Orig Life Evol Biosph (2017) 47:249–260
DOI 10.1007/s11084-016-9530-1

# Carbonaceous Chondrite Meteorites: the Chronicle of a Potential Evolutionary Path between Stars and Life

**Sandra Pizzarello**[1] · **Everett Shock**[1,2]

Received: 31 August 2016 / Accepted: 1 November 2016 /

**Abstract** The biogenic elements, H, C, N, O, P and S, have a long cosmic history, whose evolution can still be observed in diverse locales of the known universe, from interstellar clouds of gas and dust, to pre-stellar cores, nebulas, protoplanetary discs, planets and planetesimals. The best analytical window into this cosmochemical evolution as it neared Earth has been provided so far by the small bodies of the Solar System, some of which were not significantly altered by the high gravitational pressures and temperatures that accompanied the formation of larger planets and may carry a pristine record of early nebular chemistry. Asteroids have delivered such records, as their fragments reach the Earth frequently and become available for laboratory analyses. The Carbonaceous Chondrite meteorites (CC) are a group of such fragments with the further distinction of containing abundant organic materials with structures as diverse as kerogen-like macromolecules and simpler compounds with identical counterparts in Earth's biosphere. All have revealed a lineage to cosmochemical synthetic regimes. Several CC show that asteroids underwent aqueous alteration of their minerals or rock metamorphism but may yet yield clues to the reactivity of organic compounds during parent-body processes, on asteroids as well as larger ocean worlds and planets. Whether the exogenous delivery by meteorites held an advantage in Earth's molecular evolution remains an open question as many others regarding the origins of life are. Nonetheless, the natural samples of meteorites allow exploring the physical and chemical processes that might have led to a selected chemical pool amenable to the onset of life.

**Keywords** Biogenic elements · A-biotic organic chemistry · Meteorites · Chiral asymmetry

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Dedicated to Jim Ferris

✉ Sandra Pizzarello
pizzar@asu.edu

[1] School of Molecular Sciences, Arizona State University, Tempe, AZ 85287-1604, USA

[2] School of Earth & Space Exploration, Arizona State University, Tempe, AZ 85218, USA

## Introduction

The asteroid belt contains a surprising diversity of objects, ranging from primitive ice–rock mixtures that may intermittently behave like comets (Hsieh and Jewitt 2006) or bodies covered by ice (Campins et al. 2010; Rivkin and Emery 2010) to igneous rocks of the type found in terrestrial planets; however, most are small and odd-shaped planetesimals that consist of aggregate rocks and inhabit a relatively narrow ring between Mars and Jupiter at 2.1–3.3 AU (AU) from the Sun. The asteroid belt is crowded and fragments from its frequent collisions have reached Earth as meteorites since the planet formed (e.g., Bunch and Chang 1980; Strom et al. 2005). CC are a subgroup of meteorites with near-solar elemental abundances and contain 3.6–0.31 wt% C, which is mostly bound in organic materials and uniquely offer to direct laboratory analyses a record of the abiotic organic chemistry that occurred in the Solar System at ~~it's~~ a time close to the origin of Earth life.

All meteorites enter the Earth atmosphere as meteors traveling at great speed (40 times faster than the speed of sound) and, when large enough, melt their outside layers by overheating; these layers ablate during fall and, upon reaching the Earth, solidify into a thin fusion crust that leaves the cold interior untouched and still very cold, in fact some meteorites retrieved right after their falls may be found covered by ice. Within their general characterization, CC are named after the location of their fall and classified in seven groups, which take the name of the first meteorite fall for each type, e.g., CR for Renazzo-type, and whose petrologic types are given by numbers, 1–5 where 1 equals most altered by water and/or metamorphism.

