



## The preservation state of organic matter in meteorites from Antarctica

M. A. SEPTON,<sup>1\*</sup> P. A. BLAND,<sup>2</sup> C. T. PILLINGER,<sup>1</sup> and I. GILMOUR<sup>1</sup>

<sup>1</sup>Planetary and Space Sciences Research Institute, Open University, Milton Keynes, Buckinghamshire, MK7 6AA, UK

<sup>2</sup>Department of Earth Science and Engineering, Royal School of Mines, Exhibition Road, Imperial College London, South Kensington Campus, London SW7 2AZ, UK

\*Corresponding author. E-mail: [m.a.septon@open.ac.uk](mailto:m.a.septon@open.ac.uk)

(Received 30 January 2003; revision accepted 24 March 2004)

---

**Abstract**—The recovery of large numbers of meteorites from Antarctica has dramatically increased the amount of extraterrestrial material available for laboratory studies of solar system origin and evolution. Yet, the great age of Antarctic meteorites raises the concern that significant amounts of terrestrial weathering has corrupted their pre-terrestrial record. Organic matter found in carbonaceous chondrites is one of the components most susceptible to alteration by terrestrial processes. To assess the effects of Antarctic weathering on both non-Antarctic and Antarctic chondritic organic matter, a number of CM chondrites have been analyzed. Mössbauer spectroscopy has been used to ascertain pre-terrestrial and terrestrial oxidation levels, while pyrolysis-gas chromatography-mass spectrometry was used to determine the constitution of any organic matter present. Increased oxidation levels for iron bearing minerals within the non-Antarctic chondrites are likely to be a response to increased amounts of parent body aqueous alteration. Parent body processing also appears to remove ether bonds from organic material and alkyl side chains from its constituent units. The iron in Antarctic chondrites is generally more oxidized than that in their non-Antarctic counterparts, reflecting terrestrial weathering. Antarctic weathering of chondritic organic matter appears to proceed in a similar way to parent body aqueous alteration and simply enhances the organic responses observed in the non-Antarctic data set. Degradation of the record of preterrestrial processes in Antarctic chondrites should be taken into account when interpreting data from these meteorites.

---

### INTRODUCTION

Meteorites represent fragments of rock, broken from outcrops in the solar system. The collected meteorite falls are overwhelmingly dominated by fragments of asteroids (Wetherill and Chapman 1988), and those available for study amount to several hundred thousand kilograms. However, the total mass of the asteroid belt is over  $3.5 \times 10^{21}$  kg (Krasinsky et al. 2003), indicating that this astronomical study area may not be satisfactorily represented in the curated meteorite fall population. This situation is regrettable, as the asteroids are ancient remnants of materials used to construct the planets 4.56 billion years ago and provide valuable information about the formation and early evolution of the solar system. No comparable record is available on the terrestrial planets due to the extensive geological processing to which their constituent materials have been subjected.

Our access to meteorite samples of asteroids, in addition to a small portion from the Moon and Mars, was increased in

1969 when it was recognized that certain areas of the Antarctic ice sheet act as stranding planes, concentrating and exposing meteorites that have fallen on Antarctica over tens of thousands of years (Shima et al. 1973). So significant a step forward was this discovery, that, to date, there have been more meteorite finds recovered from Antarctica than the rest of the world combined.

However, the Antarctic meteorites do not represent a simple extension of the fall samples, as the two populations appear to be distinct in a number of ways. Antarctic meteorites have greater terrestrial ages, a smaller average size, and specific weathering products resulting from their unique storage conditions. The Antarctic meteorites spend their time buried in ice subjected to conserving but nonetheless extreme conditions (Koeberl and Cassidy 1991). Once exposed, the meteorites are subjected to a cold, dry climate (Koeberl and Cassidy 1991) in which liquid water is occasionally in contact with the meteorite (Gooding 1986; Schultz 1986). Due to the combination of long terrestrial residence times and harsh storage conditions, very specific

weathering processes associated with the Antarctic environment become significant for these meteorites.

The effects of weathering are, presumably, the most severe for the more labile materials such as organic matter. The organic matter in meteorites represents a valuable source of information on the early solar system (e.g., Sephton 2002). Organic matter is most abundant in the primitive carbonaceous chondrites, which contain up to 5% organic matter by weight. Over 75% is present as a complex solvent-insoluble macromolecular material, while the remainder is in the form of simpler solvent-soluble compounds. Meteoritic organic matter is, at present, our only available record of natural pre-biotic chemical evolution and appears to contain some exceedingly ancient matter that is only partially transformed from presolar starting materials. Hence, it is important to establish whether the organic matter in Antarctic meteorites is a pristine uncorrupted record of the early solar system and the interstellar cloud from which it formed or whether this information has been obscured by terrestrial alteration.

Terrestrial weathering of meteorite samples is usually associated with the oxidation of their mineral constituents. Mössbauer spectroscopy can successfully quantify the oxidation state of iron-bearing minerals and, therefore, allows samples to be placed on a scale of relative alteration. Any alteration of the overall organic constitution of small meteorite samples can be determined by using a thermal-extraction/pyrolysis procedure. The sample is introduced into an inert atmosphere and quickly raised to a temperature at which solvent-soluble compounds are evaporated and solvent-insoluble materials thermally-fragmented. The liberated compounds (the pyrolyzate) are then characterized by gas chromatography-mass spectrometry (GCMS).

