IRESS 2018

Industry-Rice Earth Science Symposium

Welcome to IRESS 2018

This workshop will consist of two parts. The first will be to redefine our understanding of sequence stratigraphy in the context of contemporary concepts in sedimentary transport, climate, sea level, tectonics, mantle dynamics, and whole Earth system models. We will highlight key developments in technology and geologic data that have made scientific advances possible. The second part will consist of understanding the complex interplays between mantle and surface processes on the origin and development of the passive margin basement from the initiation of rifting to the maturation of an ocean basin. One of the goals of this workshop is to develop a new text, outlining passive margin evolution for the next generation of students and researchers. The workshop will be published as a journal special issue to be edited by Kevin Biddle, Gerald Dickens, and Cin-Ty Lee.

Chatham House Rule

This Symposium is held under the Chatham House Rule, under which participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s), nor that of any other participant, may be revealed. The use of this rule is intended to encourage openness in discussion and, it is hoped, will make this IRESS event more useful to all the participants.

RICE

SCHEDULE- Baker Institute

Day 1: Thursday, February 22, 2018

7:30-8:10 am	Registration and Coffee

Session 1:

8:15-8:25 am	Opening remarks: Cin-Ty Lee - Rice University
8:25-8:55 am	**Lee Kump - Pennsylvania State University** *Long term carbon cycling*
8:55-9:25 am	**Mark Torres - Rice University** *The life and times of carbon in surface environments*
9:25-9:40 am	*Break*
9:40-9:50 am	Introduction: Rajdeep Dasgupta - Rice University
9:50-10:20 am	**Chris Reinhard - Georgia Tech** *The importance of nutrients for the Earth's carbon cycle*
10:20-10:50 am	**Marie Edmonds - Cambridge University** *Volcanic CO2 flux into the atmosphere*
10:50-11:20 am	Discussion: Rajdeep Dasgupta, Jerry Dickens, Cin-Ty Lee, Francis Albarede
11:30 am –1:00 pm	Lunch- Doré Commons, Baker Institute for Public Policy

Session 2:

1:05-1:15 pm	Moderator: Mitch Harris - University of Miami, Jimmy Bent - Chevron
1:15-1:45 pm	**Lori Summa & Kurt Rudolf - ExxonMobil** *From pores to plates: stratigraphic controls on hydrocarbon sources and Sinks in sedimentary basins*
1:45-2:15 pm	**Daniel Minisini - Shell** *Carbon cycling, from volcanoes to source rocks, a sedimentary perspective*
2:15-2:30 pm	*Break*
2:30-3:00 pm	**Taras Bryndzia - Shell** *Organic matter, porosity and gas production in the Marcellus shale*
3:00-3:30 pm	**Andrew Madof - Chevron** *Gas hydrates in sandy reservoirs interpreted from velocity pull up: Are Mississippi-fan turbidites diffusively charged?*
3:30-4:00 pm	Discussion: Mitch Harris, Jimmy Bent
4:00-6:00 pm	Reception and Poster Session- Keith-Wiess Geological Laboratory

6:00-8:00 pm	Dinner- Doré Commons, Baker Institute for Public Policy Keynote Speaker: **Hugh Daigle - University of Texas, Austin** *Multiphase flow in the subsurface carbon cycle from source to sink*

Day 2: Friday, February 23, 2018

7:30-8:00 am	Registration and Coffee

Session 3:

8:15-8:30 am	Opening remarks: Cal Cooper - Apache Corporation
8:30-9:00 am	**Ken Medlock – Baker Institute, Rice University** *Energy, economics and policy- shale gas*
9:00-9:30 am	**Alex Archila - President, North American Shale, BHP Billiton**
9:30-9:45 am	Discussion: Cal Cooper
9:45-10:00 am	*Break*
10:00-10:30 am	**Melodie French - Rice University** *The frontiers of rock mechanics: Pore fluid pressure and seismicity*
10:30-11:00 am	**Yingcai Zhen - University of Houston** *Seismic imaging of fractures in reservoirs*
11:00-11:30 am	Discussion: Ken Abdulah & Fenglin Niu
11:30 am-1:00 pm	Lunch & Posters- Keith-Wiess Geological Laboratory

Session 4:	Moderator: Ken Abdulah - Subsurface Clarity
1:30-2:00 pm	**Tobias Hoeink - Baker Hughes** *The quest for permeability*
2:00-2:30 pm	**Priyank Jaiswal - Oklahoma State University** *Geophysical imaging of biocementation*
2:30-2:45 pm	Discussion: Ken Abdulah & Fenglin Niu
2:45-3:00 pm	Break
3:00-3:30 pm	Closing Discussion: Cin-Ty Lee - Rice University
3:30-5:00 pm	Closing reception- Keith-Wiess Geological Laboratory

RICE

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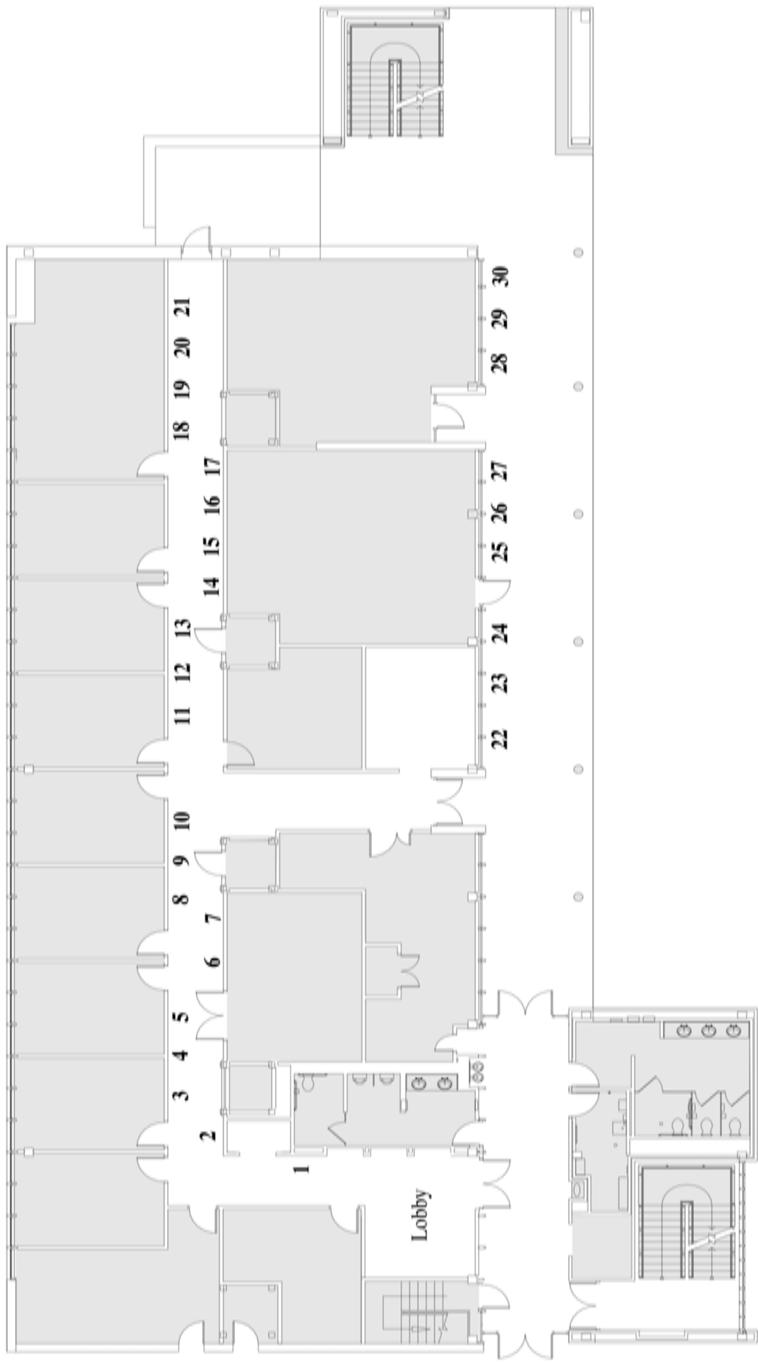
* Posters will be on the first floor corridor and patio area of the Keith Wiess Geological Laboratory

We wish to thank EEPS alumni Geoffrey Haddad, Laura Banfield, Dorothy Ballentine, and John Schneider for their generous donation of prize money for student posters.

