

of crustal fault systems required to underpin the grand challenge of earthquake prediction; new understanding and predictive capabilities of geological processes such as tectonics and mineralisation.

URL: <http://www.quakes.uq.edu.au/ACCESS>

U42B-12 1655h

A Virtual Earth Simulator to Simulate Rupture Propagation on Earthquake Faults

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The particle-based Lattice Solid Model was developed to provide a basis to study the non-linear dynamics of earthquakes and the physics of rocks. A new approach, termed LSMearth, has been developed that allows different microphysics of earthquakes to be easily studied. The model - which runs in 2D or 3D - is implemented using an object-oriented approach and enables the effect of different microphysics on macroscopic behaviour to be studied. The application provides a virtual laboratory where all measurable quantities can be visualized and where the simulation, running on a remote super-computer, can be controlled from any personal computer. Simulations are run in parallel using a message passing approach based on MPI.

Unlike laboratory experiments which are limited in scale and where direct observations of the contacts occurring between grains of rock in the gouge layer is not possible, the numerical simulations allow the study of the nucleation process as well as the propagation of the shear rupture in experiments performed with bare surfaces or a gouge layer. Because the size of a shear rupture zone is approximately one order of magnitude larger than the nucleation region size, large-scale numerical simulations are here executed to analyse both shear rupture and the nucleation process and to study the scaling of the size and the duration of the nucleation with the size of the eventual earthquake. Using such large-scale experiments, the model provides a means to improve our understanding of the nucleation process and to gain insights into the mechanisms that control the growth of the nucleation zone.

U42C MC: 134 Thursday 1730h

The Future of Climate Change Research; Presentation by Ari Patrinos; Associate Director, Health Environmental Research, U.S. Department of Energy

Presiding: M K McNutt, Monterey Bay Aquarium Research Institute

U42C-01 1730h

The Future of Climate Change Research

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There is no abstract for this presentation.

U51A MC: 134 Friday 0830h

Origin and Early Evolution of the Earth I

Presiding: K Richter, University of Arizona; D C Rubie, University of Bayreuth

U51A-01 0830h INVITED

Habitability of Terrestrial Planets in the Early Solar System

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The Protoearth, Mars, Venus, and the Moon-forming impactor were potentially habitable in the early solar system. The interiors of larger asteroids had habitable circulating water. To see when the inner solar system became continuously habitable, one needs to consider the most dangerous events and the safest refugia from them. Early geochemical and accretionary processes set the subsequent silicate planet reservoirs and hence hydrospheric and atmospheric masses. The moon-forming impact made the Moon and the Earth sterile bodies. Following the impact, the Earth passed through a rock-vapor atmosphere on the scale of 1000s of years and an internally heated steam greenhouse on the scale of 2 m.y. Minerals bearing the principle volatiles (water, Cl, and CO₂) were stable at the Earth's surface by the time it cooled to 800K. The mass of re-actable shallow material was insufficient to contain the available water and CO₂. Habitable conditions were established after CO₂ could be deeply subducted into the mantle. Vast quantities of H₂ were vented during accretion and after the moon-forming impact and eventually lost to space. It is unknown whether significant amounts of this gas were present when the Earth's surface cooled into the habitable range. The moon remained sterile because its interior is essentially devoid of water. The mantle of the Earth, in contrast, cannot hold the available water, leaving the excess to form oceans. Nitrogen may behave similarly with the excess going into the air. Impacts of large asteroids (and comets) were an ever-present danger on otherwise habitable planets. The safest niche on planets was kilometer or deeper crustal rocks habitable by thermophiles. It is inevitable that several objects, which would have left only thermophile survivors, struck the Earth. Such events were so infrequent that the conditions of such a bottleneck should not be confused with conditions for the origin of life. An alternative refugium involves ejection of life within rock fragments and return of such fragments to the surface of the home planet or transfer to another habitable planet. Mars and the larger asteroids were habitable first and provide likely sources of seed and also testable places to look for preserved evidence. Extant terrestrial life appears to have passed through thermophile bottlenecks. There are subtle hints of space transfer. The need of extant life for Ni may be a vestige of life on a young planet covered with ultramafic rocks.