In this paper, we evaluate the state of meteoritic organic matter in six carbonaceous chondrites from Antarctica and compare them with those from non-Antarctic falls of the same class. The results have implications for the use of Antarctic meteorites as an information source for the earliest phases of the solar system's history.

## EXPERIMENTAL

### Samples

Six Antarctic and six non-Antarctic samples (Table 1) were crushed in an agate pestle and mortar. 0.2 g was used for Mössbauer spectroscopy, and several mg were used for pyrolysis-GC-MS. The available amounts of Elephant Moraine (EET) 83226, EET 83250, and Yamato (Y-) 82042 were large enough to allow analysis by pyrolysis-GC-MS but not Mössbauer spectroscopy; the remaining samples were subjected to both analytical techniques. The samples were not pre-extracted with solvents and, hence, the pyrolysis-GC-MS responses represent the complete organic inventory of the meteorite.

Table 1. Mössbauer spectroscopy data of non-Antarctic falls and Antarctic finds, indicating the percentage of spectra reflecting oxidized iron-bearing minerals.

Sample	Oxidation (% Fe <sup>3+</sup> )
Non-Antarctic	
Erakot	59.9
Essebi	80.3
Kivesvaara	62.7
Mighei	56.2
Murray	71.1
Nogoya	60.4
Antarctic	
Belgica 7904	90.1
ALH 82120	88.8
EET 83226	–
EET 83250	–
Y-82042	–
Y-91824	67.3

### Mössbauer Spectroscopy

<sup>57</sup>Fe Mössbauer spectra were recorded at 298 K with a microprocessor-controlled Mössbauer spectrometer using a <sup>57</sup>Co/Rh source. Drive velocity was calibrated with the same source and a metallic iron foil. The Mössbauer spectra were fitted with a constrained non-linear least squares fitting program of Lorentzian functions. Spectra were generally fitted to five different absorptions: a paramagnetic Fe<sup>3+</sup> doublet (most likely arising from Fe<sup>3+</sup> in clay minerals), two Fe<sup>2+</sup> doublets (associated with olivine and pyroxene), and two Fe<sup>3+</sup> sextets (most likely arising from magnetite). Mössbauer spectroscopy data are presented as the percentage areas of spectra occupied by absorption characteristic of Fe<sup>3+</sup> relative to that for total Fe. A detailed explanation of how Mössbauer spectroscopy can be used to assess levels of oxidation can be found in Bland et al. (1998).

### Pyrolysis-Gas Chromatography-Mass Spectrometry

Samples were introduced as dry pellets (typically, ~1 mg) into a quartz-lined pyrojector (S. G. E., Ltd.) held at 500 °C. Separation of the pyrolysis products was performed using a Hewlett Packard 5890 gas chromatograph (GC) fitted with a Ultra 2 capillary column (50 m × 0.2 mm × 0.32 mm). During a run, the GC oven was held at 50 °C for 1 min before a ramp was employed of 10 °C min<sup>-1</sup> to 100 °C and 5 °C min<sup>-1</sup> to 300 °C, where it was held for 14 min. Compound detection and identification was performed by GC-MS using a Hewlett Packard 5890 gas chromatograph interfaced with a 5971 mass selective detector. Peak identification was based on retention order and mass spectra comparisons with the literature. In this paper, GC-MS data is presented as either total ion chromatograms (TICs), where the responses of all of the flash pyrolysis products are displayed, and summed ion

chromatograms (SICs), where a small number of ions characteristic of certain compounds are exhibited. To avoid problems of peak coelution, integration of peak areas was performed on SICs. It should be noted that, depending on chemical structure, different compounds may have strongly different response factors in GC-MS, hence, variations in peak areas between samples are indicators of relative, rather than absolute, quantitative change.

## RESULTS AND DISCUSSION

### Expected Organic Features of Parent Body Processing and Antarctic Weathering

The aim of the current study is to assess whether the extraterrestrial organic matter structure reflects either levels of secondary alteration on the meteorite parent body or Antarctic weathering following the meteorite's fall to Earth. One characteristic of parent body aqueous alteration of meteoritic organic matter appears to be a reduction in the phenol content of the pyrolyzates of more altered samples (Sephton et al. 2000). Furthermore, common effects of weathering on terrestrial organic matter are well-constrained and provide clues as to what may be expected for extraterrestrial materials. A common response of terrestrial organic matter to weathering is a reduction in the number of aliphatic structures relative to aromatic structures (Fredricks et al. 1983; Martinez and Escobar 1995; Tekely et al. 1987; Petsch et al. 2001). If present, these types of changes in organic constitution due to parent body processing and Antarctic weathering should be readily detectable by pyrolysis-GC-MS.

