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Research Paper

Planetary Resources and Astroecology. Planetary Microcosm Models of Asteroid and Meteorite Interiors: Electrolyte Solutions and Microbial Growth—Implications for Space Populations and Panspermia

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ABSTRACT

Planetary microcosms were constructed using extracts from meteorites that simulate solutions in the pores of carbonaceous chondrites. The microcosms were found to support the growth of complex algal and microbial populations. Such astroecology experiments demonstrate how a diverse ecosystem could exist in fluids within asteroids and in meteorites that land on aqueous planets. The microcosm solutions were obtained by extracting nutrient electrolytes under natural conditions from powders of the Allende (CV) and Murchison (CM2) meteorites at low (0.02 g/ml) and high (10.0 g/ml) solid/solution ratios. The latter solutions, which simulate natural extractions of asteroids and meteorites by water during aqueous alteration, were found to contain >3 mol/L electrolytes and ~1 mol/L organics, concentrated solutions favorable for prebiotic synthesis. The solutions and wet solids, inoculated with diverse microbial populations from a wetland, were found to support complex self-sustaining microbial communities for long periods (>8 months), with steady-state populations on the order of 4×10^5 CFU/ml algae and 6×10^6 CFU/ml bacteria and fungi. Planetary microcosm experiments based on meteorite materials can assist in assaying the fertilities of planetary materials and identifying space bioresources, targeting astrobiology exploration, modeling past and future space-based ecosystems, and evaluating sustainable populations in the Solar System. The results also suggest that protoplanetary nebulae can be effective nurseries for microorganisms and useful targets for directed panspermia. Key Words: Astroecology—Asteroids—Comets—Meteorites—Microorganisms—Panspermia. Astrobiology 2, xxx–xxx.

INTRODUCTION

CARBONACEOUS OBJECTS in the Solar System include meteorites, asteroids, comets, and interplanetary dust particles (IDPs). Under aqueous conditions, internal solutions that form in these objects may originate and sustain microbial life. To assess these roles requires an understanding of the chemistry and biology of these materials. The present series of experiments applies microcosm simulations, based on actual extraterrestrial materials in meteorites, to elucidate these properties (Maut-

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ner *et al*., 1995, 1997; Mautner, 1997a). The questions of interest are: What are the chemical properties of solutions formed when these materials are subjected to various aqueous environments? Can these solutions sustain complex microbial populations? The present study addresses these questions in relation to the potential roles of carbonaceous chondrites in early and future space ecosystems.

Organics on early planets

Meteorites, comets, and in particular IDPs delivered large amounts of organics to the early Earth, and presumably to Mars and the other planets (Delsemme, 1995; Oro *et al*., 1995). The rate of infall of organic carbon to Earth during the intense bombardment period was on the order of 10^8–10^9 kg/year by IDPs, 10^5–10^6 kg/year by comets, and 10^3–10^4 kg/year by meteorites (Chyba and Sagan, 1992).

Biogenesis on early planets

After infall to planets, the IDPs, comets, and meteorites can be exposed to water. Water–rock interactions in the interiors of these objects are capable of forming concentrated solutions of organics and salts in the presence of mineral catalysts. Meteorite organics, as well as phosphate and other essential inorganic biological components such as Ca, Mg, Na, K, chloride, and sulfate, are extractable under planetary conditions (Mautner *et al*., 1995). The soluble meteorite organics include amino acids and adenine, as well as membrane-forming components and polycyclics that can affect energy conversion (Deamer, 1992).

The interiors of IDPs (Kruger and Kissell, 1989; Maurette *et al*., 1995), cometary ponds (Clark, 1988), and the pores of meteorites on early Earth (Mautner, 1997a; Mautner *et al*., 1997) could allow prebiotic synthesis and the origins of life. Of these objects, meteorite pores have the advantage of trapping the chemicals and allowing chemical and microbial evolution to continue. In this respect, it has been shown that various organics can be extracted under planetary conditions and that some of these components can form vesicles (Mautner *et al*., 1995).

Biogenesis, lithopanspermia, and directed panspermia in the Solar Nebula

Similar solutions can form in the interiors of carbonaceous chondrite parent asteroids during early aqueous alteration and in cometary nuclei during perihelion passes (Bunch and Chang, 1980; Tomeoka and Buseck, 1985; Komle *et al*., 1991; Brearley and Jones, 1998; Shearer *et al*., 1998). Asteroids and cometary nuclei could serve as potential sites for biogenenesis (Chyba and McDonald, 1995) and for transporting microorganisms (Hoyle and Wikramasinghe, 1978). Similarly, solar nebulae and young solar systems in star-forming interstellar clouds could be seeded with microorganisms, possibly using solar sailing or comets as vehicles (Mautner and Matloff, 1979; Mautner, 1995, 1997b).

With regard to life in early solar systems, the survival of microorganisms on carbonaceous chondrite materials is of interest. Algae growing on meteorite dust in Greenland were observed as early as 1870 (Leslie, 1879; Maurette *et al*., 1986). The nutrient values of organic planetary materials has been demonstrated on tholin, a synthetic analog of organics formed under reducing conditions similar to those theorized to exist on Jupiter (Stoker *et al*., 1990). Carbonaceous chondrite materials from Murchison extracts can support various soil microorganisms such as the oligotrophs *Flavobacterium oryzihabitans* and *Nocardia asteroides* (Mautner *et al*., 1997). Also, experiments with *Pseudomonas fluorescens* show that meteorite organics can serve as a sole carbon source (Mautner *et al*., 1995). In contrast, the Allende meteorite has been found to inhibit biological growth in some cultures (Mautner, 1997a). It has recently been shown that various carbonaceous chondrites contain diverse microorganisms from terrestrial contamination (Steele *et al*., 2000).

Terraforming and space colonization

In the future, asteroids may be used as resources for space colonization (O'Neill, 1974; O'Leary, 1977; Lewis, 1993). Carbonaceous chondrite materials from Phobos and Deimos may be used as fertilizers in Martian terraforming (Lewis, 1997). Relating to these applications, the Murchison CM2 meteorite was observed to have soil fertility parameters comparable to productive terrestrial soils (Mautner, 1997b, 1999).

The microcosm simulations described here use realistic solid/solution ratios and complex soil microbial communities that extend the previous work on isolated species (Mautner *et al*., 1995, 1997).

MATERIALS AND METHODS

Aqueous extractions

Solid samples of the Allende and Murchison meteorites were obtained from the Smithsonian Institution and from commercial sources. The mineralogies of the meteorites are well established (Fuchs *et al*., 1973; Barber, 1981; Komacki and Wood, 1984). To achieve particle size distributions of the meteorites approximately similar to terrestrial soils, the samples were ground by hand in an agate mortar. For example, the particle size distribution of ground Murchison powder was equivalent to silty clay soils with 57% clay-size particles (<2 μm), 41% silt-size particles (2–20 μm), and 2% sand-size particles (>20 μm).

Samples that consisted of 80–200 mg of Allende powder and 40–80 mg of Murchison powder were placed in polythene tubes and washed in 10% acetic acid for 24 h to remove electrolyte impurities. Deionized water was added to the powders to achieve various solid/solution ratios for the experiments (i.e., solid/water ratios ranged between 0.02 and 10 g/ml). The solid/solution samples, which maintained a natural pH of 7.0–8.0 during the extraction period, were extracted for 4 days at 20°C with vortex shaking for 1 min twice daily to maintain a constant protocol and avoid possible alteration of the minerals or microbial interference for longer exposure times. Extractions of Ca, Mg, Na, and K showed that constant equilibrium concentrations were obtained in 2–8 days for extractions performed under similar conditions.