U51A-02 0850h INVITED

An impact origin of the Earth-Moon system

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In the leading hypothesis for lunar origin, the Moon forms from debris ejected as a result of the collision of a roughly Mars-sized impactor with early Earth (Hartmann & Davis 1975; Cameron & Ward 1976). The likelihood of giant impact events has been substantiated by over a decade of planetary accretion simulations (e.g., Wetherill 1985, 1992; Agnor et al. 1999; Chambers 2001). The most recent simulations predict a median accretion time of 50 million years for an Earth analogue to reach 90% of its final mass (Chambers 2001), in good agreement with lunar and terrestrial formation times derived from Hf-W systematics (e.g., review by Halliday et al. 2000).

Simulations of potential lunar forming impacts using a method known as smooth particle hydrodynamics, or SPH, can now achieve resolutions sufficient to study the production of bound debris necessary to yield the Moon. A wide variety of works have found that off-center, low-velocity collisions yield material in bound orbit from which a satellite may then accumulate. However, identifying impacts capable of producing the Earth-Moon system has proven difficult (Cameron 1997, 2000, 2001; Cameron & Canup 1998, Canup et al. 2001). Previous works (Cameron 1997, 2000, 2001) identified only two types of impacts capable of producing the Moon. The first involved an impact by an object with about 3 times the mass of Mars, and about twice the angular momentum of the Earth-Moon system; the second involved an impact of an object with about twice the mass of Mars with an Earth that was only about half formed. Both scenarios are more restrictive and problematic than that originally envisioned, since they require that the Earth-Moon system's mass or angular momentum be significantly modified after the Moon-forming event by either multiple large impacts, or selective subsequent accretion of material onto only the Earth and not the Moon.

Recent scaling trends identified in the SPH simulation results (Canup et al. 2001) implied that a smaller, Mars-mass impactor would be better able to simultaneously account for the Earth-Moon system mass and angular momentum (Canup & Asphaug 2001). This smaller scale impact had not been considered viable since early low-resolution SPH simulations found that

it placed too much iron into orbit to yield an appropriately iron-poor Moon (Benz et al. 1986). However, recent work using high-resolution simulations (Canup & Asphaug 2001) found that impacts by an object with 10 to 12% of the Earth's mass produce orbiting debris that is less than 3% iron by mass, and that contains sufficient mass and angular momentum to yield the Moon outside the Earth's Roche limit. This type of impact leaves the Earth-Moon system with approximately its final mass and angular momentum, and implies that the Moon formed near the very end of Earth's accretional history.

U51A-03 0905h INVITED

Review of Early Intense Bombardment and Associated Problems

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Since pre-Apollo years of the 1960s, it has been recognized that cratering on the moon must have been much more intense, averaged over the first few hundred My, than the average after 3500 My ago. This phenomenon is known as the "early intense bombardment." Initial interpretation of Apollo data raised the possibility that much of this cratering occurred in a single episode, or "spike" on the flux vs time curve, at about 3950 My ago, with a width of about 150 My. In some interpretations this was the primary source of all early cratering, known as a "catastrophic terminal bombardment." In one model Ryder has suggested that there was very little cratering before this. In other models, this is a spike superimposed on a declining flux, and there may have been various spikes.

A host of problems remain.

(1) Do we really have adequate dates for the lunar basins? The predominant opinion seems to be that virtually all visible basin were created in a burst within about 300 My. Confirming these dates would resolve the existence of the proposed catastrophe, which would then be constrained to involve numerous 50 and 100-km scale bodies hitting the moon.

(2) How does intense cratering work to remove earlier samples of igneous crustal rocks and impact melts? The original suggestion of the catastrophe was in order to explain the paucity of pre 4000-My rocks in the lunar sample. Cumulative impacts tend to destroy early rocks whether or not they are concentrated in a catastrophe. In some models, the extended declining impact, due to megaregolith production, tends to destroy impact melts because they concentrate at the surface, while dredging up (and yet also pulverizing) crustal igneous samples from deep-seated reservoirs.