Poster Session

Keith Wiess Geological Laboratory



Notes:

RICE

Abstracts:

Geology, tectonics, sedimentology

Towards a mechanistic understanding of the linkages between PETM climate modulation and stratigraphy, as discerned from the Piceance Basin, CO, USA

Eric Barefoot, Rice University

The Paleocene–Eocene Thermal Maximum (PETM) was a period of rapid climatic change when global temperatures increased by 5–8˚C in as little as 5 ka. It has been hypothesized that by drastically enhancing the hydrologic cycle, this temperature change significantly perturbed landscape dynamics over the ensuing ~200 ka. Much of the evidence documenting hydrological variability derives from studies of the stratigraphic record, which is interpreted to encode a system-clearing event in fluvial systems worldwide during and after the PETM. For example, in the Piceance Basin of Western Colorado, it is hypothesized that intensification of monsoons due to PETM warming caused an increase in sediment flux to the basin. The resulting stratigraphy records a modulation of the sedimentation rate, where the PETM interval is represented by a laterally extensive sheet sand positioned between units dominated by floodplain muds. The temporal interval, the sediment provenance history, as well as the tectonic history of the PETM in the Piceance Basin are all well-constrained, leaving climate as the most significant allogenic forcing in the Piceance Basin during the PETM. However, the precise nature of landscape change that link climate forcing by the PETM to modulation of the sedimentation rate in this basin remains to be demonstrated. Here, we present a simple stratigraphic numerical model coupled with a conceptual source-to-sink framework to test the impact of a suite of changing upstream boundary conditions on the fluvial system. In the model, climate-related variables force changes in flow characteristics such as sediment transport, slope, and velocity, which determine the resultant floodplain stratigraphy. The model is based on mathematical relations that link bankfull geometry and water discharge, impacting the lateral migration rate of the channel, sediment transport rate, and avulsion frequency, thereby producing a cross-section of basin stratigraphy. In this way, we simulate a raft of plausible, and mutually exclusive, climate-change scenarios for the case study of the Piceance Basin during the PETM, which may be compared to the stratigraphic record through field observation. The method described here represents a step towards connecting the impacts of global climate change to fluvial systems and sedimentation dynamics.

Geology, tectonics, sedimentology

Eocene Carbonate Dissolution Events in Northwest Pacific Ocean

Joyeeta Bhattacharya, Rice University

A series of carbon isotope excursions (CIEs) mark variations in the global carbon cycle and significant changes in climate through the early Paleogene. The Paleocene Eocene Thermal Maximum (PETM) ca. 56 Ma is the most pronounced and well documented of these events, having been described in many sections across the globe. The large CIE across the PETM is marked by a clay rich layer in many deep-sea sections, resulting from widespread carbonate dissolution on the seafloor, which is in turn related to shoaling of the carbonate compensation depth and lysocline. Several studies have suggested that other CIEs have a similar response, but this information is sparse. There is also debate as to how carbonate saturation in the ocean varied over the long-term. Following the prolonged greenhouse warming of Early Eocene Climate Optimum (~53-50 Ma), climate started cooling. However, this long-term cooling was also punctuated by transient warming events and increased carbonate dissolution in sea floor. Such instances have sparsely been addressed in perspective of global carbon cycling. Here we present changes in carbonate preservation in Eocene sediments at ODP Site 1209 (Shatsky Rise, northwest Pacific Ocean) to record vertical movement of lysocline through the Eocene. Combination of carbonate content record along with magnetic susceptibility and lysocline dissolution indices tied with carbon and oxygen isotopic record from bulk sediments gives a robust scope to understand lysoclinal dynamics of the Eocene and how early Eocene hyperthermals and middle-late Eocene transient warming events are related to changes in lysocline and in turn with quality and quantity of carbonate preservation at Site 1209. Such documentation allows us to better constrain relation of global warming and sea floor carbonate preservation in both short and long term warming periods.

Geology, tectonics, sedimentology

Simulating megathrust earthquakes using discrete element method

David Blank, Rice University

Large earthquakes that occur on convergent plate margin interfaces have the potential to cause widespread damage and loss of life. Recent observations reveal that a wide range of different slip behaviors take place along these megathrust faults, which demonstrate both their complexity, and our limited understanding of fault processes and their controls. Numerical modeling provides us with a useful tool that we can use to simulate earthquakes and related slip events, and to make direct observations and correlations among properties and parameters that might control them. Further analysis of these phenomena can lead to a more complete understanding of the underlying mechanisms that accompany the nucleation of large earthquakes, and what might trigger them. In this study, we use the discrete element method (DEM) to create numerical analogs to subduction megathrusts with heterogeneous fault friction. Displacement boundary conditions are applied in order to simulate tectonic loading, which in turn, induces slip along the fault. A wide range of slip behaviors are observed, ranging from creep to stick slip. We are able to characterize slip events by duration, stress drop, rupture area, and slip magnitude, and to correlate the relationships among these quantities. These characterizations allow us to develop a catalog of rupture events both spatially and temporally, for comparison with slip processes on natural faults.

Geology, tectonics, sedimentology

Tie channels on deltas: A case study from the Huanghe (Yellow River) delta, China

Brandee Carlson, Rice University

On river floodplains, tie channels convey sediment-laden water between the main channel and adjacent floodplain waterbodies. Field-based studies have documented that the bidirectional nature of flow in tie channels evacuates sediment deposited within the channel, thereby preserving an approximately consistent geometry over time. Herein, these findings are tested for an alternative fluvial environment: a deltaic system, where the distributary channel of an abandoned lobe is now occupied by a subordinate tie channel. The study region is the Yellow River delta of China; specifically, a lobe abandoned ten years ago due to a natural avulsion. An active tie channel maintains a connection between the main river and the adjacent Bohai Sea; therefore, water flux arises due to both riverine and tidal inputs. Measurements of the tie channel location, collected using remote sensing data, indicate that it has migrated laterally several hundred meters since inception, while concomitantly width has reduced by a factor of ten. Several field data sets were collected to constrain the morphological evolution of this tie channel, and compare formative processes to those known for floodplain tie channels. These data include sediment cores, measurements of water stage and flow velocity within the tie channel, and detailed elevation surveys of both the tie and abandoned distributary channels. Preliminary analyses show that, under low to moderate riverine discharge, tides are the primary driver for changes in water stage and flow velocity within the tie channel;

additionally, sedimentation arises at the main river and tie channel junction, nearly impeding movement of water between the two channels. This observation raises the question: What maintains the tie channel as an open flow conduit? It is likely that during river floods, enhanced water flux removes this sediment, thereby maintaining the tie channel as an open flow path. However, such floods have not occurred in the past two years, and there is notable encroachment of vegetation into the tie channel. Unlike oxbow tie channels, bi-directional flow may not be required to maintain geometry of deltaic tie channels; rather, it is the episodic movement of water during floods that maintains the channel over time, with narrowing due to vegetation growth during prolonged low flow periods.

Geochemistry

CO2 Release to the Atmosphere due to Magmatic Decarbonation of Crustal Carbonates

Laura Carter, Rice University

Assimilation of crustal limestone in intruding magma has been found to release potentially significant but varying amounts of CO2 to the exogenic system depending on pressure, temperature and magma composition. However, natural carbonates range from impure calcite to dolomite or ankerite and they have been found to be unstable at hydrothermal temperatures, though previous investigation at mid-crustal depth is lacking.

We have experimentally investigated both the thermal stability and reaction with arc magmas at high temperature and ~15 km depth for 3 Fe-bearing dolomite-calcite solid solutions. Dolomite breaks down into Fe-Mg oxides and CO2 at ≤800 °C. With increasing carbonate Ca/Mg, higher temperature is needed to reach a similar level of decarbonation and the transition from Fe-dolomite + Mg-calcite as stable carbonate phases to only the latter. In the presence of magmas, ferropericlase is still produced, but carbonate is Mg-calcite or calcite, and skarn silicate minerals seen in natural skarns, such as olivine, anorthite, diopside and wollastonite, crystallize.

Decarbonation increases with Mg/Ca ratios in the starting carbonate. Thus, at identical conditions, dolomite assimilation by dacite can release ~4 times as much CO2 as limestone. Moreover, with Mg/Ca≥0.48 in carbonate, release of CO2 due to thermal destabilization (≥900 °C) exceeds that from assimilation (≥1000 °C). Thus magma-carbonate interaction could have been a prominent carbon source to Earth's past atmosphere, as in the Cretaceous, which necessitates cataloging carbonate compositions globally for consideration in climate modeling.

Geophysics

Crustal and upper mantle velocity structure beneath northwestern South America revealed by the CARMArray

John Cornthwaite, Rice University

The Caribbean plate (CAR) is a fragment of the Farallon plate heavily modified by igneous processes that created the Caribbean large igneous province (CLIP) between ~110 and 80 Ma. The CAR collided with and initiated subduction beneath northwestern South America plate (SA) at about 60-55 Ma as a narrow flat-slab subduction zone with an accretionary prism offshore, but no volcanic arc. Large scale regional tomography suggests that ~1000 km of the CAR has been subducted (Van Benthem et al., 2013). The flat slab has caused Laramide-style basement uplifts of the Merida Andes, Sierra de la Perija, and Santa Marta ranges with elevations >5 km. The details of subduction geometry of the CAR plate beneath northeastern Colombia and northwestern Venezuela are complicated and remain unclear. The region of slab steepening lies below the triangular Maracaibo block (Bezada et al, 2010), bounded by major strike slip faults and currently escaping to the north over the CAR. Geodetic data suggests the this region has the potential for a magnitude 8+ earthquake (Bilham and Mencin, 2013).

