. However, other forms of terrestrial alteration, which do not involve the formation of rust, are also known. The most obvious and widely noted of these "non-rusty" alterations is the appearance of white powders or efflorescences on the surfaces of meteorites. Although relatively rare, occurring on less than 5% (fewer than 100) of the samples, the white deposits are nevertheless the second most widely recognized form of terrestrial alteration, after the formation of rust. The white deposits clearly indicate some combination of post-fall elemental redistribution and/or terrestrial contamination. Characterizing these deposits is therefore essential to understanding the nature and magnitude of weathering effects in Antarctic meteorites.

The purpose of this project is to twofold: 1) To investigate the mineralogy, chemistry, and origin of white efflorescences on the Lewis Cliff, Antarctica, 85320 (H5) chondrite (hereinafter referred to as LEW 85320). The unusual abundance of material available from LEW 85320 provided a rare opportunity to employ a variety of analytical methods. 2) To examine the occurrence of evaporite deposits on Antarctic meteorites as a function of meteorite compositional group and weathering category.

PREVIOUS WORK

Previous work on the white powdery deposits has been limited to a handful of descriptive mineralogical studies on eight meteorites (Yabuki *et al.*, 1976; Marvin, 1980; Marvin and Motylewski, 1980), which demonstrated that the deposits consist of various evaporite salts of Mg. Yabuki *et al.* (1976) identified the white material on Y 74371 as nesquehonite ($MgCO_3 \cdot 3H_2O$). Marvin (1980; Marvin and Motylewski, 1980) identified several evaporite minerals, including hydromagnesite, epsomite, leonhardite, gypsum, and nesquehonite, on seven Allan Hills meteorites, which included two H chondrites, two L chondrites, two carbonaceous chondrites, and one ureilite.

Marvin (1980) noted that "the sources of the elements and processes leading to formation of the evaporites are problematical", and opinion on the origin of the white deposits remains divided. In their discussion of the origin of the nesquehonite on Y 74371, Yabuki *et al.* (1976) favored possible external sources of magnesium, such as sea water, spring water, saline lake waters, volcanic emanations, alkaline hot springs, or hydrothermal solutions, despite the obvious difficulty in explaining how a meteorite which had been exposed to such an environment could have been found in Antarctic ice in association with unaltered meteorites. In contrast, additional work led Marvin and Motylewski (1980) to "conclude that Mg, S, and minor elements are leached from the meteorite. The source of carbon is probably atmospheric CO_2." The origin of these deposits is still uncertain.

Marvin (1980) commented that "the deposits are not restricted to any one variety of meteorite." There was no apparent correlation of evaporite occurrence with iron-oxide staining; only two of the salt-bearing meteorites exhibited any significant degree of iron-oxide staining (weathering categories B and C). Previous work involved too small a number of samples to permit any inferences regarding relationships between the occurrence of salts, and either meteorite composition, or meteorite rusting, in Antarctic meteorites.

PART I: EVAPORITES ON LEW 85320

METHODS

LEW 85320 is a large (>110 kg), moderately rusty (weathering category B) H5 chondrite. Two samples were examined in this study. Sample 40 consists of millimeter-scale chips (aggregates) of pure white powdery material, scraped from surficial accumulations which were observed in the field at the time the sample was recovered. Sample 22 consists of surficial scrapings, whose "salt and pepper" appearance suggests a mixture of white evaporite deposit and dark brown or black fusion crust. The white material of sample 22 appeared upon return of the sample to JSC, during controlled laboratory drying.

Mineralogical characterization utilized X-ray diffraction (XRD) and scanning electron microscopy with energy-dispersive X-ray spectrometry (SEM/EDS). For XRD analysis, a portion of each sample was ground in acetone on a glass microscope slide, using a glass stirring rod, and the resultant slurry was allowed to dry on the slide. These preparations were then scanned from 5° to 50-60° two-theta in a Phillips X-ray diffractometer with Cu radiation, using the following instrumental settings; 40kV, 20 mA, 1° divergence and receiving slits, scanning rate of 1° two-theta per minute, chart recorder speed of 10mm per minute, time constant of 1 second, and chart scale settings appropriate to the amplitudes of the most intense peaks.

Samples for SEM/EDS analysis were mounted on graphite stubs, using colloidal graphite as the adhesive, and a conductive coating of carbon was applied with a vacuum evaporator. Samples were examined using a JEOL-35CF SEM equipped with a PGT4000T analyzer, operating at 20kV.