### The Organic Constitution of Non-Antarctic and Antarctic CM Meteorites

Figure 1 shows the total ion chromatogram (TIC) and summed ion chromatograms (SIC) of the pyrolysis products from the Mighei meteorite. The Mighei TIC (Fig. 1a) reveals that significant amounts of volatiles co-elute early in the run, but at longer retention times, a number of discrete peaks are present. The major components consist of aromatic hydrocarbons, alkylaromatic hydrocarbons, and aromatic compounds with oxygen and sulfur-containing functional groups. No significant contribution from long chain aliphatic components are evident. Some volatilized free compounds will be represented in the TIC, but the majority of the pyrolysis products will be derived from macromolecular material, which makes up over 90% of the organic matter in CM meteorites (Sephton 2002). The pyrolysis products in Fig. 1a are consistent with theories of CM macromolecular material structure, which point to condensed aromatic, heteroatomic, and hydroaromatic ring systems with various functional groups attached (Sephton 2002, and references therein). The SICs highlight particular organic units and their

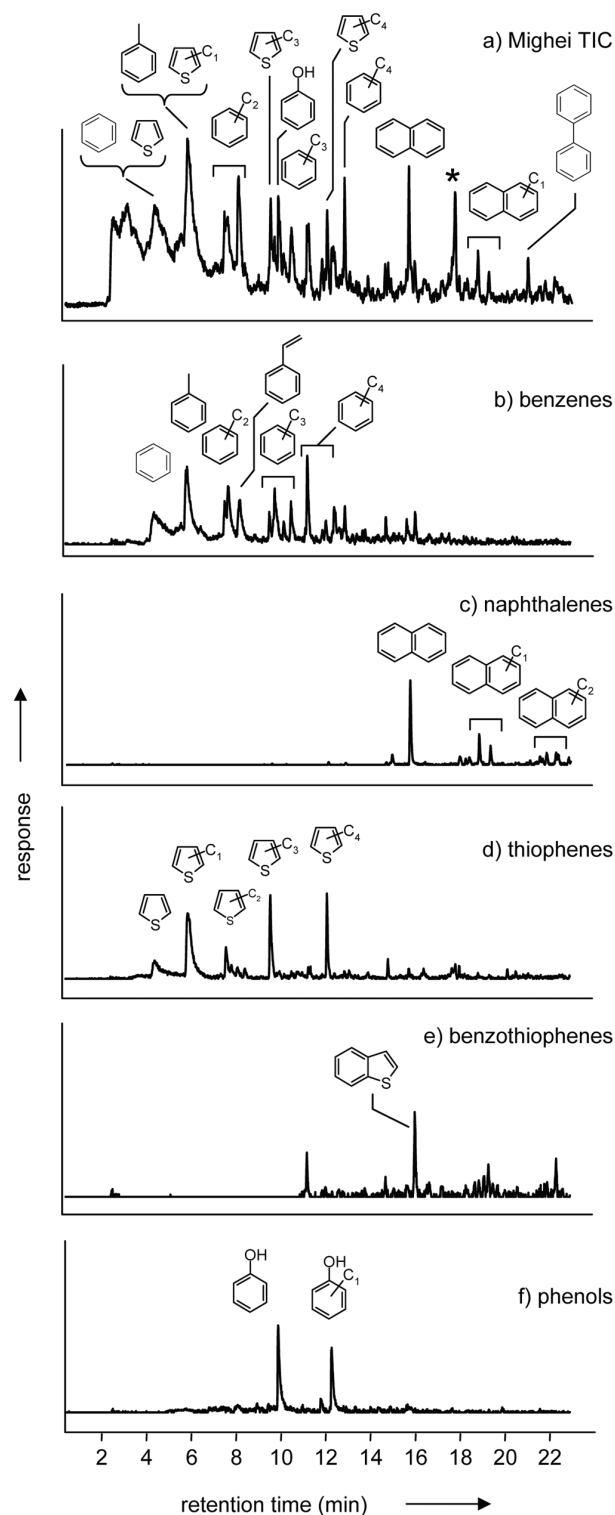


Fig. 1. GC-MS responses of the pyrolysis products from Mighei: a) TIC; b) SIC representing alkylbenzenes ( $m/z$  78, 91, 92, 115, 116, 119, 120, 133, 134); c) SIC representing alkylnaphthalenes ( $m/z$  128, 141, 142, 155, 156); d) SIC representing alkythiophenes ( $m/z$  84, 97, 98, 111, 112, 125, 126, 139, 140); e) SIC representing benzothiophenes ( $m/z$  134, 147, 148, 161, 162); f) SIC representing alkyphenols ( $m/z$  94, 107, 108, 121, 122). \* = contaminant.

alkyl homologues. Fig. 1b indicates that benzenes have alkyl chains that extend up to four carbon atoms long. There are up to two carbon atoms in alkyl chains for the naphthalenes (Fig. 1c), up to four for the thiophenes (Fig. 1d), none for the benzothiophenes (Fig. 1e), and one for the phenols (Fig. 1f). Other compounds such as the nitrogen-containing benzonitrile are also present in SICs but are shielded by co-eluting compounds in the TIC.

The organic constitution characterized for the Mighei meteorite represents a useful reference to which non-Antarctic and Antarctic samples can be compared. Fig. 2 shows the TIC of Mighei compared to those of five other non-Antarctic CM chondrites (Essebi, Kivesvarra, Erakot, Murray, and Nogoya). Each pyrolyzate appears to consist of the same principle organic units, namely volatiles, benzenes, naphthalenes, thiophenes, benzothiophenes, and phenols. Fig. 3 shows the pyrolysis-GC-MS responses for six Antarctic meteorites. As with the non-Antarctic CMs, significant amounts of volatiles co-elute early in the pyrolysis-GC-MS run, and at longer retention times, a number of discrete peaks correspond to simple mono- and diaromatic compounds with aliphatic side chains. A number of oxygen-, sulfur-, and nitrogen-containing compounds are also present.

