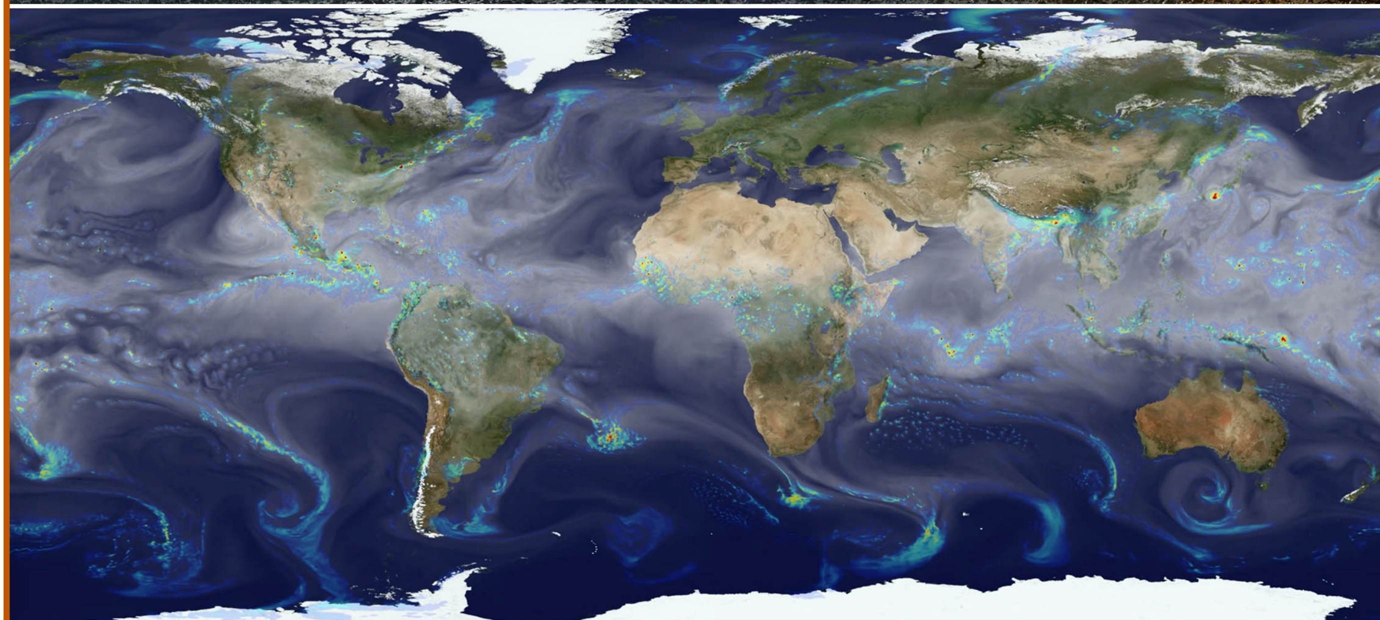
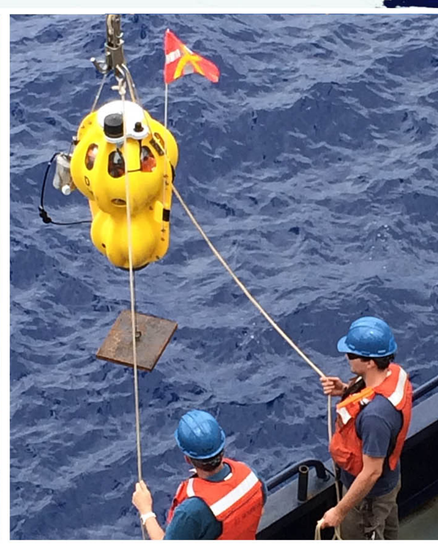
INSTITUTE FOR GEOPHYSICS

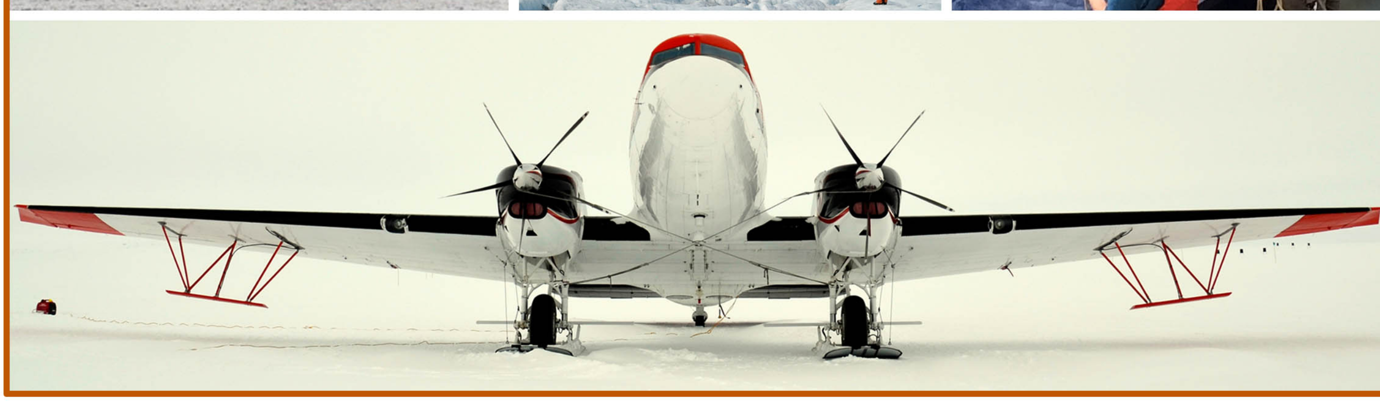
THE UNIVERSITY OF TEXAS AT AUSTIN

Science Vision

2015 - 2025







INSTITUTE FOR GEOPHYSICS
JACKSON SCHOOL OF GEOSCIENCES

UTIG Science Vision

(endorsed in Fall 2016)

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INSTITUTE FOR GEOPHYSICS
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Introduction: Understanding how worlds work

The next decade poses numerous challenges where society will look to geophysicists to provide answers to key problems. Earth is undergoing climate change while its inhabitants face a transformation in resource use and availability, and urbanization and global change will lead to increased exposure to catastrophic natural events. Using the Earth as a laboratory for geophysical processes on planets, we can also ask fundamental questions about the evolution and habitability of bodies across the solar system.

