TOTAL CARBON AND SULFUR ABUNDANCES IN ANTARCTIC METEORITES

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Abstract: Total carbon and sulfur abundances have been measured in five Antarctic meteorites. Two C2 carbonaceous chondrites Yamato-74662 and ALHA 77306 have sulfur abundances (3.490±0.040% and 3.863±0.050% respectively) similar to other C2 chondrites but their carbon abundances (1.514 ±0.050% and 1.324±0.040% respectively) are lower than previously measured C2 chondrites. The decreased carbon abundances may reflect the effects of weathering in cold environments. Carbon and sulfur abundances for one C4 carbonaceous chondrite, one E4 enstatite chondrite and one ureilite are similar to values reported previously for meteorites of the same petrologic grades.

1. Introduction

The Antarctic meteorites offer an opportunity to study meteorites which have been stored in one of the cleanest and most sterile environments on the Earth. For the most part, attempts have been made to keep the meteorites as uncontaminated as possible since their recovery. Recent studies on carbonaceous chondrites have shown that the C2 chondrites can contain non-terrestrial amino acids (KVENVOLDEN *et al.*, 1970; CRONIN *et al.*, 1979). Because of the potential for finding complex organic compounds in the carbonaceous chondrites, the detailed study of their organogenic elements is of great importance.

It is well known that carbon abundances in meteorites which are finds are greater because of contamination and weathering as compared to specimens recovered immediately after their fall (MOORE and LEWIS, 1967). Recently, GIBSON and BOGARD (1978) showed the effects of chemical alterations on the Holbrook ordinary chondrite resulting from terrestrial weathering over a period of 56 years. In a semi-arid region of Arizona the weathering caused the carbon abundances to increase threefold in as short period of time as 19 years. The weathering environment of the Antarctic ice is certainly different from that which the Holbrook chondrite experienced and the study of trace elements such as carbon should be useful in understanding the effects of weathering and potential contamination for the Antarctic meteorites. It has been shown that the terrestrial ages range up to 1.54 my for the Antarctic specimens studies to date (FIREMAN *et al.*, 1979). We have measured total carbon and sulfur abundances for five Antarctic meteorites: two C2 and one C4 carbonaceous chondrites, one E4 enstatite chondrite and one ureilite.

2. Experimental

Total carbon analyses were performed with a LECO IR-12 total carbon analyzer using the general procedures of MOORE and LEWIS (1966) and MOORE *et al.* (1970). Samples ranging in size from 20 to 50 mg were heated to 1600°C using an induction furnace in a flowing stream of purified oxygen and all of the carbon converted to carbon dioxide. An infrared Luft-cell was used to measure the resulting carbon dioxide. Detection limits were 1 μg carbon.

Total sulfur analyses were performed using LECO IR-32 total sulfur analyzer following the procedures of GIBSON and MOORE (1974). Samples ranging in size from 20 to 50 mg were heated to 1600°C using an induction furnace in a flowing stream of purified oxygen and all of the sulfur converted to sulfur dioxide. An infrared Luft-cell was used to measure the sulfur dioxide. Detection limits were 1 μg sulfur.

National Bureau of Standards steels 55e and 33d were used for calibration standards. The samples were chipped and processed under procedures used for lunar samples and Antarctic meteorite processing in the Curatorial Facility of the Johnson Space Center. The only materials which came into contact with the specimens were stainless steel, aluminum and teflon. Sample powders were prepared using a clean tool steel percussion mortar followed by hand grinding in an agate mortar and pestle. Samples were weighed directly into the combustion crucibles to minimize handling. The samples were analyzed in triplicate.

3. Experimental Results

Total carbon abundances for the Antarctic meteorites measured in this study are given in Table 1. The two C2 chondrites (ALHA 77306 and Yamato-74662) have carbon contents of 1.324±0.040 and 1.514±0.050% respectively. The total carbon contents are slightly lower than carbon values reported previously by GIBSON *et al.* (1970) for C2 chondrites. The C4 Yamato-693 carbonaceous chondrite has a carbon abundance of only 0.061±0.004% which is slightly lower than carbon abundances previously reported for C4 chondrites such as Karoonda (GIBSON *et al.*, 1970). Yamato-693 had previously been classified as a C3

Table 1. Total carbon and sulfur abundances.