At solid/water ratios <1, the suspended solids were separated from the liquid by centrifuging, and the liquid was removed for analysis. At solid/water ratios >2, however, the mixtures formed pastes that required special methods to extract the liquids. The main method used for extracting liquids from these samples was a rapid flush technique that involved extracting the samples in 3-ml polythene syringes and flushing the samples twice with 2 ml of deionized water through a prewashed filter. The deionized flushing water was in contact with the extractant/solid paste for <1 min, sufficient to dilute and remove the entrained extracts but not dissolve significant amounts of additional solutes. This assumption was tested by flushing similar quantities of nonextracted powders of Allende and Murchison meteorites. The small amounts of dissolved solutes from these nonextracted solids obtained by the rapid flush method were used as reference blanks. Some of the samples were also analyzed by the paper absorption method, where a portion of the extracts from the pastes obtained at solid/water ratios of 1.0 and 2.0 g/ml was adsorbed on dry filter paper. The filter paper was weighed to determine the amount of extract adsorbed. The total amount of filter paper-entrained extract was found to be ~50% of the amount of extract entrained using the rapid flush method. The paper was subsequently extracted into 4 ml of deionized water for solute analysis.

Trace metals were extracted from the Allende and Murchison powders at $r_{\text{solid/water}} = 0.027$ g/ml by 1 *M* ammonium acetate solution, a standard soil extractant (Blakemore *et al*., 1987).

Anions in the extracts were analyzed by ion exchange chromatography using a Waters Ion Exchange Chromatograph and Waters Baseline 810 software. The method used was Waters Ion Chromatography Method A-102 "Anion Exchange Analysis Using IC-Pak A HC Column Borate/Gluconate Eluent," with the samples filtered through an 0.1-μm-pore-size filter paper prior to analysis.

Cations were analyzed by a Shimadzu AA-6200 Atomic Absorption Flame Emission Spectrophotometer.

Phosphate was analyzed by colorimetry using malachite green solutions (van Veldhoven and Mannerts, 1987).

The uncertainty in the reported concentrations, determined from replicate measurements, was estimated as ±30%. Similarly, the SD of values obtained by the direct extraction, rapid flush, and paper adsorption methods for Allende at $r_{\text{solid/water}} = 1.0$ g/ml was ±24%, and the average SD of the constant c_{solid} values at $r_{\text{solid/water}} = 1$–10 g/ml, as shown in Figs. 3 and 4, was ±18%. From these observations, the uncertainty in the data in Table 1 is estimated as ±30%.

Microbial cultures

A main objective of the microcosm experiments was to observe the development of mixed microbial populations in meteorite microcosms simulating asteroid and cometary interiors. The main limitation of meteorite-based microcosm studies is the small amount of available materials.

The minimum sizes of usable microcosms are defined by the requirement that the amounts of

the chemicals and microorganisms should be sufficient to be detected. Consideration of the current analytical methods and the usual range of extractable materials showed that 0.001–1 g mineral samples were needed for anion and cation analysis, 0.01–0.1 g for phosphate analysis, 0.001–1 g for algal bioassays, and 10^{-6}–10^{-2} g for microbial studies. For this study 20–40 mg of meteorite material in each of the microbial cultures was used.

Repeated microbial population analysis for our microcosms required 0.2–1-ml extracts. The small microcosms were prepared in 2-ml polythene microfuge tubes. In one set of experiments two samples of Allende and Murchison material, each 20 mg, and, for reference, 20 mg of acid-washed sand were extracted and sterilized in 1 ml of deionized water at 121°C for 15 min at solid/solution ratios of 0.02 g/ml. The extracts were inoculated with 20 μl of mixed microbial populations as described below. These cultures are denoted in this paper as "extracts." In another set of experiments, 100-mg solid pieces of Allende and Murchison meteorites were inoculated by wetting them directly with 20 μl of the inoculating solution. These cultures are denoted in this paper as "wet solids." The amount of extract for the "wet solids" was estimated to contain sufficient nutrients to support post-log steady-state microbial populations of up to 10^8 CFU/ml from 4 to >31 days (see Table 2).

The inoculating solutions were collected from a natural source that contained aerobes, anaerobes, autotrophs such as algae, and heterotrophs adapted to humic or kerogen-like materials similar to those found in meteorites. Samples of liquid and wet soils were collected at various depths—from the surface to a total depth of 1 m—from a local peat bog wetland reserve (Travis Swamp, Christchurch, New Zealand). The mixed microbial sample was kept in a sealed jar terrarium that allowed a slow diffusion of air for 1 year, creating a Winogradsky column (Winogradsky, 1949). During that time the soil differentiated into a 2-cm dark brown top layer, a 0.5-cm reddish brown middle layer, and a 1.5-cm medium brown bottom layer. This layering results from the different types of microbial activity at various oxygen levels in the column. The top level supported plant and algal growth, indicating slowly exchanging aerobic conditions. The middle reddish brown layer supported sulfur or iron-oxidizing bacteria. In the oxygen-restricted environment the bottom layer of the terrarium supported microoxic or anaerobic communities.

To produce inoculants for the aerobic cultures, 2 ml of wet soil was taken from the top layer and supplemented by 2 ml of algae cultures isolated from New Zealand soils and grown in algal nutrient cultures (Hoshaw and Rosowski, 1973). The algal cultures included unicellular green algae *Chlorella* sp. and *Chlorosarcinopsis* sp., filamentous cyanobacteria *Leptolyngbya* sp. and *Phhormidium* sp., and a gold-brown diatom *Navicula* sp., all of which were identified microscopically. For microoxic/anaerobic inoculants, 2 ml of wet soil was extracted from the bottom layer of the terrarium. The inoculating soil and algal material contained many bacteria and fungi, some of which were identified in the microcosm cultures as discussed below.

The solids in each of the aerobic soil samples were washed three times with 8 ml of deionized water and centrifuged to separate the suspended solids and microorganisms. For the solids in the anaerobic soil samples a similar procedure was used, but the washing liquid was first deaerated with nitrogen. However, traces of oxygen could not be excluded. These experiments were suitable for testing for the presence of facultative anaerobes.

No buffers were used in any of the protocols to avoid carrying over the buffer materials into the microcosms. Microorganisms used in previous meteorite microcosms are known to survive similar washing procedures without lysing (Mautner *et al.*, 1997). Considering that <0.1 ml of water remained in the samples after each step, the procedure for preparing the microcosms diluted all soluble components, thereby removing soluble nutrients, by a factor of 10^6. Samples of 20 μl of the final suspension of the washed solids, which contained ~1 mg of the soil solids, were used for the inoculations.

Following inoculation, the meteorite cultures were kept at 20°C under natural light and dark cycles to allow the development of mixed populations including both photosynthetic autotrophs and heterotrophs. The culture vials were contained in sealed glass jars kept at 100% humidity to prevent drying. The jars were filled with air for the aerobic cultures and with a mix of 90% N_2 and 10% CO_2 for anaerobic cultures.

The microbial populations were monitored by plating the cultures on nutrient agar, under aerobic or anaerobic conditions as appropriate, and on

algal nutrient agar. Samples of colonies obtained from the mixed cultures were grown as isolates on separate plates and analyzed by Gram staining, oxidase and catalase responses, and 96-well carbon source test plates (Biolog, Hayward, CA).

RESULTS

Aqueous extractions

As noted in Materials and Methods, Allende and Murchison powders at solid/solution ratios <1 were extracted directly, and those with solid/solution ratios >2 were extracted by the flush or paper adsorption methods. All three methods were applied to the Allende samples at a solid/solution ratio of 1.0 g/ml. For all cations measured, the three methods gave values with SDs of less than ±30%. Consistency between the various extraction methods is similar to the replicated direct extractions. The agreement amongst the methods is illustrated by the absence of discontinuities in curves that include data points measured by all three methods, as shown in Fig. 1.

The results of the extractions may be expressed in several related ways that reflect different physical quantities. The actual measurements yield aqueous concentrations in the extracts, c_{aq} (mg/L), which can be converted into the extractable content in the solid c_{solid} (mg/g) using equation 1:

$$c_{solid}\ (\mathrm{mg/g}) = \frac{c_{aq}(\mathrm{mg/L})V_{aq}(\mathrm{ml})}{1{,}000w_{solid}(\mathrm{g})} = \frac{c_{aq}(\mathrm{mg/L})}{1{,}000r_{solid/solution}\ (\mathrm{g/ml})} \quad (1)$$

In relation to the microbial experiments, the relevant results are reported in terms of solution concentrations, as shown in Fig. 1, which shows the values of c_{aq} as a function of the solid/solution ratio used in the extractions of the Allende meteorite. The extractions of Murchison yielded similar trends although at much higher absolute solute concentrations (not shown). Figure 1 shows that the solute concentrations increased through the full range of solid/solution ratios used in these experiments.