To better understand the subduction geometry, we deployed 65 broadband (BB) stations across northeastern Colombia and northwestern Venezuela in April of 2016. The 65 stations interweave with the 32 existing Colombian and Venezuelan BB stations, forming a 2-D array (hereafter referred to as CARMArray) with a station spacing of ~35-100 km that covers an area of ~600 km by 400 km extending from the Caribbean coast in Colombia to the interior plains of Venezuela. With data from the first year of operation, we have computed finite frequency tomography. We also have measured the Rayleigh wave phase velocities and Z/H ratios in the period range of 8-40 s using both ambient noise and earthquake data recorded by the CARMArray. Finally, we generated Ps receiver functions from waveform data of teleseismic events recorded by the array. We will jointly invert the three datasets to construct a 3-D S-wave velocity model beneath the array. We report the initial results and discuss the lateral variations of crustal and upper mantle structure and their potential links with surface geology and regional tectonics.

Geology, tectonics, sedimentology

Lobe Evolution of Shelf-Edge Delta at Active Margin

Tian Dong, Rice University

Under the present conditions of sea level highstand, flooding of the continental shelf prevented formation of shelf-edge deltas. However, these systems are ubiquitous during glacial intervals, as low sea level allowed progradation of rivers to form deltas at the shelf-edge, based on observations from seismic data. The processes that govern shelf-edge delta evolution are therefore almost exclusively studied by analyzing seismic data, results from numerical and physical experiments. Validations of delta lobe growth models, and specifically water and sediment partitioning in channel networks, by field observation remain elusive. This study proposes to conduct field survey to collect water and sediment discharge partitioning data of in distributary network of a modern shelf-edge system, the Selenga River delta, to constrain spatially variable sedimentation and lobe growth pattern. Covering ~600 km2, this delta is located at the margin of the 1600 m deep, active Baikal Rift Zone in southern Siberian. Delta morphology is profoundly influenced by rift-induced earthquakes. The collected flow partitioning data from low to bankfull discharge conditions in conjunction with robust historical record (1908-2017) of earthquake subsidence rate, shoreline position, water and sedimentation pattern of the delta are used to determine the impacts of tectonic on sedimentation pattern in this shelf-edge delta. The intended results can constrain the timescale of delta lobe switching, sedimentation pattern, and impact of tectonic on such timescale, all of which from a field perspective. Results of this study can also be used to validate and improve existing models of delta lobe growth to better predict variation in sedimentation volume and pattern of shelf-edge deltas near a rift-basin, by which are proven to be some of the most prolific petroleum systems throughout the geological record.

Geochemistry

Volcanic CO2 flux into the atmosphere

Marie Edmonds (Cambridge University)

Volcanoes are a primary mechanism for the transfer of carbon from the interior of Earth (mantle and crust) to the surface environment. Over Earth history, volcanic outgassing has played a central role in setting the atmospheric concentration of CO2. Quantifying the magnitude of the volcanic CO2 flux in the present day is a significant challenge. Over the past 10 years important advances have been made in instrumentation to measure and monitor volcanic CO2, and recently the very first observations of volcanic CO2 from space were published. The magnitude of the volcanic CO2 flux into the atmosphere in the present day can now be estimated, although significant uncertainties remain. The data reveal that the volcanic CO2 flux is a small fraction (of the order of 1%) of the estimated anthropogenic flux of CO_2 into the atmosphere. Long term datasets at individual volcanoes reveal that the CO_2 flux may be highly variable with time. There are a few volcanoes and volcanic regions that dominate the volcanic CO_2 flux, including large continental volcanic centres such as Yellowstone (USA) and Mount Etna (Italy). The isotopic composition of the carbon tells us about carbon provenance: arc volcanoes outgas carbon that is isotopically heavier than typical mantle values and is derived partly from the subducting slab, and partly from the assimilation of limestones in the crust. Over geological time, it is likely that the relative importance of continental volcanoes would have waxed and waned, with implications for both the atmospheric concentration of CO_2 and the isotopic composition of Earth's surface reservoir.

Geochemistry

A new CO2 solubility model for silicate melts from fluid-saturation to graphite-saturation: Implications for the redox state of oceanic basalt source regions

James Eguchi, Rice University

The CO_2 content of natural silicate magmas influences many of their physicochemical properties. For this reason there have been several models developed to constrain the CO_2-H_2O solubility in fluid-saturated silicate magmas [e.g. 1]. However, most previous composition-dependent models of CO_2-solubility have been formulated to only treat fluid-saturated melts. With the growing number of experimental studies on CO_2 solubility at graphite-saturation, we developed a new model to quantify dissolved CO_2 contents at both fluid-saturated as well as graphite-saturated conditions over a wide range of P (0.05-3 GPa), T (950-1800 °C), and compositions (komatiite to rhyolite). The model is based on a thermodynamic framework that accounts for the effects of P, T, fCO_2, and compostion on the equilibrium constants of the CO_2 dissolution reactions.

Here, we use the model to investigate the redox state of oceanic basalt source regions that are deeper than the dry-peridotite solidus and may sample partial melts of enriched lithologies (e.g., eclogite, pyroxenite). We follow the approach of Eguchi & Dasgupta [2], who argued that CO_2 contents of many OIBs are too high to be explained by mixing with graphite-saturated partial melts of MORB-eclogite. This implies that MORB-eclogites are too oxidized for graphite to be the stable form of C at the depths where these rocks begin melt (>5 GPa). This is in contrast with cratonic xenolith records, which suggest that the redox state of the mantle should be within the graphite/diamond stability field at these depths [3]. However, MORB-eclogite produce relatively silica-rich melts, which dissolve less CO_2 compared to more silica-poor melts generated by some pyroxenites thought to contribute to oceanic basalt genesis [4]. Our new model predicts that at the same P, T, fO_2 conditions, graphite-saturated partial melts of pyroxenite dissolve $\leqslant \sim 1$ order of magnitude more CO_2 than partial melts of MORB-eclogite. We use our new model to determine CO¬2 contents at graphite-saturation for a range of partial melts thought to contribute to oceanic basalts. We then compare the results to geochemistries (e.g., CO_2 vs CO_2/Nb) of natural oceanic basalts to make inferences about the redox state of the regions of the mantle (deeper than the peridotite solidus) where partial melts of different enriched lithologies may be generated.

[1] Ghiorso, M., Gualda, G. (2015). CMP pp. 53. [2] Eguchi, J., Dasgupta R. (2017). CMP pp. 12. [3] Frost, D., McCammon, C. (2008). Ann Rev Earth Pl Sci. [4] Hirschmann, M., Stolper, E. (1996). CMP pp. 185-208.

Geology, tectonics, sedimentology

Understanding Controls on Uplift in Raukumara Peninsula, NZ: Insights from DEM Modeling

William Farrell, Rice University

It is thought that subcretion and underplating are important processes at subduction zones worldwide. Despite its proposed common occurrence, the physical mechanisms controlling if underplating occurs and the rate of its associated uplift are poorly understood. Basic questions about the tectonic and geomechanical parameters governing subduction channel stability, subcretion, and the rate and shape of associated uplift have proven difficult to answer. In this study we employ the Discrete Element Method (DEM) to address these questions, using the Raukumara Peninsula of New Zealand as the real-world basis of many of our model inputs. Raukumara Peninsula shows excellent geophysical evidence for underplated sediments at moho depths and the combined geologic, geophysical, and geodetic data sets from the region well constrain important model geometries and boundary conditions. The effects of surface processes and potential for shallow trenchward sliding are also investigated in the modeling effort.

Geophysics

The frontiers of rock mechanics: Pore fluid pressure and seismicity

Melodie French, Rice University

Rock mechanics experiments are used to understand the processes that control deformation of the lithosphere and their dependence on pressure, temperature, and the fluids that fill the pores of the rock. Technological advances in rock mechanics are being driven by emerging research questions. In the past decade, several observations suggest that the roles of fluid pressures in rock deformation are more complex than previously thought. Here I outline several seismological observations for the role of fluid pressure on the earthquake cycle. I will provide some new experimental observations that help explain contradictory observations in different tectonic settings based on rock properties. Finally, I will discuss some future directions in the field of experimental rock deformation with particular focus on the role that fluid pressures play in the earthquake cycle.