(3) How severe is the absence of pre-4000 My impact melts? Their absence has been used as an argument for the existence of a cataclysm at 3950 My ago. But the details of item (2) need to be combined with actual distributions of impact melt ages and igneous rock ages to refine these discussions.

(4) Do lunar meteorites show the same age distributions and properties as the front side Apollo samples? This may be a test of the hypothesis that Imbrium debris have contaminated the front side.

(5) Do asteroids show the same age distributions as the lunar samples? Available models of a cataclysm at 3950 My ago suggest the impactors came from the outer solar system and therefore they should have affected the asteroid belt as well.

(6) What is the significance of the "Genesis Rock," ALHA 84001, among the first 20 specimens from Mars given that astronauts were trained to look for lunar "Genesis Rocks" and couldn't find them? Mars should have been affected by the cataclysm, according to available models. Hartmann (2001) suggested it tells us that the Martian crust was not destroyed by plate tectonics as on Earth, and parts of the primordial Mars crust were exposed by erosion to provide the meteorite source. Hence Mars may be the only planet where we can access a primordial crust. The erosion must have happened after a putative cataclysm at 3950 My ago.

(7) In short, did a cataclysmic spike at 3950 My ago, how big was it in terms of forming most lunar basins and other features, and how much of the total lunar cratering was concentrated in it?

U51A-04 0920h INVITED

The Formation of a Water-Rich Earth

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It is now generally accepted that in the inner solar system the process of runaway growth ended with the formation of many "planetary embryos" of lunar to martian mass (1,2). The terrestrial planets then formed on a longer time-scale (from several tens to a hundred million years), by the high-velocity mutual collisions of these embryos (3,4,5).

The radial extent of the primordial population of planetary embryos is not known. In principle, a system of embryos originally within 2 AU from the Sun

could form terrestrial planets on time-scales compatible with geochemical constraints (4). However, an even better agreement with the geochemical time-scales is achieved if one postulates that the formation of the embryos occurred also in the asteroid belt (5). This scenario has also additional advantages: (i) the original presence of planetary embryos explains the presently observed properties of the asteroid belt (6); (ii) in 3/4 of the cases a terrestrial planet accreted at least one embryo coming from the outer asteroid belt, which was presumably heavily hydrated, on the basis of meteorite analyses and modeling of the solar nebula. This could have brought to the Earth up to 10 times the present amount of water in the crust, with the correct isotopic composition (7).

The amount of water carried to the Earth by small asteroids and comets is negligible with respect to that acquired through the accretion of an hydrated embryo, and it would not be enough to explain the current budget of water on Earth. Nevertheless this contribution may be important, because it occurred since the very beginning of the planet's formation.

selected references: (1) Wetherill and Stewart, 1989, *Icarus*, 106, 190 (2) Weidenschilling et al., 1997, *Icarus*, 128, 429 (3) Wetherill, 1992, *Icarus*, 100, 307 (4) Chambers and Wetherill, 1998, *Icarus*, 136, 304 (5) Agnor et al., 1999, *Icarus*, 142, 219 (6) Petit et al., 2001, *Icarus*, in press (7) Morbidelli et al., 2000, *Meteoritics*, 35, 1309

U51A-05 0935h

Origin of Earth's Volatiles: The Case for a Cometary Contribution

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The existence and extent of a cometary contribution to the Earth's oceans and atmosphere can be sought through studies of isotopic ratios and noble gas abundances. We learn from D/H that comets could not have delivered all the Earth's water, while $84\text{Kr}/132\text{Xe}$ and the isotopic composition of Xe show that chondrites did not deliver the atmospheric noble gases. Because its atmosphere is so thin and it lacks plate tectonics, Mars provides a useful control on models for volatile delivery. Here we find evidence for a cometary-delivered hydrosphere decoupled from a lithosphere that contains xenon with solar isotope ratios. The Martian atmosphere reveals krypton and xenon relative abundances and isotope ratios remarkably similar to Earth's, despite obvious evidence for atmospheric escape. An external source seems necessary to satisfy both Martian and terrestrial data, with the D/H result pointing toward comets. This result requires that Earth formed with its own water, to mix with the cometary component. The ratios of $15\text{N}/14\text{N}$ on Mars and Earth (in the atmosphere and rocks) are also consistent with cometary delivery of nitrogen in the form of N-compounds. The ultimate evaluation of cometary contributions will come from missions: DS-1 to C/Borrelly 22 September 2001 (results to be discussed by R. Nelson at this meeting) and CONTOUR, first stop C/Encke in 2003.