RESULTS

XRD results are summarized in Table 1. Sample 40, the pure white powdery aggregate, produced an excellent XRD pattern (Table 1), with twenty-six peaks discernable above background between 2 and 60 degrees two-theta. Eleven of these correspond to the peaks for pure synthetic nesquehonite ($MgCO_3 \cdot 3H_2O$) reported by Ming and Franklin (1985). All but one have been reported previously in natural samples of nesquehonite (Yabuki *et al.*, 1976 and Ming and Franklin, 1985, and references therein; ASTM 20-669), although some of them may be attributable to the presence of small amounts of other hydrous magnesium carbonates, such as hydromagnesite [$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$], ASTM 25-513; see also Ming and Franklin, 1985) or barringtonite [$MgCO_3 \cdot 2H_2O$], ASTM 18-768. The one anomalous peak, at 1.03 nm, is quite weak relative to the nesquehonite peaks. It probably represents trace quantities of another hydrous magnesium carbonate, the hexahydrate, "hydrophase II" [$Mg_5(CO_3)_4(OH)_2 \cdot 6H_2O$] (Ming, 1981), whose two principal XRD peaks (1.03 and 5.79 nm) are an excellent match to the 1.03 and 5.82 nm peaks in the XRD pattern of LEW 85320,40. If the weak 1.03 nm peak represents of Ming's (1981) hydrophase II, then LEW 85320,40 is the first reported natural occurrence of the hexahydrate. All peaks are attributable to nesquehonite and traces of other hydrous magnesium carbonates, suggesting that sample 40 is pure carbonate.

TABLE 1 - XRD DATA FOR METEORITIC AND TERRESTRIAL NESQUEHONITE

PRESENT WORK LEW85320 ,22		,40		Ming & Franklin Synthetic		Yabuki et al. Yamato 74371		Synth.		ASTM 1-1030	
d(nm)	I	d(nm)	I	d(nm)	I	d(nm)	I	d(nm)	I	d(nm)	I
		1.03	5								
0.651	**22**	0.651	>100	0.651	10	0.652	VS	0.646	VS	0.650	10
						0.607	vw	0.606	vvw		
		0.582	5							0.580	0.8
		0.490	2			0.491	w	0.490	mw	0.496	0.8
						0.458	vw				
		0.446	2								
		0.413	4			0.415	vw	0.417	vw		
0.385	**26**	**0.386**	**93**	0.386	9	0.386	VS	0.385	VS	0.386	8
0.359	**8**	**0.357**	**16**	0.356	3	0.359	m	0.357	m	0.358	1.6
						0.335	vvw				
0.323	**11**	**0.323**	**12**	0.322	2	0.323	m	0.323	m	0.323	1.6
0.303	**9**	**0.303**	**30**	0.302	3	0.304	S	0.305	ms	0.302	2.4
		0.298	6			0.298	w	0.298	w		
						0.288	vw				
						0.283	m				
0.278	**15**	**0.278**	**11**	0.277	2	0.278	m	0.278	m	0.277	1.6
0.262	**10**	**0.262**	**13**	0.261	2	0.262	S	0.262	S	0.261	4.8
0.252	**12**	**0.251**	**21**	0.250	4	0.251	m			0.251	4
								0.249	m		
		0.247	4			0.247	vw				
		0.234	2			0.234	m	0.234	w	0.235	0.8
						0.231	vw				
						0.220	vvw				
						0.218	w				
		0.217	**9**	0.217	1	0.217	w	0.217	w	0.217	1.6
						0.216	vw				
						0.212	vw				
		0.202	**8**	0.201	1	0.202	mw	0.201	mw	0.201	0.8
						0.201	vw				
0.193	**8**	**0.192**	**19**	0.192	3	0.193	m	0.193	m	0.192	3.2

Two-theta > 48 not reported.

BOLD FACE = synthetic nesquehonite Ming & Franklin (1985)
underline = reagent grade hydromagnesite and/or synthetic magnesium hydroxycarbonate hexahydrate (Ming, 1981)
regular face = peak unknown from well-characterized synthetic phase.

Sample 22 yielded relatively low peak intensities, most likely because of poor crystallinity of the salt (see SEM results, below), although the presence of glassy fusion crust in the sample may also have played a role. Sample 22 yielded two strong (0.651 and 0.385 nm) peaks, and some half-dozen very weak peaks, barely above background (Table 1). Despite the poor quality of the XRD pattern for this sample, all peaks which exist correspond to peaks reported from natural (Yabuki *et al.*, 1976) and synthetic (Yabuki *et al.*, 1976; Ming and Franklin, 1985) nesquehonite.