The solute concentrations of the dilute solutions obtained at $r_{solid/solution}$ of 0.02 g/ml, which

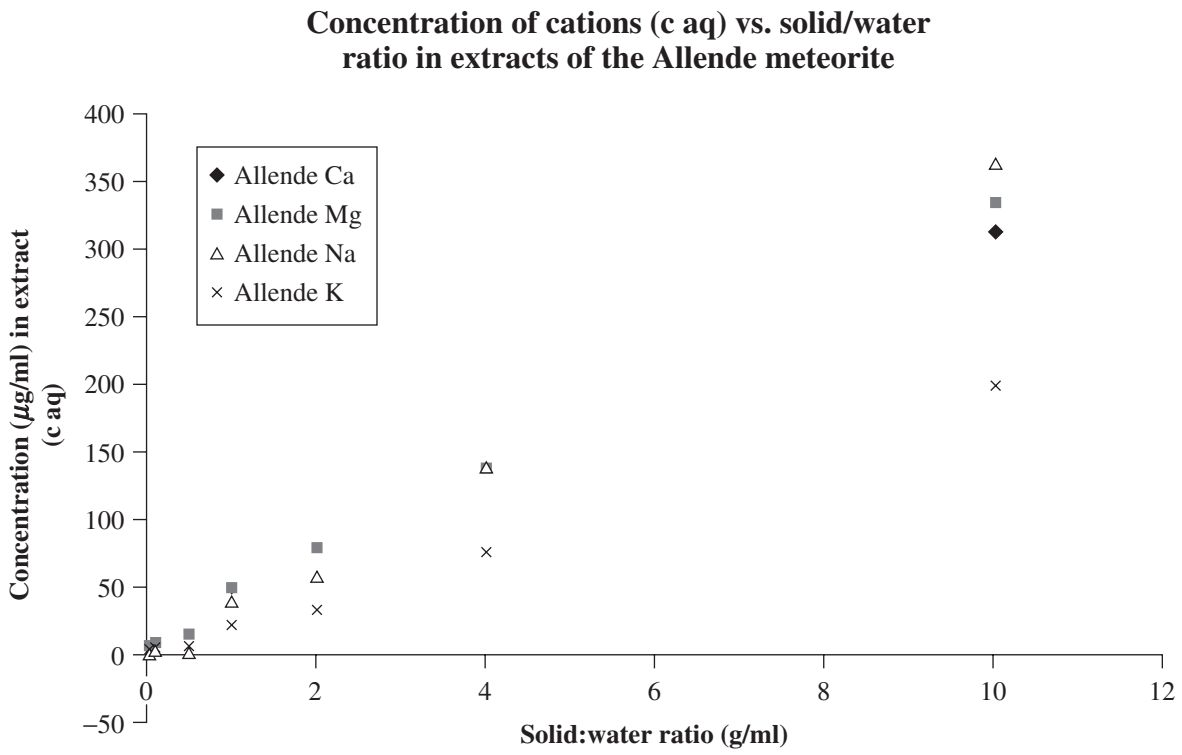

FIG. 1. Concentrations of cations in aqueous solutions, c_{aq} (mg/L), in extracts of the Allende meteorite at various solid/solution ratios (g/ml).

were used for the microbial cultures, are reported in Table 1. Concentrations obtained at $r_{solid/solution}$ of 10.0 g/ml, which simulates natural extractions by water in meteorite and asteroid pores at a porosity of 20% by volume, are also reported in Table 1. As the $r_{solid/solution}$ increased by a factor of 500 between these extractions, the concentrations of most elements increased by factors of 200–500 over this range, which suggests that most of the extractable electrolytes are present in the meteorite as soluble salts that dissolve fully even in the minimum amount of water used ($r_{solid/solution}$ = 10.0 g/ml). Had solute concentrations been controlled by adsorption/desorption equilibria on mineral surfaces, the c_{solid} extracted amounts would have increased significantly with increasing amounts of water.

Trace elements extracted by 1 *M* ammonium acetate were as follows [c_{solid} (μg/g, Allende/Murchison)]: B, 0.1/0.5; Fe, 0.4/9.0; Mn, 0.7/11.0; Al, 0.06/0.03; Cd, 0.0/3.8; Cr, 0.0/0.2; Cu, 0.004/0.04; Ni, 85/101, respectively.

Organic compounds constitute 18 mg/g in Murchison and 2.5 mg/g in Allende (Hayes, 1967). Previous studies show that 10% of the organic content is released under hydrothermal extraction at 121°C, and about half as much may be extracted at 20°C (Mautner *et al.*, 1995; Mautner, 1997a). Applying the latter results to the experiments here provides estimates of the amount of organics released by aqueous extraction for Murchison as 1 mg/g organic C and for Allende as 0.1 mg/g organic C.

Microbiology

The main culturable microorganisms that grew in the meteorite and sand extracts from the inoculates, and the steady-state populations that were established, are listed in Table 2. Two sets of cultures, in extracts and on wet solids, were grown in parallel. The development of the populations in the extracts is shown in Figs. 2–4. Table 2 summarizes the steady-state populations obtained in both sets of experiments after 31 days and the populations on the wet solids after 8 months of incubation.

Tentative identification of the observed species, obtained using Biolog carbon source plates, is listed in Table 2. Although the identifications are tentative, the tests provide useful information on the utilization of potential carbon sources in the meteorites, as discussed below. The similarity of our microorganisms to the species contained in the Biolog database is variable, with possibly reliable identification of *Eureobacterium saperdae* and *Pseudomonas putida*. However, all of the species gave distinct colonies on nutrient agar that allowed counting of the various microbial populations.

Several algae were also included in the cultures. The initial populations of the unicellular, filamentous, and diatom species described above were, in the extract cultures, 10,000, 200, and 80 CFU/ml, respectively. Plate counts of the populations were obtained 15 days after inoculation, during the post-log phase of the bacterial and fungal populations. The algal populations in the extracts and on the wet solids are listed in Table 3. The algal populations increased in all the cultures after inoculation but reached smaller populations than the bacteria, as is also the case in terrestrial soil populations.

Microbial populations that were expected to contain anaerobes were grown in preliminary experiments under microoxic conditions. The inoculating cultures were obtained from the bottom layer of the wetland Winogradsky column. Samples of the cultures were plated on nutrient agar 27 days after inoculation, and the plates were developed under microoxic conditions. Judging by colony morphology, the resulting populations resembled those in the aerobic samples. Under these conditions the main species remained *Clavibacter michiganense*, with smaller populations of the other original inoculating bacteria as shown in Table 1. However, the late takeover by *Corynebacterium* sp. and the development of the yeasts and filamentous fungi did not occur. The observations suggest that the bacterial species or strains isolated from the wetland are tolerant of microoxic conditions and can grow under such conditions on the meteorite extracts. We are investigating whether obligate anaerobes will also grow on these materials.

DISCUSSION

Applications of planetary microcosms

Microcosms are often used to simulate ecosystems under controlled conditions (Odum and Hoskins, 1957; Beyers, 1969). Studies based on actual meteorite materials provides a means to simulate some aspects of planetary ecosystems that are otherwise inaccessible.