CC organic composition~~s~~ vary extensively, in the CO, CV, CK, CH and CB groups, it consists almost exclusively of insoluble organic materials (IOM) while in CI, CM, and CR it also includes numerous soluble organic compounds. The Murchison meteorite (a CM2; Fig. 1) is possibly the best-known CC due to its propitious fall in 1969. At the time, U.S. astronauts were completing a successful trip to the Moon and NASA laboratories were equipped and ready to analyze the returning lunar rocks when Murchison fell before their return. Analyzed "for practice", its extracts soon revealed indigenous amino acids (Kvenvolden et al. 1970) and demonstrated unequivocally for the first time that abiotic organic materials in the early Solar System had preceded biochemistry. The finding was the start of comprehensive analyses continuing to this day, which have expanded to all known types of CC and showed their organic materials can be as diverse as kerogen-like insoluble macromolecules and simpler soluble compounds (e.g., Pizzarello et al. 2006; Martins 2011).

**Fig. 1** A Murchison fragment showing the interior matrix

## The Organic Composition of Carbonaceus Chondrites

### CC Soluble Compounds

The complex range of organic compounds detected in CC varies from polar species such as water-soluble amino acids or polyols to non-polar hydrocarbons extracted only by solvents (Table 1). Their abundances and distribution differ between CC types, e.g., in the CM such as Murchison, compounds within a class, e.g., amino acids, amines, etc., gradually decline in abundance with increasing chain length, favor branched carbon-chain species and hydrocarbons (alkanes, aromatic and heterocyclic)[1] have the highest overall abundances (e.g., Pizzarello et al. 2006). Conversely, in the CR meteorites analyzed more recently thanks to several findings in Antarctica, the lower molecular weight compounds of an homologous series, e.g., 2C glycine and 3C alanine for amino acids, represent most of each class' total amounts while hydrocarbons are the least abundant overall (e.g., Pizzarello et al. 2012). Albeit with differences in synthetic capabilities, however, CC organic compounds' composition appears to follow no selective trend other than that dictated by physico-chemical forces and, as such, differs greatly from life's functionally selective pools of biomolecules.

The D-, $^{13}$C-, and $^{15}$N isotopic distributions of meteoritic organic compounds (Table 1) reveal their long synthetic lineage from presolar environments. Because isotopic fractionation is a function of zero point energy differences (DE) between isotopes and local temperature, in the form: exp.(−DE/T), and D/H ratios can be especially large due to the high relative mass difference (2/1 amu between D and H), D enrichments are expected to be the largest at very low temperatures. This is confirmed by observations of dense clouds in the interstellar medium (ISM), where extremely large D-enrichments have been observed, e.g., $DHO/H_2O \approx 0.01$ compared to the average terrestrial D/H ratio of $1.5 \times 10^{-4}$ (Epstein et al. 1987).

The findings that several organic compounds in CC extracts are enriched in the heavy isotopes of C, N, and especially H (see table's references), lead to the hypothesis that these compounds, or their direct precursors, were synthesized in the cold molecular clouds of the ISM and further reacted through subsequent stages of pre-stellar, nebular and asteroidal processes (e.g., Cronin and Chang 1993). Using the δD notation, an example from the table shows amino acid values that reach +7245‰ in meteorites (Pizzarello et al. 2008), which are the highest ever recorded for extraterrestrial molecules by direct analysis and fall within those established spectroscopically for ISM molecules (+5800 to +45,000). That CC compounds could carry such isotopic signatures, likely for billions of years, would seem to further indicate that the conditions of asteroidal processes were mild enough to preserve them (Bose et al. 2014).

Could larger and complex molecules such as amino acids be formed in presolar environments as such isotopic enrichments appear to suggest? There is no definite evidence to support the proposal as yet. The observation of glycine was reported by Kuan et al. (2003) but the finding has remained controversial, (e.g. Hollis et al. 2003). However, the known distributions of interstellar molecules (e.g., Irvine and Hjalmarson, 1984) would include all the reactants necessary for amino acid formation by a Strecker-cyanohydrin synthesis, i.e., aldehydes or ketones, HCN, $NH_3$, and $H_2O$ (Scheme 2) (Peltzer and Bada 1978; Schulte and Shock 1995). Amino- and hydroxy acid syntheses from such precursors would have found suitable conditions in asteroidal parent bodies and the occurrence of both sets of compounds in Murchison and other meteorites appear to confirm a possible Strecker-cyanohydrin route (e.g. Peltzer et al. 1984).

