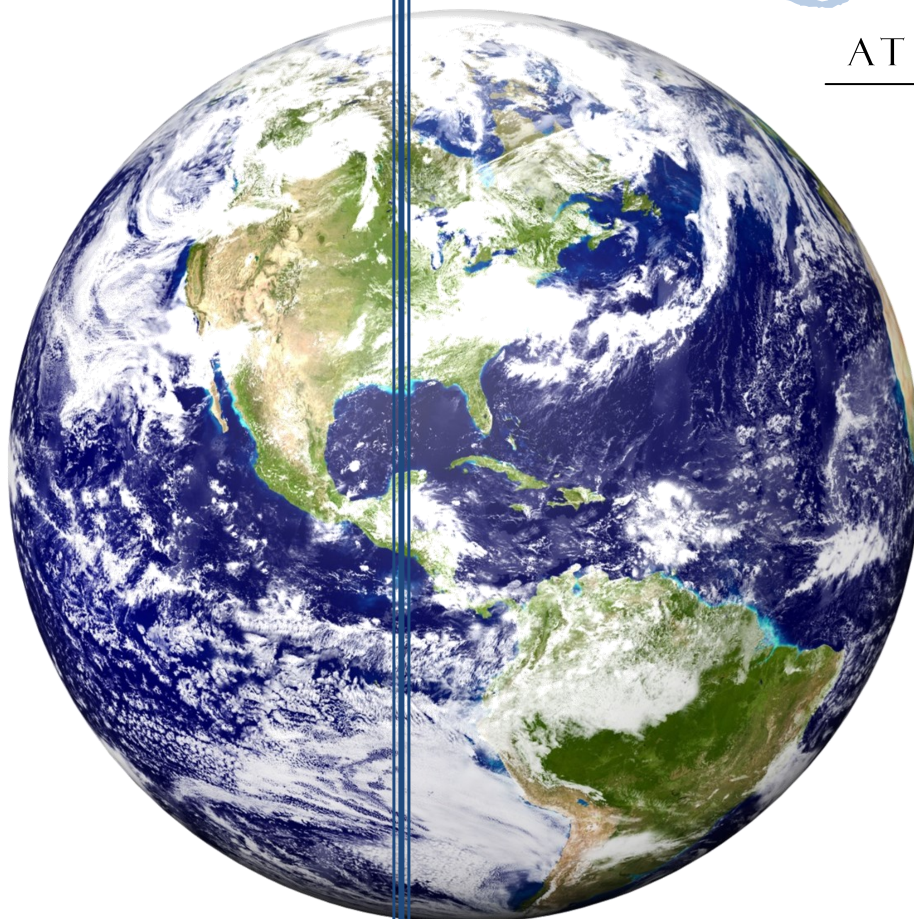

Earth & Planetary Sciences

AT HARVARD UNIVERSITY

2016 Senior Thesis Presentations

Erik Tamre
Alyssa Chan
James Duncan
Walker Evans
Tyler Barringer

Intermission and Lunch

Samuel Goldberg
Wilson Kuhnel
Ellen Robo
Cecilia Sanders
Daniel Skarzynski

April 28th, 2016 11:00-2:00 pm
Haller Hall, Geological Museum 102

Please join us for an Undergraduate End-of-Year Reception beginning at 2:00 pm in the Student Lounge (4th Floor, Hoffman Labs).