Scanning electron microscopy of aggregates from sample 40 reveals that minerals of the evaporite deposits possess two distinctive morphologies. The bulk of the material exhibits an elongate, lath-like prismatic habit. Individual laths are generally 30-60 microns long, and 5-10 microns wide. Prism faces often exhibit striae parallel to the direction of elongation. Prism edges are sharp and distinct, although the ends of the prisms are commonly somewhat rounded. The rounding of the ends of the laths may be due to small amounts of dissolution-reprecipitation taking place in the presence of water sometime after the crystals formed. The laths are arranged in a felted or jackstraw fabric. EDS analysis reveals Mg to be the only detectable metal cation. The elongate habit is characteristic of both natural (Yabuki *et al.*, 1976) and synthetic (Ming and Franklin, 1985) nesquehonite.

The second characteristic morphology is a fragile wispy form, consisting of thin (submicron) gently curved sheets. The distribution ranges from individual wisps superposed upon the prism faces and rounded edges of the laths, through small botryoidal clusters of anastomosing wisps, to large (100 micron) clumps of intricate porous intergrowths, which appear to have formed by coalescence of smaller clusters. Partial or complete encrustation of laths is also occasionally observed. EDS analysis again reveals Mg to be the only detectable metal cation. The clumps of wispy magnesian material are morphologically very similar to synthetic "hydromagnesite hydrophases" prepared by Ming (1981). Although striking in appearance, the wisps are volumetrically insignificant compared to the laths. The wispy material may be the small amount of hydromagnesite (and/or the hexahydrate "hydrophase II" of Ming, 1981) responsible for many of the non-nesquehonite peaks in the XRD results. The superposition relationship with the prismatic and rounded surfaces of the nesquehonite laths indicates that both nesquehonite precipitation and rounding of the nesquehonite crystals preceded the formation of the hydromagnesite.

Sample 22 is similar to sample 40, except that the bulk of the Mg-rich material shows no crystal faces, and appears fractured in places. This material volatilizes under the electron beam exactly as nesquehonite does, and, because it makes up the bulk of the material under the SEM, is inferred to be the crystalline phase responsible for the nesquehonite peaks in the XRD pattern for this sample. Thin superposed deposits of wispy material are identical to those of sample 40.

DISCUSSION

Conditions of nesquehonite formation on LEW 85320 can only be speculated upon, but morphological and experimental results both suggest that nesquehonite may have formed under Antarctic conditions. Ming and Franklin (1985) synthesized nesquehonite at temperatures as low as 4°C. Schultz (1986b) experimentally determined that temperatures in the interior (2 cm depth) of a sample of the Allende (CV3) meteorite exposed to Antarctic conditions reached 5°C on wind-free days during austral summer, despite the fact that the air temperature never exceeded -11°C over the study period. Thus, insolation heating of meteorites in Antarctica is sufficient to 1) raise the temperture of meteorite interiors above the freezing point of pure water, to depths of several centimeters, and 2) to attain temperatures at which nesquehonite may form directly from the resultant solutions. Therefore, the observed mineralogy and morphology of Antarctic meteoritic nesquehonite, and present knowledge of nesquehonite stability, are both consistent with direct formation of nesquehonite under Antarctic conditions.

Ordinary chondrites consist predominantly of olivine and pyroxene, with varying abundances of Fe-Ni metal and sulfides. The presence of hydrous magnesium carbonates as alteration products implies that water and carbon were also available to the weathering system. Gooding's (1981) mineralogical results and Schultz's (1986b) experimental data indicate that liquid water is at least occasionally available to Antarctic meteorites. If we assume that the Mg for the nesquehonite was derived from the meteorite itself (e.g., Marvin and Motylewski, 1980), a reaction involving the ferromagnesian silicate minerals of the ordinary chondrite is required to release the Mg. A single reaction, using olivine as the mineral reactant, can be written which accounts for all these requirements:

$$(Fe_xMg_{1-x})_2SiO_4 + 8-5xH_2O + 2-2xCO_2 + 0.5xO_2 \Longrightarrow 2-2x(MgCO_3 \cdot 3H_2O) + 2xFeOOH + H_4SiO_4$$

where x is the mole fraction fayalite in the meteoritic olivine. Carbon dioxide combines with water to form carbonic acid, which dissociates to give a hydrogen ion and bicarbonate. The hydrogen ion drives the olivine hydrolysis reaction, liberating Mg. Magnesium reacts with bicarbonate and water to form nesquehonite. Oxygen oxidizes the Fe, which reacts with water to form goethite, and silicon is released to solution, from which it can be precipitated as some form of silica.