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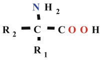
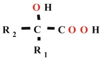
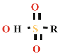
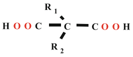
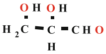
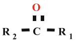
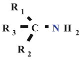
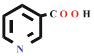
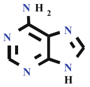
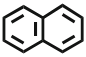
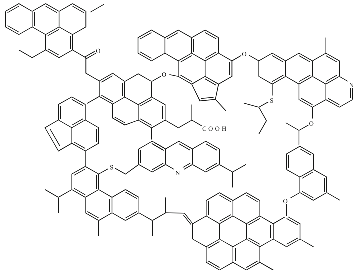
[1] Made up respectively: of alkyl chains, one or more benzene rings and other atoms besides C and H.

**Table 1** Major classes of organic compounds in CC meteorites and their isotopic distributions*

| Compound Class | Structure | δD‰ | $\delta^{13}C$‰ | $\delta^{15}N$‰ |
|---|---|---|---|---|
| **Carboxylic acids** | $R-COOH$ | +600 – +2 | +4 – +23 | --- |
| **Amino acids** |  $R_2-\overset{NH_2}{\underset{R_1}{C}}-COOH$ | +221 – +7245 | -5 – +53 | +71 – +139 |
| **Hydroxy acids** |  $R_2-\overset{OH}{\underset{R_1}{C}}-COOH$ | +406 – +3420 | -20 – +13 | --- |
| **Sulfonic[1] acids** |  $OH-\overset{O}{\underset{O}{S}}-R$ | +483 – +852 | -1 – +30 | --- |
| **Dicarboxylic acids** |  | +1121 – +3604 | +6 – +28 | --- |
| **Sugar alcohols&acids** |  $H_2\overset{OH}{C}-\underset{H}{\overset{OH}{C}}-CHO$ | +119 | -6 | --- |
| **Aldehydes & Ketones** |  $R_2-\overset{O}{C}-R_1$ | +37 – +429 | nm | --- |
| **Amines** |  | +22 – +1221 | +22 | >93 |
| **Pyridine carb. acids** |  | +129 | +20 | nm |
| **Purines & Pyrimidines** |  | nm | nm | --- |
| **Hydrocarbons:** | | | | |
| **Alyphatic** | $H_3C-R-CH_3$ | 0 – +9 | +9 | |
| **Aromatic** |  | +353 | -6 – -29 | nm |
| **Polar** |  | | +5 – +17 | |
| **InsolubleMaterial** (estimated structure)<br>**e.g., Murchison composition: $C_{100}H_{70}N_3O_{12}S_2$** |  | +728 - +930 | -14 - +24 | +7[‡] |

*Alexander et al. 2010; Cooper and Rios 2016; Pizzarello et al. 2006, 2008, 2010, 2011, 2012, 2016

[‡] Isotopic values refer to bulk IOM and do not include "hot spots" measurements

Nevertheless, it should be noted that a Strecker reaction would lead *only* to α-amino acids, i.e., a small portion of meteoritic amino acids, which have been found with C2 through C9 alkyl-chain lengths that may be linear, branched, or cyclic, and having all the possible relative distribution of the amino and carboxy functional groups along those chains (i.e., as α-, β-, γ- etc. amino acids) as well as more than one of those functional groups, as in the dicarboxylic-, and diamino acids, and secondary amino groups deriving from their alkyl substitution or inclusion in rings (e.g., as in proline and its homologs) (Pizzarello et al. 2006). Therefore many other synthetic pathways must have been at work and need to be invoked to explain these many structures.