### Mössbauer Spectroscopy of Non-Antarctic and Antarctic CM Meteorites

For non-Antarctic samples, it is likely that preterrestrial aqueous alteration would have caused an increase in the oxidation state of iron in the samples, and hence, the relative abundance of ferric mineral phases is an effective alteration index alongside which the organic features can be compared. Table 1 lists the amount of iron-bearing minerals that are present in the more oxidized ( $\text{Fe}^{3+}$ ) state for the meteorites analyzed. Iron oxidation, and therefore, inferred preterrestrial alteration, levels for the non-Antarctic CMs increase in the order of Mighei < Erakot < Nogoya < Kivesvaara < Murray < Essebi. Hence, the CM chondrites have experienced different levels of parent body aqueous alteration, and the extent of the alteration can be assessed using Mössbauer spectroscopy.

For Antarctic samples, weathering while in and on the ice is another means by which the oxidation state of iron can be changed. Overall, iron in Belgica 7904 and ALH 82120 is significantly more oxidized than that in Y-91824. Although only three of the six Antarctic meteorites were present in large enough sample amounts to be analyzed by Mössbauer spectroscopy, the results suggest that the level of oxidation displayed by the non-Antarctic samples is generally lower than the available Antarctic set. Therefore, to some extent, the overall oxidation level of iron-bearing mineralogies can be used to discriminate between the non-Antarctic and Antarctic meteorite populations.

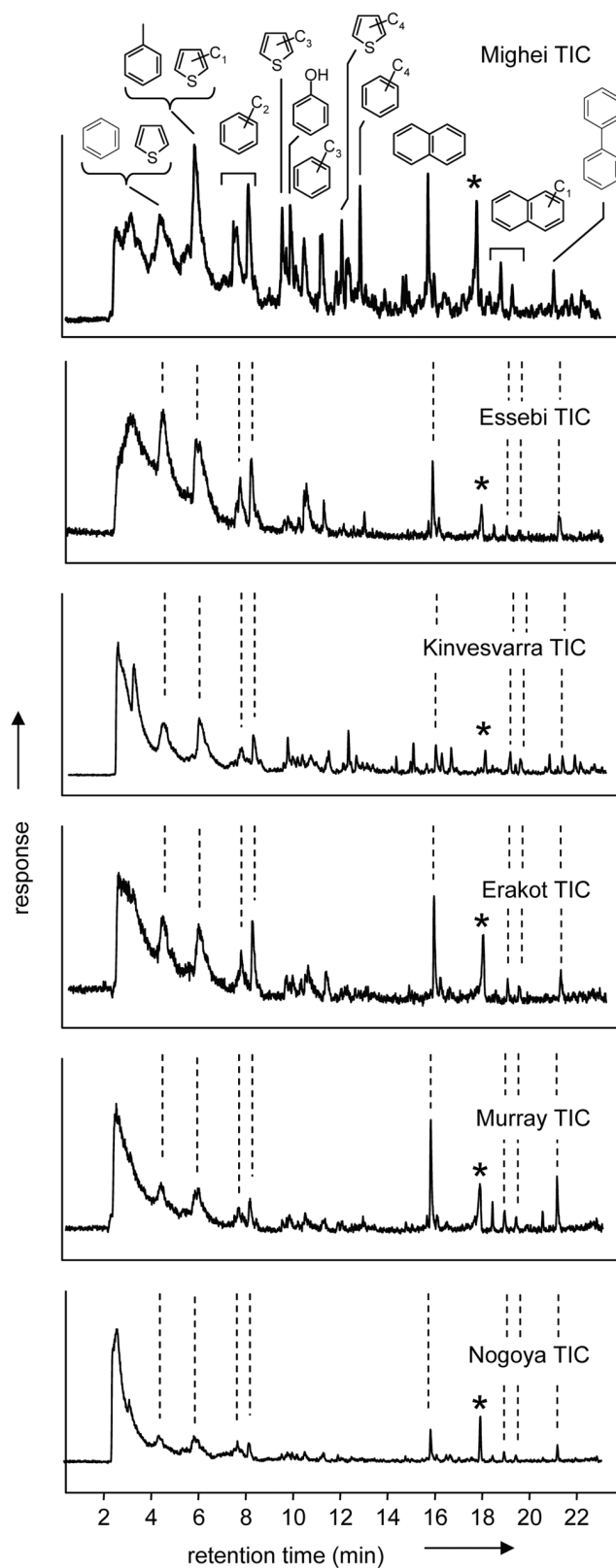


Fig. 2. GC-MS responses (TIC) of the pyrolysis products from the non-Antarctic CM chondrites Mighei, Essebi, Kivesvarra, Erakot, Murray, and Nogoya. \* = contaminant.