UTIG, with its identity of combining daring expeditions and data analysis with state-of-the-art computing, has identified four major, interconnected research directions to address earth and planetary science questions of global significance in the coming decade. These initiatives in climate dynamics, polar and planetary geophysics, marine geosciences, seismology and tectonophysics, and energy geosciences, provide a collaborative research environment where creativity can flourish and UTIG science will lead the community.

UTIG will bring the full geophysical campaign, experiment, and instrumentation development perspective to these problems with an international, entrepreneurial, and collaborative outlook. However, it is clear that these problems also cross disciplines, as does UTIG, and the Institute is fortunate to be able to rely on the additional resources of the co-located Bureau of Economic Geology and the Department of Geological Sciences at the Jackson School, along with other collaborations within the University of Texas at Austin, such as the Texas Advanced Computing Center.

In pushing to answer some of the key geophysical questions that face society, UTIG recognizes that a wide range of outlooks and backgrounds is an institutional and community strength. UTIG is also committed to educating the next generation of geophysical problem-solvers for academia and industry through active involvement of student scientists and postdoctoral fellows.

1. Climate Dynamics

1.1. Strategic goals in the community

Climate change caused by human activities poses a significant threat to our society, economy, agriculture, and marine and terrestrial ecosystems. The *Intergovernmental Panel on Climate Change 5th Assessment Report* (IPCC AR5) concludes, "warming of the climate system is unequivocal" and "human influence on the climate system is clear". This increased certainty on the anthropogenic causes of global warming relative to previous reports came about through improved in climate observations, numerical models, and statistical attribution methodologies. However, progress in anticipating and interpreting the causes of future climate also reveal a number of important issues:

- While models are capable of predicting century-long **global** warming trends associated with increasing greenhouse gases, they are severely limited in predicting **regional** climate changes on time scales of a few years to decades that are vitally important for planning.
- Observations over the instrumental record are not sufficient to study slow climate variations nor reliably estimate the climate sensitivity to external forcing, including volcanic forcing. Therefore, there is a need to characterize the full spectrum of natural variability.
- It is becoming increasingly important to understand how the dynamics of the ocean and atmosphere interact with the other components of the Earth system, notably the cryosphere and biosphere.
- There is a strong need to develop strategies to expand and sustain the number of high-quality observational assets that are available to future generations with which to assess future climate changes, including more observations of past climates.

1.2. UTIG approach and strengths

UTIG has an important role to play in helping the climate community develop strategies in model-data synthesis to interpret what can be interpreted, to quantify interpretation uncertainties, and to leverage predictive models to identify what new observations are needed. The need for these crucial skills stems from the limited observational record that is available to develop and test our understanding of climate phenomena. Moreover the processes that control these phenomena are often only indirectly related to what can be observed. This is particularly true for the paleoclimate proxy data that provides a unique perspective on regional climate variability on a range of time scales. UTIG has experience in developing model-data synthesis strategies including those for data inversion, data assimilation, and Bayesian and applied math approaches to uncertainty quantification. UTIG's unique strengths are further enhanced by partnerships with UT's Institute for Computational Engineering and Sciences, Center for Space Research, and the Texas Advanced Computing Center.

Figure 1 – UTIG leverages advanced processing centers such as the Texas Advanced Computing Center (left) for large scale computation and visualization for climate dynamics, cryosphere, and energy geoscience studies. UTIG acquires a range of observations in the Arctic (center) and the Antarctic to inform and constrain a variety of models necessary to understand and estimate processes affecting future sea level change. UTIG has also established particular expertise with paleoclimate proxies, such as stalagmites (right), critical for climate reconstructions and constraints on hindcasting.

1.3. Priorities and opportunities in climate dynamics

1.3.1. Climate variability and regional climate change

Climate fluctuates from year to year and from decade to decade owing to dynamics internal to the climate system. This natural climate variability will continue to have significant impacts on our society under global warming and cause uncertainty in the prediction of future regional climate change. Understanding the basic dynamical mechanisms of climate variability is crucial not only for the regional climate prediction but also for detection and attribution of observed climate changes. A challenge is that instrumental records have been inadequate to fully characterize natural climate variability; What is the range of decadal climate variability in the Pacific and Atlantic Oceans? Can global warming affect natural climate variability and its impacts, especially those associated with the El Nino-Southern Oscillation? What are the dynamical and physical mechanisms that may cause abrupt climate changes? In order to further our understanding of basic mechanisms and test model predictions, we need to be more creative with our strategies to observe and test hypotheses with instrumental and paleoclimate proxy data. UTIG is uniquely positioned to tackle this important scientific problem through the development of decadally resolved paleoclimate proxies and their interpretation in terms of theory and modeling.

1.3.2. Water availability

The global hydrological cycle is expected to accelerate over the next few decades as the water content of the atmosphere increases due to Global Warming. Evaporation will increase, resulting in drying of subtropical areas and increasing precipitation in the deep tropics and higher latitudes. While models agree on these broad latitudinal patterns, they offer little consistency on the regional details of how rainfall will change, except for a general notion that warmer regions tend to get wetter, and regions that warm less tend to get drier. Models also offer wildly diverging pictures of future changes in the monsoons, the most important source of water in highly populated areas in Asia. Models' ability to anticipate persistent droughts is also questionable because they fail to simulate so-called "Mega droughts" seen in tree ring records. Overall, these uncertainties about future precipitation make it difficult for decision-makers to plan, particularly in arid regions such as the Sahel in Africa and southwestern North America.

UTIG can contribute with the following approaches to increase our confidence in these model projections: improve our mechanistic understanding of patterns of warming, improve the simulation of key climate variables such as the formation and dynamics of clouds, quantify the full spectrum of rainfall variability, particularly on multi-decadal and centennial timescales using paleoclimate data. Paleoclimate records could continue to provide useful information for the evaluation of models regarding the role of patterns of warming, sensitivity of Monsoons to external forcings, and the full spectrum of low frequency variability. Quantitative approaches to synthesize model and proxy data, such as forward-proxy modelling, should be considered, as they could allow a more accurate evaluation of the models' low frequency variability and how proxies record climate information.