Among the complex suite of soluble organics identified in CC, several have identical counterparts in the biosphere, such as thirteen biological amino acids (Pizzarello et al. 2012). Since amino acids carry a unique prebiotic significance as constituents of terrestrial proteins, their findings have spurred suggestions of a possible exogenous delivery of biochemical precursors to early Earth from comets and meteorites. As for meteoritic compounds overall, however, the suites of meteoritic and terrestrial amino acids differ greatly: meteorites host over 75 amino acids with complete structural diversity up to 7-carbon long (C7) (e.g., Pizzarello et al. 2006) while terrestrial protein amino acids are just twenty-one, functionally specific and the clear product of a strict compositional selection.

On the other hand (it turns out literally), the two groups of compounds may also share an important similarity in that some amino acids of meteorites display enantiomeric excesses (*ee*) (Cronin and Pizzarello 1997) of the same configuration as the amino acids of terrestrial protein, which are almost exclusively of the L-configuration. Chiral, or chirality, refers to objects or molecules that can exist in two mirror image forms, which are not super-imposable and called enantiomers in the case of molecules. Common examples are the hands, from which the word derives, and organic molecules containing a carbon with four different substituents (Fig. 2).

Two chiral objects/molecules have identical components and properties but, because of the different spatial distribution of their components, may interact more or less advantageously with other chiral entities through physico-chemical processes (Fig. 2, e.g., The Royal Swedish Academy of Sciences 2001; Pizzarello and Groy 2011). Because evolution and, most likely, these capabilities have made chiral homogeneity essential to the structure and function of extant life's biopolymers and for many stereospecific reactions of metabolism, it could be postulated that homochirality was an attribute necessary for the origin and/or development of life. It is interesting, therefore, that the *ee* found in meteorites represent to date the only case of molecular chiral asymmetry measured outside the biosphere.

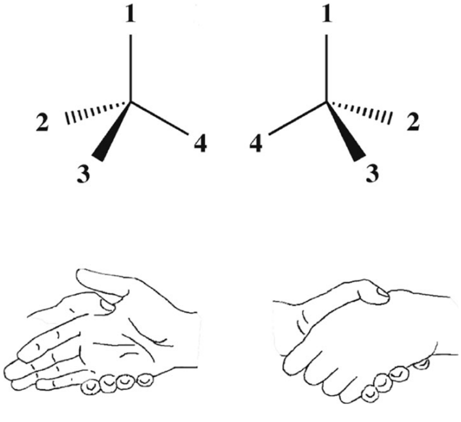


**Fig. 2** Examples of chiral objects: top, spatial distribution of bonds for a C-atom bound to four different substituents; bottom, two ways to join right and left hands

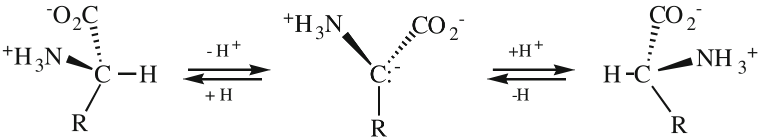
Chiral compounds with *ee* have been found in various types of CC extracts and so far include ten amino acids, one hydroxy acid, several polyols and two amines (e.g., Pizzarello and Groy 2011; Cooper and Rios 2016; Pizzarello and Yarnes 2016). All are characterized by large heterogeneity and their *ee* vary significantly, from 0 to 60%, even within short distances in the same meteorite (e.g., Pizzarello et al. 2003, 2012; Pizzarello 2016). Of the amino acids, most have a 2-methyl substituent (2maa) and cannot racemize, i.e., change from one configuration to the other in water with time as 2-H species do, by the stochastic loss and re-acquisition of a proton through their carbanion intermediate (Scheme 1).

As for the origin of meteoritic compounds' *ee*, the possibility of abiotic chiral asymmetry was debated since before its detection in meteorites. Early hypotheses (e.g., Rubenstein et al. 1983), proposed that irradiation of chiral presolar compounds by UV circularly polarized light (UV CPL), itself chiral by having either right-, or left-rotating field vectors, could lead to differential photodecomposition of chiral molecules' enantiomer resulting in *ee*. Although appealing for the broad range of known environments that could have participated towards obtaining *ee*, these proposals could not match the findings in meteorites.