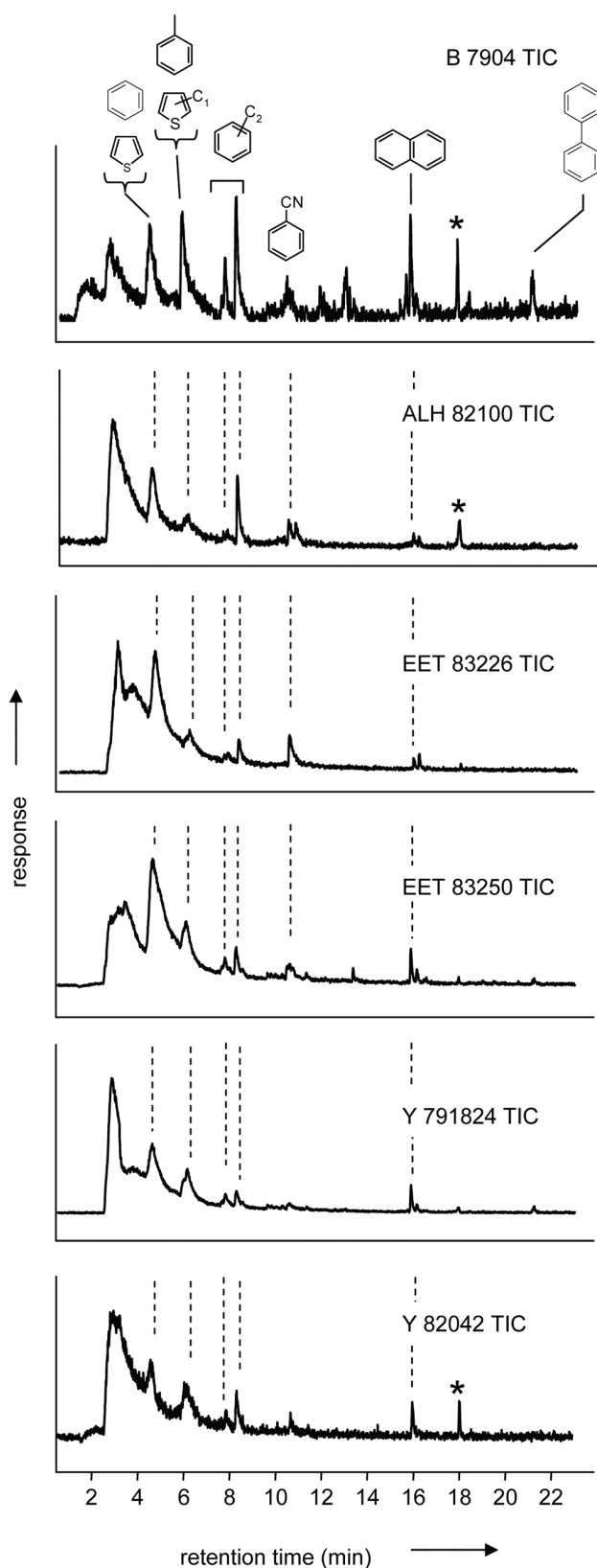


Fig. 3. GC-MS responses (TIC) of the pyrolysis products from the Antarctic CM chondrites B 7904, ALH 82100, EET 83226, EET 83250, Y-791824, and Y-82042. \* = contaminant.

### Pre-Terrestrial Alteration Effects in Non-Antarctic CM Meteorites

Figure 4 is a ternary diagram that shows variations in ratios of GC-MS responses for compound classes between the non-Antarctic CM pyrolyzates. This diagram divides the major resolvable organic entities identified in the pyrolyzates (Fig. 2) into three groups: aromatic hydrocarbons, thiophenes, and phenols. Integration of peak areas was performed on SICs to avoid problems of co-eluting peaks with different chemical structures. Because these groups represent both non-heteroatomic (aromatic hydrocarbon) and heteroatomic structures (thiophenes and phenols), any variation in the amount of heteroatom-containing organic matter resulting from parent body processing can be assessed. Apparently, the relative abundance of the principle organic units is approximately constant within the CM chondrites. However, by comparing Fig. 4 and Table 1 in detail, it becomes clear that some of the least altered CM chondrites are those that still produce phenols on pyrolysis. This observation is consistent with previous pyrolysis-based work on extraterrestrial

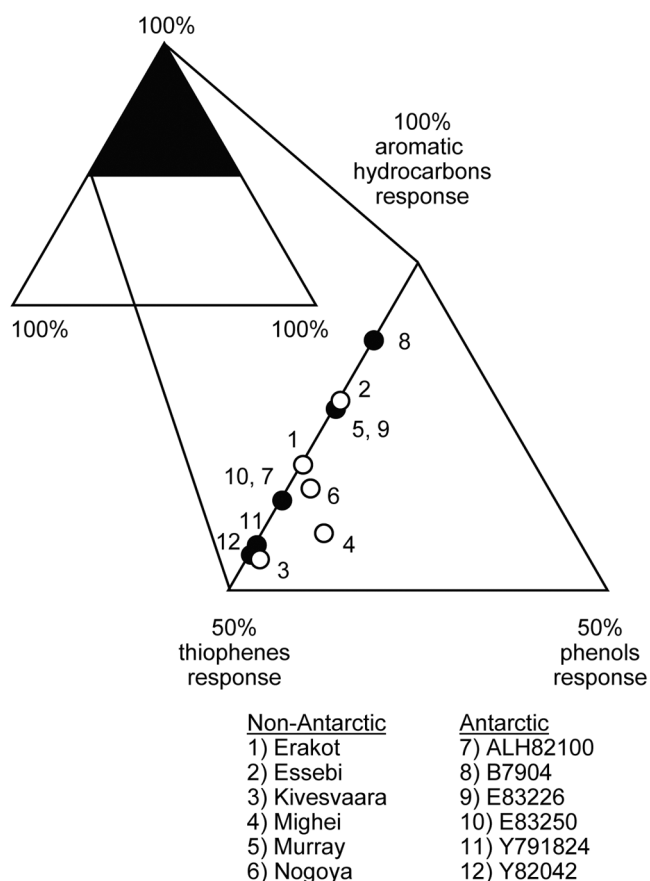


Fig. 4. Ternary diagram that illustrates variations in the ratios of GC-MS responses for aromatic hydrocarbons, thiophenes, and phenols between the non-Antarctic (open circle) and Antarctic (closed circle) CM chondrite pyrolyzates. The molecules that constitute the compound classes are identified in Figs. 1, 2, and 3.

organic matter. Pyrolytically-liberated phenols appear to be the products of ether bond cleavage, and more extensively altered meteoritic organic matter is depleted in the macromolecular phenol precursors (Sephton et al. 2000).