1.3.3. Bounds to future sea level rise

The potential exists for significant losses to the Greenland and Antarctic ice sheets, which would lead to dramatic sea level rise. There are large uncertainties in potential rates of change in the ice sheets, largely because of hard-to-observe processes that govern melt at the ice-ocean interface and sliding at the ice-bed interface. In addition, the polar atmospheres and the surface mass balance of the Greenland and Antarctic ice sheets are affected by uncertain local and global cloud feedbacks. While we observe dramatic changes within some sectors of both ice sheets, it is still not clear whether these changes are manifestations of internal variability, the continued equilibration of the polar atmosphere-ocean-ice system to changes coming out of the last ice age, or early manifestations of this region's response to global warming. UTIG can play a significant role in addressing these uncertainties through its ability to field observational campaigns, exploitation of geophysical data collection tools and interpretation, data assimilation, and forward modeling of component systems (most notably the land ice and ocean components). For the community as a whole and UTIG in particular, the synthesis of these predictive models with data has only been attempted in part. Thus there is a lot of potential to exploit UTIG advantages even while expanding our capacities to simulate key processes and to develop testable hypotheses.

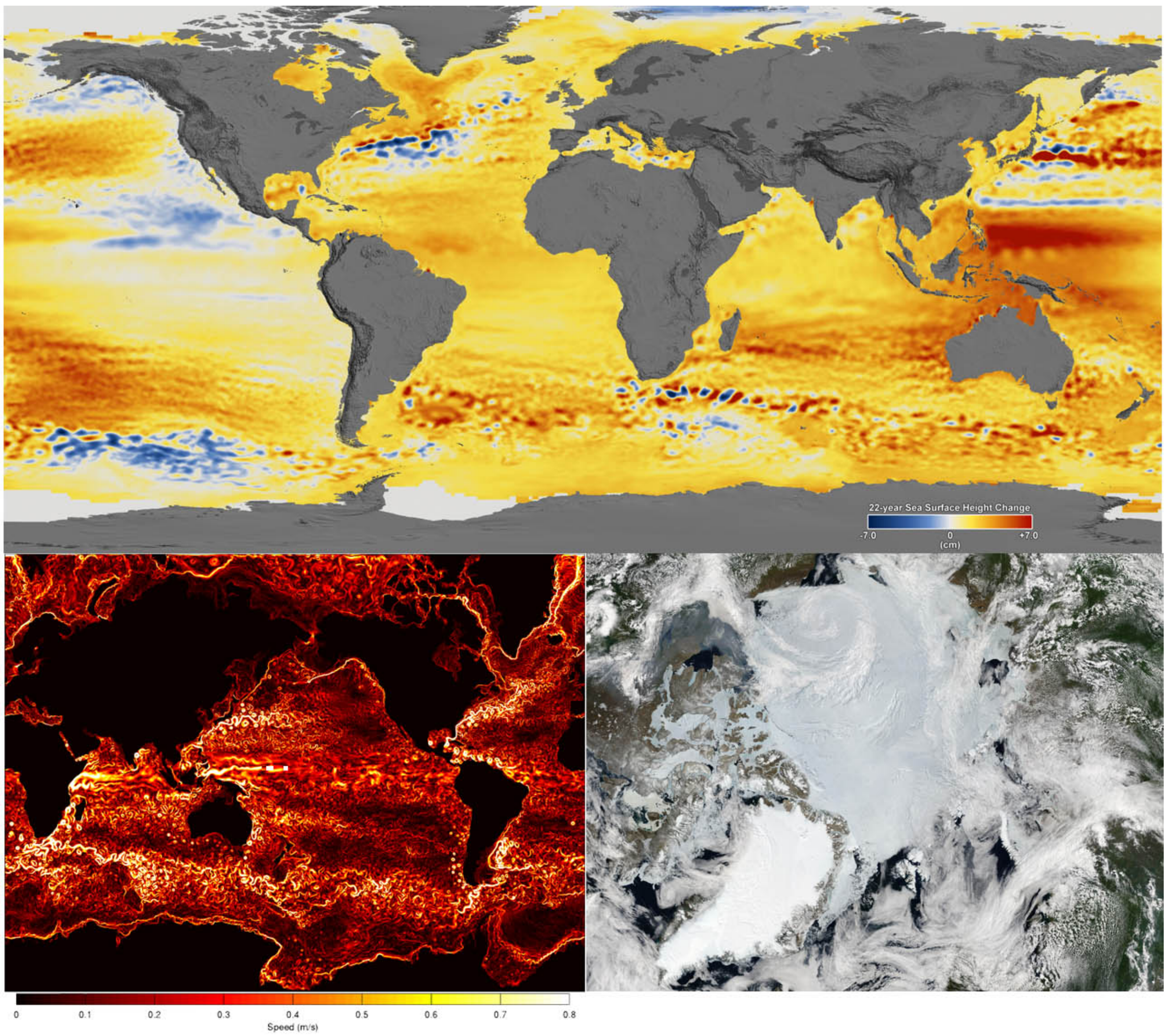

Figure 2 – Global, multi-platform observations assimilated into climate and ocean simulations will be used to address major problems in climate dynamics such as predicting the rate of sea level rise (top; 20-year record of satellite-derived sea surface height change, NASA GSFC Scientific Visualization Studio). UTIG is becoming a leader in the use of global and regional data-assimilating climate and ocean models such as the MITgcm/ECCO2 project (bottom left; snapshot of upper 16-meter ocean current) necessary to quantify global heat storage changes and changes in heat transport to regions highly susceptible to increased warming, such as the Arctic (bottom right; NASA MODIS Rapid Response Team).