Specimen	Classification	Carbon abundances		Sulfur abundances	
		Replicate, %	Mean, %	Replicate, %	Mean, %
ALHA77306	C2	1.317, 1.353, 1.299	1.324±0.040	3.810, 3.920, 3.858	3.863±0.050
Yamato-74662	C2	1.472, 1.528, 1.541	1.514±0.050	3.511, 3.402, 3.557	3.490±0.040
Yamato-693	C4	0.062, 0.058, 0.064	0.061±0.004	1.620, 1.610, 1.588	1.604±0.015
Yamato-691	E4	0.438, 0.507, 0.412	0.419±0.020	6.698, 6.514, 6.612	6.606±0.080
Yamato-74659	Ureilite	3.020, 3.003, 3.042	3.022±0.020	0.503, 0.517, 0.533	0.518±0.020

chondrite but the recent work of CLAYTON *et al.* (1979) has clearly shown it to be a C4 chondrite similar to Karoonda. Yamato-691 (E4) contains carbon abundances of 0.419±0.020% which is identical with values reported for other E4 enstatite chondrites (MOORE, 1971). Analysis of the ureilite Yamato-74659 indicated that it contained carbon abundances (3.022±0.020%), similar to values reported by GIBSON (1976) for ureilites.

Total sulfur abundances for the five Antarctic meteorites are given in Table 1. The sulfur abundances for ALHA 77306 and Yamato-74662 are 3.863±0.050% and 3.490±0.040% respectively. The sulfur abundances are similar to values previously found for C2 chondrites. The sulfur content of Yamato-693 (C4 chondrite) is similar to values noted for other C4 meteorites. The sulfur abundances for the enstatite chondrite Yamato-691 (6.606±0.080%) is approximately 10 percent greater than previously reported sulfur abundances for E4 chondrites (MOORE, 1971). Analysis of the ureilite Yamato-74659 showed sulfur abundances identical with previously studied ureilites (GIBSON, 1976).

4. Discussion of Results and Conclusions

A comparison of the total carbon and sulfur abundances measured for the Antarctic meteorites with previously measured meteorites is given in Table 2. Comparison of the total carbon abundances for the two Antarctic C2 chondrites measured in this study with previously studied C2 chondrites (Fig. 1) shows that the Antarctic samples contain lower carbon abundances than previously measured samples of the same classification. Comparison of the sulfur abundances for the two Antarctic C2 chondrites shows similar sulfur values as seen in previous work.

It is well known that C2 chondrites contain a variety of low temperature mineral phases (Summarized in NAGY, 1975; MCSWEEN, 1979) which might be susceptible to weathering during the freeze-thaw cycles which would exist on the Antarctic ice sheets from which the specimens were removed. It seems very likely that the dark brown to black exteriors of the carbonaceous chondrites would absorb large amounts of heat from the sunlight, resulting in melting of

Table 2. Comparison of carbon and sulfur abundances with other meteorites.

Meteorite	Classification	(% Carbon and sulfur)			
		Carbon		Sulfur	
		Range	Mean	Range	Mean
ALHA77306	C2	1.299-1.353	1.324	3.810-3.920	3.863
Yamato-74662	C2	1.472-1.541	1.514	3.402-3.557	3.490
Previous studies	C2	1.80 -2.57 (6)	2.11	2.80 -5.44 (7)	3.36
Yamato-693	C4	0.058-0.064	0.061	1.588-1.620	1.604
Previous	C4	0.07 -0.20 (3)	0.14	1.31 -2.14 (3)	1.86
Yamato-691	E4	0.407-0.438	0.419	6.514-6.698	6.606
Previous	E4	0.36 -0.56 (3)	0.39	5.65 -6.12 (3)	5.85
Yamato-74659	Ureilite	3.003-3.042	3.022	0.503-0.533	0.518
Previous	Ureilites	2.07 -4.10 (4)	2.49	0.179-0.58 (4)	0.294

Numbers in parentheses are the number of samples previously analyzed and do not include any Antarctic specimens.

Data Sources: GIBSON (1976), GIBSON *et al.* (1971), GIBSON and MOORE (1974), MOORE (1971), GIBSON (unpublished data).