Erik Tamre

Concentrations: Earth and Planetary Sciences and Physics

The cumulative effect of temperature and other factors on tablet thickness in bivalve nacre

Advisor: **Andy Knoll**, Fisher Professor of Natural History and Professor of Earth and Planetary Sciences

The thickness of aragonite tablets in bivalve nacre has recently been proposed as a proxy for ancient seawater temperature. To evaluate the proposed proxy and understand the underlying correlation between tablet thickness and growth temperature with better resolution, I examined two species of modern bivalves: the black-lip pearl oyster (*Pinctada margaritifera*) and the rigid pen shell (*Atrina rigida).* Despite a clear correspondence between mean tablet thickness and temperature in previous work, I found that any influence temperature exerts on tablet thickness is complicated by other factors: for example, tablet thickness patterns seem to depend on the location of the analysed area within the shell. Furthermore, I could identify no correlation between tablet thickness and temperature in *P. margaritifera* shells grown in controlled-temperature water, and the temperature values I reconstructed from *A. rigida* based on previously reported correlation curves did not agree with the temperature record from growth location. The departures from previous observations likely stem from slight differences in the analysed species or the experimental set-up: for example, previous studies only examined shells grown in natural seawater, where temperature is coupled to other parameters that could influence tablet thickness. For nacre tablet thickness to provide a useful paleoenvironmental proxy, continuing experimental and modelling work must consider these details and show that the influence of temperature on tablet thickness is strong and distinct enough to rise consistently above a background of other factors.

Daniel T. Skarzynski

Concentration: Earth and Planetary Sciences

Os isotopic chemostratigraphy of Mid-Ordovician sediments and implications for the interactions of tectonics, weathering and climate leading up to the Hirnantian Glaciation

Advisor: **Francis Macdonald**, John L. Loeb Associate Professor of the Natural Sciences and co-Head tutor

Oceanic $^{187}Os/^{188}Os$ ratios preserved in the rock record can be used to help interrogate the connections and interactions between tectonics, weathering, and climate. These ratios serve as a proxy for the determination of primary weathering fluxes into the ocean during sedimentation. When analyzed in conjunction with other data, such as proxies for temperature and tectonic reconstructions, oceanic Os ratios can provide additional explanatory evidence for the dynamics underlying the interactions of climatic and tectonic processes during a given period. The Ordovician is a period ideally suited for the application of Os isotopic chemostratigraphy, as there is significant tectonic and climatic data available from past studies. The interaction between tectonics and climate explored herein is based around the negative climatic feedback that is silicate weathering. Through the weathering of rocks, CO_2 is removed from the atmosphere. As it is, climate will gradually cool, and slow weathering rates. As CO_2 then begins to again build up and the climate warms, weathering rates increase, and complete the negative feedback cycle which balances long-term climate. Certain lithologies, especially basalts and volcanic rocks, are significantly more efficient at consuming CO_2,and thus have a greater impact on this climatic system. As such, it is hypothesized that a drastic increase in subaerial exposure of these highly weatherable lithologies caused by a tectonic event could destabilize the feedback system, and lead to global cooling. As volcanic lithologies have a different isotopic signature than continental sources, Os can be used to help connect changes in weathering patterns to climatic variability. As such, the Ordovician period, which was characterized by a general cooling trend leading up to the end-Ordovician Hirnantian glaciation, is well suited for testing this proposed connection. In addition, while a chemostratigraphic curve for Sr has previously been produced for the Ordovician, and di produce data to suggest an increase in volcanic weathering, the shorter residence time of Os in seawater allows it to record changes in fluxes with a higher resolution than other isotopic proxies. In addition, this study employed the use of multi-collector-inductively coupled plasma-mass spectrometry (MC-ICP-MS) as well as negative thermal ionization mass spectrometry (N-TIMS) in order to test whether the more rapid and cost effective MC-ICP-MS could be used on older Os samples. It has been used previously, for Os isotope stratigraphy, but the Ordovician represents a much older period than its previous Cenozoic uses. It proved to be a relatively reliable alternative, and thus merits further trial and study in the future.