The hypothesized internal source for Mg requires mass transfer from meteoritic silicates to the surficial evaporites, but formation of evaporites in the observed amounts would have no detectable effect on the MgO content of the bulk meteorite. Approximately one gram of evaporite was recovered from the 110kg LEW 85320 H chondrite. Pure nesquehonite is about 28% by weight MgO; thus, the recovered mass of evaporite contains 0.28g of MgO. If LEW 85320 has the average MgO content of Antarctic H chondrites (21.82 wt%; Fulton and Rhodes, 1984), the total MgO inventory of the meteorite is 24kg. Therefore, the amount of MgO in the evaporite deposit is about 10^{-5} of the meteorite's MgO inventory, an amount so small that its removal from the meteorite interior would not even affect the last decimal place in MgO analyses reported to four significant figures.

The olivine-nesquehonite reaction illustrates how the terrestrial atmosphere and hydrosphere can react with meteoritic ferromagnesian silicates to form all of the widely observed terrestrial alteration products of Antarctic meteorites, *without* resorting to external sources for any lithophile cations. Hydrous magnesium carbonates result directly from this reaction. The iron oxy-hydroxide, goethite, contributes to the abundant metallic rust (e.g., Gooding, 1986a) which is the most conspicuous alteration phenomenon of Antarctic meteorites, and the silica is available to contribute to "sialic rust", which was analyzed and discussed by Gooding (1986a).

PART II: DISTRIBUTION OF EVAPORITES ON ANTARCTIC METEORITES

METHODS

If the occurrence of salt were independent of meteorite composition and controlled exclusively by conditions in the weathering environment, we might expect that the number of occurrences of evaporite deposits on meteorites of any individual class would be proportional to the relative abundance of individuals of that class among all Antarctic meteorites. In other words, if 1) meteorite class Z constitutes 20% of all Antarctic meteorites, 2) all meteorites are equally likely to encounter evaporite-forming environments (there's no giant magnet selectively drawing some classes of meteorites towards salt-forming environments), and 3) all meteorites are equally likely to form evaporite minerals if subjected to salt-forming environments, then meteorite class Z should constitute 20% of the reports of salt-bearing meteorites. Thus, if occurrence of salt were independent of meteorite composition (as Marvin's, 1980, preliminary data suggested), all meteorites would be equally vulnerable to salt-formation, and occurrences of evaporite salts would be apportioned among all groups of meteorites in proportion to the groups' relative abundances.

To test the hypotheses that occurrence of evaporite salts is independent of meteorite composition or weathering class, a census of evaporite occurrences on Victoria Land, Antarctica, meteorites was taken, using data from several sources: 1) Previous work on salt weathering of Antarctic meteorites (Marvin, 1980); 2) Preliminary descriptions of Antarctic meteorites (from the Antarctic Meteorite Newsletter [AMN]); and 3) Examination of photographs in the Antarctic Meteorite Collection at the NASA/Johnson Space Center. Results were tabulated both on the basis of individual unpaired samples, and compensated for pairing. Pairing was accounted for by counting all samples from a given pairing (AMN) as one meteorite, and assigning it to the weathering category of the most highly weathered individual sample. The results of this census were then compared with data on Antarctic meteorite abundances (uncorrected and corrected for pairing) provided by R. Score (written communication, June 30, 1987, and personal communication, July 15, 1987). This census of white evaporite deposits covers all U.S. Antarctic meteorites described and/or photographed before mid-July, 1987.

RESULTS

Results of this census are summarized in Table 2. (A complete list of all evaporite-bearing meteorites is available from the author upon request.) Ratios of evaporite-bearing-to-total meteorites in each category are shown as percentages in Table 3.

This study reveals that the occurrence of evaporite salts is definitely influenced by meteorite composition, for certain groups of meteorites. Evaporite occurrence is also correlated with rustiness, but salt coexists with different weathering classes among different compositional groups of meteorites. The influence of environmental factors can be seen in the data for paired meteorites.

Major features of the census results indicate:

1) A strong compositional influence is suggested for carbonaceous chondrites. Although carbonaceous chondrites make up less than two per cent of the total number of Antarctic meteorites, they constitute nearly one-fifth (19.4%) of the described occurrences of white evaporite deposits. A much larger number of carbonaceous chondrites possess salts than would be expected if all classes of meteorites were equally vulnerable to salt formation. Composition appears to play a major role in determining the distribution of evaporite salts in carbonaceous chondrites.

2) A compositional influence is also suggested for the E chondrites, LL chondrites, and possibly the achondrites. E chondrites make up less than one percent of the total population of Antarctic meteorites, yet they constitute more than 4% of the reported occurrences of white deposits. LL chondrites make up 5% of the total population, yet no occurrences of salt-bearing LL chondrites have been reported. Achondrites constitute less than 4% of the total population, yet make up more than 10% of the evaporite-bearing meteorites.

