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 EarthOs 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 hasnt long ago given thought to. While the Moon was struck by tens of basin-forming impactors (100 km objects making $\sim$ 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 volcanos: 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 dont know about the volcanos, 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 –CO_2 was especially vulnerable to this sort of scouring. The climate, under a faint sun and with little CO_2 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 exreme heat and steam following the larger impacts. In sum, the age of impacts seems sufficiently unlike the more familiar Archaean 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 where capable to 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 $\sim 3.0\text{x}10^{11}$ g N yr^{-1} at the time of the origin of life when the CO_2 levels presumably were high to $\sim 2.6\text{x}10^9$ g N yr^{-1} for the low CO_2 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 CH_4 or O_2 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 process 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 Kernouve 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 shows 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 H_2O. 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 acapulcoites 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.

U52A-0002 1330h POSTER

Constraints on Core Formation Mechanisms From Metal-Silicate Equilibration Kinetics

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The concentrations of siderophile elements in the Earth's mantle provide important constraints on the processes of core formation. Based on measured metal-silicate partition coefficients, siderophile element concentrations are too large to be explained by chemical equilibrium during the separation of liquid metal from silicates at low pressures. However, partition coefficients for elements such as Ni and Co decrease with increasing pressure at an oxygen fugacity just below the IW buffer and reach appropriate values at 25-30 GPa. It has therefore been proposed that the concentrations of such elements in the mantle are the result of metal-silicate equilibration at the base of a magma ocean 700-800 km deep. According to this model, liquid metal ponds at the base of a silicate magma ocean and, after equilibrating chemically, descends as diapirs to form the Earth's core. This scenario is also consistent with silicon being a light element in the core.

We are investigating the kinetics of metal-silicate equilibration in order to place new constraints on processes of core formation. Equilibration rates are controlled by chemical diffusion through a silicate liquid boundary layer adjacent to the liquid metal. We consider two models: (1) Reaction between a layer of segregated liquid metal and overlying silicate liquid at the base of a 700 km deep convecting magma ocean, as described above. (2) Reaction between settling liquid metal droplets and silicate melt in a convecting magma ocean. In the liquid-metal layer model, the convection velocity of the magma ocean controls both the equilibration rate and the rate at which the magma ocean cools. Results indicate that time scales of chemical equilibration are orders of magnitude longer than the time scales of cooling and crystallization of the magma ocean. In the falling metal droplet model, the droplet size and settling velocity are critical parameters. For a typical silicate liquid viscosity at 2600 K, the stable droplet diameter is estimated to be ~1 cm with a settling velocity of ~0.5 m/s. Using such parameters, liquid metal droplets are predicted to equilibrate chemically after settling a distance of <200 meters. These models indicate that the concentrations of moderately siderophile elements in the mantle could be the result of chemical interaction of a silicate magma ocean with settling metal droplets but not with a layer of liquid metal that has segregated at the base of the magma ocean.

U52A-0003 1330h POSTER

A Small Metallic Core in the Moon? A Reassessment Considering Siderophile Elements and Giant Impacts

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The issue of whether the Moon has a small metallic core is re-examined in light of new information: improved dynamical modelling, new geophysical constraints on core size, and high temperature and pressure metal-silicate partition coefficients. Although the Moon has similar Co and W depletions to the Earth, it has distinctly different Ni, Mo, Re, P and Ga depletions, consistent with the presence of a small metallic core. Because impact modelling predicts the Moon is made of mantle material from the impactor, bulk Moon compositions are considered from "hot", "warm" and "cool" impactors and proto-Earths (deep, intermediate, and shallow melting, respectively). If the Moon is made of mantle material from either a "hot" impactor or a "warm" impactor or proto-Earth, a small metallic core (0.7 to 2 percent) is predicted. If the Moon is made from mantle material from a "hot" proto-Earth, the lunar mantle would be more depleted in W or P than is observed. Scenarios in which the Moon is made from impactor or proto-Earth mantle material that has equilibrated with metal at low pressures and temperatures ("cool" scenarios) predict a much larger metallic core than is observed; silicates would be depleted in siderophile elements in such scenarios, but would be physically mixed with metal due to the inefficiency of metal segregation at low P and T conditions. Consistency of siderophile element concentrations in the lunar mantle with an impactor bulk Moon composition eliminate previous geochemical objections to an impactor origin of the Moon.