Geophysics

Homogeneous bubble nucleation in rhyolite: Curvature dependence of surface tension

Sahand Hajimirza, Rice University

The large bubble number densities, up to 10^16 bubbles per volume of melt, often observed in explosively erupted silicic magma requires a large nucleation rate. In the absence of impurities, large nucleation rate is a consequence of a large degree of supersaturation to overcome the energy barrier of formation of a new interface between melt and gas, which is a function of surface tension. Direct measurements of surface tension during nucleation, however, is impossible, because nuclei are very small in size and ephemeral, makes prediction of nucleation rate during eruptions fraught with uncertainty. The aim of this study is to improve our ability to predict homogeneous bubble nucleation during silicic eruptions by finding an empirical formulation for surface tension of rhyolitic melt. For this purpose, we performed decompression experiments in which water-saturated rhyolitic melt was decompressed and bubble number density (Nm) was measured after quenching. We then modeled bubble nucleation and growth during the experiments in order to predict Nm. We found an empirical formulation for surface tension by minimizing the difference between observed and predicted bubble number density for all experiments by performing a grid search. Our results are consistent with the fact that surface tension of a nucleus deviates from macroscopic values with a degree that depends on the radius of curvature of the nucleus. This deviation corresponds to the so called Tolman correction. Two different types of nucleation are predicted in our experiments. In the first type, nucleation rate peaks and continues until the sample is quenched. Final Nm in these samples is very sensitive to surface tension. In the second type, nucleation take place in a very narrow time interval and at very high rate. Final Nm in these samples is ontroled by the competition between decompression rate and diffusion rate of water into bubbles.

Industry: exploration and production

Controls on water production in unconventional wells of the Vaca Muerta Formation, Argentina

Jessica Hinojosa, Organic Geochemist, Shell

The rapid development of unconventional oil and gas resources has transformed the energy landscape. While the boom has accelerated the shift from coal to natural gas and contributed to lower energy prices, there are also consequences of this energy production method. In particular, disposal of wastewater from unconventional wells has been a challenge, both logistically and geologically, as this practice has been linked to increased seismicity. In addition to the environmental impact, the water-oil ratio (WOR) of unconventional wells plays a key role in well economics, as those wells with relatively high water-cuts are less productive, economical and desirable. Thus, prediction of water saturation prior to drilling and/or acreage acquisition has been a central theme in subsurface evaluation of unconventional plays.

However, work remains to understand the controls on water saturations in target strata. Here, we discuss two primary influences – hydrocarbon charge into existing pore space, and basin burial and uplift history. We use the Vaca Muerta Formation, a prolific source rock of the Neuquen Basin, Argentina, as a case study. Four wells were selected from throughout the basin, all of which landed in different stratigraphic units and produced different amounts of water during production. We discuss how source rock quality and associated hydrocarbon charge and retention may have influenced each well and explore how this information can be extrapolated within the basin.

In addition to discussion of these primary factors (charge and retention), we invite feedback on other possible influences on water saturation. What controls retention of formation water and mineral bound water during the basin history? How do faults and fractures play a role? What rock properties may exert control?

Finally, we link the life cycle of Vaca Muerta source rocks to the global carbon cycle, including how deposition and transformation in the subsurface contribute to carbon budgets over time.

Geophysics

The Quest for Permeability

Tobias Hoeink, Baker Hughes, a GE company

The only economical way to extract hydrocarbons from low-permeability shale reservoirs is to increase reservoir contact. Horizontal drilling, multi-stage completion, and hydraulic fracturing have proven key technologies in this respect. Yet, there is more to consider when engineering for optimal recovery on the quest for permeability. Many reservoirs are blessed with networks of natural fractures that are thought to act as hydrocarbon highways and contribute significantly to production. Focusing on fractured reservoirs, we will review how fractures across many length-scales contribute to permeability improvements that make unconventional reservoirs economically viable. We will discuss recent technology advances in fracture modeling, fracture network analysis techniques, and case studies that highlight the influence of fractures on stimulation and on the importance of integrated technology application for successful production.

Geology, tectonics, sedimentology

Continental Arcs as Both Carbon Source and Sink in Regulating Long Term Climate

Hehe Jiang, Rice University

The long-term variability of atmospheric pCO2 is determined by the balance between the rate of geologic inputs of CO¬¬2 (e.g., magmatic/metamorphic degassing, carbonate weathering) and the rate of carbonate precipitation driven by silicate weathering. The Late Cretaceous-Early Cenozoic was characterized by elevated atmospheric pCO2 and greenhouse climate, likely due to increased magmatic flux from continental arcs. However, it has been suggested that continental arc magmatism is accompanied by rapid uplift and erosion due to magmatic/tectonic thickening of the crust, thus continental arcs likely enhance the chemical weathering flux, in turn increasing the carbon sink. To assess the contribution of continental arcs to global carbon inputs and sinks, we conducted a case study in the Cretaceous Peninsular Ranges batholith (PRB) and associated forearc basin in southern California, USA, representing one segment of the Cretaceous Cordillera arc-forearc system. Arc magmatism occurred between 170-85 Ma, peaking at 100 Ma, but erosion of the arc continues into the early Eocene, with forearc sediments representing this protracted arc unroofing. During magmatism, we estimate up to 5 km elevation increase due to magmatic thickening, and the CO2 degassing flux from the PRB was at least ~5-25*105 mol·km-2·yr-1. By calculating the depletion of Ca and Mg in the forearc sediments relative to their arc protoliths, we estimate the silicate weathering/carbonate precipitation flux to be ~106 mol·km-2·yr-1 during Late Cretaceous magmatism, decreasing to ~105 mol·km-2·yr-1 by the Early Eocene. We show that in continental arcs, the CO2 degassing flux is comparable to CO2 consumption driven by silicate weathering in the arc. However, after magmatism ends, a regional imbalance arises in which the arc no longer contributes to CO2 inputs but continued silicate weathering of the arc drives carbonate precipitation such that the arc indirectly becomes CO2 sink. We propose that the development of continental arcs increases weatherability through mountain building processes, and therefore may increase the strength of the global negative feedback between silicate weathering and climate.

Geology, tectonics, sedimentology

Volcanic ash as a driver of enhanced organic carbon burial in the Cretaceous

Cin-Ty Lee, Rice University

On greater than million year timescales, carbon in the ocean-atmosphere-biosphere system is controlled by geologic inputs of CO2 through volcanic and metamorphic degassing. High atmospheric CO2 and warm climates in the Cretaceous have been attributed to enhanced volcanic emissions of CO2 through more rapid spreading at mid-ocean ridges and, in particular, to a global flare-up in continental arc volcanism. Here, we show that global flare-ups in continental arc magmatism also enhance the global flux of nutrients into the ocean through production of windblown ash. We show that up to 75% of Si, Fe and P is leached from windblown ash during and shortly after deposition, with soluble Si, Fe and P inputs from ash alone in the Cretaceous being higher than the combined input of dust and rivers today. Ash-derived nutrient inputs may have increased the efficiency of biological productivity and organic carbon preservation in the Cretaceous, possibly explaining why the carbon isotopic signature of Cretaceous seawater was high. Variations in volcanic activity, particularly continental arcs, have the potential of profoundly altering carbon cycling at the Earth's surface by increasing inputs of CO2 and ash-borne nutrients, which together enhance biological productivity and burial of organic carbon, generating an abundance of hydrocarbon source rocks.

Geology, tectonics, sedimentology

Filling Process of the Abandoned River Channel Based on Sediment Budget: the Example of the Yellow River

Zhaoying Li, Rice University

As inevitable production of fluvial development process, abandoned estuary is the crucial component of river system and offshore environment, playing a significant role in source to sink course. As time goes by, the serious eroded abandoned channel provides abundant materials to coastal waters, with sediment accumulation in channel simultaneously. The research about abandoned channel filling process concentrates on qualitative observation and description without quantitative analysis and pattern at present. Based on morphodynamic principles, this paper infers the sediment thickness- time formula in abandoned estuary from Exner sediment continuity equation. As an example, Qingshuigou distributary, an abandoned downstream channel of Huanghe River (the Yellow River), is used for verification in this paper. The grain size analysis of sediment core AC2 collected from abandoned estuary shows a variational depositional environment, especially the obvious change around artificial diversion in 1996 with sediment thickness of 39cm approximately. Combined with measured data of hydrodynamic condition near Qingshuigou abandoned estuary, the sediment-time pattern between 1996 and 2015 can be calculated, and the variation tendency is demonstrated by plotting. The result indicates that sedimentation of Qingshuigou distributary was in a stage of accumulation with decreasing deposition rate in 20 years with a maximum value of 0.15 m yr-1.

Geophysics

Gas hydrates in sandy reservoirs interpreted from velocity pull up: Are Mississippi-fan turbidites diffusively charged?