3) For some groups of meteorites (L and H chondrites, and irons/stony-irons), the proportion of meteorites of that group among the evaporite-bearing meteorites is similar to (within a factor of three of) their relative abundance among the total population of Victoria Land meteorites, suggesting that there is no significant difference in the susceptibility of these meteorites to evaporite formation.

4) Composition is not, however, the sole determining factor. There are several paired meteorites for which different individual samples have different weathering classifications. In the case of one carbonaceous chondrite with nearly a dozen evaporite-bearing pieces, weathering classifications for individual samples ranged

TABLE 2 - SALT WEATHERING STATISTICS

	WEATHERING CATEGORY					SALT-BEARING		ALL ANTARCTIC[1]	
GROUP	A	A/B	B	B/C	C	#	%	#	%
C	6	2	5	1		14	19.4	26	1.9
LL						0		66	4.8
L	1	1	11	4	3	20	27.8	415	30.4
H	1		11	9	4	25	34.7	782	57.2
E		1		1	1	3	4.2	9	0.7
ACHONDR.	3	3	1		1	8	11.1	49	3.6
IRONS & STONY IRONS						2	2.8	20	1.5
TOTAL[2]						72	100	1367	100
TOTAL[3]	11	7	28	15	9	70			
%	15.7	10.0	40.0	21.4	12.9	100			

[1] Includes 78 classified meteorites (irons and stones) which were not assigned a weathering category.

[2] Includes two salt-bearing irons.

[3] Does not include the 2 salt-bearing irons, because irons are not assigned a weathering category.

Table 3 - Ratios of Evaporite-bearing/Total for Each Group and Weathering Category (%)

	Weathering	category				Proportion of
Group	A	A/B	B	B/C	C	entire group
C	85.7	25.0	55.6	50.0		53.8
LL						
L	2.8	1.3	5.9	6.9	5.9	4.9
H	2.4	0	4.0	5.5	2.1	3.4
E	0	50.0	0	100.	50.0	33.3
Achondr.	27.3	20.0	7.1	0	50.0	16.7

from A to B/C! There are also several reports of paired meteorites in which only one individual possesses white deposits. Differences in the weathering behaviors of paired meteorites cannot be due to differences in meteorite composition; therefore, some external environmental factor must account for non-identical weathering of such pairs.

5) Almost two-thirds (65.7%) of the evaporite-bearing stony meteorites are classified as weathering categories A, A/B, or B. Most of the evaporite-bearing but less-rusted meteorites are carbonaceous chondrites of weathering categories A and B, and achondrites of weathering categories A and A/B. Significant evaporite formation is correlated with the earliest stages of rusting (weathering categories A and B) in carbonaceous chondrites. Sixth-sevenths (85.7%) of the carbonaceous chondrites of weathering category A possess salt. The absence of evaporite-bearing carbonaceous chondrites from weathering category C does not indicate negative correlation between salt and rust in these meteorites, but merely the fact that there are no carbonaceous chondrites in this weathering category.

6) Most evaporite-bearing ordinary chondrites are assigned to weathering category B. Evaporite formation is infrequently associated with the earliest stages of rusting of ordinary chondrites (3 evaporite-bearing meteorites out of 223 H and L chondrites in weathering categories A and A/B), but dominates in weathering categories B, B/C and C, in these meteorites (42/916).

DISCUSSION

The susceptibility of an individual meteorite to evaporite formation is a function of meteorite group. For example, carbonaceous chondrites make up a much larger proportion of the salt-bearing population than they make up of the overall population of Antarctic meteorites, and more than half of all C chondrites possess white deposits. Apparently, the high volatile content of carbonaceous chondrites is conducive to the formation of salts, possibly because these meteorites are capable of supplying their own oxidizable carbon and/or sulfur, which can combine with water to supply acid for silicate hydrolysis reactions and acid anions for evaporite formation.