U51A-06 0950h

New Experimental Constraints on Crystallization Differentiation in a Deep Magma Ocean

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Most of Earth's mass probably accreted as a consequence of numerous impacts between large bodies and proto-Earth, and a giant impact with a Mars-sized object is the most plausible explanation for a Moon-forming event. 1 Physical models show that large impacts would have caused high-degrees of melting and a global magma ocean. 2 Crystallization differentiation in a deep magma ocean could impart stratification in the solidified mantle, forming large geochemical domains. To accurately model crystallization in a deep magma ocean the liquidus phase-relations of peridotite, as well as mineral/melt element partitioning, must be known at lower mantle conditions. Here, we report the results of liquidus experiments on fertile model peridotite compositions at 23 - 33 GPa. Experiments were performed in 6/8-type multi-anvil apparatus using carbide

and sintered-diamond second-stage anvils with 4 and 2 mm truncations, respectively. Samples were encapsulated by either graphite or Re. High-temperatures were generated using LaCrO₃ or Re furnaces, and temperatures were held from 2 to 50 minutes at 2300 - 2500 C. Run products were analyzed for major and trace elements using EPMA and SIMS. At 23 GPa the liquidus phase is majorite, followed closely down temperature by ferropervovskite (Fp) and Mg-perovskite (Mg-Pv). At 24 GPa the liquidus phase has changed to Fp, followed closely by majorite and Mg-Pv. Ca-perovskite (Ca-Pv) is present only at much lower temperatures close to the solidus. At approximately 31 GPa Mg-Pv is the liquidus phase followed down-temperature by Fp then Ca-Pv. At ~ 33 GPa Ca-Pv crystallizes closer to the liquidus, within about 50 C, at a similar temperature to Fp. Thus, important phases crystallizing in a deep magma ocean are Mg-Pv, Ca-Pv and Fp. Crystallization models based on major element partitioning show that only very modest amounts of crystal separation of a Mg-Pv + Fp assemblage can be tolerated before Ca/Al, Al/Ti and Ca/Ti ratios become unrealistic for estimates of primitive upper mantle (PUM). 3 However, even small amounts of Ca-Pv in the crystal assemblage effectively buffer these ratios at values close to the starting composition (e.g. chondritic). Further, based on our new trace element partitioning data, models involving considerable Mg-Pv fractionation generally show poor matches with model PUM. For example, model PUM has sub-chondritic REE/Ti, whereas these ratios increase considerably during Mg-Pv crystallization. Notable exceptions are super-chondritic Zr/Ti, chondritic Sr/Ti, and sub-chondritic Zr/Nb and Sm/Yb ratios, all of which are well matched by considerable Mg-Pv crystallization. Although trace element Ds for Ca-Pv are not yet measured quantitatively, the observed affinity of Ca-Pv for REE could conceivably account for the sub-chondritic REE/Ti ratios in PUM. Ca-Pv also concentrates K, and could be an important source of heat from radioactive decay in the lower mantle.

1. Canup, R. and Agnor, C., Origin of the Earth and Moon, Righter and Canup, eds., U. Arizona Press, 113-144, 2000. 2. Melosh, H., Origin of the Earth, Newsom and Jones, eds., Oxford Press, 69-84, 1990. 3. McFarlane, E. et al., *Geochimica et Cosmochimica Acta*, 51:61-51:72, 1994.