Andrew Madof, Chevron

Gas hydrates are recognized as an emerging energy resource and submarine geohazard; they are also thought to be a modulating mechanism on the global organic carbon budget and on past climate change. Although identified primarily from reflectivity changes at the base of the stability zone, gas hydrates located above this boundary are regularly difficult to interpret. Here, I introduce a non-reflectivity travel-time based method to detect gas hydrates in sandy reservoirs. The technique uses seismic travel-time deficits below high-velocity deposits in the stability zone to identify gas hydrate accumulations, and magnitudes of velocity pull up (VPU) to quantify in-situ saturation. The approach has been applied to a portion of the central Gulf of Mexico and has uncovered continuous high-velocity accumulations contained within sandy turbidites of the Quaternary Mississippi fan. Deposits extend more than 175 km southeast, and are interpreted to be vast and previously unidentified gas hydrates locally reaching saturations >70%. Based on reflection character and a marked lack of faulting, accumulations are inferred to have been sourced by short-migration diffusion of gas, making them one of the only known interpreted seismic examples of a non-focused-flow gas hydrate system. Further application of the VPU method can be used to provide insight into gas-migration mechanisms, and to catalogue worldwide distributions of gas hydrates in sandy reservoirs.

Geochemistry

The Deep Carbon Observatory: A ten-year quest to study carbon in Earth

Andrea Mangum, Deep Carbon Observatory

The Deep Carbon Observatory (DCO) is a ten-year quest to explore the quantities, movements, forms and origins of carbon in Earth's deep interior. This ambitious program aspires to bring transformative change to our understanding of Earth's deep carbon, which may include over 90% of our planet's total carbon. Launched in 2009 with seed funding from the Alfred P. Sloan Foundation, the DCO has evolved into a highly leveraged network connecting on the order of 1,000 scientists in 45 countries who work and collaborate across traditional disciplinary boundaries. Through its combined efforts, this global community has forged a new and integrative field of deep carbon science.

DCO's overarching mission is to understand Earth's deep carbon cycle beyond the atmosphere, oceans, and shallow crustal environments. To carry out this mission, the DCO has four Science Communities (Extreme Physics and Chemistry, Reservoirs and Fluxes, Deep Energy, and Deep Life) and four crosscutting initiatives (instrumentation, field studies, data science, and modeling and visualization). In addition, the DCO Engagement Team facilitates community involvement and communicating program achievements, and the DCO Secretariat provides program management, oversight, and coordination.

During the past eight years, members of the DCO science network have contributed over 1,000 peer-reviewed publications including more than 80 papers in *Nature*, *Science,* and *Proceedings of the National Academy of Sciences*. As the DCO approaches the culmination of the initial decadal program in 2019, a concerted effort is in progress to synthesize knowledge within and across DCO's communities. The DCO is sharing what has been learned and what remains unknown, and perhaps unknowable, about Earth's deep carbon cycle. The DCO is also exploring and encouraging options for promoting deep carbon science beyond 2019 by identifying structures and organizations to carry DCO legacy efforts forward and by proposing new DCO-inspired ventures that capitalize on the DCO's international and interdisciplinary science network.

Geophysics

Shallow structure S wave velocity model beneath the Gulf of Mexico passive margin by joint inversion of Rayleigh wave ellipticity and phase velocity

Wenpei Miao, Rice University

Although many seismic researches have been done on the Gulf of Mexico passive margin, its shallow structure is still poorly understood due to the existing of heavy sedimentary and thick salt deposits. Rayleigh wave ellipticity, or Z/H (vertical to horizontal) amplitude ratio is sensitive enough to constrain shallow structure beneath seismic stations and the Transportable Array (TA) deployed under the Earthscope project with an interval spacing of about 70 km makes it possible to study the sediment structure. In this study, we present a new 3D seismic model of Gulf of Mexico passive margin in a rectangular area of 100°-87° west and 28°-37° north based on joint inversion of Rayleigh wave ellipticity measurements and phase velocity at 6-40 s. We use daily continuous ambient noise data from totally 215 seismic stations of the TA. The measured Z/H ratios are spatially well correlated with the surface geological features and have lower values within the basins. At shallow depth, the 3D model is featured by strong low-velocity anomalies that are well consistent with the basins in the area. Sediment thickness increases from the south of Ouachita orogeny to the coast and the Gulf Coastal Basin has the thickest sedimentary which may reaches to ~10-15 km. Moho depth decreases significantly at the south of Ouachita orogeny, which means that the prior extension of Gulf of Mexico did not initially focus within the orogen but was adjacent to the orogen. Crystalline crustal thickness decreases toward southeast, due to an increase of sediment thickness and a decrease of Moho depth from northwest to southeast. This is consistent with a northwest to southeast extension prior to the opening of the Gulf of Mexico and nearly perpendicular to the NNE-SSW opening of the Gulf.

Geochemistry

Carbon Cycling, from Volcanoes to Source Rocks, a sedimentary perspective

Daniel Minisini, Shell

The deep Earth processes (e.g., tectonism, magmatism, volcanism) control the first order shape of the continental margins, the surface Earth processes (e.g., climate, erosion, sediment supply) reshape them through the redistribution of sediment. The interaction between the deep and the surface Earth processes impacts, among other things, the stratigraphic record and the carbon cycle. This contribution shows the interaction between volcanism, whose products drive long-term inputs of carbon dioxide and represent nutrients for marine organisms, and sedimentation, whose deposits include mudstones rich in organic carbon derived from the blooms of marine organisms, hence representing carbon sinks. The mudstones rich in organic carbon represents also a fundamental element of the petroleum system (together with migration, reservoir, trap, seal). Furthermore, since the "Unconventional Revolution" helped geologists to see the petroleum system with different eyes, the buried mudstone rich in organic carbon is considered now a stand-alone petroleum system that includes all the aforementioned elements. A rich and multidisciplinary dataset at different scales will show the connection of volcaniclastic material and organic matter, with cases from the Mesozoic in South and North America, and from the Holocene in the Mediterranean Sea. We will see how these rocks formed, what was their environment of deposition, and how we can produce energy from them. This simplified exposition of basic concepts important to the hydrocarbon exploration aims to bring together the mindsets of Industry and Academia, juxtaposing complex disciplines that rarely interact. I hope this form of interaction around the "carbon cycle" allows address in new ways some of the key questions we are tackling nowadays in hydrocarbon exploration: e.g., which are the predisposing factors and the triggers that allow the thickest and highest concentration of organic matter? How can we estimate quantities of hydrocarbon in these organic-rich mudstones? How do fluids migrate in pores just slightly larger than molecules? How do we optimize the production of hydrocarbons?

Geology, tectonics, sedimentology

Modeling deltaic lobe-building cycles and avulsions of the Yellow River delta, China

Andrew Moodie, Rice University

River deltas grow by repeating cycles of lobe development, whereby amalgamating lobes produce a deltaic landform over time. The growth of deltas is therefore impacted by lobe switching, which arises due to channel avulsion. Existing predictive models for backwater mediated avulsions fail to capture delta evolution over more than one lobe development cycle, and this represents a significant gap in modeling delta evolution. Herein, a reduced-complexity numerical model of deltaic avulsion and multiple lobe development cycles is introduced. The model is calibrated by a well-constrained case of lobe development on the Yellow River delta, China. It is determined that the development of deltaic lobes decreases the frequency of avulsion and increases the avulsion length, in contrast to the case where lobe development is ignored and not modeled. The avulsion location is pushed upstream because lobe development causes an understeepend fluvial slope, that is subsequently filled producing aggradation through the entire topset. Furthermore, the time and location of channel avulsions are sensitive to variations in avulsion criteria, including setup conditions due to channel bed aggradation, and trigger conditions related to overbank flow. For example, it is found that the time to avulsion is enhanced by increasing the necessary proportion of channel bed aggradation relative to overall flow depth, and/or increasing the required proportion of overbank flow. While this study is validated by data from the Yellow River delta, the numerical framework is rooted in physical relationships and may therefore be extended to other deltaic systems. Increasing anthropic influence through river engineering on deltas requires management strategies that balance the natural progression of the delta with society's need for system stability so as to maximize deltaic sustainability.