The design of planetary microcosm experi-

TABLE 1. SOLUTE CONCENTRATIONS IN EXTRACTS OF THE ALLENDE AND MURCHISON METEORITES, OBTAINED BY EXTRACTIONS AT LOW AND HIGH SOLID/SOLUTION RATIOS

	Concentration (mg/L)											
	Ca[a]	*Mg*[a]	*Na*[a]	*K*[a]	*Mn*[b]	*Fe*[b]	*Ni*[b]	*Cl*[a]	*NO_3-N*[a]	*SO_4-S*[a]	*PO_4-P*[c]	*C (organic)*[d]
Allende												
$r_{s/w}$ = 0.02 g/ml	1.8	2.0	1.3	0.44	0.014	0.008	1.7	0.7	0.044	1.2	0.08	2
$r_{s/w}$ = 10 g/ml	420	380	340	180	7	4	850	730	68	320	44	1,000
Murchison												
$r_{s/w}$ = 0.02 g/ml	64	56	52	4.2	0.22	0.18	2.0	7.6	0.22	188	0.1	20
$r_{s/w}$ = 10 g/ml	1.4E4	1.7E4	1.9E4	1,100	110	90	1,000	1,800	120	5.7E4	51	1E4
Soil solutions	32	25	15	3.5				10		5	0.005	
(median; range)[e]	1–60	0.7–100	9–30	1–11	0.02–2	0.1–0.25		7–50	2–800	3–5,000	0.001–30	
Bacterial biomass (μg/g)[f]	5,100	7,000	4,600	1.2E5	30	250		2,300	9.6E4	5,300	3.0E4	4.9E5
c (CFU/ml)												
Allende[g]	4.1E10	2.7E10	3.7E10	7.5E8	1.2E11	8.0E9		1.6E11	3.5E8	3.0E10	7.3E8	1.0E9
Murchison[g]	1.4E12	1.2E12	2.1E12	4.5E9	1.8E12	1.8E11		3.9E11	6.3E8	5.4E12	8.5E8	1.0E10

[a]Concentrations (mg/L or ppm) in extracts obtained at 20°C for 4 days at low (average data from 0.02–0.1 g/ml) and high (1.0–10.0 g/ml) solid/solution ratios. The corresponding concentrations of extractable elements in the solids (c_{solid}; mg/g) may be obtained by dividing the listed values by $10^3 r_{solid/solution}$ (g/ml). The average values obtained at solid/solution ratios of 1, 2, 4, and 10 g/ml are given for the 10.0 g/ml extractions. Estimated uncertainty was ±30%, except Cl and NO_3-N measured at low concentrations in extracts obtained at $r_{solid/solution}$ = 0.1–1.0 g/ml, where an uncertainty of a factor of 2 may apply.

[b]Based on c_{solid} measured by extraction by 1 *M* ammonium acetate for 24 h at a solid/solution ratio of 0.028 g/ml. Solution concentrations calculated using this c_{solid} value and $r_{solid/solution}$ = 0.02 or 10.0 g/ml in equation 1.

[c]Based on c_{solid} measured by extraction in 4 days at a solid/solution ratio of 1.0 g/ml (Mautner and Sinai, submitted for publication), and using this c_{solid} value and $r_{solid/solution}$ = 10.0 g/ml and in equation 1.

[d]Estimated as half of the yield of organic carbon obtained at 121°C for 15 min at solid/solution ratios of 0.01–0.04 g/ml (Mautner *et al.*, 1995).

[e]Elemental concentrations in soil solution. Concentrations in ppm (Bowen, 1966).

[f]Elemental concentrations in bacterial dry biomass in ppm (Bowen, 1966).

[g]Calculated maximum bacterial populations (CFU/ml) allowed by the concentration of a given nutrient in the extracts of Allende and Murchison obtained by extractions by $r_{solid/solution}$ = 10.0 g/ml as given in rows 2 and 4. Calculated using equation 4 for bacteria with radius of 1 μm, dry mass of 2×10^{-12} g, and elemental content per gram bacterial dry mass as in row 6 (Bowen, 1966).

Table 2. Microorganisms and Populations Observed in Meteorite Cultures Inoculated with a Mixed Microbial Population Isolated from a Peat Bog Extract

Biolog 96-well carbon source ID	Gram stain/ Cat/Oxy tests[a]	Biolog sim, distance[b]	Allende		Murchison		Sand solution[c]
			Extract[c]	Wet solid[d]	Extracts[c]	Wet solid[d]	
C. michiganense	GP rod	0.398	8E4	1.0E6[d]	6.6E5	9.0E5[d]	1.6E6
	Cat +	1.74		2.8E6[e]		2.0E6[e]	
	Oxy +						
M. imperiale	GP rod	0.278	6E4	4.6E5[d]	3.4E5	9.4E5[d]	—
	Cat +	12.78		4.0E5[e]		3.4E5[e]	
	Oxy +						
E. saperdae	GP rod	0.706	6E4	—	—	—	—
	Cat +	4.35					
	Oxy +						
P. putida	GN	0.61	6E4	1.6E5[d]	1E5	—	1.2E5
	Oxy +	5.99		4.0E4[e]			
Corynebacterium sp.	GP rod		1.6E6	4.2E5[d]	3E6	3.7E6[d]	
	Oxy −			3.0E4[e]		2.8E4[e]	
Yeast			1E4				
Filamentous fungus			1E4		7E4	2.6E5	2E5
Total population			1.9E6	2.0E6[d]	4.2E6	5.8E6[d]	1.9E6
				4.7E6[e]		4.8E6[e]	

[a]GP, gram-positive; GN, gram-negative; Cat, catalase; Oxy, oxidase.
[b]Indicators of reliability of Biolog plate identification.
[c]Post-log-phase steady-state populations in meteorite and sand extracts cultured for 31 days. Extracts refer to cultures in extracts obtained at solid/solution ratios of 0.02 g/ml.
[d]As in footnote c, for populations in the liquid phase over the wetted solids after 31 days. Wet solids refer to cultures at solid/solution ratio of 1.0 g/ml.
[e]As in footnote d, populations in the same cultures after 8 months. In addition to the species listed, the long-term Allende cultures contained a new species with globular yellow colonies, 1.2×10^6 CFU/ml, and with small green-yellow colonies, 2.1×10^5 CFU/ml. The long-term Murchison cultures contained the species with globular yellow colonies, 1.2×10^6 CFU/ml, and a species with flat cream yellow colonies, 1.1×10^6 CFU/ml.

ments depends on the objectives of the simulation, such as models of early life or future terraforming. Early life on Earth or in asteroids and comets would probably be anaerobic, while the aim of terraforming is to create habitable oxygen-rich environments. The latter aerobic systems are addressed in this work.

The minimum usable sizes of microcosms are defined by the requirement of measurable amounts of chemicals and microorganisms. Current common analytical methods and the usual range of extractable contents require 0.001–1 g of meteorite or mineral samples for nutrient analysis and for algal assays and 10^{-6}–10^{-2} g for microbial studies. Typical experimental series require several times this amount for various treatments and replicates.

Solution chemistry of asteroid and cometary interiors

Carbonaceous chondrite materials may be exposed to water in nature at widely varying solid/solution ratios. For example, meteorites that land in oceans or lakes are extracted at virtually infinite dilutions at very low solid/solution ratios. At the other extreme, water filling the pores of meteorites that fall on land is extracted by the penetrating water at a high excess of solid at solid/solution ratios of ~10 g/ml, given the porosity of ~20% by volume of CM2 meteorites (Corrigan *et al*., 1997). The latter conditions also apply in asteroids during aqueous alteration when the internal pores are filled with water.

A high concentration of soluble electrolytes in such fluids was implicit in our previous data (Mautner *et al*., 1995; Mautner, 1997a) and more recently in discussions by other authors (Bodnar and Zolensky, 2000; Cohen and Coker, 2000). The temperatures in these objects may range from 25 to 150°C for thousands of years (Bunch and Chang, 1980; Tomeoka and Buseck, 1985; Brearley and Jones, 1998; Shearer *et al*., 1998).

