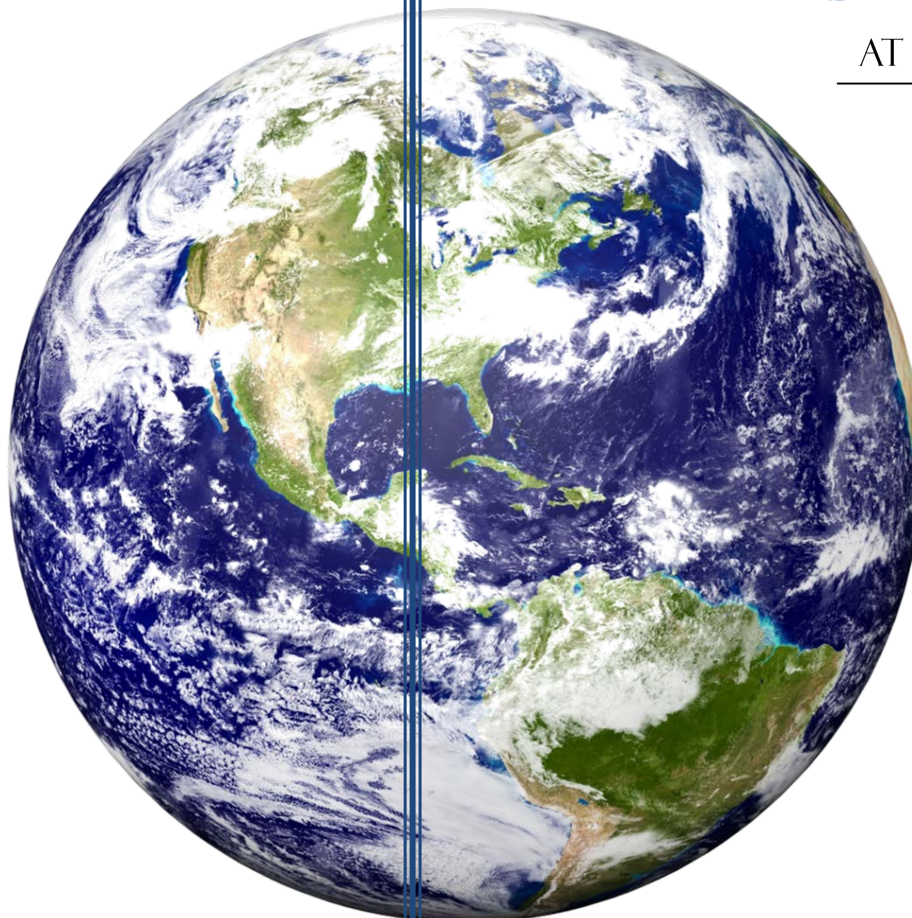

EARTH & PLANETARY SCIENCES

AT HARVARD UNIVERSITY

2018 Senior Thesis Presentations

Samuel J.C. LoBianco

Catherine A. Polik

Hanon McShea

Barra Peak

Hannah Byrne

Tuesday, May 1st, 2018 1:00-2:45 pm
Haller Hall, Geological Museum 102

Please join us for an Undergraduate End-of-Year Reception beginning at 3:00 pm in the Student Lounge (4th Floor, Hoffman Labs).

Please join us for a reception honoring
all of our EPS Undergraduates
3:00 pm
Student Lounge
4^{th} Floor, Hoffman Labs

Thank you for your support!

WELCOME

Message from the Co-Head Tutors:

Thank you for joining us as we celebrate the accomplishments of our senior thesis writers who spent much of their senior year tackling an exciting range of scientific problems. The senior thesis provides an opportunity for students to gain first hand experience in the full scope of research, from in-depth background study, to identification of core questions, design of a research program, collection and analysis of data, and formation of rigorous conclusions. This year's theses help refine the geological history of Peru, solve mysteries of paleotemperature proxies and the evolutionary history of nitrogenase, evaluate the impact of earth structure on glacial isostatic adjustment, and use models to identify the mechanisms of induced seismicity. Their efforts would not be possible without the support of faculty advisors, graduate students, and post docs. We thank these mentors and congratulate our seniors on their achievement.