Close inspection of the pyrolyzates reveals that they also differ in the degree of alkylation of the main organic units (Table 2). It is possible that the variation in structural diversity is reflecting the degree of secondary processing that the organic matter has experienced on the meteorite parent body. Oxidation reactions occurring during aqueous process would have selectively removed alkyl side chains in free and macromolecular organic matter. In summary, the more altered samples liberate fewer phenols during pyrolysis and exhibit lesser amounts of alkylation of the main organic units.

### Antarctic Weathering Effects in CM Meteorites

Scrutiny of the non-Antarctic and Antarctic data sets reveals that both the pyrolysis-GC-MS and Mössbauer responses of Nogoya and Y-82042 are similar, illustrating the potential harmony between organic and inorganic records of alteration. It should also be noted that the relatively unweathered Y-82042 is a comparatively pristine Antarctic sample worthy of further investigation. Fig. 3 shows that the Antarctic pyrolyzates are completely devoid of phenols. It appears that Antarctic weathering removes phenol precursors from the organic macromolecular material. Hence, Antarctic weathering has extended the natural pre-terrestrial alteration process that operated in the non-Antarctic CMs. Another feature that appears to distinguish the non-Antarctic and Antarctic samples is the dramatic reduction in amounts of alkylation of the main organic units in the Antarctic samples (Table 2). Similar effects are apparent in toluene/benzene ratios from the pyrolysis-GC-MS data, which must reflect some differences in chemical structure between macromolecular materials (Fig. 5). Benzene consists of a single aromatic ring, while toluene is the same compound

with a methyl group attached. Preferential oxidation of the methyl group of toluene would transform this compound into benzene. This weathering process would explain the relative increase in benzene for the Antarctic CMs. The ultimate products of methyl group or alkyl side chain oxidation, carbon dioxide and water, would be removed from the meteorites easily, leading to a loss of carbon.

Hence, Antarctic weathering of the organic matter in CM chondrites continues structural changes brought about by parent body aqueous alteration (loss of phenol precursors and reduction in side chains), and these effects are readily detectable by pyrolysis-GC-MS.

### Implications for the Antarctic Chondrite Record of Preterrestrial Processes

The majority of Antarctic meteorites have terrestrial ages averaging around 100,000 years (Nishiizumi et al. 1989), while non-Antarctic falls represent the last two centuries. In addition to providing a better understanding of the nature of the various meteorite parent bodies in the solar system, the old terrestrial age of Antarctic meteorites allows us to study how meteorite populations may have changed over time. Yet, the long terrestrial age of Antarctic meteorites presents the problem that terrestrial weathering may have corrupted parts of the preterrestrial record. Over the great lengths of time spent in the ice, even subtle processes acting on meteorites can produce substantial effects (Koeberl and Cassidy 1991).

The features that reflect parent body aqueous alteration in non-Antarctic CMs are enhanced in the Antarctic counterparts, suggesting that liquid water may be an agent of change in the Antarctic sample set. Although stored in a frozen environment, the impact of solar energy on dark meteorites warms the surroundings enough to produce small amounts of melt water. Insolation heating of meteorites in Antarctica can raise the temperature of meteorite interiors

Table 2. Compounds and their extent of alkylation in pyrolyzates of whole rock CM meteorites.