Figure 1 and Table 1 illustrate that the equilibrium concentrations of ions in these solutions can vary widely with solid/solution ratio. Table 1

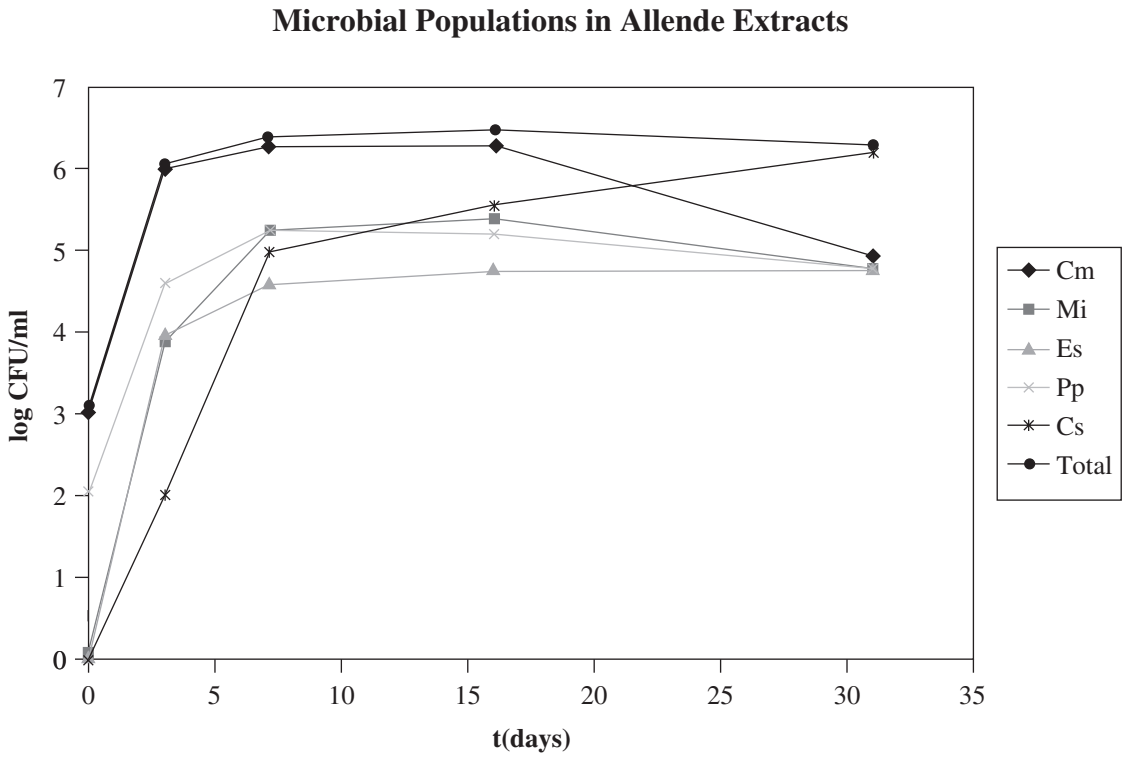

FIG. 2. Microbial populations in Allende extracts. Cm, *C. michiganense*; Mi, *M. imperiale*; Es, *E. saperdae*; Pp, *P. putida*; Cs, *Corynebacterium* sp.

compares the concentrations of the extracted electrolytes from Allende and Murchison with terrestrial soil solutions. The results show that the concentrations in the dilute Allende extracts obtained at $r_{solid/solution}$ = 0.02–0.1 g/ml are generally below soil solutions or in the lower range of soil solutions. The concentrations of electrolytes in Murchison extracts at this solid/solution ratio are remarkably close to the median soil solution values except for higher levels of sulfate and phosphate.

For the solutions obtained at $r_{solid/solution}$ = 10 g/ml in Allende, the concentrations of cations and Cl exceeded the upper limits of soil solutions by about an order of magnitude, while NO_3-N, SO_4-S, and PO_4-P were in the range of terrestrial soil solutions. However, the concentrations of cations in the Murchison extracts at $r_{solid/solution}$ = 10 g/ml were higher than the upper range of soil solutions by over two orders of magnitude. Even the concentrations of NO_3-N and PO_4-P are comparable to the upper range of soil solutions. Sulfate is in large excess, with some possible implications discussed below. The high concentrations in these Murchison extracts may be in the toxic range for plants. The micronutrients and possibly toxic elements Mn and Fe were found to be higher than the upper limit in typical surface soil solutions by factors of 55 and 360, respectively, and Ni was present at very high levels. However, some of these elements may also serve as oxidizable energy sources for microbial communities.

In molar units, the total concentration of the ions at $r_{solid/water}$ = 10.0 g/ml in the Allende extract is 0.097 mol/L with an ionic charge of 0.15 Eq/L, and that in the Murchison extract is 3.8 mol/L with an ionic charge of 6.6 Eq/L (Table 2). The latter values are much higher than the median electrolyte concentration of 0.031 mol/L and ionic charge of 0.034 mEq/L in average surface soil solutions. The high electrolyte concentrations in the meteorite solutions imply that these solutions have high ionic strengths and osmotic pressures.

The amount of organic carbon that can be extracted from Murchison at 20°C is ~1 mg/g (Mautner, 1997a). If this applies at $r_{solid/solution}$ = 10 g/ml, the concentration of organic carbon in the asteroid fluids can be estimated as 10 g/L or ~1 mol/L in the pores of carbonaceous chondrites. This represents only 10% of the total organic carbon in Murchison, the rest remaining as insoluble compounds and organic polymer. If

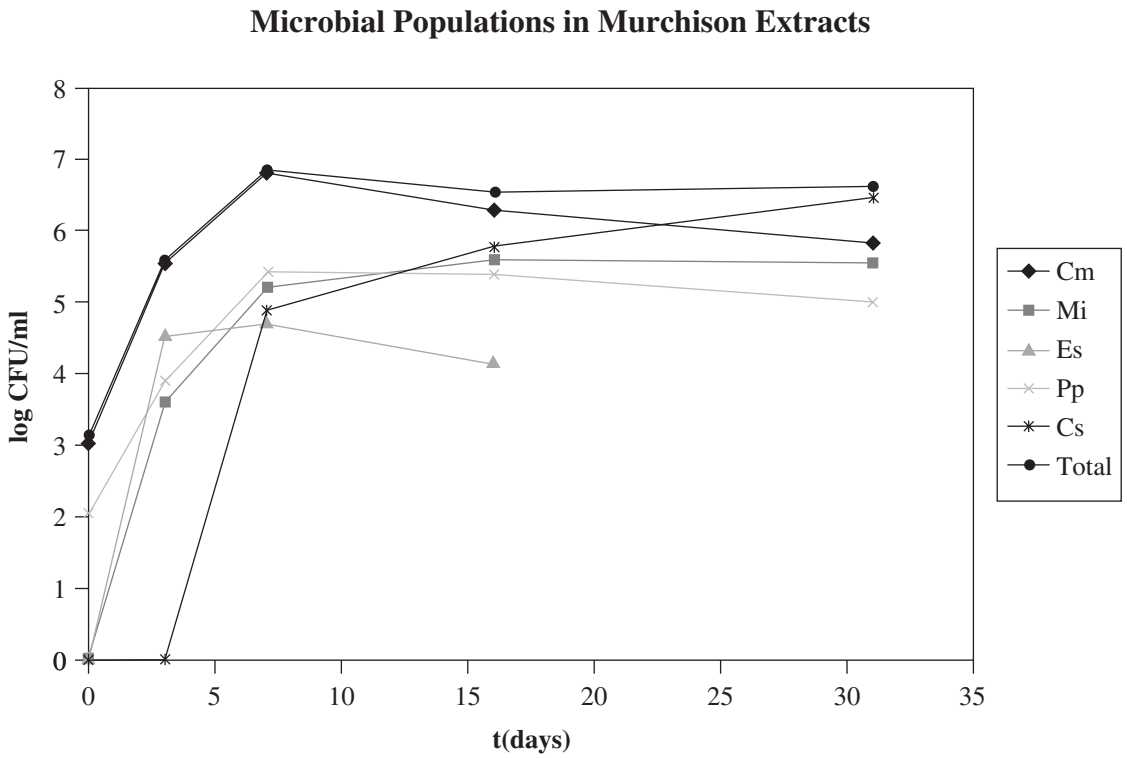

FIG. 3. Microbial populations in Murchison extracts. Notation as in Fig. 2.

this insoluble carbon was present in the parent bodies originally as unpolymerized soluble material, the concentration in solutions in the parent asteroid or cometary fluids may have been in the range of 10 mol/L.

Biogenesis in carbonaceous chondrite asteroids and meteorites

The preceding section suggests that the pores of carbonaceous meteorites and asteroids contain strong electrolytes with a total ionic concentration of >3 mol/L, composed of the ions in Table 1; silicates; organic C (1–10 mol/l); catalytic minerals including clay-like phyllosilicates with a large specific surface area of 3.7×10^4 m^2/kg (Mautner, 1999); and pH 7–8 (Mautner, 1997a). The dissolved metals, clays, and minerals such as FeS can serve as catalysts (Bernal, 1951; Cairns-Smith and Hartman, 1986). The high concentrations and catalysts are conducive to complex organic synthesis, and the trapped products can undergo further reactions leading to large molecules.

