"RARE" OR "PREVALENT" EARTH? CONDITIONS SUITABLE FOR LIFE WERE ESTABLISHED RAPIDLY ON THE YOUNG EARTH. N. L. Cates[1] and S. J. Mojzsis[1], [1]Department of Geological Sciences, Center for Astrobiology, University of Colorado at Boulder, 2200 Colorado Ave, UCB 399, Boulder, Colorado 80309-0399, USA, (nicole.cates@colorado.edu; mojzsis@colorado.edu).

Introduction: An important prerequisite for the search for life in extrasolar planetary systems is to determine when conditions suitable for sustained biological activity (liquid water, energy resources, and organic raw materials) arise on an Earth-like planet. Without an observational basis to constrain the establishment of a stable surface and hydrosphere on the early Earth, parameters used to argue whether Earth-like planets are rare [1] will remain conjectural. However, recent discoveries have offered unprecedented insight into the nature of the Earth's history in the first 500 m.y. and offer a glimpse into just how quickly a habitable surface becomes established.

While there are as yet no known terrestrial rocks that preserve evidence of surface conditions older than ca. 3.83 Ga [2-3], proxy data from detrital zircons as old as 4.38 Ga [4], have extended our understanding of the basic conditions on the Earth that were conducive to life to within 180 m.y. of solar system formation [5].

Until recently, the only direct records of surface conditions from before ~3.7 Ga were from metamorphosed volcano-sedimentary sequences captured in ca. 3.60-3.87 Ga granitoid gneisses of the *Itsaq Gneiss Complex* in West Greenland [6] at the *Isua supracrustal belt* [7], and in the scattered enclaves of the *Akilia association* [8]. Recent documentation of coeval pre-3.76 Ga metamorphic volcano-sedimentary sequences at the *Nuvvuagittuq supracrustal belt*, Minto Block, northern Québec (Canada) [9] now greatly expands the inventory of rocks from this pivotal time wherein life may have already originated [10,11].

Water: Evidence for the presence of liquid water early in Earth's history is recorded as elevated $^{18}O/^{16}O$ of some Hadean zircons [12,13]. Oxygen isotopic compositions can track the outcome of weathering and low-temperature alteration because the products are isotopically heavy ($\delta^{18}O_{VSMOW} \geq +10$‰ [14] so that the rocks and minerals derived, either in whole or in part, by such weathering products will also be enriched in ^{18}O. Zircon is resistant to re-equilibration of primary zircon oxygen isotopic values, even at high metamorphic grades [15,16]. These and other data for zircons can provide a robust measure of melt chemistry at the time of formation [17].

In the apparent absence of a sedimentary rock record from the pre-4 Ga Hadean Earth, it cannot be known if there was an extensive ocean or even if a continuous source of water has been present since that time. However, the elevated $\delta^{18}O$ values in some Hadean zircons suggest that the surface was at least temporarily cool enough at times to stabilize liquid water [12,13]. What is clear is that by about 3.8 Ga there is incontrovertible evidence for an ocean in the form of water-borne sediments (e.g. banded iron-formations) and the preservation of pillow structures in some metavolcanic rocks [2,3,6-9, and references therein].

Continents: Amphibolites from the pre-3.75 Ga *Isua*, *Akilia*, and *Nuvvuagittuq* supracrustals share arc-like geochemical compositions. These arc-like signatures are similar to those seen forming at many contemporary back-arc systems [3,6,8,9]. Although, there is little evidence for continental input into the detritus of early Archean sediments, evidence from both Hf isotopes [4] and Ti-in-zircon thermometry [18] in pre-4.0 Ga zircons strongly suggests that there was extensive continental crust formation in the Hadean.

Atmosphere: Mass-independently fractionated (MIF) sulfur isotopes [19], provide a powerful new tool for elucidating the nature of the early Earth's atmosphere. It has now been widely documented that Archean sedimentary sulfides and sulfates can preserve

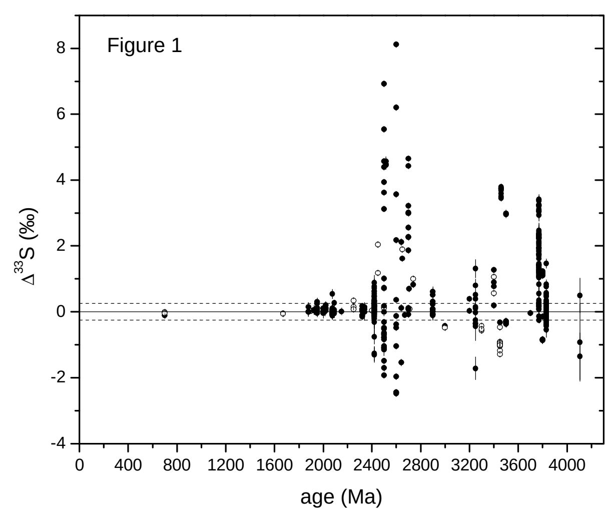

Fig.1. Sulfur multiple isotope data (expressed as $\Delta^{33}S$) for sedimentary sulfides and sulfates as a function of age. A large range in $\Delta^{33}S$ values for samples older than 2.42 Ga most likely reflects a change in atmospheric oxygen concentration past the $pO_2 = 10^{-6}$ PAL threshold [20] associated with the oxygenation of the surface.