U52A-0004 1330h POSTER

Potassium Partitioning Between Iron Sulfide and Peridotite Melt at 2.0 GPa

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Radioactive decay of potassium-40 in the Earth's core could provide the heat required to sustain the Earth's magnetic field. If potassium is present in the core, it was incorporated early in Earth's history, during segregation of a sulfur-bearing iron metal liquid. Recent studies by Gessmann and Wood (Spring AGU 1999) and Chabot and Drake (EPSL, 1999) have started to provide constraints on the concentration of K in the core through measurements of K partitioning between Fe-S and silicate liquids at relatively low pressure (1.5 - 2.5 GPa). As a further step towards designing high-pressure experiments at conditions relevant for metal segregation during core formation, we have studied extensively the effects of capsule material and experiment duration on measured metal-silicate distribution coefficients (K_d values) of K. Experiments were performed at pressures of 2 GPa, temperatures between 1423 and 2673 K, and run durations between 5 seconds and 1 hour.

Starting material for all our experiments is a mixture of KLB-1 peridotite, $K_2Si_2O_5$ silicate glass, FeS and Fe, with a bulk composition close to Bulk Earth estimates for all elements except K (2.31 wt% K_2O). All experiments were performed in a piston cylinder apparatus, using either single graphite capsules, or graphite inner capsules within a noble metal outer capsule. In all runs, the metal phase quenches to a mixture of Fe and Fe-S blebs. At 2073 K, a minimum of 15 minutes experimental duration is needed to achieve equilibrium Fe-S liquid compositions. At high temperature, the peridotite melt quenches to an intimate mixture of olivine quench crystals and interstitial quench glass, while occasionally large pools of homogeneous glass are formed.

K contents in metal and silicate phases were measured using an electron microprobe. During all stages of the experimental and analytical process, any contact with water and ethanol was avoided to prevent dissolution of potassium sulfides. Nevertheless, duplicate measurements show a gradual decrease in the K content of FeS melt globules over time, with all K disappearing within 2 weeks of the time of experimentation. Mass balance calculations show that at high temperature (2073 K) some K is lost from graphite capsules even in runs lasting only 5 minutes, precluding determination of reliable metal-silicate partition coefficients. Double capsules do retain K quantitatively. At constant temperature, K_d values in these experiments increase by up to a factor of 4 from 15 to 35 minute experiments, suggesting K incorporation into iron sulfides is a time-dependent process. At 2073 K, the equilibrium K_d value is 0.042 ± 0.012, significantly higher than the estimate of 0.006 given by Chabot and Drake (1999).

U52A-0005 1330h POSTER

Radiogenic Lead in Iron Meteorites Revisited

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Lead in iron meteorites has long been known to be of surprisingly radiogenic isotope composition (e.g. [1-3]). Primordial Pb is only found (if at all) after very extensive leaching of the samples in strong mineral acids. The widely accepted explanation for this observation is that Pb of radiogenic composition represents terrestrial contamination, although the exact source and mode of contamination have eluded the isotope geochemists.

In the most recent study (with the lowest laboratory blanks) Göpel et al. [3] found that leachates and residues of progressively leached group IAB iron meteorites (Canyon Diablo, Toluca and Odessa) have, within analytical uncertainty, identical radiogenic and primordial Pb isotope components. The combined data yield an apparent regression age of 4534±8 Ma, identical to the Ar-Ar plateau age of the winonaite Pontlifny (4531±12 Ma; [4]), which is believed to represent the silicate counterpart to IAB iron meteorites.

We will present high precision MC-ICPMS Pb-isotope data for eight progressively leached magmatic and non-magmatic iron meteorites, as well as Pb-isotopes and rare earth element patterns of bulk dissolutions of iron meteorites.