Geology, tectonics, sedimentology

Bar migration behavior in the lowermost Yellow River

Minglong Pan, Rice University

The Yellow River (Huanghe), China, avulses frequently due to its high sediment load. Avulsions are driven by sediment accumulation, which reduces the channel cross-sectional area, ultimately driving water flow to an alternative pathway. Typically, this occurs in regions of a reduced water surface gradient, such as the backwater zone, which lowers sediment transport capacity. This study seeks to identify the primary mechanisms of sediment accumulation within the fluvial-deltaic region of the Huanghe. Specifically, by assessing the extent to which bars migrate within the river channel in two study sites: 1) a backwater-mediated avulsion site, located between Lijin and Kenli, and 2) a deltaic avulsion site, located within the actively building lobe. For both sites, the avulsion timescale is ~10 years. At the backwater mediated avulsion site, GPR and core data were collected on a channel bar near Kenli; for both locations, Landsat data were used to track bar movement through time. Image analysis of Landsat data show that bars between Lijin and Kenli are relatively stationary from 1999 to 2017; here, GPR data show planar layers with small channels, and few structures that indicate mobility. Cores exhibit primarily very-fine sand with some mud layers, and the sand composition resembles that of the bed material in the active channel. The stationary behavior of bars in the backwater mediated avulsion site is in contrast to downstream at the delta avulsion site, where bars freely migrate and, in some locations, cluster and amalgamate. It is inferred that this process impedes flow and therefore sets up deltaic avulsions. These results indicate that bar migration patterns in the lowermost Huanghe differ between the fluvial and deltaic regions, and may be used to indicate future avulsion possibilities.

Geology, tectonics, sedimentology

Localized failure promoted by heterogeneous stresses in tectonic mélanges

Noah Phillips, McGill University

Within the shallow (<10 km depth) portion of subduction zones, tectonic mélanges are produced by distributed shear within downgoing sediments above the oceanic plate. Basaltic slabs (incorporated into the sediments through plucking and underplating) and sandstone layers form boudins within a shale dominated matrix due to strength contrasts within this zone of distributed shear. These tectonic mélanges are the host rocks of seismicity in subduction zones at shallow depths. Fluidized gouge and pseudotachylytes are evidence for paleoseismicity within exposures of mélanges, and occur preferentially along the contacts between shale matrix mélange and sandstone or basaltic layers. Detailed mapping within the Mugi Mélange, Japan has revealed basalt boudins enclosed by a cataclasite matrix derived from basalt. We model the stress concentrations around the strong basaltic boudins and slabs using the Power-Law Creep (PLC) toolbox developed at the University of Maine, which uses Asymptotic Expansion Homogenization (AEH) over a finite element mesh to determine the instantaneous stress distributions in a multiphase system. We model the shale matrix mélange to be deforming through a modified flow law for viscous creep based on coupled frictional sliding and pressure solution, where at a strain rate of 10-12 s-1 the flow stress is ~10 MPa under the temperature (190 ºC) and pressure (~100 MPa) conditions during deformation, and describe the behaviour of the basaltic blocks using experimentally-derived power law flow laws. The results show that at the strain rates calculated based on plate-rate motion, differential stresses high enough to cause comminution of the basalts (~300 MPa) correspond strongly to areas around the blocks with basalt derived cataclasites. Within the basalt derived cataclasites, thin zones of ultracataclasite record localized slip. We hypothesize that the heterogeneous stress distributions within subduction mélanges: 1) fractures the strong basalt thereby facilitating weakening through fluid-rock interactions, and 2) promotes localized slip (and occasionally seismicity) within these zones of altered basalt along the margins of strong intact basalt.

Geochemistry

In-situ **Biofilm Detection using field seismic methods**

Priyank Jaiswal, Oklahoma State University

Biofilms are ubiquitous in subsurface environments and are used in a variety of engineering and remediation applications. Yet, their in-situ field detection remains a challenge. In this pioneering study, how surface seismic can be used for detecting biofilms in-situ in field settings is shown. The study is conducted at a landfill site in Norman, Oklahoma, where interaction of a mobile leachate plume with groundwater has been ongoing for several decades promoting biogeochemical processes. In the experiment, both transmission and surface-wave coda are acquired along a 130 m long profile and inverted for seismic velocity and attenuation structure of the upper few meters of the subsurface. Results show that within the water table oscillation zone (a biogeochemical hotspot) S-wave velocity and P-wave attenuation increase by up to 60% and 80% respectively. Environmental scanning electron microscope images as well as X-ray diffraction images of soil samples strongly suggest that the seismically anomalous behavior of the water table oscillation zone is more likely to be due to high biofilm saturation (>5%) rather than changes in sediment composition. Field inferences are consistent with laboratory studies of similar nature. Further, a simple mechanistic model of biofilms coating quartz grains can explain the anomalous increase in S-wave velocity. The approach developed in this paper opens doors to remotely detecting biofilms in a variety of settings such as hyporehic zones and contaminant plume fringe and for a variety of purposes such as soil remediation and carbon sequestration.

Geochemistry

The importance of nutrients for Earth's carbon cycle

Chris Reinhard, Georgia Institute of Technology

The global carbon cycle links together the biosphere, planetary climate, and the chemistry of the oceans and atmosphere. The cycling of carbon at Earth's surface is in turn governed by feedbacks linking it with the oxygen and sulfur cycles, the cycling of major and trace nutrients, and the exchange of volatiles with Earth's interior. In particular, life on Earth requires ~30 chemical elements for the synthesis of structural compounds, enzymes, and nucleic acids. The cycling of these biological essential elements – nutrients – is a critical factor regulating the productivity of Earth's biosphere. On arbitrarily long timescales, it is thought that the cycling of phosphorus (P) provides the ultimate limitation on biospheric fertility, making the global phosphorus cycle critical for the long-term transfer of organic carbon into Earth's sedimentary reservoirs and, through attendant impacts on Earth's oxygen cycle, the recycling of carbon from Earth's crust back into the ocean-atmosphere system. Earth's rock record suggests that these processes and linkages depend strongly on the amount of oxygen in Earth's ocean-atmosphere system, in ways that are at times counterintuitive. For example, while local anoxia can enhance the burial of carbon in marine sediments, pervasive anoxia can dramatically decrease the productivity of the biosphere. In this light, it is the dynamics of nutrient cycling at Earth's surface that to a considerable extent modulate the activity level of the biosphere and thus global carbon fluxes.

Science Communication and Outreach

EEPS Reach: The New Department of Earth, Environmental and Planetary Sciences Outreach Program

Sriparna Saha, Alana Gambini Semple, Laura Carter, Eric Barefoot, Michael Lara, Linda Welzenbach, Rice University

Considering the fact that scientists often struggle to convey the true nature of their science to the public and the need of a proper forum to facilitate the interaction between scientists and non-experts we initiated an outreach program in the Department of Earth, Environmental and Planetary Sciences. Integral to our objective of bringing science to the public is an outreach program where we aim to educate and excite the public about geology and science. This is especially relevant in a city like Houston, where the job infrastructure is heavily dependent on the nature of geology here. The outreach program comes with the incentive of equipping young people with the required understanding that will enable them to make decisions about policies and decisions relevant to their lives. This project will also provide graduate students with opportunities beyond academia and industry to improve their communication skills, when working with public and make a positive impact on the community. We aim to address the inquisitiveness in the minds of the young and old alike by answering their queries and building a level of trust that enables them to question and evaluate situations relating to both policies and everyday life alike. This initiative involves teaching geology lessons and activities at schools and using platforms like the radio or social media to reach a wider audience. Future endeavors to build in collaborations with other departments from Rice University would eventually develop a stronger community that would benefit both Rice and the greater Houston community as a whole.

Geology, tectonics, sedimentology

Comparing the erosive effects of dissolution, abrasion, and bed roughness: A flume investigation of carbonate bedrock incision

Juliana Spector, Rice University

Traditionally, the chemical dissolution and erosion of bedrock in eroding river channels has been viewed as minor to negligible in comparison to mechanical weathering processes, such as impact wear from transported bedload sediment. However, for relatively soluble rocks, such as carbonates and evaporites, dissolution could be a significant contributor to erosion. The motivation for this project is to understand controls on the relative importance of bedrock dissolution and abrasion under different lithological and hydrological conditions. I hypothesize that physical and chemical erosion will cause subsequent increases in bed roughness that will enhance dissolution. In addition, I hypothesize that dissolution will result in a more spatially uniform distribution of erosion scales as compared to abrasion because chemical dissolution is the product of water running over the entire bed whereas abrasion is the end result of sediment particles impacting the bed in localized areas.

Through laboratory experiments, we actively eroded a flume bed made of plaster of paris (gypsum, $CaSO_4 \cdot 2H_2O$) with water and very fine gravel to observe the processes of dissolution and abrasion. Plaster of paris was used as a proxy for carbonate rock in these experiments due to its high solubility relative to carbonates and ability to be easily cast into a suitable size and shape. High resolution measurements of topography were made with a triangulating laser and 3-D scanner to quantify changes in the bed form as physical and chemical erosion occurred. The spatial and temporal evolution of erosion rates and surface roughness were quantified from topography. Electrical conductivity was measured throughout the experiments to infer rates of gypsum dissolution and link water chemistry with changes in physical bed topography.

I find that the spatial distributions of erosion are dependent on whether the bed topography has evolved due to dissolution or abrasion. The erosion distributions for both dissolution and abrasion are positively skewed with the most of the changes in bed topography being in contained areas of high erosion. However, across experiments, the erosion distributions for dissolution are closer to normal than the distributions for abrasion.