Cecilia Sanders

Concentrations: Earth and Planetary Sciences and Astrophysics

Impact gardening as a mechanism for hydrothermal alteration and atmospheric evolution on Noachian Mars

Advisors: **Robin Wordsworth**, Assistant Professor, Harvard School of Engineering and Applied Sciences; Affiliated Faculty Member of Earth and Planetary Sciences
Francis Macdonald, John L. Loeb Associate Professor of the Natural Sciences and co-Head tutor

On Noachian Mars (4.1-3.7 Ga), frequent meteor impacts associated with the Late Heavy Bombardment (4.1-3.8 Ga) may have led to increased rates of serpentinization and atmospheric evolution. The mechanism is simple: meteor impacts till the planetary crust, filling with it with fractures and effectively increasing the availability of unweathered mafic rock (Sleep and Zahnle 2001, Rubin 2012, Lindgren et al. 2014). In the subsurface, fresh rock generated by impacts may interact with fluids from impact-induced melting. Water, pressure, and abundant $(Fe,Mg)2SiO_4$ provide the conditions for serpentinization, a process that generates H_2 and, indirectly, methane (Oze and Sharma 2006, McCollom and Bach 2008, Quesnel et al. 2009, Guzmán-Marmolejo et al. 2013, Chassefière et al. 2013). H_2 in turn affects the redox potential of the atmosphere, and can even behave as a greenhouse gas when it is in high enough abundance to collide frequently with background molecules (Wordsworth and Pierrehumbert 2013, Ramirez et al. 2013).

I present models that test this mechanism, utilizing simple parameterizations of the Martian lithosphere, cryosphere, and atmosphere to demonstrate the possible extent of impact-induced serpentinization and predict the changes in atmospheric chemistry that may have followed. These models consider accepted constraints on Noachian impact rates (Hartmann 1971), the depth of the Martian cryosphere (Clifford and Parker 2001), and the relationship between impactor size and the mass of shocked material (Sleep and Zahnle 2001). I also include models for the decay of hydrothermal systems post-impact (Barnhart et al. ii 2010).

Preliminary results suggest that impact-induced serpentinization could not have contributed significantly to the reducing power of the Noachian atmosphere, as impact-generated hydrothermal systems grow dormant too quickly for serpentinization to persist for more than several thousand years. This has implications for early life, not simply because of the melting of large portions of the cryosphere, but because there are extremophilic organisms on Earth who rely on H_2 and other reducing species as a metabolic staple (Osinski et al. 2013). In addition, I also consider the possible influences of other impact-induced hydrothermal reactions, as illuminated by impact melt breccias from terrestrial impact sites.

Alyssa L. Chan

Concentrations: Earth and Planetary Sciences and Chemistry

Evaluation of sterols as an atmospheric oxygen isotope proxy for biogeochemical applications in Earth history

Advisors: **Dave Johnston**, Professor of the Natural Sciences and co-Director of Graduate Studies
Ann Pearson, Murray and Martha Ross Professor of Environmental Sciences,

The relationship between atmospheric oxygen and life is well established, and thus stable isotope studies of O_2 have long been considered a potential window through which to better understand the size and distribution of the biosphere over time. Constructing an isotopic record of atmospheric oxygen has historically been challenging, due to its short residence time and the relatively few reactions that use O_2 as a substrate. Ice cores preserve oxygen records but provide data with limited temporal and spatial resolution. This work investigates the potential of sterols, a biologically abundant class of lipid, to serve as a proxy for atmospheric oxygen isotopes. Sterols are well suited to this purpose for two reasons: first, their only known synthesis pathway requires atmospheric oxygen, and second, they are known to be resilient and relatively unreactive. Exchange reactions were conducted to assess the potential of sterols to preserve original atmospheric oxygen composition over geologic timescales. Two common sterols, androstanol and stigmasterol, along with a negative control, tricosanone, were continually exposed to ^{18}O-enriched water, and periodically analyzed by mass spectrometry to monitor oxygen exchange over time. An exchange model was created to quantify the half-life of exchange ($t_{1/2}$) of each compound based on the observed $\delta^{18}O$ data. Results showed that the lower bounds of exchangeability of androstanol and stigmasterol correspond to a $t_{1/2}$ on the order of 10-30 ky. Thus, these compounds exhibit great promise as atmospheric oxygen isotope proxies, and are particularly relevant to future studies of Holocene paleoclimate and paleoproductivity.