All leachates and bulk dissolutions of the different iron meteorites (excluding the non-magmatic group IAB representatives) display excellent colinearity in the common lead isotope diagram. The slope of the regression line corresponds to an apparent age of 4568.5±4.6 Ma, within uncertainty equal to the Pb/Pb age of Ca-Al rich inclusions in the carbonaceous chondrite Allende [5]. Excellent colinearity of Pb data is also found in thorogenic Pb space, where the slope of the regression line corresponds to a κ-value of 3.816±29, which is equal to that of chondritic meteorites (i.e. 3.806±88) but different from average continental crust. Data for individual IAB meteorites also define excellent colinearity but yield somewhat younger apparent ages. For example, the regression date for our Canon Diablo leachates is 4546.5±7.6 Ma, within uncertainties identical to that of Göpel et al. [3].

Chondrite normalized rare earth element patterns of unleached bulk samples of iron meteorites prove absence of terrestrial contamination. Probability for selective contamination of iron meteorites with terrestrial Pb was calculated by comparison with different terrestrial data pools. For a single contamination event of all studied samples with average terrestrial lead the probability is 0.69%. Individual contamination for the different iron meteorites yields a probability as low as 0.0048%. Low probabilities of contamination reflect the well-known observation that the accessible Earth plots well to the left of the meteorite isochron in common Pb space (i.e. the first Pb-isotope paradox) and that average continental crust (and sediment) has a higher time-integrated Th/U ratio than chondritic meteorites. In view of the consistency in Pb-isotope composition of the radiogenic component in iron meteorites, the lack of contamination of other trace elements, and low estimated probabilities for terrestrial contamination we propose to reconsider the possibility of in situ grown (though now largely unsupported) radiogenic lead in iron meteorites. Implications for early planetary evolution and core formation will be discussed.

[1] Oversby, V.M. (1970), Geochim. Cosmochim. Acta 34, 65. [2] Chen, J.H. and Wasserburg, G.J. (1983), Geochim. Cosmochim. Acta 47, 1725. [3] Göpel et al. (1985), Geochim. Cosmochim. Acta 49, 1681. [4] Benedix et al. (1998), Geochim. Cosmochim. Acta 62, 2535. [5] Manhès et al. (1988), Geochim. Cosmochim. Acta 69-70, 32.

U52A-0006 1330h POSTER

Origin of the Ocean and Continents: Towards a Unified Theory of the Earth

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The time period from the formation of the Earth (4.5 Ga) to the establishment of plate tectonics at the beginning of the Proterozoic (2.5 Ga) remains largely hidden and unknown. During this time period, the ocean, atmosphere, and continents formed, and the geochemical and physical processes that allowed the development and evolution of life were established. Our knowledge of these beginnings is scant, with theories changing as each new line of evidence emerges. Perhaps most troubling is that we have no coherent, unified theory that simultaneously addresses the formation of the oceans, atmosphere, and continents. The key idea necessary for the development of a unified theory that explains the origin of the oceans, continents, and atmosphere, is the recognition that the timing of the growth of continental crust is an earmark for the presence of abundant water on the surface of the Earth and its entry into the mantle by subduction. Strontium isotopes, europium anomalies, and zircon populations all suggest that rapid growth of the continental crust did not begin until 3.0 Ga when the Earth was already 1.5 billion years old. The implication is that widespread hydration of the oceanic crust did not occur until about 3.0 Ga; thus volumes of water sufficient to cover the Archean analogues to mid-ocean spreading ridges did not exist prior to this time. No existing theory of ocean origin by outgassing or rapid accretion on a very young Earth survives falsification. The unifying theory that explains both the origin of the ocean and the continents is the slow and gradual accumulation of water on the surface of the Earth by extraterrestrial accretion.

U52A-0007 1330h POSTER

Numerical Mantle Convection Models of Crustal Formation in an Oceanic Environment in the Early Earth

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The generation of basaltic crust in the early Earth by partial melting of mantle rocks, subject to investigation in this study, is thought to be a first step in the creation of proto-continents (consisting largely of felsic material), since partial melting of basaltic material was probably an important source for these more evolved rocks.

In the early Archean the earth's upper mantle may have been hotter than today by as much as several hundred degrees centigrade. As a consequence, partial melting in shallow convective upwellings would have produced a layering of basaltic crust and underlying depleted (lherzolitic-harzburgitic) mantle peridotite which is much thicker than found under modern day oceanic ridges.