Geology, tectonics, sedimentology

From Pores to Plates: Stratigraphic Controls on Hydrocarbon Sources and Sinks in Sedimentary Basins

Lori Summa and Kurt Rudolph, ExxonMobil

The global energy system is in the midst of a profound transformation to lower carbon fuel sources and greater efficiencies, even as energy demand continues to grow. Most energy forecasts assume, however, that oil and gas will continue to play a prominent role in the world's energy mix, with natural gas use likely to increase in the near-term to meet growing electricity demand. Efforts to meet that demand in an efficient, and environmentally responsible manner have led to new challenges for geoscientists, e.g. new exploration and development strategies for shale and tight-liquids resources; tools to pursue deeper and more subtle plays in existing petroleum provinces; and effective use of varied and growing datasets.

We focus on one approach to addressing these challenges through integrated analysis of fundamental plate- to pore-scale physical, chemical, and biologic processes that control hydrocarbon sources and sinks in sedimentary basins. All sedimentary basins are unique, and inherit characteristics from multiple stages of their development. However, geologic processes are common, and can be recognized with incomplete data and conceptual models. The combinations and timing of the geologic processes determine the viability of hydrocarbon systems, and the nature of carbon sources and sinks. Geoscientists can investigate these processes using "genetic" approach that begins by evaluating plate-scale controls on basin formation and fill, and uses that understanding to predict sediment architecture, and ultimately, the interactions between sediments and fluids through time. Length scales of the analysis vary from hundreds of kilometers to microns, and time scales vary from millions of years to days. In this talk, we use field examples drawn from US and global assets to illustrate the fundamental concepts and evolving tools for analyzing hydrocarbon systems, and discuss our current ability to predict hydrocarbon resources and their associated uncertainties.

Geology, tectonics, sedimentology

Predicting coastal barrier response to sea-level rise along the Texas Gulf Coast

Travis Swanson, Rice University

The Texas portion of the Gulf Coast spans nearly 600 kilometers and is chiefly composed of barrier islands and peninsulas that shelter numerous landward communities from damaging storm surge and waves. Presently, this coastal barrier system is evolving at an unprecedented rate, as sediment that comprises these protective barriers is being depleted while sea-level rise is accelerating, reducing the resilience of coastal communities. To help explain the morphodynamic response of Texas' coastal barrier system to anticipated accelerated sea-level rise, a reduced complexity morphodynamic model is constructed from a combination of extant models of barrier morphodynamics, alongshore sediment transport, and time-variable ravinement depth. The model is initialized using a simplified geometric depiction of the barrier system morphology obtained from regional bathymetric and topographic surveys, and sediment composition from best-available subsurface geodatabases. Simulation timesteps capture the morphodynamic response of coastal barriers to accelerated sea-level rise by tracking the motion of key geomorphic boundaries within the barrier system: ravinement depth, shoreline, and bay line. The motion of these boundaries is calculated via parameterized expressions of alongshore, cross-shore, and barrier over-wash sediment transport that represent the time-integrated effect of short-term coastal processes, such as day-to-day waves and storms, and longer-term processes such as sea-level rise, dynamic barrier morphology, and barrier sediment composition. Model results are comparable with historical records and geological interpretations of regional coastal change sampled over a broad range of time and spatial scales.

Geochemistry

The life and times of carbon in surface environments

Mark Torres, Rice University

The geologic cycling of carbon is multifaceted and key to Earth's long-term habitability. Central to many aspects of the C cycle is the physical transport of terrestrial materials to the ocean and the biogeochemical transformations that occur during transport. Here, we use data and coupled models of fluvial morphodynamics and carbon cycling processes to infer how transport processes interact to control the quantity and character of both fossil sedimentary organic matter and newly produced "biospheric" organic carbon delivered to the ocean by rivers. These results are considered in the context of a new carbon cycle model to derive expectations for the limits and drivers of organic matter burial over geologic timescales.

Geology, tectonics, sedimentology

A Discrete Element Method Approach to Progressive Localization of Damage and Associated Seismicity

Harsha Vora, Rice University

Brittle failure in rock under confined biaxial conditions is accompanied by release of seismic energy, known as acoustic emissions (AE). The objective of our study is to understand the influence of rock type and its stress state on deformation patterns, and associated seismicity in granular rocks. Discrete Element Modeling is used to simulate biaxial tests on granular rocks of defined grain size distribution. Acoustic Energy and seismic moments are calculated from microfracture events as rock is taken to conditions of failure under different confining pressure states. Dimensionless parameters such as seismic b-values and degree of localization, D-values, are used to quantify seismic character and distribution of damage in rock.
Initial results suggest that confining pressure has the largest control on distribution of induced microfracturing, while fracture energy and seismic magnitudes are highly sensitive to elastic properties of rock. At low confining pressures, localized deformation (low D-values) and high seismic b-values are observed. Deformation at high confining pressures is distributed in nature (high D-values) and exhibit low seismic b-values as shearing becomes the dominant mode of microfracturing. Seismic b-values and fractal D-values obtained from microfracturing exhibit a linear inverse relationship, similar to trends observed in earthquakes. Modes of

microfracturing in our simulations of biaxial compression show mechanistic similarities to propagation of fractures and faults in nature.

Geology, tectonics, sedimentology

Plate velocities relative to hotspots and implication of motion of hotspots.

Chengzu Wang, Rice University

It is widely believed that groups of hotspots in different regions of the world are in relative motion at rates of 10 to 30 mm a–1 or more. Here we present a new method for analyzing geologically current motion between groups of hotspots beneath different plates. In an inversion of 56 globally distributed, equally weighted trends of hotspot tracks, the dispersion is dominated by differences in trend between different plates rather than differences within plates. Nonetheless the rate of hotspot motion perpendicular to the direction of absolute plate motion, vperp, differs significantly from zero for only three of ten plates and then by merely 0.3 to 1.4 mm a–1. The global mean upper bound on |vperp| is 3.2 ±2.7 mm a–1. Therefore, groups of hotspots move slowly and can be used to define a global reference frame for plate motions. Further implications for uncertainties in hotspot trends and current plate motion relative to hotspots will be discussed.

Geophysics

Numerical simulations of forearc deformation and stress switching after the great 2011 Tohoku-Oki earthquake

Xiaoyu Wang, Rice University

The large magnitude of the 2011 Mw 9.0 Tohoku-Oki earthquake, which occurred off the east coast of Japan, was not expected or predicted by any previous studies. The large megathrust earthquake was accompanied by surprisingly large displacement at the toe, contributing to a huge and destructive tsunami. Many questions remain as to why this earthquake was so large, and its implications for seismic hazard analyses. In addition to the large coseismic displacement along the plate interface near the trench, another surprising observation was the sudden change in stress state; local earthquakes confirmed a compressional stress state before the main shock, whereas an extensional stress state was evident after the main shock. Researchers have not yet reached a consensus on the mechanism for the stress change for Tohoku area, and its process is not well understood either. With the aid of Discrete Element Method (DEM) modeling and comparisons with stability diagrams based on Critical Coulomb Wedge (CCW) theory, the aims of this project are to reproduce the stress change after the main shock, and to explore the conditions that can cause stress switching both on- and offshore Tohoku. Numerical analysis is used to discover the feature of stress evolution and internal deformation, and data mining method is also used to find the pattern of stress data and calibrate friction coefficients. This project will also test two possible explanations for such stress changes to determine if there is a universal explanation for this phenomenon, or if the possibility of stress-switching depends on site-specific conditions that are uniquely found in the Tohoku area.

Geology, tectonics, sedimentology

True Polar Wander and the Origin of the Hawaiian-Emperor Bend: New Evidence

Daniel Woodworth, Rice University

We present an updated apparent polar wander (APW) path for the Pacific plate constructed from paleomagnetic poles determined from the skewness of marine magnetic anomalies, from equatorial sediment facies, and from paleocolatitudes of vertical cores of igneous rock. While paleocolatitude data provide some constraints, their usefulness is limited because they only limit the pole position in one direction, and the uncertainty in that direction is large because of the challenges of averaging secular variation. In contrast, secular variation contributes negligibly to the poles from skewness data, which give compact confidence limits for a well-defined interval of time. We review, update, or present six useful poles available for chrons 12r, 20r, 25r, 26r, 27r-31, and 32, corresponding respectively to 32 Ma, 44 Ma, 58 Ma, 60 Ma, 65 Ma, and 72 Ma. Moreover, we incorporate spin axis locations inferred from equatorial sediment facies [Suárez and Molnar; 1980; Gordon and Cape, 1981; Parés and Moore, 2005] and estimate their 95% confidence limits.
An APW path for Pacific hotspots can be obtained by moving each Pacific plate paleomagnetic pole with the Pacific plate relative to the hotspots to a reconstruction that corresponds to the age of the pole. This path has a stillstand from 44 Ma to 12 Ma at a location (P1) about 3° from the present spin axis and a second stillstand from 81 Ma to 58 Ma at a location (P2) about 11° from the present spin axis. We hypothesize that the shift from P2 to P1 records an episode of true polar wander sometime between 58 and 44 Ma and that the shift from P1 to the present spin axis records another episode of true polar that has occurred since 12 Ma and may continue today. We test these hypotheses by comparing the APW path of Pacific hotspots with the APW path of Indo-Atlantic hotspots and find them in agreement. Our results imply that global hotspots have moved in unison with respect to the spin axis and that the Hawaiian-Emperor Bend (HEB) does not record a change in motion through the mantle of the Hawaiian plume. Instead the HEB records a change in Pacific plate motion over a stationary plume as originally proposed by W. J. Morgan.