The concentrations and osmotic pressures of these solutions can be comparable to those of a cell interior. Chemistry similar to that in cells can therefore occur in the meteorite/asteroid fluids without the need for enclosure in membranes. With such solutions a saturated meteorite or asteroid, or a solution layer in a comet, may function as a giant cell. This hypothesis is supported by the relative concentrations of N, P, K, soluble C, Ca, Mg, Na, Cl, and S in these solutions, which are similar to those in bacterial or algal biomass. Alternatively or later, primitive cells bound by inefficient or weak membranes may form (Deamer, 1985, 1992) and survive without osmotic rupture under these conditions, dividing the solution into cells.

The asteroid environments would have also included CO_2 and H_2 captured from gases in the Solar Nebula, significant amounts of sulfur and sulfides (3% in Murchison), and temperatures of 25–150°C in the mesophilic, thermophilic, and hyperthermophilic range. These conditions are suitable for archaea, possibly methanogens, and sulfur bacteria. In other words, the conditions in the asteroids, or in similar solutions on meteorites that landed on early aqueous planets such as Earth and Mars, are therefore consistent with the possible origins of life in the interiors of car-

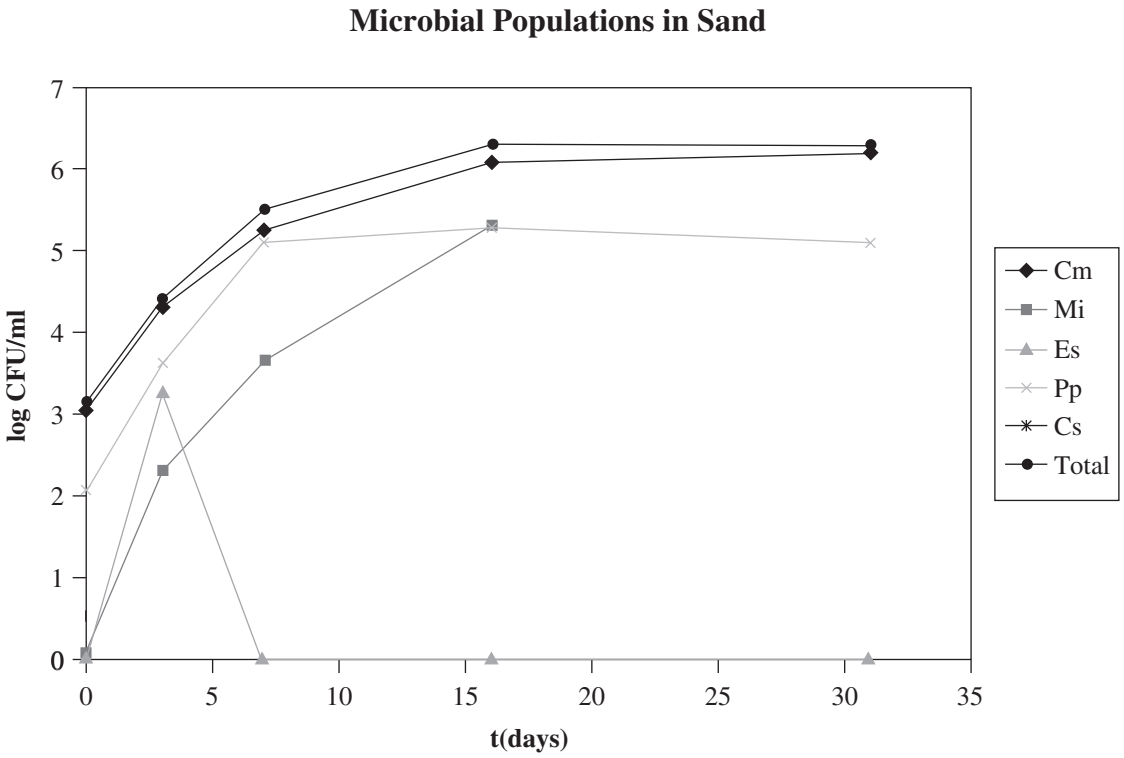

FIG. 4. Microbial populations in extracts of acid-washed sand. Notation as in Fig. 2.

bonaceous chondrite objects, or early adaptation to such environments. These conditions were at least as suitable for the primitive microorganisms as hydrothermal vents. In addition, the asteroid and meteorite interiors had the advantage of trapping chemicals and microorganisms for thousands of years, allowing for continued chemical and biological evolution. Although the amount of organics delivered by meteorites was only a fraction of the amount delivered by IDPs, the 10^{14} kg of carbonaceous meteorites that landed in the first 10^8 years (Chyba and Sagan, 1992), which con-

TABLE 3. ALGAL POPULATIONS IN METEORITE EXTRACTS AND WET SOLIDS (CFU/ML)

	Concentration (CFU/ml)			
	Green unicellular[a]	*Brown diatom*[a]	*Blue-green filamentous*[a]	*Total*
Extracts				
Initial, all extracts	1E4	2E2	8E1	1.0E4
Allende	4.8E4	4E3	1E3	5.3E4
Murchison	4E4	8E3	4E2	4.8E4
Sand	4E4	1E4	4E2	4.8E4
Wet solid				
Initial, all solids	5E5	1E4	4E3	5.1E5
Allende	0	4E4	0	4E4
Murchison	4E5	1E4	2E3	4.1E5
Sand	8E4	8E4	2E3	1.6E5

Algal populations in the mixed bacterial and algal cultures were assayed after the initial inoculation and after 15 days. Extracts refer to cultures in extracts obtained at solid/solution ratio of 0.02 g/ml. Wet solids refer to cultures at solid/solution ratio of 1.0 g/ml.

[a]Green unicellular algae, *Chlorella* sp. and *Chlorosarcinopsis* sp.; brown diatom, *Navicula* sp.; filamentous cyanobacteria, *Leptolyngbya* sp. and *Phormidium* sp.

tained ~0.1 g/kg of soluble complex organics, could have accommodated at least 10^{10} kg biomass in 10^{24} microorganisms (see below), more than enough for a first evolving biota.

Microbial populations in meteorite solutions

As an extension of the previous studies of pure microbial populations (Mautner, 1997a; Mautner *et al*., 1997), the present experiments used complex microbial inoculants. The results in Tables 2 and 3 show that complex microbial communities, which include bacteria, fungi, and algae, can grow on the meteorites. Table 2 shows that comparable population densities were observed in the dilute extracts and in the liquid on the wet solids.

Figures 2 and 3 and Table 2 show that the extracts of the two meteorites developed comparable microbial populations, with the Allende populations being slightly lower possibly because of the lower concentration of nutrients in these extracts. On the other hand, Allende solutions yielded the most diverse microbial populations, and in the long term its populations reached comparable levels to those in the Murchison solutions. Several additional microorganism species, not shown in Table 2, were also observed in Allende in small numbers. However, microorganisms in the extracts of both meteorites exhibited overall similar growth profiles, including the replacement of *C. michiganense* by *Corynebacterium* sp. as the dominant species after ~~15 days.

The long-term survival of microorganisms on these materials was tested by measuring the populations after 8 months of incubation. Table 2 shows that the populations survived and in fact increased during this long period. The main species—*C. michiganense*, *Microbacterium imperiale*, and *Corynebacterium* sp.—reached practically identical populations in both the Allende and Murchison cultures. Both also showed large populations of an additional unidentified species that formed yellow globular colonies and some additional new species in smaller numbers. The total population counted after 8 months in both cultures was also practically identical, 4.7–4.8 $\times 10^6$ CFU/ml.

The general similarity of microbiology in the two meteorites is notable considering the much higher concentration of electrolytes in the Murchison extracts. Given that some of the microorganisms also grew and survived on nutrient-free acid-washed sand indicates that these species may be oligotrophs possibly living on organics from the laboratory air. We demonstrated in the past that Murchison organics can provide the sole carbon source for microorganisms (Mautner *et al*., 1997). The long-term survival of microorganisms on the wet meteorite solids after 8 months of incubation showed that the Murchison meteorite solutions do not contain toxic components that would prevent microbial growth.