2. Polar and Planetary Geophysics

2.1. Strategic goals in the polar and planetary science communities

Earth polar geoscience community priorities for the coming decade focus on understanding the drivers, rates, and feedbacks associated with climate change and sea level rise. The Earth's high latitude regions are presently undergoing changes in climate, landscape and ecosystem that are more profound than those at lower latitudes. Loss of ice from glaciers and ice sheets is leading to global sea level rise, however, the future rates of sea level rise have large uncertainties. To better understand and predict the future state of the Arctic and Antarctic, as well as the effects of these changes on ecosystems and human populations, the polar research community at large and within UTIG carries out two types of research. These include 1) observational studies aimed at quantifying the extent and rates of change of ice sheets, glaciers, sea ice, permafrost, seasonal snow, and their associated ecosystems; and 2) process and system studies aimed at elucidating the physical controls on these changes. Beyond sea level rise projections, these approaches are identifying thresholds for further, unforced environmental change, and the additional consequences of diminishing sea and land ice in the past, present and future. Internationally, the state of polar science is summarized by the Assessment Reports of the Intergovernmental Panel on Climate Change and the Scientific Committee on Antarctic Research Horizon Scan. Within the United States, strategic goals are summarized in the planning documents of the Interagency Arctic Research Policy Committee, *The Arctic in the Anthropocene* by the National Research Council (NRC), *A Strategic Vision for NSF Investments in Antarctica and Southern Ocean Research* by the National Academies of Sciences, Engineering, and Medicine, and in the NRC's decadal survey, *Earth Science and Applications from Space*.

The planetary science community defines its strategic goals through the Planetary Science Decadal Survey, a publication of the United States National Research Council produced for NASA and other United States Government Agencies such as the National Science Foundation. NASA also issues a series of documents, including Strategic Plans, Science Plans, and Roadmaps, to guide the agency to "do the best science, not just more science", according to NASA Administrator Charles Bolden. The planetary science research goals are to: 1) Explore and observe the objects in the solar system to understand how they formed and evolved; 2) Advance the understanding of how the chemical and physical processes in our solar system operate, interact and evolve; 3) Explore and find locations where life could have existed or could exist today; 4) Improve our understanding of the origin and evolution of life on Earth to guide our search for life elsewhere; 5) Identify and characterize objects in our solar system that pose threats to Earth, or offer resources for human exploration.

The application of knowledge derived from terrestrial studies has served as a long standing approach toward understanding planetary systems across our solar system. In recent years, planetary science has reciprocated this trend, serving as laboratories to address questions fundamental to Earth and humanity. UTIG embraces these synergies and has combined polar and planetary geophysics into a single initiative to reflect the importance of water for habitability and the role of ice in shaping planetary landscapes. Synergies with other directives will be further cultivated in the next decade.

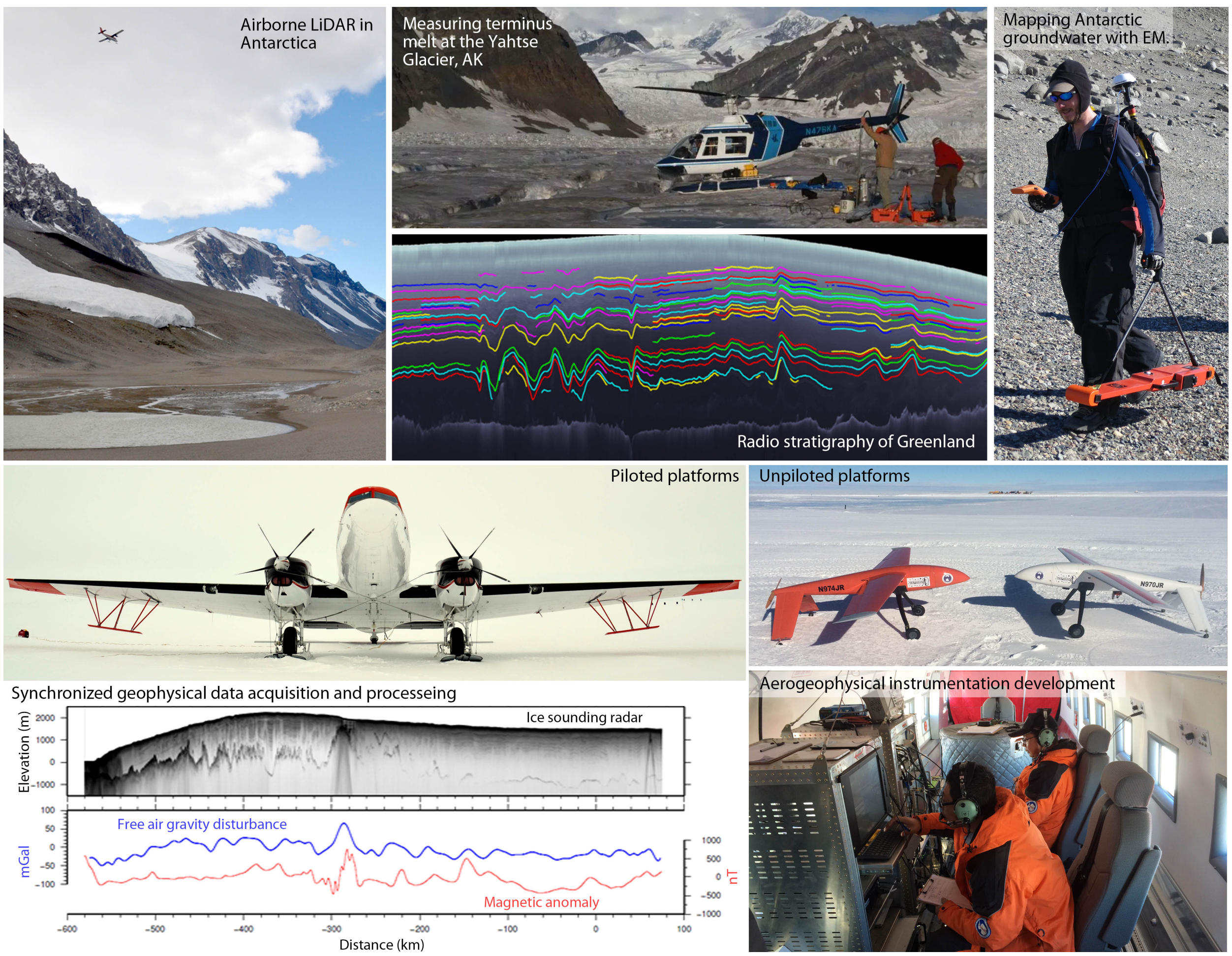

Figure 3 – UTIG conducts state-of-the-art data acquisition in the polar regions for polar geophysics and planetary geophysics through analog studies. UTIG is a leader in the acquisition and analysis of ground-based and airborne data to understand ice-covered lithosphere and water bodies. In the lab, UTIG develops piloted and autonomous fixed wing and rotary aerogeophysical platforms as well as instrumentation such as ice sounding radar and centralized data acquisition systems. In the field, UTIG leads science planning and operations for acquisition of diverse but complementary data. Our goal is to produce boundary conditions and perform monitoring activities for assimilation within regional and global earth system models.