James W. Duncan V

Concentration: Earth and Planetary Sciences

Structural characteristics of the northern lobe of the deepwater Niger delta and their implications for petroleum prospectivity

Advisor: **John Shaw**, Harvey C. Dudley Professor of Structural and Economic Geology and Harvard College Professor, Department Chair

This study documents the influence of variations in the basal detachment level on structural styles and petroleum prospectivity of the northern lobe of deepwater Niger Delta. Using about 20,000 km^2 of 2D seismic reflection profiles and several 3D surveys, we analyzed more than 150 faults in the area, thoroughly mapped three detachment levels with the early Tertiary Akata Fm., and interpreted two Oligocene - Miocene stratigraphic horizon levels throughout the region. Through this data analysis, we assess variations in critical taper wedge behavior, structural styles, and the activity of three detachment levels in the area. We classified three main structural domains (Zone A, B, and C) based on the presence and activity of three basal detachments levels. Although the entire region holds a fairly low critical taper, indicating high basal fluid pressure, we found the taper angle generally increases from north to south. This increase may indicate changing fluid pressures, with the northern region characterized by a detachment at the top of the Akata Fm. that helps maintain elevated fluid pressures. In contrast, the southern region has detachment levels and associated thrust ramps within the Akata Fm., permitting upward fluid migration. Along with this structural data,we analyzed 62 wells in the northern and southern delta lobes and found fold traps to have higher prospectivity than fault traps. Moreover, hydrocarbon charge was more prevalent in the southern region, presumably due to faults rooted in the deeper detachment levels that traverse the Akata Fm. source rocks providing vertical charge pathways into the overlying reservoir units.

Ellen T. Robo

Concentrations: Earth and Planetary Sciences and Physics

Relationship between precipitation and precipitable water vapor over the maritime continent

Advisor: **Zhiming Kuang**, Gordon McKay Professor of Atmospheric and Environmental Science

Many questions about the Madden Julian Oscillation (MJO) are still unanswered. One among them is why, when it passes over the Maritime Continent, the deep convection associated with the MJO weakens. One theory as to why this happens is a strong diurnal cycle associated with the high percentage of land mass in the Maritime Continent provides a high frequency forcing that disrupts the otherwise low frequency MJO.

In this study, to better understand whether the diurnal cycle is the cause of the convection weakening, the relationship between precipitation and precipitable water vapor is investigated for observations taken over the ocean and over land to see whether they differ. Three different temporal resolutions of precipitation are used to better understand how precipitation changes over the course of a day and as more time is included around a precipitable water vapor observation. The diurnal cycles of precipitation and precipitable water vapor are further investigated as well.

This study finds that the relationship between precipitation and precipitable water vapor differs significantly and statistically over land and ocean. Furthermore, the difference in the relationship is a function of the distance the point of land is from a coast. Land far from a coast experiences cutoff in precipitation for high value of precipitable water vapor. Findings related to the changes seen in the relationship of precipitation and precipitable water vapor as the temporal resolution is changed support a strong diurnal forcing over the land that may be causing the weakening of the MJO as is passes over the Maritime Continent.