U51A-07 1025h INVITED

Rare Gas Constraints on Early Earth History

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The characteristics of mantle rare gases provide important constraints on events in early Earth history. The presence of primordial, unrecycled isotopes within the Earth can be accounted for by only a limited number of incorporation mechanisms to bury these unreactive, highly volatile species. Nonradiogenic isotope data indicate that solar rare gases are in the mantle. Radiogenic isotope systematics further demonstrate that at present there is a considerable abundance stored within the deep Earth.

The long-term storage of rare gases may be in an isolated deep mantle reservoir. In this case, radiogenic isotope signatures require that initially there was 100 times more gases than at present, with extensive losses from both within the Earth and the atmosphere in the first 100Myrs. Initial trapping of this amount of rare gases can be achieved by gravitational capture of a hot dense solar composition atmosphere. This would have occurred if the Earth was largely assembled prior to dispersal of the solar nebula. Melting under this atmosphere then would have allowed extensive dissolution of rare gases into a magma ocean. The calculated amount of dissolved gases then depends upon both the pressure at the planetary surface (and so the amount of gas being partitioned into the melt) and the surface temperature (and so the depth of melting) that had been achieved. The final amount of trapped gases would have depended upon the coupled thermal history of the Earth and atmosphere. Rare gases in the present atmosphere are distinctly nonsolar and were modified by subsequent fractionating losses.

Alternatively, rare gases may have been initially stored in the core. From the flux into the mantle required to account for mantle gas observations, the required concentrations in the core can be constrained. From this it appears that the concentrations needed within the early Earth during core segregation are high, but can be achieved by models of solar gas capture.

Solar rare gases in the mantle must be accompanied by other solar volatiles (C,N,H) and must be considered in mantle volatile budgets. However, elemental fractionations are likely to have occurred during initial incorporation in the Earth and during core formation. While there are substantial ambiguities in distinguishing solar volatiles from recycled species and in determining volatile behavior during Earth formation, the possible importance of solar volatiles stored in the

mantle and core can be evaluated, along with the role of other mantle volatile sources.

U51A-08 1040h INVITED

The Oxygen and Strontium Isotopic Compositions of the Moon and the Volatile Inventories of the Earth

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New laser fluorination data reveal that the oxygen isotopic composition of the Moon lies on a fractionation line that is identical to that of the Earth to within 0.005‰/‰ (99.7% confidence interval). Therefore, assuming the Giant Impact (GI) model to be correct, the proto-Earth and the Moon-forming impactor planet (Theia) probably formed from an identical mix of components at a similar heliocentric distance. However, the moderately volatile / refractory element ratios of the Moon are far lower than that of the Earth. This difference does not appear to be the result of nebular processes. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ of the Moon is higher than the solar system initial ratio despite its volatile-depleted nature. The time-scale required to accomplish this increase in $^{87}\text{Sr}/^{86}\text{Sr}$ with a solar Rb/Sr is > 10 Myrs, more than an order of magnitude longer than expected for cooling the nebula in the terrestrial planet forming region. A portion of the alkali depletion is therefore likely to be late and possibly associated with the GI itself. On this basis the Moon's present Rb/Sr (0.006) contrasts with the time-integrated Rb/Sr (~ 0.07) for the material from which it formed, consistent with Theia being even less volatile-element-depleted than the present Earth (Rb/Sr = 0.03). The time integrated Rb/Sr of Theia is similar to the present Rb/Sr of Mars (0.07) and, possibly, the proto-Earth (~ 0.09). Therefore, at one stage, prior to the GI, large objects in the inner solar system may have had concentrations of moderately volatile elements similar to those found in volatile-depleted carbonaceous chondrites. Correlations between Rb/Sr ratios in early objects and ratios of other volatile elements to Sr can be used to infer the time-integrated composition of precursor materials. Calculated bulk concentrations so determined indicate that the cores of the proto-Earth and Theia may have had 0.6-1.5% C and 4-10% S. If preserved since that time, S could be the dominant light element in the Earth's present core. Carbonaceous chondrite planetary embryos have been viewed as likely candidates for supplying water to the Earth, post-GI. The O isotope data place constraints on models for the nature and quantities of post-GI accretion. Both the $\Delta^{17}\text{O}$ and $\delta^{18}\text{O}$ of the Earth and Moon are identical within uncertainty. The size of a single impacting embryo of CI composition that could be added to the Earth is limited to ~2% Earth mass. However, if chondritic material is accreted to the Moon in proportion to relative cross sectional area the amount that can be added to the Earth is <1%. Larger amounts of post-GI accretion can be accommodated if the average provenance of material was the same as that of the proto-Earth and Theia.