Francis Macdonald and Jerry Mitrovica
Co-Head Tutors

Marine Denolle, Roger Fu, Zhiming Kuang, Francis Macdonald, Jerry Mitrovica, Ann Pearson
Undergraduate Curriculum Committee

Esther James and Annika Quick
EPS Preceptors

Chenoweth Moffatt
Academic Program Manager

Hannah Byrne

Concentration: Earth and Planetary Sciences

An Experiment in Earthquake Control at Rangely, Colorado Revisited: A Coupled Flow-Geomechanical Analysis of Induced Seismicity

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

Seismicity induced by subsurface fluid injection has grown in prevalence in recent years, posing a significant seismic hazard and necessitating an improved understanding of its underlying mechanistic behavior. Here, we present the application of coupled flow-geomechanical simulation technology (Juanes et al., 2016, 2017) to a famous experiment in induced seismicity that was conducted within the Rangely Oil Field in Colorado between 1969 and 1974 (Raleigh et al., 1976). The availability of geologic and seismologic data from the field, including well pressure measurements and constraints on the tectonic stress state, allow for both the objective testing of these methods and the determination of fault and earthquake properties that are otherwise difficult to obtain. The goals of this study are to: 1) assess the mechanisms that cause the seismicity, including the relative roles of poroelastic effects (reservoir volume changes) and fluid pressure changes; 2) characterize the frictional properties of the strike-slip fault that sourced the earthquakes; and 3) determine the proportion of critical stress on the fault which was introduced through anthropogenic activities. Our model includes a detailed representation of the reservoir and faults in the Rangely field, and simulates the changes of pressure and stress within the reservoir and on the faults for periods of fluid injection and withdrawal over the duration of the experiment. A high correlation between simulated and reported pressure values supports the accuracy of the model's outputs. Our analysis concludes that: 1) fluid pressure changes dominated variations in the Coulomb Failure Function (DCFF) acting on the faults that initiated and halted the earthquake sequences, mechanistically confirming the results of the Raleigh et al. (1976) paper; 2) the coefficient of friction for the fault is 0.2, agreeing with recent studies that suggest natural faults are much weaker than values derived in classic laboratory studies (Byerlee, 1978; He & Lu, 2007; Lockner, Morrow, Moore, & Hickman, 2011; M. D. Zoback et al., 2017); and 3) a small percentage (~ 1%) of the critical failure stress was anthropogenic in origin, indicating that these events were "triggered" rather than "induced." This last conclusion lends support to the idea that faults throughout the crust are critically stressed (Zoback, 1992). This analysis demonstrates the effectiveness of the coupled flow-geomechanical methods, and provides important insights into the properties of faults that can help us better understand the processes that control both induced and tectonic earthquakes.

Barra Peak

Concentration: Earth and Planetary Sciences

Glacial Isostatic Adjustment in Regions of Complex Earth Structure

Advisor: **Jerry X. Mitrovica**, Frank B. Baird, Jr. Professor of Science and co-Head Tutor, Earth and Planetary Sciences Department, Harvard University

Sea level reconstruction is an important component of paleoclimate research. However, certain assumptions made in standard modeling may bias these results. This thesis looks at the simplification of Earth structure commonly made in sea level models. More accurate, complex Earth structure is frequently ignored in numerical models of sea level change because of the huge computational expense its inclusion requires. However, the Earth *is* structurally complex with regards to lithospheric thickness and mantle viscosity, particularly in the vicinity of plate boundaries. This thesis investigates the effect of including this complexity in sea level reconstructions from Last Glacial Maximum (~21 ka) to present using a finite-volume numerical sea level model in comparison to a traditional spherically-symmetric sea level model that ignores complex Earth structure. Both models include contributions to sea level from glacial isostatic adjustment (GIA). The effects of mantle and lithospheric structure are explored specifically in the Red Sea, a tectonically complex area. Sea level calculated using the finite-volume model is found to show a significant (12% or greater) difference from sea level calculated using a spherically-symmetric Earth model, which has implications for global ice volumes inferred from sea level.