2.2. UTIG approach and strengths

For two decades, research scientists at the University of Texas Institute for Geophysics (UTIG) have employed space-based, airborne, land-based, and marine geophysical methods to better understand ice sheet evolution, climate, and geologic processes in the polar regions. Polar and planetary scientists collaborate at UTIG to devise and implement investigations that use cutting edge tools and field campaigns to monitor current oceanographic, glacial, and ice sheet processes, to determine past rates of polar geological evolution, and to predict how elements of the polar Earth system will evolve in the future. Across the diverse array of polar scholarship at UTIG, many research scientists have pursued observationally-motivated studies of the processes controlling mass loss from Earth's ice masses. UTIG researchers seamlessly transfer technologies, tools, and approaches from polar science to bring new insights to planetary exploration. This interplay between expeditionary polar science and planetary missions and data analysis also allows planetary discoveries and technologies to feed back into the development of new tools and new understandings of Earth system processes.

The impact of fresh and oceanic coastal water on the dynamics and mass balance of the ice sheets is a significant strength of UTIG polar researchers. Our scientists have identified the pathways and mechanisms by which meltwater affects the motion of the Greenland Ice Sheet, the nature of the hydrologic system beneath the Antarctic Ice Sheet, the pathways for warm ocean water to access the margin of a large sector of Antarctica, the effect and rates of ocean melting on a Greenland glacier terminus, and a tool to track changes in the amount of water flow beneath glaciers and ice sheets.

Explorations of the Greenland and Antarctic Ice Sheets through geophysical methods is also a major strength, including radar, seismology, gravimetry, magnetometry, GPS, electromagnetic methods, lidar, and multibeam sonar. The use of radar is a particular focus. UTIG's work using radar sounding has greatly improved ice sheet bed maps of unknown sectors of Antarctica, which have profound implications for future ice sheet stability and mass loss. These techniques have also allowed mapping of the subglacial geothermal heat flux and the state of ice sheet beds. Analysis of ice sheet radar internal reflections enables mapping the age structure of the entire Greenland Ice Sheet and of surface to bed connections for meltwater transport. The thermal state of the Greenland Ice Sheet has also been mapped. These projects have addressed significant questions posed by the broader community of polar researchers and improved our understanding of the processes controlling ice mass loss from the ice sheets, and therefore sea level rise. UTIG's reputation for hypothesis-driven platform, instrumentation, and algorithm design has positioned it as a leader of international polar research consortia and resulted in UTIG-designed hardware and software used by multiple nations on an array of piloted and autonomous fixed-wing and rotary aircraft.

As the cryosphere program developed, synergies with other bodies in the solar system led to a distinctly geophysical approach for planetary science at UTIG. Similar to the approach pursued during Earth-focused cryosphere research, the planetary focus at UTIG is on understanding the physical processes in our solar system. The Dry Valleys of Antarctica were noted to be analogs for Mars, and floating ice shelves were natural analogs for Jupiter's moon Europa. These planetary targets are also the most likely to be and/or have been habitable in our solar system. The primary tool for these early studies was ice-penetrating radar to measure the thickness of the ice as well as to map internal stratigraphy. Building upon this terrestrial expertise, UTIG research scientists are now involved with orbital radar sounding of Mars to understand the current state of Mars' ice; investigate processes governing the distribution, history, and role of ice in Mars climate evolution; and identify landing sites for future missions. More recently, UTIG has grown to include a broader spectrum of geophysical disciplines, such as geomorphology and hydrology. The terrestrial analog approach remains a strong component of this research and has expanded to include alpine environments and debris-covered glaciers, also of great interest on Earth due to their unique response to climate change and abundance in major mountain ranges in the US, Asia, and Europe.

UTIG's program to study Europa and other icy satellites has similarly grown. In addition to using Cassini radar to understand the geomorphology of the Saturnian satellite Titan, UTIG is also leading the development of the ice-penetrating radar instrument to fly onboard NASA's upcoming Europa Mission with the primary goals of characterizing shallow subsurface water, searching for the ice-ocean interface, and understanding material exchange, between the atmosphere, surface, ice shell, and ocean. Complementary to these mission-based efforts, UTIG has a developed a terrestrial analog and geophysical modeling program with an emphasis on understanding the oceanography of ice-covered ocean worlds and how the ocean and ice shell are coupled intrinsically. In combination, this suite of approaches will address the habitability of extreme terrestrial environments as well as ice-covered ocean worlds.

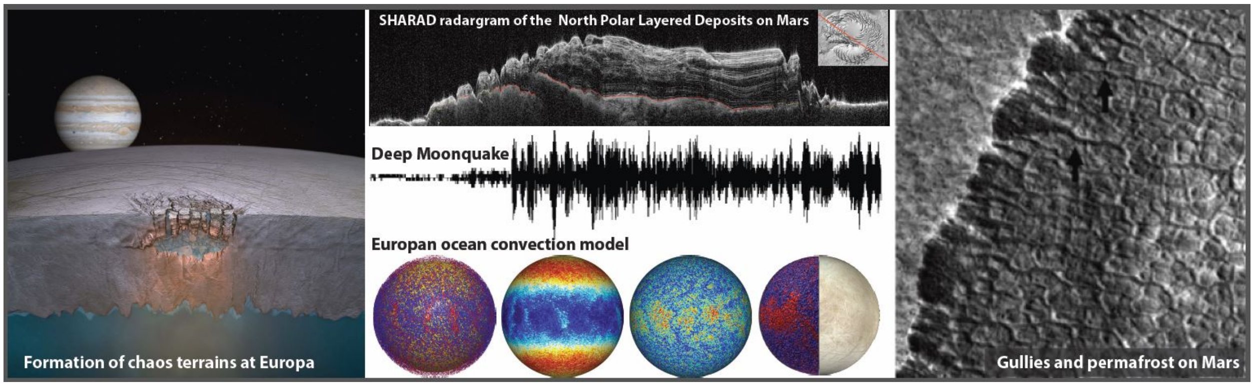

Figure 4 – UTIG is building the scientific and technical foundations to lead the next generation of planetary missions, instruments, and discoveries. We use the tools of mission science related to radar sounding and seismology, terrestrial analog observations, and geophysical modeling to study planetary systems. In particular, we focus on processes relating to planetary cryospheres and hydrospheres, deep interiors, and shallow subsurfaces. We specialize in problems relating to Mars, Europa and other icy bodies, and the Moon.