When a basaltic crustal layer becomes sufficiently thick, a phase transition to eclogite may occur in the lower parts, which would cause delamination of this dense crustal layer and recycling of dense eclogite into the upper mantle. This recycling mechanism may have contributed significantly to the early cooling of the earth during the Archean (Vlaar et al., 1994). The delamination mechanism which limits the build-up of a thick basaltic crustal layer is switched off after sufficient cooling of the upper mantle has taken place.

We present results of numerical modelling experiments of mantle convection including pressure release partial melting. The model includes a simple approximate melt segregation mechanism and basalt to eclogite phase transition, to account for the dynamic accumulation and recycling of the crust in an upper mantle subject to secular cooling. Finite element methods are used to solve for the viscous flow field and the temperature field, and lagrangian particle tracers are used to represent the evolving composition due to partial melting and accumulation of the basaltic crust.

We find that this mechanism creates a basaltic crust of several tens of kilometers thickness in several hundreds of million years. This is accompanied by a cooling of some hundred degrees centigrade.

Vlaar, N.J., P.E. van Keken and A.P. van den Berg (1994), Cooling of the Earth in the Archaean: consequences of pressure-release melting in a hotter mantle, Earth and Planetary Science Letters, vol 121, pp. 1-18

U52A-0008 1330h INVITED POSTER

Extraterrestrial matter and atmospheric aerosols

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In situ measurements of the composition of stratospheric aerosols detected Fe, Mg, Na, K, Ca, Ni, and other meteoritic material in a large number of particles. These particles include ablated meteoric material that has recondensed, descended from the upper atmosphere, and combined with the sulfate in the stratosphere. Along with laboratory calibrations and a knowledge of the stratospheric sulfur budget, these measurements allow estimates of the flux of extraterrestrial material reaching the present-day earth. The stratospheric particles are depleted in the more refractory elements, suggesting that some of the incoming material is not ablated. Consideration of the much larger flux of meteors in the earths early history suggests that ablated meteoric material could have altered the properties of the early atmosphere in ways that might be relevant to the origin of life.

U52A-0009 1330h POSTER

Lithosphere-Hydrosphere Interactions on the Hadean (>4 Ga) Earth

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Sources of information about environments for emergent life are provided by rare and scattered exposures of the oldest known granitoid gneisses and supracrustal enclaves, which are only between 3.8-4.0 Ga. The time period after primary accretion of the planets and the first appearance of a rock record has long been considered off-limits to geologists. Studies of the isotopic record of planetary evolution on Earth, the Moon and meteorites point to rapid planetary accretion, core formation and the differentiation of some incompatible-element rich crust at an early stage. To investigate conditions existing at the Earth's surface prior to 4 Ga requires discovery of yet older materials. Indeed, such ancient materials appear to have survived to the present. Archean (3 Ga) quartzites of the Narryer Gneiss Complex in Western Australia host detrital zircon populations with ages >4 Ga and new work has identified some of these as between 4.3 and 4.4 Ga, thereby establishing them as the oldest known terrestrial materials. Trace element distributions as well as oxygen isotope compositions in zircon reflect the evolution and bulk geochemical characteristics of the parent melt. Recently reported in situ U-Pb and oxygen isotope results for the >4 Ga zircons from Western Australia have revealed details on the age and composition of their source magmas and represent the first steps toward directly exploring the nature of the Hadean crust.

What was this earliest terrestrial environment like? Could the "hydrosphere" have been present as a steam atmosphere as a result of a highly energetic early impact environment? It is generally thought that the early Earth experienced episodes of intensive bolide impacts in the time period 4400 to 4000 Ma. Yet, the lunar impact record appears to lack evidence of major impacts for most of this time aside from a peak in impact frequency centered at 3850 Ma associated with the late heavy bombardment. These zircons are so ancient, some may be compelled to ask: Are they really terrestrial? Meteoritic zircons are very rare and REE and trace element compositions of these ancient zircons preclude a meteoritic origin. If early impacts were important modifiers to the stability of an incipient surface biosphere during the Hadean, life may have emerged from protected environments e.g., habitats in the crust or regolith or deep hydrothermal systems where the concentration and polymerization of biochemically important molecules could occur. In such subterranean nurseries for life, events at the surface may have had little consequence.