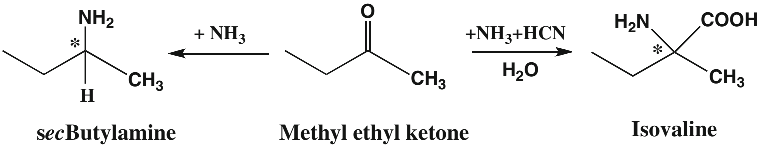
Differential photolysis derives from the unequal absorption of UVCPL by the enantiomers of a chiral molecule and is expressed by its anisotropy factor, which dictates the *ee* extent achieved *before both* enantiomers are completely decomposed. For amino acids, this factor is rather low (e.g., Nishino et al. 2002) and restricts their possible *ee* by UVCPL to a maximum of ~10%, i.e., far lower than determined for meteoritic compounds. Moreover, if we assumed that UVCPL could have induced chiral asymmetry in precursors molecules of higher anisotropy, precursors for 2-methyl amino acids and 2-methyl amines are non-chiral ketones (due to their double bonded O, Scheme 2) and would exclude that possibility as well.

The overall experimental data together with the puzzling heterogeneity of *ee* determined within and between meteorite stones for the same compound clearly leave several open questions about the origin of *ee* in meteorites. The large *ee* variability for isovaline in MN (Pizzarello et al. 2003; Pizzarello and Groy 2011), had first suggested a possible relation between *ee*, asteroidal processes and, in particular, the mineral phases ensuing from aqueous stages. At the time, the comparison of the relative abundance of isovaline to alanine (a 2-H amino acid showing no *ee* in MN) appeared to follow the serpentine/olivine ratios obtained by X-ray diffraction of the powders. The data suggested that the two groups of compounds might have both acquired *ee* but the excesses' survival differed during asteroidal aqueous alteration, as expected for alanine that racemizes in water (Scheme 1) and 2maa that cannot. The initial attainment of these *ee*, however, was still left unexplained.

The recent finding of *ee* for two chiral amines *only* in type-2 CR meteorites, i.e., showing mineral alteration from hydrous phases (Pizzarello and Yarnes 2016), allowed expanding those earlier hypotheses. Based on the new experimental results, it has been proposed that chiral amines formed from the same ketone precursors as 2maa (Scheme 2), during a warm hydrous stage of the asteroidal parent body, via a reductive amination process in the presence of large abundance of ammonia and where the precursors' adsorption upon mineral phases possessing



**Scheme 1**



**Scheme 2**

asymmetry offered opportunities for chiral induction.[2] Magnetite, described with a helical structure in meteorites (e.g., Chan et al. 2015, 2016), was the example specifically indicated (Fig. 3). Albeit needing further experimental tests, these new data suggest possible important roles for asteroidal and small planetary bodies, their aqueous phases and ensuing minerals in promoting meteoritic compounds' syntheses as well as their chiral asymmetry. Given the importance of homochirality for extant life, the discourse could also reasonably be extended to the effects of these minerals upon life's emergence and development on the Earth.