U51A-09 1055h INVITED

A Proto-atmosphere and the Environment of the Earth During Accretion

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The earliest surface environment of the Earth is reconstructed in accordance with a recent planetary formation theory. The recent planetary formation theory suggests 2 stages of planetary formation; the stage of runaway growth followed by the stage of giant impacts.

A Mars-sized planet forms in 10^6 years at the stage of the runaway growth. Since solar nebula likely exists at this stage, the proto-Earth at this stage should have attracted the nebula gas and have a distended solar-composition ($\text{H}_2 < \text{ETH} > \text{He}$) atmosphere. Also, we expect impact degassing from Earth-forming planetesimals to form a degassed atmosphere, which sometimes called 'a steam atmosphere.' Hence, a mixed proto-atmosphere of solar-type and degassed components would have formed. Though the structure of the mixed atmosphere embedded in the nebula gas is not well understood yet, it would be similar to that of degassed atmosphere with extended upper atmosphere while the planet is relatively small. Then, the surface

temperature is controlled by that of the degassed atmosphere. Since the actual energy release occurs intermittently, the atmosphere may cool before the next planetesimal impact if the mean impact interval of planetesimals is longer than the cooling time of a hot atmosphere. However, judging from the frequency and thermal effects of planetesimals impacts, we consider that the proto-atmosphere has a strong thermal blanketing effect and a surface magma ocean is formed. Thus, dissolution of volatile components into the mantle is expected. Segregation of metallic iron from silicate also occurs at the super heated impact points. This will also lead to reaction of volatile components with metallic iron.

Very large infrequent impacts are expected at the giant impacts stage. Though the solar nebula has likely been lost by this stage, the mixed proto-atmosphere would have survived the nebula dissipation, because the atmosphere is tightly bounded by the Earth's gravity field. Each impact may drive off the existing atmosphere. However, it is not able to desiccate the interior of the Earth. Therefore, the atmosphere will soon recover through degassing or re-accretion of impact-generated circumterrestrial disk. It should also be noted that refractory Moon can be formed even from a volatile containing disk. Since a long impact interval is expected, the atmosphere may condense to form oceans between impacts at this stage. The interior of the Earth, at least at the upper mantle region, remains in a partially molten state during this stage and chemical differentiation is expected.

U51A-10 1110h INVITED

The Hadean Atmosphere

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It is more useful to define the Hadean Eon as the time when impacts ruled the Earth than to define it as the time before the rock record. For decades now it has been obvious that the coincidence between the timing of the end of the lunar late bombardment and the appearance of a rock record on Earth is probably not just a coincidence. I doubt I am pointing out something that the reader hasn't long ago given thought to. While the Moon was struck by tens of basin-forming impactors (100 km objects making ~1000 km craters), the Earth was struck by hundreds of similar objects, and by tens of objects much larger still. The largest would have been big enough to evaporate the oceans, and the ejecta massive enough to envelope the Earth in 100 m of rock rain. Smaller impacts were also more frequent. On average, a Chicxulub fell every 10^5 years. When one imagines the Hadean one imagines it with craters and volcanoes: crater oceans and crater lakes, a scene of mountain rings and island arcs and red lava falling into a steaming sea under an ash-laden sky. I don't know about the volcanoes, but the picture of abundant impact craters makes good sense—the big ones, at least, which feature several kilometers of relief, are not likely to have eroded away on timescales of less than ten million years, and so there were always several of these to be seen at any time in various states of decay. The oceans would have been filled with typically hundreds of meters of weathered ejecta, most of which was ultimately subducted but taking with them whatever they reacted with at the time—CO₂ was especially vulnerable to this sort of scouring. The climate, under a faint sun and with little CO₂ to warm it, may have been in the median extremely cold, barring the intervention of biogenic greenhouse gases (such as methane), with on occasion the cold broken by brief (10s to 1000s of years) episodes of extreme heat and steam following the larger impacts. In sum, the age of impacts seems sufficiently unlike the more familiar Archean that came after that it seems useful to give this time its own name, a name we already have, and that, if applied to the Hadean that I have described, actually has some geological value.