W. Wilson Kuhnel

Concentration: Earth and Planetary Sciences

Investigation into K-isotope fractionation in terrestrial minerals and implications for magmatic evolutions, K-Ar radiometric dating, and other geological processes

Advisor: **Stein Jacobsen**, Professor of Geochemistry

Advances in ICP-MS hexapole collision cells designed to reduce argon- and other ion-based spectroscopic interferences coupled with our group's improved ion-exchange chromatography elution method has led to improvements in potassium isotopic measurements an order of magnitude more precise than previous studies. Such development has allowed us to observe inter-mineral K isotopic fractionation for the first time, with plagioclase displaying a statistically significant fractionation of $\delta^{41}K_{BSE} = 0.925 \pm 0.031‰$ and biotite displaying a $\delta^{41}K_{BSE} = -0.147 \pm 0.025‰$, arrangements incorporating heavier and lighter isotopes respectively. This finding can also help in verifying broader inter-mineral equilibrium isotopic fractionation predicted by theories modeling the bond vibrational frequencies of various minerals. Our finding has the potential to change the way geochemists use K as a reference tracer across K-bearing samples, define K isotopic abundances for use in the K-Ar dating system, reference plagioclase-rich lunar anorthosites and their development from the proto-Moon, and place granitic and other igneous rocks in the context of the global K cycle currently under development. Further studies within the group will test lunar anorthosite samples for similar isotopic fractionation to better integrate terrestrial and lunar magmatic processes as well as improve upon our understanding of the Earth and Moon origins. Given potassium's ubiquity across geological disciplines, these revised information particulars are imperative to constraining and evaluating crust and mantle processes, radiometric dating, the Earth and lunar origins, and a broad range of geological systems.

Walker Evans

Concentration: Statistics

Determining earthquake source faults in Southern California: Statistical models for historical and future earthquakes

Advisors: **Natesh Pillai**, Associate Professor of Statistics and Co-Director of Graduate Studies, Department of Statistics
John Shaw, Harvey C. Dudley Professor of Structural and Economic Geology and Harvard College Professor, Department Chair

Our work proposes statistical models that systematically assign probabilities to the possibility that each fault in the Southern California Community Fault Model (Plesch et al., 2007) is the source of a given earthquake. Using data that is commonly recorded and rapidly available in the wake of an earthquake, we produced a model that can be used for historical earthquakes to identify their source faults. For future earthquakes, we produced a separate model that can identify their source faults in near real-time. When tested, our historical model predicts that the correct association is most likely for over 87% of the events that originated on faults that are represented in the Community Fault Model. For events that originated on faults not represented in the Community Fault Model, the historical model determined that such an unrepresented fault was the most likely source 80% of the time. Our model for use on future events was successful in these ways 97% and 38% of the time, respectively, though this testing was, by necessity, performed on an earlier representation of the faults than that on which this real-time model should be applied in practice. While the earthquake dataset on which we tested our models is not a random sample, an examination of our known data's characteristics in comparison to the full population of earthquakes in our catalogues combined with the strength of our results show that our models can be expected to produce reliable associations for earthquakes outside of our dataset. We utilize the associations that our models provide to quantify to what extent and where our knowledge of the potentially hazardous earthquake-causing fault system in Southern California remains incomplete. We also discuss how the given associations could be useful for promoting the efficient allocation of emergency response resources in the wake of an earthquake and in identifying foreshock sequences to warn of impending large earthquakes.

Tyler Barringer

Concentrations: Environmental Science and Engineering and Earth and Planetary Sciences

Solar photovoltaic power: short-term volatility and its future under climate change

Advisors: **Na Li**, Assistant Professor in Electrical Engineering and Applied Mathematics, School of Engineering and Applied Sciences
Dan Schrag, Sturgis Hooper Professor of Geology and Professor of Environmental Science and Engineering; Director of Harvard University Center for the Environment; Co-Area Dean for Environmental Science and Engineering

Solar power is becoming increasingly important as a source of energy in the United States. While solar represents a low-emission source of energy, integrating it into the electrical grid is challenging. The power output of solar is not controlled by operators, but is instead determined by the weather. Since solar power is not able to be controlled as a typical power station would be, analyzing its behavior is essential. This paper looks at three main points: the significance of short term variability in solar power output, mitigation techniques for short term variability, and how solar resources could change over the 21st century.