U52A-0010 1330h POSTER

Archean Hydrothermal Activity

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Seafloor hydrothermal systems are an integral component of a complex, dynamic heat engine by which energy brought towards the seafloor by mantle convection is transferred to the ocean by a combination of thermal conduction and hydrothermal venting. Modern seafloor hydrothermal circulation accounts for approximately 33% of the heat transferred through the seafloor and plays an important role in global geochemical cycling. Moreover, the discovery of chemotrophic hyperthermophilic microbes living at seafloor hydrothermal vents has led to the idea that life on Earth, and perhaps on other planetary bodies, originated in hydrothermal environments characteristic of the early Earth. Greater seafloor spreading rates caused by higher heat flux, coupled with younger plate subduction ages, suggest that hydrothermal activity was more vigorous during the Archean than at present. We first estimate the total heat loss from oceanic lithosphere as a function of geologic time from 4.0 Ga to present by using simple models of plate creation rates and subduction ages over geologic time and by assuming heat loss follows a simple half space cooling law. We consider three possible continental growth models: (a) constant continental area of 40%, (b) linear growth between 4.0 and 2.5 Ga and constant 40% area from 2.5 Ga to present, and (c) episodic continental growth between 4.0 and 2.5 Ga and constant 40% area from 2.5 Ga to present. We then attempt to quantify hydrothermal heat and fluid fluxes from 4.0 Ga to present. We assume that hydrothermal circulation is absent in lithosphere > 60 my old and that the ratio of hydrothermal heat loss to lithospheric flux is the same in the Archean as at present. Our calculations show that high temperature (350°C) hydrothermal heat and fluid fluxes were ∼ 7-10 x greater during the early Archean (3.5 Ga) and ∼ 2 x greater during the late Archean (2.5 Ga) than at present. During the early Archean, ocean chemistry would likely have been dominated by hydrothermal inputs and the rapid removal of Mg by high temperature water-rock reactions may have led to lower Mg levels in the early Archean ocean. Moreover, shallower ridge crests would have resulted in more prevalent two-phase flow with concomitant changes in vent fluid chemistry.

U52A-0011 1330h POSTER

Feldspar palaeo-isochrons from early Archaean TTGs: Pb-isotope evidence for a high U/Pb terrestrial Hadean crust

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Feldspar lead-isotope data for 22 early Archaean (3.80-3.82 Ga) tonalitic gneisses from an area south of the Isua greenstone belt (IGB),West Greenland, define a steep linear trend in common Pb-isotope space with an apparent age of 4480±77 Ma. Feldspars from interleaved amphibolites yield a similar array corresponding to a date of 4455±540 Ma. These regression lines are palaeo-isochrons that formed during feldspar-whole rock Pb-isotope homogenisation a long time (1.8 Ga) after rock formation but confirm the extreme antiquity (3.81 Ga) of the gneissic protoliths [1; this study]. Unlike their whole-rock counterparts, feldspar palaeo-isochrons are immune to rotational effects caused by the vagaries of U/Pb fractionation. Hence, comparison of their intercept with mantle Pb-isotope evolution models yields meaningful information regarding the source history of the magmatic precursors. The locus of intersection between the palaeo-isochrons and terrestrial mantle Pb-isotope evolution lines shows that the gneissic precursors of these 3.81 Ga gneisses were derived from a source with a substantially higher time-integrated U/Pb ratio than the mantle. Similar requirements for a high U/Pb source have been found for IGB BIF [2], IGB carbonate [3], and particularly IGB galenas [4]. Significantly, a single high U/Pb source that separated from the MORB-source mantle at ca. 4.3 Ga with a $^{238}U/^{204}Pb$ of ca. 10.5 provides a good fit to all these observations. In contrast to many previous models based on Nd and Hf-isotope evidence we propose that this reservoir was not a mantle source but the Hadean basaltic crust which, in the absence of an operating subduction process, encased the early Earth. Differentiation of the early high U/Pb basaltic crust could have occurred in response to gravitational sinking of cold mantle material or meteorite impact, and produced zircon-bearing magmatic rocks. The subchondritic Hf-isotope ratios of ca. 3.8 Ga zircons support this model [5] provided that the redetermined ^{176}Lu decay constant of Scherer et al. [6] is correct. Our model of a stable basaltic Hadean shell for the pre-plate tectonic era explicitly refutes operation of processes such as sediment recycling or melting of hydrated material in subduction zones as far back as 4.4 Ga (as recently suggested by [7]; and [8]). Instead, we propose that initiation of terrestrial subduction occurred at ca. 3.75 Ga, at which stage most of the Hadean basaltic shell (and its differentiation products) was recycled into the mantle, because of the lack of a stabilising mantle lithosphere. We further argue that >3.75 Ga terrestrial rocks and minerals were not preserved by chance, but because of creation of a lithospheric mantle keel concommitant with intrusion of voluminous granitoids *immediately* after establishment of global subduction. In other words, the only portions of >3.75 Ga crust (basaltic and otherwise) that survived were those that were involved in voluminous arc magmatism along the earliest subduction zones.