MIF $|\Delta^{33}S| > 0.20‰$ values (**Fig. 1**), which stands in contrast with almost all sulfides and sulfates younger than 2.32 Ga which have mass-independent $\Delta^{33}S$ values from -0.30 to +0.30‰ [20]. These gas phase reactions are modulated by intense UV in anoxic atmospheres, so the presence of MIF in sedimentary sulfur from ca. 3.83 to 2.4 Ga suggests that the atmosphere was transparent to UV throughout its early history [reviewed in 21]. This observation not only has implications for very low partial pressures of molecular oxygen in the early atmosphere and no ozone layer (pO_2 «10^{-5} PAL), but also for pCO_2 (**Fig. 2**) which cannot have been above 0.5 bar [19,22] and low pCH_4,which may not have been sufficient to cause the formation of a UV-blocking haze [cf. 23]. The Hadean-early Archean Earth may have been cold for the most part [24].

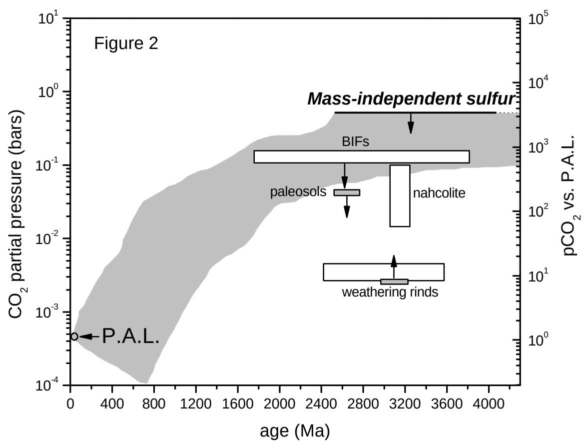

Fig.2. Changing CO_2 levels in the Earth's atmosphere over time expressed as both partial pressure of CO_2 in bars (left), and against present atmospheric level (PAL; right). The grey shaded region is the range of concentrations required to compensate for the fainter young Sun [25]. Other data points shown are reviewed in [26].

The "Prevalent Earth" hypothesis: Mounting evidence for a planet that was much more hospitable for life in the first billion years is gradually coming to light:

(i) geochemical support for extensive continental crust and plate-boundary processes suggests that several key physical parameters had more similarities than differences with today;

(ii) the preservation of $\Delta^{33}S$ points not only to the effective absence of free oxygen in the atmosphere, but also that methane and CO_2 were not present at levels sufficient to inhibit penetration of deep solar UV; and

(iii) the presence of water within ~150 m.y. of planet formation suggests that the Earth quickly became habitable, with the oceans and deep crustal habitats able to provide refugia from harmful UV radiation and meteorite bombardments.

Hence, the rapid development of at least one habitable world in our solar system may warrant a more optimistic view for the discovery of a multitude of other habitable worlds in the galactic neighborhood.

References: [1] Ward, P.D. and Brownlee, D. (2000) Rare Earth: Why complex life is uncommon in the universe. New York, Copernicus, 333 p. [2] Mojzsis S.J. and Harrison T.M. (2002) *EPSL, 202*, 563-576. [3] Manning, C.E. et al. (2006) *Am. J. Sci., 306*, 303 – 366. [4] Harrison, T.M. et al. (2006) *Science, 310,* 1947-1950. [5] Amelin Y. (2005) *Science, 310*, 1914 – 1915. [6] Nutman A. P. et al. (1996) *Precamb. Res., 78,* 1-39. [7] Myers J.S. (2001) *Precamb. Res., 109*, 129-141. [8] Cates N.L. and Mojzsis S.J. *GCA, 70*, 4229-4257. [9] Cates N.L. and Mojzsis S.J. (2007) *EPSL, in press*. [10] Mojzsis S.J. et al. (1996) *Nature, 384*, 55-59. [11] McKeegan et al. submitted. [12] Mojzsis S.J. et al. (2001) *Nature, 409*, 178-181. [13] Cavosie A.J. et al. (2006) *GCA, 70*, 5601-5616. [14] Muehlenbachs K. (1986) *Rev. Min. Geochem., 16*, 425-444. [15] Valley J. W. et al. (1994) *EPSL, 126*, 187-206. [16] Watson E. B. and Cherniak D. J. (1997) *EPSL, 148*, 527-544. [17] Valley J. W. (2003) *Rev. Min. Geochem., 53*, 343-385**.** [18] Watson E.B. and Harrison T.M (2005) *Science,308*, 841-844. [19] Farquhar, J. and Wing, B. (2003) *EPSL 213*, 1-13. [20] Pavlov A. A. and Kasting J. F. (2002) *Astrobiology, 2*, 27-41. [21] Mojzsis S.J. et al. (2003) *GCA, 67*, 1635-1658. [22] Shemansky, D.E. *J. Chem. Phys., 56*, 1582-1587. [23] Sagan C. and Chyba C.F. (1997) *Science, 276*, 1217-1221. [24] Zahnle, K. (2006) *Elements, 2*, 217-22. [25] Kasting, J.F. (1993) *Science, 259*, 920-926. [26] Rollinson, H. (2007) Early Earth Systems : A geochemical approach. Oxford, Blackwell, pp. 198-207.

Acknowledgments: This research was supported by the NASA Astrobiology Institute and a Cooperative Agreement with the University of Colorado Center for Astrobiology, the NASA Exobiology Program NAG5-13497 "Mission to Really Early Earth" and the University of Colorado.