## CC Insoluble Organic Materials and their Possible Release of Simple Molecules

The larger fraction of CC organic carbon, up to 90% of total, is present as complex and macromolecular IOM, which can be obtained from meteorite powders only after repeat extractions and demineralization with acids (e.g., Alexander et al. 2010). It is often referred to as kerogen-like because, like terrestrial kerogens, it is insoluble, contains all the biogenic elements and can only be characterized whole, by spectroscopy, pyrolytic decomposition and microscopy. The IOM appears as undifferentiated material, whose general composition varies between classes of meteorites, e.g., from $C_{100}H_{70}N_3O_{12}S_2$ for MN to $C_{100}H_{46}N_{10}O_{15}S_{4.5}$ for the ungrouped Tagish Lake meteorite (e.g., Pizzarello et al. 2001), and is shown to contain condensed aromatic, hydroaromatic, and heteroaromatic macromolecules with alkyl branching, bridged by alkyl chains, ether (R-O-R) and sulfide (R-S-R) linkages, plus functional groups such as OH and COOH (e.g., Cody et al. 2011). The IOM isotopic composition of MN (Table 1), would be consistent with at least part of the IOM components being of presolar origin, as confirmed by more recent findings of extremely high D in concentrated IOM regions appropriately called "hot spots" for their anomalous δD values (up to 19,400 ‰, e.g., Remusat et al. 2006). IOM $^{15}N$ isotopic enrichments are also observed but may, at least in part, be attributed instead to solar process (e.g., Pizzarello and Bose 2015).

Interpretations of IOM data have evolved through time following the understanding of solar and presolar environments. Polycyclic aromatic hydrocarbons (PAHs) were first proposed as the primary ISM components, however, more recent astronomical observations assigned the infrared features originally attributed to PAHs to combined aromatic and aliphatic components of no fixed arrangements (e.g., Kwok and Zhang 2011). These findings agree with experimental studies pointing to the possible formation of presolar aggregates (Schutte et al. 1993) and IOM formation in particular by polymerization of formaldehyde, which is an abundant component of the ISM organic inventory and, presumably, the solar nebula where the first reaction steps would follow a sequence as shown in Scheme 3 (Cody et al. 2011; Kebukawa and Cody 2015).

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[2] According to chemical nomenclature, asymmetric induction describes the preferential formation of one enantiomer over the other in a chemical reaction resulting from the influence of a chiral feature present in the substrate, reagent, catalyst or environment.

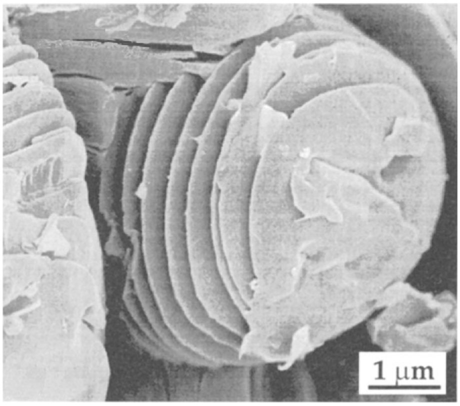
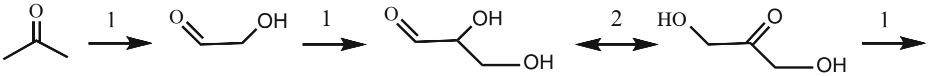


**Fig. 3** Scanning Electron Image of a spiral magnetite plaquette in Orgueil matrix (Hua and Buseck 1998)

Just as for the organic and inorganic makeup of CC matrixes, IOM compositions may vary upon nebula and/or planetary effects. For example, Alexander et al. (2014) showed this for Tagish Lake and proposed a model whereby aqueous alteration drove transformations of preexisting IOM resulting in nearly complete conservation of C during conversion of aliphatic to aromatic material. These reactions would require loss of H and result in oxidation of the IOM. Support for the aliphatic-to-aromatic transition during alteration is provided by the greater abundance of aliphatic bonds in IOM of interplanetary dust particles, which are nearly unaltered, compared with meteoritic IOM, where aromatic structures dominate (Vollmer et al. 2014). Recent evidence for the oxidation state of Fe in minerals thought to be alteration products on CR chondrites is explained by H loss as well (Le Guillou et al. 2015).