This thesis also tests an important assumption made in the literature regarding the sea level history of the Red Sea. This history has been assumed to be representative of eustatic (global average) sea level (Siddall et al., 2003, 2004) although other studies (e.g. Lambeck et al., 2011) have shown, using spherically-symmetric models, that there is a significant GIA component to sea level in addition to eustasy. We verify this conclusion with our spherically-symmetric model and also investigate the impact of lateral variability in Earth structure using the finite-volume model. We find that the finite-volume GIA model results in a maximum difference from eustatic sea level of ~36 m at 16 ka, making the eustatic assumption inadvisable for the Red Sea. This has implications for archaeological work done in the region in addition to climate and ocean research.

Samuel J.C. LoBianco

Concentration: Earth and Planetary Sciences

Formation and Inversion of the Mesozoic Arequipa Basin of the Central Andean Cordillera

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

The Mesozoic tectonic evolution of the South American Cordillera is recorded in Jurassic basins throughout Southern Peru. A recent tectonic model proposed by Hildebrand & Whalen (2014) invokes a major accretionary event that would have sutured the tectonic block underlying Southwestern Peru, the Arequipa Massif, to the metamorphic Marañon Complex of the eastern Amazonian Craton in the Late-Cretaceous. This model rejects the widely-held interpretation of a tectonically-homogeneous Central Andean margin and predicts passive margin sedimentation throughout the Mesozoic with westward subduction beneath an off-board Arequipa Massif, until the Late-Cretaceous. Furthermore, it attributes emplacement of the Peruvian Coastal Batholith to slab break-off magmatism and invokes a subsequent subduction polarity reversal to restore modern westward-dipping subduction. Here, I report geological mapping, stratigraphic, geochronological, geochemical, and petrographic data from two field sites in Southern Peru to document the formation and inversion of the Mesozoic volcanic arc and back-arc Arequipa Basin. New Early-Jurassic U-Pb detrital zircon ages from the Ongoro Fm. in the Majes Valley correlate with the regional Chocolate Fm. and indicate widespread basin formation and sedimentation as early as ~200 Ma in the back-arc. New Middle-Jurassic U-Pb detrital zircon ages from the Rio Grande Fm. in the coastal San Fernando Reservation indicate significant arc-volcanism on the Arequipa Massif between ~180-170 Ma, coinciding with a period of diachronous sub-basin formation controlled by westward migration of the arc. Furthermore, new geochemical, geochronological, and petrographic data from both field sites indicate a calc-alkaline volcanic arc-setting and the inheritance of Ordovician basement material that correlates with similar Famatinain intrusives within both the Arequipa Massif and Marañon Complex. These various data unequivocally constrain the adjacency of the Arequipa Massif to the South American continent through the Mesozoic, thereby refuting the Late-Cretaceous accretionary model for the Arequipa Massif. Furthermore, these data reveal a ~10-20 Ma diachroneity between sub-basin formation within the incipient Arequipa Basin, behind the westward-migrating Jurassic arc.