Geology, tectonics, sedimentology

Impacts of variable channel hydraulics on the stratigraphic record: an example provided from the Tullig Sandstone, Western Irish Namurian Basin

Chenliang Wu, Rice University

River hydrodynamic conditions are modified where a system approaches its terminal basin, characterized by the onset of non-uniform “backwater” flow. A decrease in boundary shear stress in the backwater region reduces transport capacity and results in sediment deposition on the channel bed. Although such morphodynamic conditions are common in modern fluvial-deltaic channels, the extent to which these processes are prevalent in the stratigraphic record remains unclear. For example, a few studies documenting changes in fluvial sandstone channel dimensions and grain size distributions near a river terminus attributed this variability to backwater hydrodynamics. However, quantitative tests using morphodynamic models bolstered by a variety of field observations, which could then be linked to sediment depositional patterns and stratigraphy, have yet to be produced. Here we calibrate a one-dimensional river flow model with measurements of paleo-slope and channel depth, and use the output to constrain a sediment transport model, with data from the Tullig Sandstone in the Western Irish Namurian Basin. Based on the model results, our analyses indicate that: (1) backwater hydrodynamics influence the spatial variation of sandstone dimensions and grain size across the delta, and (2) backwater hydrodynamics drive channel bed aggradation and progradation of the river mouth for conditions of constant sea level. Field data indicate that the reach-average story thickness increases, and then decreases, progressing downstream over the backwater reach. Based on the inferred transport and depositional processes, the measured deltaic stratigraphy patterns shown here are assumed to be associated with backwater hydrodynamics, and are therefore largely autogenic in origin. These analyses indicate that non-uniform hydrodynamics can generate stratigraphic patterns that could be conflated as arising due to allogenic effects, based on traditional geometric or diffusion-based depositional models. Moreover, the signals of river hydrodynamics preserved in the stratigraphic record can be a useful tool for differentiating between short-term autogenic and long-term allogenic processes.

Geophysics

Joint inversion of high resolution S-wave velocity structure underneath North China Plain

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North China plain is one of earthquake prone areas in China. Many devastating earthquakes occurred in the last century and before, such as the 1937 M7.0 Heze Earthquake, 1966 M7.2 Xingtai Earthquake and 1976 Tangshan Earthquake. Knowing the structure of the sediment cover is of great importance to predict strong ground motion caused by earthquakes. Quantitative estimates of the amount of extension of the North China plain is important to understand the thinning and evolution of the eastern North China craton and the underlying mechanism. In principle, it can be estimated from sediment and crust thickness. In this study, we jointly invert the Rayleigh wave phase velocity dispersion and Z/H ratio data to construct a 3-D S-wave velocity model beneath North China area. We use 4-year ambient noise data recorded from 249 temporary stations, and 139 earthquake events. Our results show a relatively low Z/H ratio and low velocity anomaly at the shallow part of sediment basins.

Geology, tectonics, sedimentology

The Malpelo Plate Hypothesis and Implications for Non-closure of the Cocos-Nazca-Pacific Plate Motion Circuit

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The non-closure of the Cocos-Nazca-Pacific plate motion circuit by 15.0 mm a–1± 3.8 mm a-1 (95% confidence limits throughout this abstract) [DeMets et al. 2010] represents a daunting challenge to the central tenet of plate tectonics—that the plates are rigid. This misfit is difficult to explain from known processes of intraplate deformation, such as horizontal thermal contraction [Collette, 1974; Kumar and Gordon, 2009; Kreemer and Gordon, 2014; Mishra and Gordon, 2016] or movement of plates over a non-spherical Earth [McKenzie, 1972; Turcotte and Oxburgh, 1973]. Possibly there are one or more unrecognized plate boundaries in the circuit, but no such boundary has been found to date.

To make progress on this problem, we present three new Cocos-Nazca transform fault azimuths from multibeam data now available through Geomapapp's global multi-resolution topography [Ryan et al., 2009]. We determine a new Cocos-Nazca best-fitting angular velocity from the three new transform-fault azimuths combined with the spreading rates of DeMets et al. [2010]. The new direction of relative plate motion is 3.3° ±1.8° clockwise of prior estimates and is 4.9° ±2.7° clockwise of the azimuth of the Panama transform fault, demonstrating that the Panama transform fault does not parallel Nazca-Cocos plate motion.

We infer that the plate east of the Panama transform fault is not the Nazca plate, but instead is a microplate that we term the Malpelo plate. We hypothesize that a diffuse plate boundary separates the Malpelo plate from the much larger Nazca plate. The Malpelo plate extends only as far north as ≈6°N where seismicity marks another boundary with a previously recognized microplate, the Coiba plate [Pennington, 1981, Adamek et al., 1988]. The Malpelo plate moves 5.9 mm a-1 relative to the Nazca plate along the Panama transform fault.
When we sum the Cocos-Pacific and Pacific-Nazca best-fitting angular velocities of DeMets et al. [2010] with our new Nazca-Cocos best-fitting angular velocity, we find a new linear velocity of non-closure of 11.6 mm a–1± 3.8 mm a-1, i.e., the non-closure is reduced by 3.4 mm a–1. The non-closure still seems too large to be due entirely to intraplate deformation and suggests that one or more additional plate boundaries remain to be discovered.

Geology, tectonics, sedimentology

Insights into crystal growth rates from a study of orbicular granitoids from western Australia

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The purpose of this study is to develop new tools for constraining crystal growth rate in geologic systems. Of interest is the growth of crystals in magmatic systems because crystallization changes the rheology of a magma as well as provides surfaces on which bubbles can nucleate. To explore crystal growth in more detail, we conducted a case study of orbicular granitoids from western Australia. The orbicules occur as spheroids dispersed in a granitic matrix. Most orbicules have at least two to three concentric bands, composed of elongate and radially oriented hornblende surrounded by interstitial plagioclase. We show that mineral modes and hence bulk composition at the scale of the band is homogeneous from rim to core. Crystals number density decreases and crystal size increases from rim to core. These observations suggest that the orbicules crystallized rapidly from rim to core. We hypothesize that the orbicules are blobs of hot dioritic liquid injected into a cold granitic magma and subsequently cooled and solidified. Crystals stop growing when the mass transport rate tends to zero due to the low temperature. We estimated cooling timescales based on conductive cooling models, constraining crystal growth rates to be 10^-6 to 10^-5 m/s or ~1-2 cm/hr. We also show that the oscillatory banding is controlled by disequilibrium crystallization, wherein hornblende preferentially crystallizes, resulting in the diffusive growth of a chemical chemical boundary layer enriched in plagioclase component, which in turns results in crystallization of plagioclase. We show that the correlation between the width of each crystallization couplet (band) with distance from orbicule rim is linear, with the slope corresponding to the square root of the ratio between chemical diffusivity in the growth medium and thermal diffusivity. We estimate chemical diffusivities of 2*10^-7 m^2/s, which is remarkably fast for silicate liquids but reasonable for diffusion in hot aqueous fluids, suggesting that crystallization occurred during water-saturated conditions. Combined with estimates of the boundary layer thickness, we use these diffusivities to estimate the diffusive flux, arriving at crystal growth rates similar to that constrained by thermal modeling. In the presence of fluids, we show that crystal growth rates in magmatic systems may be under-estimated.

Geology, tectonics, sedimentology

Seismic Imaging of fractures in reservoirs

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Commercial production of unconventional resources has introduced many disruptive changes to the energy industry ranging from business aspects to technologies. As of now, about 2/3 of the U.S. oil production is from shale whereas such production was nearly nonexistent a decade ago. Previously, seismic imaging was primarily used to map geological boundaries and structural traps. However, in the development of unconventional resources, seismic imaging technologies shall be adapted to address the uneven spatial distribution characteristics of resources and the associated environmental concerns. I will talk about how seismic waves can be used to address these issues and in particular to characterize natural fracture distributions to infer permeable pathways to increase productivity.ork with methane hydrates, organic shales, and nanoparticles informs this understanding.

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