UTIG's planetary geophysics program began in 1969 when the Apollo program placed the first seismometers on the moon. These first direct seismic observations of an extraterrestrial object, which are still being analyzed with more advanced processing techniques today, led to an invaluable understanding of the dynamics and internal structure of the Moon. Terrestrial seismic experiments carried out by UTIG research scientists have also been, and continue to be, used to study impact crater processes, with the Chicxulub Impact Crater in the Yucatán Peninsula of Mexico being a prime example. The lunar program has also expanded to now include geophysical modeling focusing on magnetic field generation within the Moon and other solar system bodies.

2.3. Priorities and opportunities in polar geophysics

The overarching goal of polar geophysics at UTIG will be to improve the understanding of the processes controlling the evolution of the Earth's cryosphere in response to rapid climate change. In order to achieve this goal, we suggest that UTIG pursue the following:

2.3.1. Interactions between ice sheets or glaciers and their bounding oceans

Interactions between ice sheets or glaciers and their bounding oceans remains a critical community topic and UTIG is poised to build on its legacy of leadership on this front. Expanding on this, UTIG should broaden our expertise to include geological and hydrological controls on grounded ice evolution and ocean forcing on floating ice and tidewater glaciers to better understand the ice sheet-ice shelf transition and its response to our changing climate. This research frontier synergistically expands and builds on the strengths of the UTIG climate dynamics group.

2.3.2. Ice sheet mass balance

UTIG should develop new expertise in the surface mass balance and runoff of water from the surface, subsurface, and base of the ice sheets. Negative surface mass balance and runoff plays a role comparable to marine ice discharge in governing Greenland Ice Sheet change. Surface melt and runoff will increase in importance along the Antarctic Peninsula and potentially West Antarctica as the climate warms.

2.3.3. Biogeochemistry and surface processes

UTIG should identify the connections between surface and subsurface processes pertinent to biogeochemistry, including carbon and sulfur cycles, climate modeling, hydrocarbons, terrestrial-atmosphere interactions and ice-ocean interactions.

2.3.4. Field science, remote sensing, and development of platforms and observing networks

UTIG should continue supporting existing strengths in observationally-driven field and remote sensing science as well as lead the development and deployment of polar terrestrial/ocean observing networks (e.g. POLENET, Arctic Ocean Network, and Southern Ocean Observing System), marine infrastructure (e.g. R/V Palmer and Araon), and airborne research platforms (e.g. Operation IceBridge and UTIG's own ICECAP consortium supported by the U.S., U.K., Australia, France, Italy, China, and India). Autonomous platforms stand to become high-capability, low cost/carbon footprint, distributed systems useful for both monitoring and exploration.

2.4. Priorities and opportunities in planetary geophysics

The overarching goal of planetary geophysics at UTIG will be to understand the physical processes controlling the evolution of solar system objects (and their implications for habitability).

2.4.1. Geophysical processes in planetary bodies

UTIG should further develop its expertise in understanding the physical processes that control solar system objects and their implications for habitability. In addition to UTIG's traditional focus on the cryosphere/hydrosphere, deep interior, shallow subsurface, and impacts, new directions should build collaborations across the Institute and include: understanding crustal deformation, mantle dynamics, and core processes of other planets; understanding the processes that control planetary atmospheres, oceans, and ice shells/glaciers; and understanding the formation and release of clathrates on planetary bodies and implications for their physical and chemical environments.

2.4.2. Planetary geophysics across the solar system

UTIG is well-poised to expand from our contemporary targets of the Moon, Mars, and Europa to include the other inner planets, the outer giant planets, additional ocean worlds such as Titan and Enceladus, dwarf planets such as Pluto and Ceres, and exoplanets.

2.4.3. Mission science, terrestrial analog observations, and geophysical modeling

To address these challenges, UTIG will continue to use the large spectra of investigation techniques we have developed over the institute's history: radar sounding, seismology, and imagery technologies through expeditions to terrestrial analogs and participation in orbital, flyby and lander missions. UTIG should also further utilize existing mission data and numerical models to better understand geophysical processes of the solar system bodies.

Through these recommendations, UTIG will have the capability to study the full array of processes that govern planetary evolution and habitability across the solar system, ranging from cores and dynamo action, to mantles and thermal evolution, to crusts and geomorphology, to cryosphere/hydrosphere and climate evolution, and linking back to magnetospheres created by core dynamos.

3. Marine Geosciences, Seismology, and Tectonics

3.1. Strategic goals in the community

Many potential core opportunities of research in Marine Geosciences, Seismology, and Tectonics are the focus of federal agencies and scientific partnerships such as the NRC, NSF, NASA, USGS, IODP and as well as industry partners. Two main areas of growth are emerging in the Geosciences community at large: 1) Natural hazards (earthquakes, tsunamis, landslides, hurricanes): history of past events, controls and triggers of future events, and impact on society and surface processes, and 2) The study of the physical conditions that sustain and lead to the evolution of life. In many cases these are inexorably linked. For example, the flow of fluids and volatiles through pores and fractures in the lithosphere is one of the major factors controlling the physical conditions favorable to the emergence of life, but it also controls how tectonic faults slip, allowing the lithosphere's accommodation of the deep plate tectonic engine, and at times producing destructive earthquakes. Our observational and modeling strengths at UTIG make us well-poised to take leadership roles in these areas.

3.2. UTIG approach and strengths

Research at UTIG tackles issues ranging from the physical underpinnings of natural hazards such as earthquakes, tsunamis and hurricanes, to the inner workings of the plate-tectonic engine, to the fluids that sustain, and potentially gave rise to life on Earth. UTIG "crosses the shoreline" to determine the structure and dynamics of orogens, subduction zones, and continental margins, by deploying seismometers and GPS receivers, imaging the subsurface with seismic techniques, and interrogating geological relationships with field campaigns and underwater vehicles. Many of the Earth's most impressive and destructive processes are highly non-linear and thus studies require powerful computational resources, the versatility to mount field campaigns, and insights from experimental and theoretical work.