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U52A-0012 1330h POSTER

A Novel Theory For The Origin And Evolution Of Stars And Planets, Including Earth, Which Asks, 'Was The Earth Once A Small Bright Star?'

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Improved prediction methods for earthquakes and volcanic activity will naturally follow from our theory, based on new concepts of the earths interior composition, state and activity.

In this paper we present a novel hypothesis for the formation and evolution of galaxies, stars (including black holes (BHs), neutron stars, giant, mid-size, dwarf, dying and dead stars), planets (including earth), and moons. Present day phenomenon will be used to substantiate the validity of this hypothesis. Every body is a multiple type of star, generated from modified pieces called particle proliferators, of a dislodged/expanded BH (of category 2 (c-2)) which explodes due to a collision with another expanded BH (or explodes on its own). This includes the sun, and the planet earth, which is a type of dead star. Such that, if we remove layers of the earth, starting with the crust, we will find evidence of each preceding star formation, from brown to blue, and the remains of the particle proliferator as the innermost core is reached.

We show that the hypothesis is consistent with both the available astronomical data regarding stellar evolution and planetary formation; as well as the evolution of the earth itself, by considerations of the available geophysical data. Where data is not available, reasonably simple experiments are suggested to demonstrate further the consistency and viability of the hypothesis.

Theories are presented to help define and explain phenomenon such as how two (or more) c-2 BHs expand and collide to form a small big bang (It is postulated that there was a small big bang to form each galaxy, similar to the big bang from a category 1 BH(s) that may have formed our universe. The Great Attractors would be massive c-2 BHs and act on galaxy clusters similar to the massive c-3 BHs at the center of Galaxies acting on stars.). This in turn afforded the material/matter to form all the galactic bodies, including the dark matter inside the galaxies that we catalogue as category-3 BH(s). We conceive that c-3 BHs form gas and dust clouds, inside galaxies, that are the incubators for new stars and planets.

The start and development of the planet earth, initially as an emergent piece from the colliding c-2 BHs, is given special attention to explain the continuing expansion/growth that takes place in all stars and planets. We present a new cross section of the earth (as a dead star). Although the dimensions of the inner core, outer core, and the mantle (inner and outer) are about the same as presently known, new insight is given to their formation, evolution and composition. We explain the formation of the land, the growing/expanding earth (proportional to the ocean bed growth), the division of the continents, and the formation of the ocean beds (possibly long before the oceans existed). Attempts will be made to explain the source of the supply of water on earth.

We explain various planetary phenomenon including: how/why the earth is growing/expanding (not based on current plate tectonic theory) causing it to retard its rotation; why the oceans are different sizes (the Pacific is about twice the Atlantic); why the masses at the poles are shifting into the Atlantic Ocean (may provide an alternative explanation for the ice ages); why various types of earthquakes occur (a new source is presented), why volcanoes occur (two types are discussed); and improved prediction methods for earthquakes and volcanic eruptions; the making/forming of the mountains from bending and compression buckling, and shear failures of the outer surfaces of the earths brittle outer skin of the 1st crust (and also from eruptions) due to reduction in curvature of the crust.