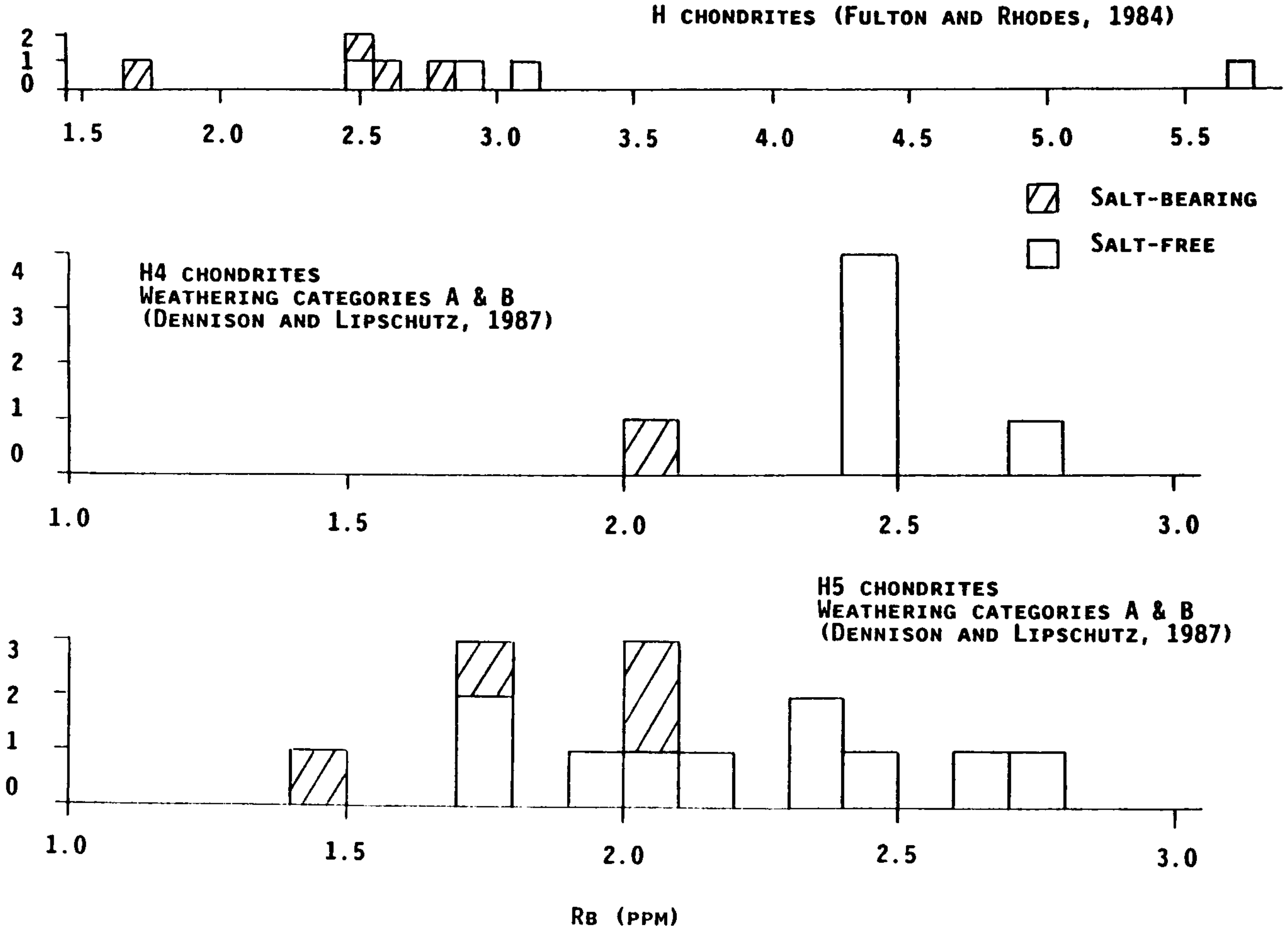
As noted above, the formation of evaporite efflorescences requires either remobilization of elements from within the sample or addition of elements from outside. It is thus evident from the large number of evaporite occurrences on "unweathered" and "moderately weathered" meteorites that, despite assertions to the contrary (e.g., Dennison and Lipschutz, 1987), even meteorites of weathering categories A, A/B, and B may have experienced significant element redistribution and/or contamination as a result of terrestrial exposure.

These findings may require re-evaluation of earlier conclusions regarding the influence of Antarctic meteorite weathering on elemental composition. For example, evaporite-bearing meteorites of weathering categories A and B were included in several previous compositional studies of Antarctic ordinary chondrites (Dennison and Lipschutz, 1987; Fulton and Rhodes, 1984). These previous workers concluded that meteorites of weathering categories A, A/B, and B were "compositionally uncompromised" by weathering. However, all but one of the ostensibly "uncompromised" meteorites which possess salt deposits have interiors which contain below-average abundances of Rb (Figure 1). Similarly, Kallemeyn (1986) noted that two other salt-bearing chondrites show some depletion of Ca. There are no corresponding reports of Mg depletion from the interiors of evaporite-bearing meteorites, but, as noted above, small losses of Mg most likely would go unnoticed due to the large absolute amount of Mg in most stony meteorites.