UTIG strengths in Marine Geosciences, Seismology, and Tectonics make us uniquely poised for the frontier research problems in solid-earth and surficial processes that cross the shoreline. Active-source seismic imaging of the subsurface, analysis of earthquakes, unraveling the stratigraphic record of sediment flux, incorporation of proxies for sea-level change, coral paleogeodesy, GPS geodesy, computational seismology and tectonics, all make up our research strengths.

The accumulated strength of UTIG in imaging the lithosphere and its fluids, mapping the seafloor, monitoring tectonic motions of the seafloor in different tectonic environments and modeling of both wave propagation and the deformation processes in the lithosphere are critical assets in studying and providing bounds on the rate and the magnitude of fluid and volatile flow in the lithosphere in different tectonic environments. This in turn could be used to provide an understanding of the processes linking slip on faults to fluid flow through fractures and the emergence of life connected to flow of fluids and volatiles at mid-ocean ridges, subduction zones, or rifts.

A key component of UTIG's research is to use observations, experiments, and theory to better understand geophysical signatures of hazardous processes and fluid flow in the Earth. Through merging geophysical efforts with observations of rock properties and experimental data we can shed light on the subsurface environment for everything from earthquakes, to basin structures, to volcanic systems, to impact craters, to hydrothermal vent processes. Partnering with efforts to deploy autonomous underwater vehicles or observatory efforts we can leverage our impressive computational resources and knowledge base to infer subsurface processes.

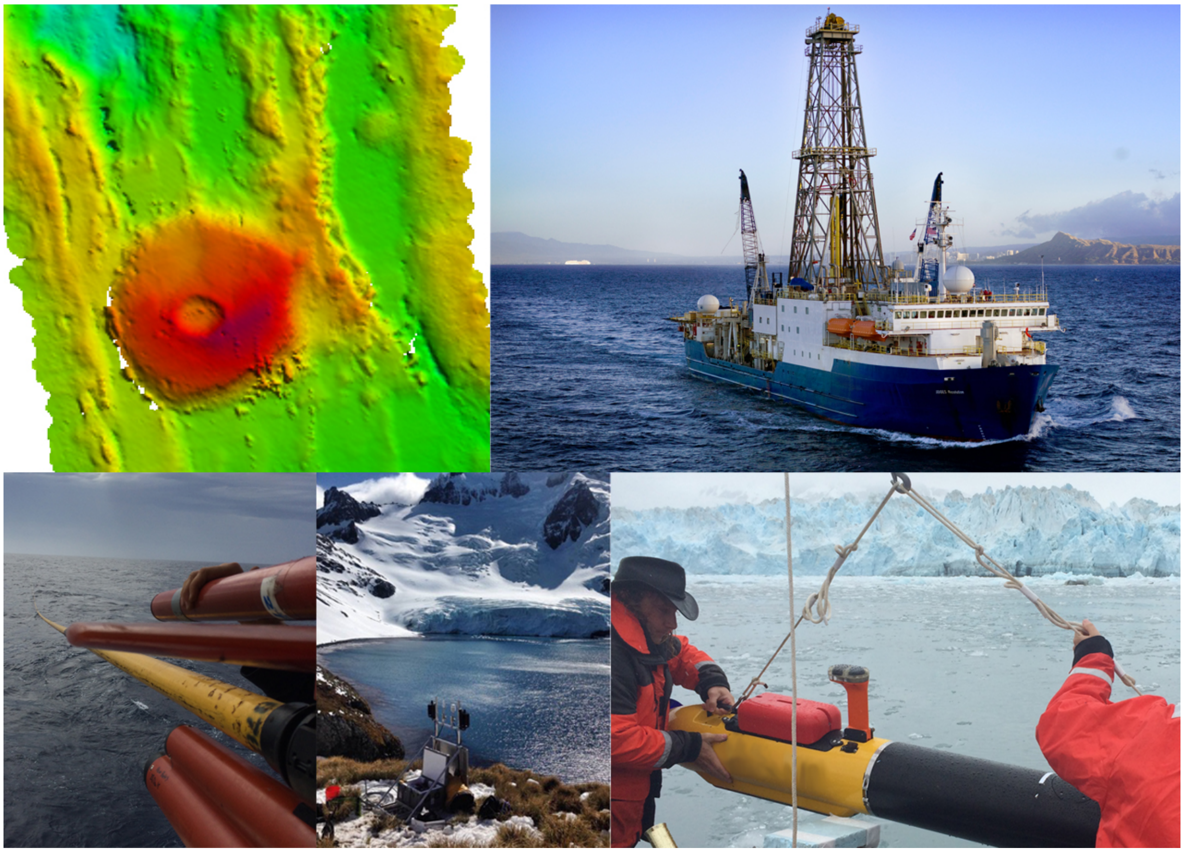

Figure 5 – UTIG applies an array of baseline platforms and methods to address problems in marine geosciences, seismology, and technophysics including multibeam swath mapping, IODP drilling (upper right), multi-channel seismic imaging (bottom left), GPS reference stations (bottom center), ocean bottom seismometers (cover image) while developing new avenues for data acquisition with emerging tools such as Autonomous Underwater Vehicles (bottom right).

3.2.1. Natural hazards: History of past events; controls and triggers of future events

Natural hazards continue to increase in their impact on society by virtue of the distribution and densification of human activity and clustering of events due to the nonlinear nature of the hazardous systems, in many cases exacerbated by human activity. Storms and flooding events are intimately connected with sediment transport along riverine and coastal systems. Submarine mass movement poses risk to hydrocarbon production activities, communications networks, and coastal areas via tsunamis and landslides. Earthquakes and tsunamis are amongst the most destructive natural hazards; the Tohoku earthquake killed at least 16,000 people and cost a measurable 35 billion dollars, and reset the global outlook on everything from seismic hazards to nuclear energy. The physics that underlie these hazardous processes are becoming better understood every day, and many UTIG scientists focus on their underlying mechanisms. Equally important, observational work on these systems provides the critical data needed to test hypotheses and explore their expressions in both real time and the geologic record.