U52A-0013 1330h POSTER

Atmospheric Nitrogen Fixation by Simulated Corona Discharge in the Early Precambrian Earth

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In the early evolution of life on Earth, the production of reactive nitrogen species was a fundamental prerequisite. Reactive nitrogen could have been delivered to the early Earth by exogenous contributions or fixed by endogenous sources. Exogenous sources would have had a modest role in terms of the abiotic nitrogen fixation, while it is predicted that the endogenous sources largely supplied the primitive Earth with nitrogenated compounds. Volcanic lightning could have been the most important source of reactive nitrogen (NO and NO_2) in the terrestrial troposphere (with a production rate of $\sim 10^{12}$ - 10^{13} g NO yr^{-1}), followed closely by thunderstorm lightning ($\sim 10^{12}$ g NO yr^{-1}) and post-impact plumes ($\sim 10^{12}$ g NO yr^{-1}). While the relevance of lightning as a source of fixed nitrogen has been largely studied and confirmed, the contribution of corona discharges still remain unelucidated. Here we present the first experimental simulation of the production of nitrogen oxides by corona discharge in the primitive Earth's atmosphere during the Hadean and the Archean eras. NO was detected as the main product whereas N_2O as the secondary product. Assuming that the global coronal discharge energy available on early Earth was $\sim 5 \times 10^{17}$ J yr^{-1}, our results imply that the maximum annual production rates of NO and N_2O were of the order of 10^9 g yr^{-1} and 10^8 g yr^{-1} respectively. These rates are low and therefore corona discharges did not play a significant role in the overall pool of reactive nitrogen needed for the emergence of life.

U52A-0014 1330h POSTER

Preliminary Phase Diagram for the Richardton H-Chondrite

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The earliest history of the accreting Earth involved the removal of metallic liquids to the core and segregation of silicates into a layered Earth. One hypothesis for core formation is that descending metallic liquids equilibrated with silicate liquids in the deep mantle. Of current interest is the possibility that a primordial magma ocean may have acted as a host for both silicate and metallic liquid segregation. The silicate liquid composition may have changed by processes such as crystal settling or flotation during accretion as the planet increased in size. If these were equilibrium processes, a P-T phase diagram of representative accretion material could be used to constrain the chemical evolution of the Earth by identifying silicate minerals and liquidus phases present at elevated pressures and temperatures (Agee, 1990; Agee et al., 1995).

Experiments were carried out in a "Walker-type" 6-8 multi-anvil device in a 1100 ton press. Pressures from 5 to 11 GPa, at temperatures from 1050 to 2100 $^{\circ}$C, have been investigated using an 8 mm TEL assembly with a LaCrO3 furnace and either MgO or graphite capsules. Experiment durations were from 4 to 31 minutes. We chose the Richardton H-chondrite as starting material because it is a reasonable representation of the bulk Earth. An ongoing problem with these experiments is containment of the liquids within the MgO capsules. Additionally, the MgO capsule reacts with the silicate liquids, elevating the MgO content of the silicate melt and reducing the FeO content. Experiments conducted in graphite capsules do not have a containment problem. Phases present were tentatively identified using EDS spectroscopy.

In the investigated P-T range, run products contain olivine of intermediate composition, low- and high-Ca pyroxene, and small amounts of garnet in subsolidus experiments. Runs conducted at 1700 $^{\circ}$C contain silicate liquid, olivine, and low Ca pyroxene at 6 GPa, but silicate liquid, olivine, low and high Ca pyroxene at 9 GPa. At 1800 $^{\circ}$C and 9 GPa runs contained silicate liquid, olivine and garnet. All runs contained metal-sulfide liquids.

Our preliminary data indicates the liquidus near 9 GPa occurs at about 1975 $^{\circ}$C. This falls within the expected range between 1875 $^{\circ}$C for the Allende meteorite (Agee et al., 1995), and 2100 $^{\circ}$C for peridotite (Zhang and Herzberg, 1994). Future experiments will more fully characterize the slope of the liquidus, particularly in the pressure range of 20 to 27 GPa, the pressures most relevant to a deep magma ocean.