Recent analytical methods make it possible to visualize and analyze IOM as it occurs in close association with minerals in meteorites (e.g., Piani et al. 2015). These advances allow new models for the effects of aqueous alteration on the IOM and, by extension, the processing of organic compounds elsewhere in the solar system including the early Earth. Studies of the CR MET 00426 led Le Guillou and Brearley (2014) to argue that accretion assembled organic matter (OM), water ice, sulfides and amorphous silicates, and that subsequent melting of ice allowed hydration of the amorphous silicates and redistribution of the organic materials, including soluble compounds. The authors relate their observation of the preferential association of OM with alteration phases including tochilinite (a sulfide-hydroxide layered mineral) to nucleation near locations of initial association of OM and water ice. This interpretation is supported by several related investigations of other chondrites that provide~~s~~ additional evidence of redistribution and aromatization of OM during aqueous alteration, including the observation of diffuse OM that contains carboxylate groups associated with phyllosilicates and possibly representing the soluble fraction (Le Guillou et al. 2014). Recent results show that nitrogen is doubly and triply bonded to carbon in IOM grains and also occurs in heterocyclic compounds, which Vollmer et al. (2014) argue, would be consistent with aqueous transformations of formaldehyde in the presence of ammonia.



**Scheme 3** Formaldehyde condenses with itself (reaction 1) to form glycoaldehyde and sequential aldol condensations yield polyalcohols. Intramolecular hydride transfer (reaction 2). intraconverts glyceraldehdye to dihydroxy acetone and aldol condensation (reaction 1) with dihydroxyacetone leading to branched polyalcohols

Complementary hydrothermal experiments on the reactivity of individual organic compounds show that reversible reactions leading to metastable equilibria are common (e.g., Yang et al. 2014). Specifically, the hydration/dehydration reactions between alcohols and alkenes are reversible, as are the hydrogenation/dehydrogenation reactions between ketones and alcohols and between alkenes and alkanes. Furthermore, mineral surfaces appear to catalyze the breaking and making of specific bonds (Shipp et al. 2014), and dissolved metals can participate in coupled organic/inorganic oxidation/reduction reactions (Yang et al. 2015). The implication is that organic compounds can react and rearrange according to external constraints during parent body processes, such as aqueous alteration and metamorphism, and may do so for analogous processes on ocean worlds and the early Earth.

However, the most valuable insights into the nature of the IOM, its molecular makeup as well as the inventory possibly made available to solar planetary bodies upon exogenous delivery, have come through laboratory experiments that analyzed the effects on these materials by treatment at high temperatures and pressures similar to those found in terrestrial hydrothermal systems (300 °C, 100Mpa; Yabuta et al. 2007). These analyses have shown that the most abundant organic component of meteorites, albeit insoluble upon extraction, can release soluble compounds under appropriate and relatively mild conditions.

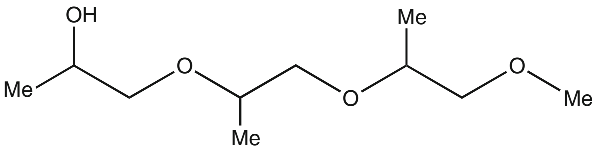
All CC types that release soluble compounds upon water and solvent extractions may also release several of these hydrothermally (HT) from the IOM and, since HT conditions are expected to have also occurred on the early Earth, may have contributed to its organic pool. IOM-released molecules include a large variety of hydrocarbons, dicarboxylic acids up to 17-carbon chain length, N-, and O-containing hydroaromatic and aromatic compounds, N-, O-, and S-containing aromatic compounds, plus a large number of their isomers and homologs, a series of PAHs of up to five rings, together with non-condensed aromatic species, such as substituted benzenes, biphenyl and terphenyls as well as their substituted homologs, and hydrated PAHs (Yabuta et al. 2007).

Even meteorites with low content of soluble organic species have given surprising and prebiotically appealing results. Such is the case of the Sutter's Mill meteorite, which fell in northern California in 2013 and was found to be unique in regard to the molecular species released from the IOM (Pizzarello et al. 2013). In addition to O-containing aromatic compounds, many of these included complex polyether- and ester-containing alkyl molecules (Scheme 4) of prebiotic appeal due to their chemical stability and amphiphilic properties, which suggest possibilities of membrane formation on early Earth.