The total algal populations in the Allende extracts were also found to be comparable to those in the Murchison extracts as seen in Table 3, while in the concentrated solutions on the wet solids Allende gave lower algal populations than Murchison or the wet sand. This suggests that the concentrated Allende solutions inhibited algal growth. Similar inhibitory effects of Allende extracts were observed on potato tissue cultures (Mautner, 1997a).

Both meteorites supported more diverse microbial populations than inert sand. The meteorite extracts also showed the development of *Corynebacterium* sp. as the dominant species after ~15 days. The large populations of *C. michiganense* and *P. putida* in the extracts of inert sand suggest that these microorganisms are oligotrophs. The fungi in later stages of the cultures may utilize the biomass produced by autotrophs and the detritus from the bacterial and algal populations.

The biomass that can be supported by any given nutrient x in the solid soil or meteorite can be calculated by equation 2:

$$m_{\text{biomass,xl}}\ (\text{g}) = 1{,}000 c(x)_{\text{solid}}\ (\text{mg/g})\ m_{\text{solid}}\ (\text{g}) / c(x)_{\text{biomass}}\ (\mu\text{g/g}) \quad (2)$$

Here $m_{\text{biomass,xl}}$ is the amount of biomass that can be obtained if limited by nutrient x, $c(x)_{\text{solid}}$ is the concentration of extractable x in the solid, m_{solid} is the mass of the solid extracted, and $c(x)_{\text{biomass}}$ is the concentration of bioavailable x in the dry biomass.

For calculating the limiting microbial population in the aqueous extract of the solid, the amount of microbial biomass in the solution can be expressed by equation 3:

$$m_{\text{biomass,aq}}\ (\text{g}) = c_{\text{microorganisms}}\ (\text{CFU/ml})\ V_{\text{aq}}\ (\text{ml})\ m_{\text{microorganism}}\ (\text{g}) \quad (3)$$

Here $m_{\text{biomass,aq}}$ is the amount of biomass in V_{aq}

volume of solution, contained in organisms each of $m_{\text{microorganism}}$ dry biomass. Combining equations 2 and 3 yields the limiting microbial population density in solution:

$$c_{\text{microorganism(aq),xl}}\ (\text{CFU/ml}) = \frac{1{,}000c(x)_{\text{solid}}\ (\text{mg/g})r_{\text{s/w}}(\text{g/ml})}{c(x)_{\text{biomass}}\ (\mu\text{g/g})m_{\text{microorganism}}(\text{g})} \quad (4)$$

Here $c_{\text{microrganisms(aq),xl}}$ is the concentration of microorganisms allowed if x is the limiting nutrient, $r_{\text{s/w}}$ is the solid/solution ratio in the extraction, and $c(x)_{\text{solid}}$ is the concentration of nutrient x in the solid that is extractable at this solid/solution ratio.

The last two rows of Table 1 show the sustainable populations of typical bacteria with a radius of 1 μm and dry mass of 2×10^{-12} g calculated using equation 4. The results show, for example, that the Ca content in the concentrated Allende solutions (at $r_{\text{solid/solution}} = 10.0$ g/ml) can sustain 4.1×10^{10} bacteria/ml, while the NO_3-N content in the extract is sufficient only for 3.5×108 bacteria/ml. These calculations show that NO_3-N, PO_4-P, K, and even soluble C limit the bacterial populations to quite comparable levels of $3.5–10 \times 10^8$ bacteria/ml in the concentrated Allende extracts. The nutrients K and P lead to similar limiting levels also in the Murchison extracts, consistent with the similarity of the observed populations in the two extracts as shown in Table 2. The limiting nutrients in the meteorite extracts are nitrate, phosphate, and potassium, similar to those in many terrestrial ecosystems.

The other essential nutrients—Ca, Mg, Na, and SO_4-S—are all sufficient to provide larger populations: $>10^{10}$ bacteria/ml in the Allende and $>10^{12}$ bacteria/ml in the Murchison solutions.

Note that soluble elements in the group N, P, K, and C and elements in the group Ca, Mg, Na, Cl, and S in the meteorite extracts can support mutually similar populations of bacterial biomass. This is a consequence of equation 4 as $c(x)_{\text{solid}}$ and $c(x)_{\text{biomass}}$ are similar in these groups of elements. In other words, the relative concentrations of the soluble forms of these elements in Murchison are similar to their relative amounts in bacterial biomass.

The high concentrations of sulfate and Ni, and possibly Fe and Mn, may be toxic to some organisms. However, we did not observe toxic effects, as the microbial populations in the concentrated solutions on the wet solids were comparable to or larger than those in the more dilute solutions (Table 2).

The Biolog tests provided some useful information on the possible meteorite components utilized by the microorganisms. All of the microorganisms can use glycerol, a polyalcohol that may be present in Murchison considering the presence of various alcohols and other hydroxylated compounds such as carboxylic and amino acids. One of the microorganisms, *P. putida*, also utilizes other Murchison components such as acetic acid and alanine. Murchison also contains a large number of other likely nutrients for heterotrophs that were not included in the Biolog tests.

IMPLICATIONS

Indications of past microbial activity?

Some of our observations are consistent with the hypothesis of possible biological activity in the carbonaceous chondrite parent bodies (Claus and Nagy, 1961; Urey, 1962). Previously, we found that the composition of the Murchison materials resembles biologically developed terrestrial soils in its overall organic content, C/N ratio, cation exchange capacity, and concentrations of the available macronutrients (Mautner, 1997b, 1999). The effects of the Murchison meteorite on microorganisms are also similar to the effects of biologically developed soils (Mautner, 1997b; Mautner *et al*., 1997). As noted above, the ratios of soluble N, P, K, C, Ca, Mg, Na, Cl, and S in the meteorite are also remarkably similar to those in biological materials. This observation is consistent with the deposition of the soluble elements from a microbial biomass. Alternatively, the present biological elemental ratios may reflect the conditions of early life in carbonaceous chondrite asteroids or meteorites.

The large concentration of soluble sulfate, 9.4 mg/g, observed in Murchison (Table 1 and Mautner, 1997a), is also consistent with a microbial activity hypothesis. This concentration is much higher than in the other types of meteorites we analyzed, where the soluble sulfate concentrations are <1 mg/g, including stony and Martian meteorites, igneous terrestrial analogs, and serpentine. Though the Murchison parent body formed under reducing Solar Nebula conditions in the absence of oxygen, it is uncertain whether

oxidized sulfur can be formed chemically under these conditions. Alternatively, sulfide-oxidizing bacteria could oxidize sulfur under these conditions. We are testing this hypothesis by examining the SO_4-S isotopic composition in carbonaceous chondrites for biological signatures.

Sustainable populations on asteroid resources

The measured amounts of bioavailable nutrients allows an experiment-based estimate of the biomass that could have existed in the early Solar System or that could be established in the future, based on carbonaceous chondrite resources. The biomass that could be obtained as limited by nutrient x is obtained from equation 2, using $m_{solid} = 10^{22}$ kg as the total mass of the carbonaceous asteroids (Lewis, 1997); the allowed microbial population is obtained from $m_{biomass,xl}/m_{microorganism}$, where $m_{microrganism} = 2 \times 10^{-12}$ g is used as an estimated average. Further, the allowed human population can be calculated by assuming, for example, 10^4 kg biomass supporting a human on a terraformed planet or space colony:

$$n_{population} = 10^{-4} c(x)_{solid} \text{ (mg/g) } m_{solid} \text{ (g)} / c(x)_{biomass} \text{ } (\mu g/g) \quad (5)$$

Given the similarity of equations 4 and 5, the allowed biomass (kg) and human population, based on carbonaceous chondrite Murchison CM2 type asteroids, are obtained by multiplying the last row in Table 2 by 2×10^9 and 2×10^5, respectively. This again yields NO_3-N and PO_4-P as the limiting nutrients. Both lead to similar values, with an NO_3-N limited biomass of 1.3×10^{18} kg in 6.5×10^{32} microorganisms, supporting a human population of 1.3×10^{14}, or $\sim 10^{-4}$ kg biomass/kg asteroid material. The values based on PO_4-P are similar, being larger by a factor of 1.4. Note that the actual populations in Table 2 are lower by about a factor of 100 than the calculated nutrient-limiting populations. The asteroid-based populations would be lower by a factor of 100 using these actual observed populations.