Just as the interiors of many evaporite-bearing meteorites appear to be depleted in alkali and alkaline-earth elements, exteriors of evaporite-bearing meteorites appear to be enriched in these elements. The exterior of evaporite-bearing ureilite ALHA77257 (Marvin, 1980) is significantly enriched in Rb and Cs (Biswas *et al.*, 1980; Lipschutz, 1982).

Evaporite-bearing meteorites seem to have interiors depleted in Rb (and Ca?). The presence of alkaline-earth salts, and observed enrichment of meteorite surfaces in alkalis, require a source of alkali and alkaline earth elements. External derivation and contamination of exterior surfaces (Biswas *et al.*, 1980; Lipschutz, 1982) is an unsatisfactory hypothesis, because it would not account for below-average Rb contents in the interiors of salt-bearing meteorites. Parsimony favors a meteoritic origin for the alkaline earth elements of the evaporite deposits. Leaching and transfer of alkalis and alkaline earths from meteorite interiors, followed by reprecipitation of those elements as salt deposits on meteorite exteriors, would qualitatively satisfy material balance requirements, and account for all these observations without resorting to external sources for these elements. This explanation is consistent with the inferences of Marvin and Motylewski (1980) and Gooding (1981).

FIGURE 1 - RB IN ANTARCTIC H CHONDRITES



SUMMARY, AND IMPLICATIONS FOR CLASSIFICATION OF METEORITE WEATHERING

The distribution of evaporite deposits varies with meteorite compositional group and degree of rustiness. Proportions of salt-bearing meteorites vary among compositional groups. There is no one-to-one correspondence between evaporites and rust; salts coexist with all degrees of rustiness in all groups of meteorites. Within compositional groups, certain weathering categories contain higher proportions and abundances of evaporite-bearing meteorites, but this association of salt with rust varies from group to group.

Interiors of evaporite-bearing meteorites of weathering categories A, A/B, and B have lower Rb concentrations than interiors of equally rusty salt-free meteorites. This suggests three things: 1) Dennison and Lipschutz (1987) are correct in suggesting that leaching is the principal mode of trace- (and major-?) element mobilization during Antarctic meteorite weathering. However, 2) contrary to Dennison and Lipschutz's (1987) and Fulton and Rhodes' (1984) conclusions, meteorites of weathering categories A and B also exhibit leaching effects. 3) Leaching of elements from the interiors of chondrites of weathering categories A and B is associated with the formation of visible evaporite deposits (Figure 1; Table 1). Thus, evaporite efflorescences serve as a warning that, despite minimal rusting, the sample in question is compositionally compromised.

Given the fact that evaporite occurrence is not directly correlated with rustiness, and that evaporite occurrence indicates element redistribution, it is apparent that the present description of weathering categories is inadequate to describe potentially compromised samples. Until a more objective "weatherometer" (Gooding, 1986b) is developed, I propose an interim solution. A lower-case "e" can be appended to the weathering category entry for all meteorites possessing visible evaporite salts or other efflorescences. This follows the same approach as that used to add information on shock metamorphism to the compositional classification of meteorite groups (Dodd, 1981). Thus, for example, the weathering category entry for ALHA77257 would be "Ae", indicating both the minor degree of rustiness, and the presence of white evaporite deposits. This proposal involves minimal modification of existing data-bases, yet it provides a warning flag to meteorite investigators, informing them of the presence of a potentially significant terrestrial weathering feature which is not included in the present weathering classification.

CONCLUSIONS

The distribution of white evaporitic deposits differs among different meteorite compositional groups and weathering categories in Antarctic meteorites. Salts occur with unusual frequency on carbonaceous chondrites, and are especially common in carbonaceous chondrites of weathering categories A and B. Among achondrites, weathering categories A and A/B show the most examples of salt weathering. Unlike carbonaceous chondrites and achondrites, most salt-bearing ordinary (H and L) chondrites are from rustier meteorites of weathering categories B, and, to a lesser degree, B/C and C. LL chondrites are conspicuous by their complete lack of salt-weathering products.

Almost two-thirds of all evaporite-bearing meteorites belong to weathering categories A, A/B, and B. Where chemical and/or mineralogical data are available, there is a persistent suggestion that evaporite formation is accompanied by elemental redistribution from meteorite interiors. The distribution of evaporite salts militates against the hypothesis that meteorites of weathering categories A, A/B, and B are "compositionally uncompromised" by weathering. Evaporite formation during terrestrial weathering is a significant consideration in geochemical, cosmochemical, and mineralogical studies of Antarctic meteorites.