Catherine A. Polik

Concentration: Earth and Planetary Sciences

Impacts of Paleoecology on the TEX_{86} Paleotemperature Proxy

Advisor: **Ann Pearson**, Murray and Martha Ross Professor of Environmental Sciences; Harvard College Professor, Earth and Planetary Sciences Department, Harvard University
Felix Elling, Postdoctoral Fellow, Earth and Planetary Sciences Department, Harvard University

The TEX_{86} proxy, based on the distribution of isoprenoid glycerol dialkyl glycerol tetraethers (GDGTs) from planktonic Thaumarchaeota, has been widely used to reconstruct sea surface temperature (SST). Recent observations of species-specific and regionally dependent relationships between TEX_{86} and SST in cultures and the modern ocean raise the question of whether ecological factors such as community composition may impact TEX_{86} in the paleorecord. Here we evaluate the effects of rapid and dramatic ecological changes on GDGT distributions using one Pliocene and two Pleistocene sapropels from the Mediterranean Sea. During sapropel events, the Mediterranean experienced transient eutrophic and stratified euxinic conditions before returning to an oligotrophic background state. We find that $U^{K'}_{37}$-derived SSTs exhibit stable or monotonically increasing trends, thus forming a baseline against which ecological effects on TEX_{86} can be investigated. TEX_{86}-derived SSTs deviate from $U^{K'}_{37}$-derived SSTs before, during, and after each sapropel. TEX_{86}-derived SSTs are consistently warmer than $U^{K'}_{37}$-derived SSTs in the Pleistocene, while the Pliocene samples exhibit both warmer and cooler TEX_{86}-derived SSTs, by up to 10°C. The GDGT distributions from all three sapropels differ systematically from both globally distributed and Mediterranean core top samples within the same temperature range. They are marked by increased abundances of GDGT-2 and the crenarchaeol regioisomer. Compound-specific carbon isotope compositions ($\delta^{13}C_{GDGT}$) and the Branched and Isoprenoid Textraether (BIT) index indicate a thaumarchaeal source of GDGTs and no confounding influence on TEX_{86} from exogenous sources, such as methanotrophs or terrestrial Thaumarchaeota. Therefore, we interpret the changing relationship between TEX_{86} and SST through time to be a result of shifts between distinct thaumarchaeal communities. Through characteristic GDGT distributions, we identify three independent populations of Thaumarchaeota in the Pliocene, Pleistocene, and modern Mediterranean Sea, respectively. Importantly, these communities prevailed not only during sapropel events but also during oligotrophic conditions. Our findings imply that shifts in thaumarchaeal ecology may affect TEX_{86} paleorecords even within short geologic timeframes.

Hanon McShea

Concentration: Integrative Biology

The Evolutionary History of Nitrogenase: Using Ancestral Protein Reconstruction to Investigate Adaptation to Precambrian Selective Pressures

Advisor: **Betul Kacar**, Assistant Professor of Molecular and Cellular Biology, University of Arizona
Scott Edwards, Professor of Organismic and Evolutionary Biology, Harvard University
David Johnston, Professor of Earth and Planetary Sciences, Harvard University

Nitrogenase is the enzyme responsible for the whole planet's biological nitrogen fixation. It has redox-sensitive metal cofactors (Fe/Mo/V) and is irreversibly inactivated by oxygen, but it is thought to have originated in the Archean or early Proterozoic and thus has evolved through at least one massive change in atmospheric oxygen concentration over geologic time. We used ancestral protein reconstruction to search for signatures of adaptation in the protein's evolutionary history that may be linked to selective pressure imposed by increases in oxygen stress. Reconstructing ancestral protein sequences at each node in a phylogeny reveals which mutations most likely occurred along each one of its branches, and modeling ancestral protein structures allows us to measure the extent to which mutations on a branch are clustered in biochemically functional domains. Potential adaptive events were distinguished from background neutral evolution as instances in the protein's evolutionary history (branches in its phylogeny) where mutations are significantly clustered, rather than dispersed, in its physical structure. In our nitrogenase phylogeny, mutations were significantly clustered in the protein's structure on branches between clades of proteins in organisms with different oxygen tolerances and metabolisms. On the stem lineage of the monophyletic clade of nitrogenases from cyanobacteria, mutations are clustered in subunit termini thought to play a role in controlled protein degradation, the mechanism by which cyanobacteria protect nitrogenase from inactivation by oxygen.