U51A-11 1125h INVITED

The transition from abiotic to biotic chemistry: When and where?

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The origin of life on Earth was marked by the transition from purely chemical reactions to autonomous self-replicating molecules capable of evolving by natural selection into ones of increasing efficiency and complexity. Two views on how this happened are presently popular (1): A) organic compounds in the primordial oceans, derived from "home grown" synthetic reactions and the infall of organic rich materials from space, underwent polymerization which produced increasingly complex molecules, some of which by chance were capable of catalyzing their own self-replication; and B) a primitive type of "metabolic life" characterized by a series of self-sustaining chemical reactions based on organic compounds made directly from simple constituents arose in the vicinity of mineral-rich hydrothermal systems.

In the first scenario, organic compounds would need to be concentrated in order to polymerize. This could be accomplished by absorption onto mineral surfaces followed by polymerization, a process that has been demonstrated in the laboratory. Since absorption onto minerals involves the formation of weak non-covalent bonds, it would be most efficient at cool temperatures. Concentration could also be accomplished by evaporation of shallow water deposits, such as tidal lagoons, and by eutectic freezing of seawater, which could have taken place if the early Earth was extensively ice covered. Low temperatures are also favorable for the survival of organic compounds and thus the "primordial soup" origin of life scenario would most likely have taken place if the early Earth was chilly rather than boiling hot. Because of the reduced luminosity of the Sun, the early Earth may have been totally ice covered during its early history and it was under these conditions the first self-replicating molecular entities originated from the prebiotic mix of organic compounds.

The second scenario could have conceivably taken place in any type of environment as long as the reactant/product molecules survived long enough to be part of the reaction chain although most researchers who have advanced this scenario favor hydrothermal temperatures. Of the various reactions that have so far been proposed and investigated none have been demonstrated to be autocatalytic. In addition, the reactions are probably not unique to hydrothermal temperatures and would also occur at lower temperatures albeit at slower rates. Based on the estimated Arrhenius activation energies for the synthesis/decomposition reactions of the reactant/product molecules it is likely that they would have been more favorable at lower temperatures. This stability argument is especially important as the autocatalytic reactions advanced to the point of synthesizing informational molecules such as nucleic acids which have very short life times at elevated temperatures. Thus even "metabolic life" as it evolved into biochemistry as we know it would likely only have been feasible if the early Earth was cool.

If the transition from abiotic chemistry to biochemistry on the early Earth indeed required cool temperatures, the transition could have occurred during cold, quiescent periods between large bolide impacts. The first life that arose, regardless of the process, may not have survived subsequent bolide impacts, however. Life may have originated several times before surface conditions became tranquil enough for periods sufficiently long to permit the survival and evolution of the first living entities into the first cellular organisms found in the fossil record 3.5 billion years ago.

1. C. Wills and J. L. Bada, 2000. "The Spark of Life: Darwin and the Primeval Soup" (Perseus Publishing, Cambridge MA) 291 pp.

U51A-12 1140h INVITED

The Nitrogen Crisis for Archean Life due to Reduced Nitrogen Fixation by Lightning