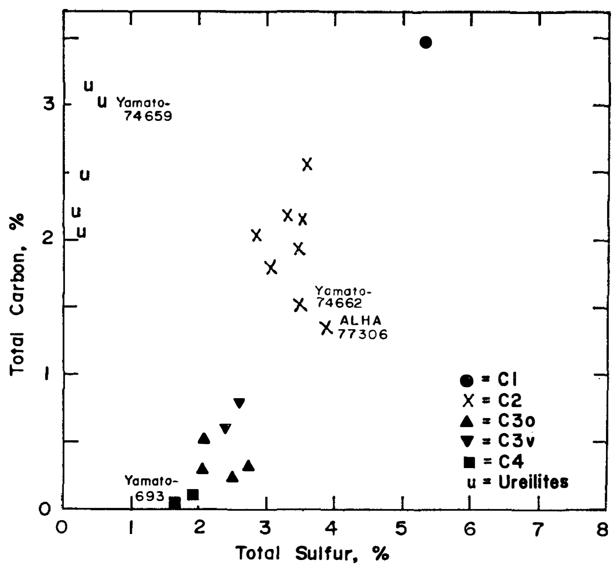

Fig. 1. Total carbon and sulfur abundances in carbonaceous chondrites and ureilites. Note the carbon depletion in the C2 carbonaceous chondrites from Antarctica as compared to previously measured carbon abundances for meteorites of the same petrologic grade. Data for non-Antarctic meteorites are from: GIBSON (1976), GIBSON et al. (1971), GIBSON and MOORE (1974), MOORE (1971) and GIBSON (unpublished).

some of the ice within the cracks and fractures in the specimens. In fact, most of the low grade chondrites returned from Antarctica have numerous cracks and fractures which would assist the thermal degradation of individual specimens. Loss of the water-ice from the sample might result in the selective removal of some low-temperature mineral phases such as carbonates and hydrates. In fact, MASON (personal communication, 1979) noted that mineral nesquihonite ($MgCO_3 \cdot 3H_2O$) has been identified as a white evaporite deposit on the surfaces of some of the Yamato meteorites. Removal of this secondary alteration product would be relatively easy in the Antarctic environment. This removal from the specimens could account for a portion of the carbon depletion in the carbonaceous chondrites collected in Antarctica.

In order to evaluate whether the Antarctic weathering processes have selectively removed the volatile elements, one must remember that if leaching were an important process, the soluble sulfates (which C2 meteorites possess (NAGY, 1975; MCSWEEN, 1979)) would have been lost from the samples. The sulfur abundances observed for the C2 samples are almost identical to previously measured values. Thus, the normal sulfur abundance indicates that this has not happened. Similarly, the water-soluble carbon compounds should have been among the first phases to go in the leaching process if it occurred. In fact, CRONIN (written communication, 1979) notes that only 6–7% of the total carbon of C2 chondrites is extractable even under such stringent conditions as boiling a crushed specimen for 24 hours. In addition, CRONIN *et al.* (1979) find amino acid abundances only partially depleted in the Antarctic specimens which they have studied. The finding of extractable amino acids in the Antarctic meteorites also mitigates against a thoroughgoing water leaching. Terrestrial solution geochemistry studies have shown that the solubility of carbonate ions in water solutions increases with decreasing temperatures (BERNER, 1971). Such increases in carbonate ion solubilities would contribute to the carbon depletion only slightly because of the low abundance of carbonates present in C2 chondrites. Most of the carbon in C2 meteorites is present typically as insoluble residue which should be more resistant to leaching processes than the sulfur-bearing phases. Yet we observe carbon abundances which appear to be depleted and sulfur abundances "normal" in the Antarctic C2 chondrites. It is obvious that our knowledge of meteorite light element geochemistry is not fully understood for specimens which have undergone weathering in cold environments.

The carbon abundances measured for the C4 carbonaceous chondrite may be lower than previously measured values for C4 chondrites, but the sampling of C4 is too small to know if a real depletion has occurred. It is difficult to know if the carbon depletion in Yamato-693 is accounted for by selective removal of low-temperature minerals. The C4 carbonaceous chondrites do not typically have low-temperature minerals present within their groundmass (NAGY, 1975; VAN SCHMUS and HAYES, 1974). The ureilite studies (Yamato-74659) contained the greatest amount of carbon of any Antarctic meteorite studied. Carbon is found in the ureilites in a variety of forms. Most of the carbon is present as graphite or diamond with minor traces of lonsdaleite. No low-temperature carbon-bearing phases such as hydrocarbons or carbonates are present in ureilites (GIBSON, 1976). Because of the form of carbon present in ureilites, the weathering environment of Antarctica probably did not selectively remove carbon from the ureilites as apparently occurred with the C2 carbonaceous chondrites.

If additional studies of the inorganic chemical, mineralogy-petrology, light element and organic properties of the carbonaceous chondrites recovered from Antarctica indicate elemental depletions and/or enrichments, selected weathering experiments under cold environments will be required before the carbon and sulfur cycles are fully understood for the Antarctic specimens.

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