Sample	Alkylbenzenes	Naphthalenes	Thiophenes	Benzothiophenes	Phenols
Non-Antarctic					
Erakot	C <sub>0</sub> -C <sub>4</sub>	C <sub>0</sub> -C <sub>2</sub>	C <sub>0</sub> -C <sub>5</sub>	C <sub>0</sub>	n.d. <sup>a</sup>
Essebi	C <sub>0</sub> -C <sub>4</sub>	C <sub>0</sub> -C <sub>1</sub>	C <sub>0</sub> -C <sub>1</sub>	C <sub>0</sub>	n.d.
Kivesvaara	C <sub>0</sub> -C <sub>4</sub>	C <sub>0</sub> -C <sub>2</sub>	C <sub>0</sub> -C <sub>5</sub>	C <sub>0</sub>	C <sub>0</sub>
Mighei	C <sub>0</sub> -C <sub>4</sub>	C <sub>0</sub> -C <sub>2</sub>	C <sub>0</sub> -C <sub>5</sub>	C <sub>0</sub>	C <sub>0</sub> -C <sub>1</sub>
Murray	C <sub>0</sub> -C <sub>4</sub>	C <sub>0</sub> -C <sub>1</sub>	C <sub>0</sub> -C <sub>2</sub>	C <sub>0</sub>	n.d.
Nogoya	C <sub>0</sub> -C <sub>4</sub>	C <sub>0</sub> -C <sub>1</sub>	C <sub>0</sub> -C <sub>4</sub>	C <sub>0</sub>	C <sub>0</sub>
Antarctic					
Belgica 7904	C <sub>0</sub> -C <sub>2</sub>	C <sub>0</sub>	C <sub>0</sub> -C <sub>2</sub>	C <sub>0</sub>	n.d.
ALH 82100	C <sub>0</sub> -C <sub>2</sub>	C <sub>0</sub>	C <sub>0</sub> -C <sub>1</sub>	C <sub>0</sub>	n.d.
EET 83226	C <sub>0</sub> -C <sub>2</sub>	C <sub>0</sub>	C <sub>0</sub> -C <sub>1</sub>	C <sub>0</sub>	n.d.
EET 83250	C <sub>0</sub> -C <sub>3</sub>	C <sub>0</sub>	C <sub>0</sub> -C <sub>2</sub>	C <sub>0</sub>	n.d.
Y-791824	C <sub>0</sub> -C <sub>3</sub>	C <sub>0</sub>	C <sub>0</sub> -C <sub>2</sub>	C <sub>0</sub>	n.d.
Y-82042	C <sub>0</sub> -C <sub>2</sub>	C <sub>0</sub>	C <sub>0</sub> -C <sub>1</sub>	C <sub>0</sub>	n.d.

<sup>a</sup>n.d. = not detected.

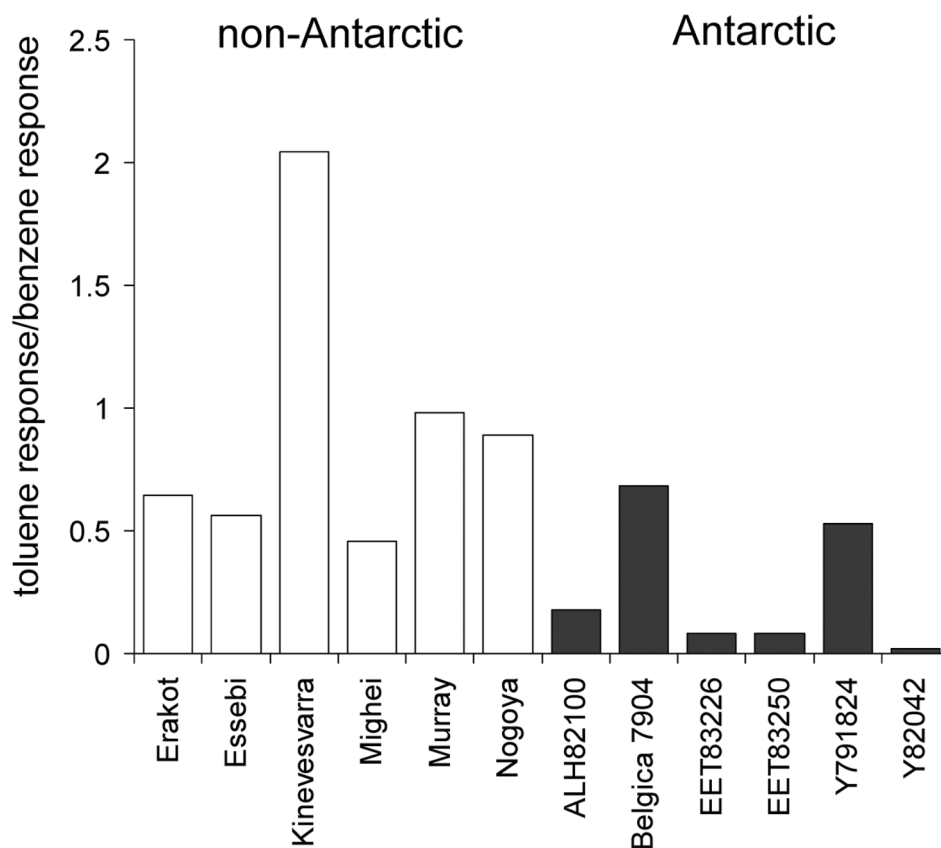


Fig. 5. Histograms illustrating the variation in the ratio of GC-MS responses for toluene/benzene in the pyrolyzates of non-Antarctic and Antarctic CM chondrites.

above the melting point of water to depths of several centimeters (Velbel et al. 1991). The efficiency of meltwater production by insolation was proven experimentally by equipping a sample of the Allende (CV3) meteorite with a temperature sensor and placing it on the Antarctic ice sheet (Schultz 1990). It was discovered that temperatures within Antarctic meteorites could reach up to +5 °C on sunny, windless days. Therefore, it is likely that, during storage in the Antarctic ice, opportunities existed for aqueous processes to alter the organic constitution of the samples.

When considering how Antarctic weathering processes involving liquid water affect organic matter in ways comparable to aqueous alteration on the meteorite parent body, it is interesting to reflect on similar interpretations for the inorganic record in chondritic meteorites. Cronstedtite is an iron-rich phyllosilicate mineral that is rare on the Earth yet common both in CM meteorites subjected to aqueous alteration on the parent body and in chondritic meteorites that have experienced Antarctic weathering (Lee and Bland 2004). Thus, there may be many similarities between the chemical microenvironments occurring within chondrites undergoing weathering on the Antarctic ice at the present day and conditions during aqueous alteration on carbonaceous chondrite parent bodies 4.56 billion years ago.