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Nitrogen is an essential element for life and is often the limiting nutrient for terrestrial ecosystems. The principal reservoir of nitrogen is molecular nitrogen in the atmosphere. However to be available for organisms nitrogen must be in the form of ammonia or nitrate, forms known as fixed nitrogen. Due to the strength of the triple bond in N₂, nitrogen fixation, while thermodynamically favored is kinetically restricted. The development of biological nitrogen fixation must have occurred early in earth history when the biological demand exceeded the main abiotic source: production of nitric oxide by lightning in the early atmosphere composed of carbon dioxide and dinitrogen. Here we report an experimental study of the nitrogen fixation rate over the evolution of the pre-oxygenic atmosphere: from predominantly carbon dioxide to predominantly dinitrogen. Our results indicate that the production of nitric oxide drastically decreased from $\sim 3.0 \times 10^{11}$ g N yr⁻¹ at the time of the origin of life when the CO₂ levels presumably were high to $\sim 2.6 \times 10^9$ g N yr⁻¹ for the low CO₂ levels determined at 2.2 Gyr ago, just before the start of the rise of oxygen in the atmosphere. This reduction in NO production may have caused an ecological crisis that triggered the development of biological nitrogen fixation before a new increase in abiotic nitrogen fixation resulted from either the rise of atmospheric CH₄ or O₂ from biological activity.

Navarro-González, R., McKay, C.P. & Nna Mvondo, D.: 2001, *Nature* 412, 61-64.

U52A MC: Hall D Friday 1330h

Origin and Early Evolution of the Earth II

Presiding: J L Bada, University of California at San Diego; A N Halliday, ETH Zentrum

U52A-0001 1330h POSTER

Metal - Silicate Separation in a Deformation Regime: Implications for Early Differentiation Processes

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The segregation of metallic cores from silicate mantles is one of the earliest, and most important, differentiation processes involved in the evolution of the Earth and other terrestrial planetary bodies. The physical segregation of Fe-rich metal from silicate imparted a strong geochemical signature on early silicate mantles due to the preferential incorporation of siderophile elements into the core. Reconciling our estimates of primary bulk silicate mantle with candidate planetary bulk compositions requires an understanding of the geochemical consequences of the different regimes in which core forming material may have been mobile. This includes not only the possible differentiation processes that occurred in the terrestrial planets, but also understanding the differentiation processes in the meteorite parent bodies. Although a magma ocean model is possible for efficient core formation, some scenarios call for segregation of the core from solid silicate and the geochemical consequences can be significantly different.

Experimental studies are one way in which insight can be gained into the possible geochemical signatures of metal-silicate segregation. Deformation experiments in addition provide a dynamic component, which allows liquid metal to segregate from solid silicate. Starting materials are cored from a slab of the Kermouf fall which is composed of olivine, pyroxene, plagioclase, chromite and chlorapatite; Fe-Ni metal and sulfide form 20-25% of the sample. Experimental conditions are 1.0-1.4 GPa confining pressure with strain rates of 10-4/s to 10-6/s. Temperatures ranging from 900° C to 1050° C produce variable amounts of silicate melt and different mechanisms of metal segregation are observed. In experiments which are below the silicate solidus, mobility of FeS is extensive and deformation textures are cataclastic. Geochemical analyses show that migration of Fe-S-Ni-O metal through fractures and along grain boundaries produces extensive modification to the solid silicate matrix, particularly at the slower strain rates. New Fe-rich olivine is produced by reaction between Fe and Mg-opx, whereas cpx and primary Mg-olivine become Fe-enriched. At moderate silicate melt fractions (below ~12.5 vol%), we observe preferential segregation of the silicate melt fraction from quench Fe-S, Fe(Ni) and occasionally, Fe-P, by deformation-induced pressure gradients. At the highest silicate melt fractions, metal is fully separated from the silicate melt rich portion of the samples. The silicate solidus is lower than expected and analyses show that silicate glass at 1000° C and 1050° C contains small amounts of Cl (0.01-0.09 wt%), S (0.03-0.07 wt%) and P (0.3 wt%). We suggest the presence of H₂O. Chlorapatite, possibly in conjunction with the products of terrestrial weathering may represent a source of Cl, P and OH in the experiments. These results are also providing insight into differentiation processes in meteorite parent bodies which have undergone early differentiation. Different degrees of partial melting concomitant with deformation-enhanced separation of the silicate melt portion may be responsible for the formation of the parent bodies of acaulchondrites and lodranites which formed from precursor chondrites. The experimental results contribute to our understanding of dynamic differentiation process, through which these different meteorite types may be linked, and to the formation of some of the earliest planetary compositions.