In order to provide meteorite investigators adequate warning of possible salt-related element redistribution and/or terrestrial contamination, a lower-case "e" can be appended to the weathering category entry for all Antarctic meteorites possessing visible evaporite salts or other efflorescences. This proposal involves minimal modification of existing data-bases, yet it provides a warning flag to meteorite investigators, informing them of the presence of a potentially significant terrestrial weathering feature which is not included in the present weathering classification.

REFERENCES

Biswas, S.; Ngo, H.T.; and Lipschutz, M.E.: Trace element contents of selected Antarctic meteorites, I: Weathering effects and ALHA-77005, A77257, A77278 and A77299. Zeitschr. fur Naturforschung, vol. 35a, 1980, pp. 191-196.

Dennison, J.E.; and Lipschutz, M.E.: Chemical studies of H chondrites. II: Weathering effects in the Victoria Land, Antarctic population and comparison of two Antarctic populations with non-Antarctic falls. Geochim. Comsochim. Acta, vol. 51, 1987, pp. 741-754.

Dodd, R.T.: Meteorites, a Petrologic-Chemical Synthesis. Cambridge University Press, Cambridge, 1981.

Fulton, C.R.; and Rhodes, J.M.: The chemistry and origin of the ordinary chondrites: Implications from refractory-lithophile and siderophile elements. Proc. 14th Lunar Planet. Sci. Conf., Part 2, Jour. Geophys. Res., vol. 89, Supplement, 1984, pp. B543-B558.

Gooding, J.L.: Mineralogical aspects of terrestrial weathering effects in chondrites from Allan Hills, Antarctica. Proc. 12th Lunar Planet. Sci. Conf., 1981, pp. 1105-1122.

Gooding, J.L.: Clay-mineraloid weathering products in Antarctic meteorites. Geochim. Cosmochim. Acta, vol. 50, 1986a, pp. 2215-2223.

Gooding, J.L.: Weathering of stony meteorites in Antarctica. In International Workshop on Antarctic Meteorites, J.O. Annexstad, L. Schultz, and H. Wanke, eds., Lunar and Planetary Institute Tech. Report 86-01, 1986b, pp. 48-54.

Kallemeyn, G.W.: A compositional study of the ungrouped Y793495 carbonaceous chondrite and several CM chondrites from Antarctica. Meteoritics, vol. 21, 1986, p. 410.

Lipschutz, M.E.: Weathering effects in Antarctic meteorites. In Catalog of Meteorites from Victoria Land, Antarctica, 1978-1980, U.B. Marvin and B. Mason, eds., Smithsonian Contrib. Earth Sci., no. 24, 1982, pp. 67-69.

Lipschutz, M.E.; and Cassidy, W.A.: Antarctic meteorites: A progress report. EOS (Trans. Amer. Geophys. Union), vol. 67, 1986, pp. 1339-1341.

Marvin, U.B.: Magnesium carbonate and magnesium sulfate deposits on antarctic meteorites. Antarct. Jour. U.S., vol. 15, 1980, pp. 54-55.

Marvin, U.B.; and Motylewski, K.: Mg-carbonates and-sulfates on Antarctic meteorites. Lunar and Planetary Sci. XI, 1980, pp. 669-670.

Ming, D.W.: Chemical and Crystalline Properties of Minerals in the MgO-CO_2-H_2O System. M.S. Thesis, Colorado State University, 1981.

Ming, D.W.; and Franklin, W.T.: Synthesis and characterization of lansfordite and nesquehonite. Soil Sci. Soc. Amer. Jour., vol. 49, 1985, pp. 1303-1308.

Nishiizumi, K.: Terrestrial and exposure histories of Antarctic meteorites. In International Workshop on Antarctic Meteorites, J.O. Annexstad, L. Schultz, and H. Wanke, eds., Lunar and Planetary Institute Tech. Report 86-01, 1986, pp. 71-73.

Schultz, L.: Terrestrial ages of Antarctic meteorites: Implications for concentration mechanisms. In International Workshop on Antarctic Meteorites, J.O. Annexstad, L. Schultz, and H. Wanke, eds., Lunar and Planetary Institute Tech. Report 86-01, 1986a, pp. 80-82.

Schultz, L.: Allende in Antarctica: Temperatures in Antarctic meteorites. Meteoritics, vol. 21, 1986b, p. 505.

Yabuki, H.; Okada, A.; and Shima, M.: Nesquehonite found on the Yamato 74371 meteorite. Sci. Papers Inst. Phys. Chem. Res., vol. 70, 1976, pp. 22-29.