Natural and directed panspermia

Comets were proposed as vehicles for natural panspermia (Hoyle and Wikramashinge, 1978). As noted above, comets may contain pockets of water that contain fluids similar to the concentrated Murchison extracts. During perihelion passes, the water pockets of comets can reach temperatures of 20–100°C. Comets could also be used deliberately for directed panspermia by seeding them with microorganisms that can grow to a substantial biomass during perihelion passes. The microorganism-bearing comets could then be fragmented and propelled or allowed to eject naturally to interstellar space (Mautner, 1997b).

However, comets have limited potential for directed panspermia as liquid water may not form, or may be lost rapidly by evaporation. This also limits the surface temperatures to <180°K, too low for microorganisms (Komle *et al.*, 1991; Lewis, 1997). At best, liquid water may exist for short periods under those conditions in small pockets shielded by carbonaceous deposits. These conditions are not favorable for complex chemistry, however, and do not allow sustained evolving microbial populations.

In contrast, asteroid interiors during aqueous alteration could contain large volumes of water for thousands of years. For example, a 10-km radius asteroid or cometary nucleus of $\sim 10^{16}$ kg with 10% water content can contain $>10^{15}$ L of nutrient electrolyte solutions similar in composition to those in Table 1. Following the calculations in the preceding section, this asteroid may accommodate a biomass of 10^{12} kg in 5×10^{26} bacteria and $\sim 10^{24}$ algae. As noted, the total asteroidal mass of 10^{22} kg could accommodate $>10^{32}$ bacteria and 10^{30} algae.

In fact, large numbers of asteroids simultaneously undergo aqueous alteration. Collision amongst these objects are frequent (Lewis, 1997), and impact collisions can distribute microorganisms (Mileikowsky *et al.*, 2000). Even small meteorites ejected by these collisions can provide enough shielding to protect microorganisms in space for months (Horneck *et al.*, 1994), until recapture by another object. These considerations, combined with the present results, suggest that significant microbial populations can grow in aqueous asteroids. Collisions could have distributed microorganisms efficiently in the early Solar System.

Part of this population would be preserved at low temperatures in the interiors of asteroids and comets, and a fraction subsequently delivered to planets. Other asteroids and comets would be ejected to interstellar space, and some of these would spread the microorganisms to other protoplanetary nebulae where they could multiply and be propelled to yet further nebulae. This

mechanism therefore proposes asteroids, protoplanetary nebulae, and early solar systems for the growth and dispersion of microbial life, instead of or in addition to the cometary proposals (Hoyle and Wickramasinghe, 1978).

A similar mechanism can be applied in directed panspermia (Crick and Orgel, 1973; Mautner and Matloff, 1979; Mautner, 1995, 1997b). For example, comets may be seeded with microorganisms. Natural melting during perihelion passes may allow the microorganism to multiply. Microbial inoculants may also be inserted deeper into the cometary nuclei along with artificial heat sources to melt the ices and create subsurface pools. Given the possible relations between carbonaceous asteroids and comets, concentrated solutions in these pools may be similar to those observed in the Murchison extracts and can allow similarly the growth of large microbial populations. Eventually, the comet may be fragmented and ejected into interstellar space toward new solar systems in star-forming clouds, carrying the microbial payload. If nonperiodic comets in parabolic orbits are seeded, this ejection will occur naturally.

The cometary interiors can shield the microbial content from prolonged space radiation, although the effects over transit times of millions of years are not known. If long-lived radioactive heat sources were present, a self-recycling microbial community could renew itself genetically during the long interstellar flights. The microorganisms could multiply and disperse collisionally in the target protoplanetary nebulae and asteroids, seed local planets, and eventually disperse by comets to further solar systems. Using the above relations between nutrients and biomass, the 10^{25} kg of comets in the Oort cloud could yield 10^{21} kg biomass comprising $>10^{35}$ microorganisms, sufficient to seed new solar systems throughout the entire Milky Way galaxy (Mautner and Matloff, 1979; Mautner, 1995, 1997b). It is also possible that intelligent civilizations evolving in the seeded habitats would deliberately propagate life further in the galaxy.

Terraforming and space agriculture

Carbonaceous chondrites are likely to be the main sources of carbon and water in space-based agriculture. In space colonies and in terraformed asteroids, they may be used as soils and fertilizers. The carbonaceous moons Phobos and Deimos may be mined for soils and fertilizers in Martian terraforming.

Algae are likely to be used as colonizing microorganisms (Friedmann and Ocampo-Friedmann, 1995). A viable soil ecology will subsequently require a diverse microbial population and the recycling of nutrients by bacteria and fungi. The microbial results above demonstrate that carbonaceous chondrite soils can sustain diverse microbial ecosystems.

If ground into particles as in the present study, the Murchison soil is similar in particle size distribution to silty clay. In this form the agriculturally useable moisture content will be between the wilting point at 20% (wt/wt) and field capacity at 40% (wt/wt). These moisture contents are in the range used in the extractions above and will yield nutrient ion concentrations similar to those of the concentrated solutions in Table 1. The dilute solutions noted in Table 1 may also be used for hydroponics. Using the data in the preceding section, the total asteroid materials used as synthetic soils would allow a biomass of 10^{18} kg and support a human population of 10^{14} in these terraformed colonies.

SUMMARY AND CONCLUSIONS

The previously reported studies on carbonaceous chondrites (Mautner, 1997a; Mautner *et al*., 1997) have been extended here to natural aqueous conditions of high solid/solution ratios. The main experiment-based conclusions are:

1. Planetary microcosms, based on actual extraterrestrial materials in meteorites, are useful tools in experimental astroecology.
2. Based on microcosm studies, the interiors of carbonaceous chondrite meteorites can contain highly concentrated solutions of electrolytes, nutrients, and organics (i.e., >3 mol/L electrolytes, 1–10 mol/L organics).
3. The interiors of asteroids during aqueous alteration, or meteorites landed on aqueous planets, are therefore suitable for potential biogenesis.
4. Microorganisms can grow in the interior solutions of meteorites.
5. The biomass-like ratios of macronutrients in extracts from both meteorites, and the high sulfate content in Murchison, are consistent with past biological activity in carbonaceous

chondrite meteorites (i.e., soil fertility properties of Murchison are similar to those of biologically developed soils; organic polymer is similar to coal; ratios of soluble N, P, K, C, Ca, Mg, Na, Cl, and S are comparable to those in bacterial biomass).
6. Complex recycling communities of algae, bacteria, and fungi develop and survive for substantial periods in solutions prepared from extracts of carbonaceous chondrite meteorites (i.e., algal populations of $>10^5$ and microbial populations $>10^6$ CFU/ml of six species surviving over 8 months on *wet* Allende and Murchison).

The experiments described here provide a means to examine separately the nutrient contents and the microbial populations in the microcosms. In real ecosystems, microbial activity and available nutrients are interdependent and should be monitored simultaneously.

Theoretical calculations based on the results of this study suggest:

1. Carbonaceous asteroids containing nutrient solutions could distribute micoorganisms during a period of collision-mediated panspermia in the Solar Nebula and in the early Solar System (i.e., available nutrients allow a biomass of 10^{18} kg in a population $>10^{32}$ microorganisms in the asteroid belt).
2. Similarly, comets could be used as vehicles, and protoplanetary nebulae used as targets and incubators in directed panspermia missions for seeding new planetary systems with microbial life (i.e., the nutrients in the Oort belt comets could allow a biomass of 10^{21} kg containing 10^{35} microorganisms, sufficient to seed all new solar systems in the galaxy).
3. Carbonaceous chondrites provide suitable soil resources for planetary terraforming and space colonization (i.e., based on the limiting nutrients NO_3-N and PO_4-P, the total asteroid material could support a population of 10^{14} humans).

In combination, the results of planetary microcosm studies and theoretical considerations have a wide range of applications that include assaying the fertilities of planetary materials; targeting astrobiology exploration; identifying bioresources and estimating sustainable populations in the Solar System; and modeling ecosystems for terraforming, space colonization, and directed panspermia.

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ABBREVIATION

IDP, interplanetary dust particle.

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