Also most interestingly from the viewpoint of a possible exobiology, large amounts of ammonia were released from the IOM of several meteorite types in far larger abundance than hydrocarbons (μg/mg compared to μg/g at best in 100 °C water extracts of untreated meteorite powders; Fig. 4) and with varying $^{15}$N enrichment (Pizzarello et al. 2011). Furthermore, these enrichments vary with the type of CC (Pizzarello and Williams 2012), i.e., the mineral compositions that offer the metric for their classification.

Recent work has proposed a novel scenario whereby $^{15}$N–enriched ammonia is produced in the solar nebula by UV-photodissociation of $N_2$, incorporated by carbonaceous materials and

**Scheme 4** Example of a polyether molecule detected upon hydrothermal treatment of the Sutters Mill meteorite IOM



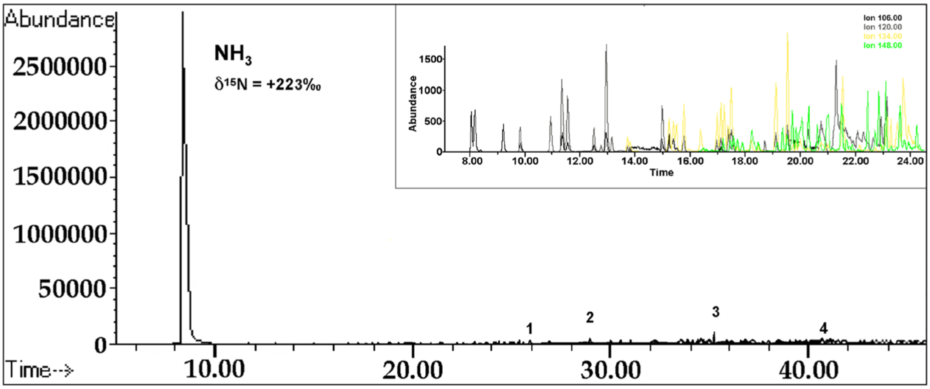


**Fig. 4** Water and solvent extracts of hydrothermally treated IOM from an Antarctic CR meteorite, combined to scale to emphasize the overwhelming abundance of ammonia. Main panel: chromatogram from Gas Chromatography-Mass Spectrometric analyses: 1-naphthalene, 2-pentadecane, 3-heptadecane, 4-phenanthrene. Insert: expanded view of the elution of $C_2$-$C_5$ branched benzenes ($C_2$ black, $C_3$ grey, $C_4$ yellow, $C_5$ green), $\delta^{15}N$ value were from separate isotopic analyses

delivered to early Earth by comets and meteorites (Pizzarello and Bose 2015). This scenario establishes two important paradigms: 1) that because the experimental release of ammonia from the IOM closely mimics known terrestrial conditions, we may assume that abundant reduced nitrogen was repeatedly made available to our early planet, disposing of concerns for its rapid loss of ammonia by photolytic decomposition (Ferris and Nicodem 1972); 2) that since reduced nitrogen is a required component in origins of life theories, the habitability of our nascent planet and possibly other planetary systems was significantly affected by exogenous input from meteorites.

These IOM findings, when combined with those of abiotic chiral asymmetry in meteoritic soluble compounds, its possible dependence upon planetesimal environments, and the discovery of asteroidal alteration leading to molecules with membrane forming potential, seem to offer selective links between solar and terrestrial chemical evolution and point to possible environments that might have enhanced early Earth habitability and opened pathways to the emergence of terrestrial life.

**Acknowledgements** SP is grateful for the many years of funding from the NASA Astrobiology and Exobiology division and the current NASA support under Agreement No. NNX15AD94G for the program "Earths in Other Solar Systems"; ES appreciates financial support from NASA (NNX15AH73G and NNX16AO82G) and the Deep Carbon Observatory. Both authors wish to thank an anonymous reviewer for corrections, comments and suggestions.

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