U52B MC: 134 Friday 1330h

Archaeological Evidence for Historic and Prehistoric Earthquakes and Volcanic Eruptions and Their Impact on Human Settlements

Presiding: **A Nur,** Stanford University; **R L Kovach,** Stanford University

U52B-01 1330h

The Collapse of Ancient Societies by Great Earthquakes

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Although earthquakes have often been associated with inexplicable past societal disasters their impact has thought to be only secondary for two reasons: Inconclusive archaeological interpretation of excavated destruction, and misconceptions about patterns of seismicity. However, new and revised archaeological evidence and a better understanding of the irregularities of the time-space patterns of large earthquakes together suggest that earthquakes (and associated tsunamis) have probably been responsible for some of the great and enigmatic catastrophes in ancient times.

The most relevant aspect of seismicity is the episodic time-space clustering of earthquakes such as during the eastern Mediterranean seismic crisis in the second half of the 4th century AD and the seismicity of the north Anatolian fault during our century. During these earthquake clusters, plate boundary rupture by a series of large earthquakes that occur over a period of only 50 to 100 years or so, followed by hundreds or even thousands of years of relative inactivity. The extent of the destruction by such rare but powerful earthquake clusters must have been far greater than similar modern events due to poorer construction and the lack of any earthquake preparedness in ancient times.

The destruction by very big earthquakes also made ancient societies so vulnerable because so much of the wealth and power was concentrated and protected by so few. Thus the breaching by an earthquake of the elites fortified cities must have often led to attacks by (1) external enemies during ongoing wars (e.g., Joshua and Jericho, Arab attack on Herods Jerusalem in 31 BCE); (2) neighbors during ongoing conflicts (e.g., Myceneas fall in @1200 BCE, Sauls battle at Michmash @1020 BCE); and (3) uprisings of poor and often enslaved indigenous populations (e.g., Sparta and the Helots @465 BCE, Hattusas @1200 BCE?, Teotihuacan @ 700 AD).

When the devastation was by a local earthquake, during a modest conflict, damage was probably limited and may have required a few tens of years to rebuild. But when severe ground shaking is widespread, and when it happened during a major military conflict the devastation may have been so great that it took hundreds of years for a society to recover- going through a dark ages period during which many of the technical skills (e.g., writing) are abandoned (e.g., the cessation of linear B), construction and repairs of monumental buildings ceased, and looting of building materials by surviving squatters was common. In contrast we can imagine the pastoral countryside, especially away from the tsunami prone coastal areas, to have been much less affected (and perhaps even flourished a little as their tax burden to the ruling elite is reduced).

During a regional seismic crisis an entire region must have been subjected to a series of devastations by earthquakes over a short period of time. The catastrophic collapse of the main eastern Mediterranean civilizations at the end of the Bronze Age may be a case in point, with the Sea People being mostly squatters and refugees.

U52B-02 1350h

Earthquake Archaeology: a logical approach?

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Ancient earthquakes can leave their mark in the mythical and literary accounts of ancient peoples, the stratigraphy of their site histories, and the structural integrity of their constructions. Within this broad cross-disciplinary tramping ground, earthquake geologists have tended to focus on those aspects of the cultural record that are most familiar to them; the physical effects of seismic deformation on ancient constructions. One of the core difficulties with this 'earthquake archaeology' approach is that recent attempts to isolate structural criteria that are diagnostic or strongly suggestive of a seismic origin are undermined by the recognition that signs of ancient seismicity are generally indistinguishable from non-seismic mechanisms (poor construction, adverse geotechnical conditions).

We illustrate the difficulties and inconsistencies in current proposed 'earthquake diagnostic' schemes by reference to two case studies of archaeoseismic damage in central Greece. The first concerns fallen columns at various Classical temple localities in mainland Greece (Nemea, Sounio, Olympia, Bassai) which, on the basis of observed structural criteria, are earthquake-induced but which are alternatively explained by archaeologists as the action of human disturbance. The second reexamines the almost type example of the Kyparissi site in the Atalanti region as a Classical stoa offset across a seismic surface fault, arguing instead for its deformation by ground instability. Finally, in highlighting the inherent ambiguity of archaeoseismic data, we consider the value of a logic-tree approach for quantifying and quantifying our uncertainities for seismic-hazard analysis.

U52B-03 1410h

Fault-Related Sanctuaries

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Beyond the study of historical surface faulting events, this work investigates the possibility, in specific cases, of identifying pre-historical events whose memory survives in myths and legends. The myths of many famous sacred places of the ancient world contain relevant telluric references: sacred earthquakes, openings