In summary, the degradation of the organic and inorganic records of preterrestrial processes in Antarctic chondrites should be taken into account when interpreting data from these meteorites. Although subtle, the effects are significant and appear to mimic genuine preterrestrial processes, particularly parent body aqueous alteration.

## CONCLUSIONS

1. The inorganic and organic constituents of CM chondrites exhibit responses to both parent body aqueous alteration and terrestrial weathering.
2. Increased oxidation levels for iron-bearing minerals within the non-Antarctic chondrites are likely to be a response to increased amounts of parent body aqueous alteration. Using the Mössbauer responses as a guide, it appears that parent body processing removes ether bonds from organic material and alkyl side chains from its constituent units.
3. Mössbauer spectroscopy indicates that the level of alteration (oxidation) displayed by iron-bearing minerals in the Antarctic samples is generally higher than the non-Antarctic sample set. Organic responses to Antarctic weathering proceed in a similar way to parent body

aqueous alteration, enhancing the organic responses observed in the non-Antarctic data set.

4. The inorganic and organic records in Antarctic meteorites are not pristine, uncorrupted records of preterrestrial processes. Their contents have been altered in a subtle way that mimics genuine preterrestrial events.

*Acknowledgments*—We would like to thank Sylvie Derenne and one anonymous reviewer for their constructive comments. This work was supported by the Particle Physics and Astronomy Research Council and the Royal Society.

*Editorial Handling*—Dr. Scott Sandford

## REFERENCES

- Bland P. A., Sexton A. S., Jull A. J. T., Bevan A. W. R., Berry F. J., Thornley D. M., Astin T. R., Britt D. T., and Pillinger C. T. 1998. Climate and rock weathering: A study of terrestrial age dated ordinary chondritic meteorites from hot desert regions. *Geochimica et Cosmochimica Acta* 62:3169–3184.
- Fredricks P. M., Warbrooke P., and Wilson M. A. 1983. Chemical changes during natural oxidation of a high volatile bituminous coal. *Organic Geochemistry* 5:89–97.
- Gooding J. L. 1986. Weathering of stony meteorites in Antarctica. In *International workshop on Antarctic meteorites*, edited by Annexstad J. O., Schultz L., and Waenke H. Houston: Lunar and Planetary Institute. pp. 48–54.
- Koeberl C. and Cassidy W. A. 1991. Differences between Antarctic and non-Antarctic meteorites—An assessment. *Geochimica et Cosmochimica Acta* 55:3–18.
- Krasinsky G. A., Pitjeva E. V., Vasilyev M. V., and Yagudina E. I. 2003. Hidden mass in the asteroid belt. *Icarus* 158:98–105.
- Lee M. R. and Bland P. A. 2004. Mechanisms of weathering of meteorites recovered from hot and cold deserts and the formation of phyllosilicates. *Geochimica et Cosmochimica Acta* 68:893–916.
- Martinez M. and Escobar M. 1995. Effect of coal weathering on some geochemical parameters. *Organic Geochemistry* 23:253–261.
- Nishiizumi K., Elmore D., and Kubik P. W. 1989. Update on terrestrial ages of Antarctic meteorites. *Earth and Planetary Science Letters* 93:299–313.
- Petsch S. T., Smernik R. J., Eglinton T. I., and Oades J. M. 2001. A solid state  $^{13}\text{C}$ -NMR study of kerogen degradation during black shale weathering. *Geochimica et Cosmochimica Acta* 65:1867–1882.
- Schultz L. 1986. Allende in Antarctica; Temperatures in Antarctic meteorites. In *49th annual meeting of the Meteoritical Society*, edited by Prinz M. Houston: Lunar and Planetary Institute. p. E-6.
- Schultz L. 1990. Terrestrial ages and weathering of Antarctic meteorites. In *Workshop on Antarctic meteorite stranding surfaces*, edited by Cassidy W. A. and Whillans I. M. Houston: Lunar and Planetary Institute. pp. 56–59.
- Sephton M. A. 2002. Organic compounds in carbonaceous meteorites. *Natural Product Reports* 19:292–311.
- Sephton M. A., Pillinger C. T., and Gilmour I. 2000. Aromatic moieties in meteoritic macromolecular materials: Analyses by hydrous pyrolysis and  $\delta^{13}\text{C}$  of individual compounds. *Geochimica et Cosmochimica Acta* 64:321–328.
- Shima M., Shima M., and Hintenberger H. 1973. Chemical composition of four new detected Antarctic meteorites. *Earth and Planetary Science Letters* 19:246–249.
- Tekely P., Nicole D., Delpuech J., Totino E., and Muller J. 1987. Chemical structure changes in coals after low temperature oxidation and demineralization by acid treatment as revealed by high resolution solid state  $^{13}\text{C}$ -NMR. *Fuel Processing Technology* 15:225–231.
- Velbel M. A., Long D. T., and Gooding J. L. 1991. Terrestrial weathering of Antarctic stone meteorites—Formation of Mg-carbonates on ordinary chondrites. *Geochimica et Cosmochimica Acta* 55:67–76.
- Wetherill G. W. and Chapman C. R. 1988. Asteroids and meteorites. In *Meteorites and the early solar system*, edited by Kerridge J. F. and Mathews M. S. Tucson: University of Arizona Press. pp. 35–67.