New England is the geographical focus of the analysis of short term variability as well as the geographical focus of the mitigation analysis. This region was chosen because its climate makes it especially susceptible to short term variability. Additionally, its solar industry is already being affected by policy decisions where short term variability plays a role. This study found that short term variability of solar photovoltaic arrays was significant in both magnitude and frequency. Over the course of a year, panels could be expected to fluctuate over 95% of their rated power output in a 5 minute time interval. Additionally, a strong seasonal correlation was found with short term variability. Variability reached a minimum in the winter, while peaking in the late spring and early autumn.

The mitigation analysis found that the addition of a storage system could effectively moderate the effects of short term variability produced by solar panels. The driving factor of the effectiveness of the storage system in mitigating variability was its maximum power output.

The Southwestern United States is the focus for the analysis on how solar resources may change in the 21st century. This region was chosen because it currently has the best solar resources in the US, which may lead to expensive and long-lasting infrastructure being installed in the area. Thus, the projected climate of the region becomes important. This study finds that solar resources in the Southwestern United States are projected to remain relatively steady over the coming century. The quality of the solar resources in the Southwest is expected to be maintained even under a medium or high carbon dioxide emissions scenario. Interestingly, the average cloudiness of the region is expected to increase with no effect on the amount of solar radiation the region receives.

Samuel Goldberg

Concentration: Earth and Planetary Sciences

Sea level change since last glacial maximum

Advisor: **Jerry Mitrovica**, Frank B. Baird, Jr. Professor of Science and co-Head Tutor

This thesis explores the spatial and temporal variation in sea level since the Last Glacial Maximum (LGM). The first component examines the geophysical effects of a potential flooding event in the Black Sea during postglacial sea level rise as the shallow Bosphorus sill was breached by the rising Mediterranean Sea. I present a suite of gravitationally self-consistent predictions of sea-level change since LGM that combine the sea level effects of glacial isostatic adjustment and a range of flood scenarios in the Black Sea. The predictions are tuned to fit a relative sea level record at the island of Samothrace in the north Aegean Sea, and include 3-D variations in the Earth's rheologic structure, including lateral heterogeneity in mantle viscosity and lithospheric elastic thickness, as well as weak plate boundary zones. The results demonstrate that 3-D Earth structure and the magnitude and timing of the flood event both have significant (~10 m) impact on the relative sea level at the Bosphorus sill, which in turn affects inferences of flood timing and/or sill depth at the time of reconnection. The results are summarized in a relationship between the three unconstrained flood parameters – timing, magnitude of the flood, and sill depth. These results will be useful for future research investigating the details of this highly debated event.

The second component of this thesis uses geologic sea level indicators in the far- field to improve predictions of a spatially diverse set of sea level records and to constrain ice volumes since LGM. Specifically, the goal is to reconcile the misfits of a Barbados-tuned model to a number of other far-field sites, notably the long record at Tahiti. A range of model parameters were assessed for their impact on far-field predictions, by varying both the ice model and Earth model inputs into a sea level model. The results suggest that it is unlikely that both the Barbados and Tahiti records can be fit with the same spherically symmetric model. However, a model tuned to the Tahiti record without consideration of the Barbados record provides a better fit to far-field sites in the Pacific, Indian, and Atlantic Oceans. This suggests that the Barbados record is anomalous. The consistency of Barbados sea level with other sites in the Caribbean indicates that the Barbados record is part a regional sea level anomaly in the Caribbean that cannot be captured with a spherically symmetric sea level model, and that the Barbados record should not be adopted for calibrating such 1-D models if the goal is to provide an accurate global prediction. Preliminary model results demonstrate that the incorporation of 3-D structure greatly reduces the misfit of a Tahiti-tuned model at Barbados; it is likely that further investigation will produce a model that is able to eliminate this misfit and bring the Caribbean sea level history in accord with other far-field records. The 3-D results also suggest that eustatic sea level at LGM was at least 10 m lower than ICE-6G predicts.