Scientific areas regarding natural hazards that UTIG can address include: 1) Better understanding these events by studying past records preserved in the sub-seafloor geologic record, as well as new events after they happen; 2) Why some systems are linked with destructive earthquakes, tsunamis, and landslides and others are not; 3) Measuring ephemeral properties of these events by acquiring 'baseline' data from at-risk areas and conducting 'rapid response' programs after hazards manifest. There is a rich dataset to be attained from the aftermath of destructive events that can aid policymakers, engineers, and the general public in the future.

3.2.2. Physical conditions that sustain and lead to the evolution of life: Fluids in the solid Earth

Fluids, no matter what their form, connect most, if not all, of the Earth's systems. Fluids exert a large control on the mechanics of the Earth's crust and mantle, link the marine and tectonic systems with the atmosphere, and are a necessary ingredient in which life evolves. Many UTIG researchers focus on the role of fluids in the Earth via the study of the marine geological system, hydrothermal processes in the oceanic crust and mantle, and numerical studies of fluid-rock interaction. We are well poised to tackle the frontier areas in this field that is the underpinning of so many fundamental science goals. Future research at UTIG can focus on the role of fluids through programmatic foci on flow in the subsurface, chemical-biological-mechanical interactions, and sediment flux in the marine system.

3.3. Priorities and opportunities in marine geosciences, seismology, and tectonophysics

Below we provide specific examples of how the present strength in Marine Geosciences, Seismology, and Tectonics at the Institute places it in a strategic position to address fundamental questions in the community:

3.3.1. Continental dynamics and deep Earth - surface interactions

Planetary evolution is controlled by thermo-chemical mantle convection and the interactions between tectonics and the hydro- and biospheres. In particular, the plate-tectonic cycle records changes in Earth's convective state that are associated with paleo-environmental transitions. UTIG will harness its expertise in plate reconstruction, geodynamics and structural seismology to develop plate reconstructions for the last 500 Ma with full uncertainties and robustness estimates for a flexible range of geological and geophysical constraints, while integrating advanced geodynamic plate interaction models. These will be applied to study the evolution of topography and orogeny on Kyr to Gyr timescales by means of global convection computations as well as regional geological and geophysical studies for key natural laboratories (e.g., Andes of South America and the Banda arc of south East Asia). Through our work we will enable "first principles" modeling of thermo-chemical convection in Earth like planets using large-scale computations including the mechanics of strain-localization, plate boundary formation and maintenance, and the general effects of deformation memory in continental plates.

3.3.2. Formation and evolution of the oceanic lithosphere

Active source reflection and refraction acquisition and computationally intensive analysis have led UTIG to fundamental advances both in the global marine system formed at mid-ocean ridges, as well as key margins and basin areas. At mid-ocean ridge spreading centers, UTIG should focus on how ocean crust forms, with emphasis on how faults control hydrothermal circulation and vent distribution, as well as fluid linkages to sub-seafloor processes. In addition, UTIG should elucidate lithospheric evolution from ridge to trench, emphasizing interactions via mantle convection with the underlying asthenosphere.

3.3.3. Subduction zones and slip mechanisms

Subduction zones are significant not only as a mechanism for crustal growth and as a tectonic system that links the crust with the mantle, but as one of the Earth’s most violent natural hazards via M>8 earthquakes and associated tsunamis. UTIG has used seismic imaging techniques, geological investigations both along the seafloor and in analog settings, coral records of subsidence and uplift generated by the seismic cycle, and now are at the forefront of GPS geodesy and earthquake seismology. UTIG should focus on the role of subduction zones in determining earthquakes and tsunamis with a special emphasis on the subduction zone interface including where it is “locked” and the role of episodic slow slip and geofluids at this boundary.

3.3.4. The structure and geologic record of rifts and passive margins

Passive margins evolve at the intersection of climate, tectonics, and deep-earth volcanism. Because of this, UTIG should focus on processes that cause continents to split apart and new ocean basins to form, with a special emphasis on seafloor morphology and the sediment record to constrain the spatial and temporal scale of natural hazards as well as processes that control extreme events and trigger submarine slides, including the role of geofluids and climate variability.

3.3.5. Natural hazard impacts on the coastal zone

The world’s coastlines are a critical zone, simultaneously bearing the brunt of rising population/ecological pressures and rising sea levels. Consequently, natural hazards such as hurricanes and tsunamis are having greater and greater impacts, both in loss of life, habitations and infrastructure, and in loss of protective beach sands and barrier island systems. After "superstorm" Sandy in 2012, the US Bureau of Ocean and Energy Management (BOEM) was tasked with the major goal of improving the sustainability of the nation's coastlines in the face of these trends. These developing efforts range from individual, community-based projects to establishing a catalog of potential sand resources within the entire EEZ for the purpose of future beach replenishment. Much of the funding for this work will be funneled through state agencies, such as Texas' General Land Office (GLO). UTIG, with a stable of marine geophysical survey equipment and research experience in coastal and shelf studies, is well-poised to take advantage of this emerging opportunity. Furthermore, our experience in rapid response efforts, as well as access to JSG resources dedicated for this purpose, make us uniquely capable of investigating the impacts of natural hazards on coastal sedimentary processes. Guiding questions include: 1) What is the "sediment budget" of a hurricane; i.e., where is sediment lost and gained? 2) What impact does a hurricane have on the sustainability of the coastal barrier island system, particularly given the loss of sand inputs due to river damming? 3) Where can sands be found offshore that would be suitable for beach replenishment?

3.3.6. Leveraging potential synergies in community infrastructure

Seismic imaging, computational modeling on relatively modest CPU systems, rock-mechanics and physical experiments, geological field campaigns, and study of earthquakes are several cornerstones of research at UTIG. Several new techniques afford additional opportunities:

Computing power is a cornerstone of the University of Texas (e.g., TACC), and UTIG scientists are at the forefront of harnessing that power by developing new numerical techniques for large deformation coupled with fluid flow in porous media. The latest inversion techniques, model routines, management of large datasets, and visualization and dissemination are part and parcel of UTIG science. In the future, UTIG can move into "Large-N" science, using intermediate to high-frequency arrays (~1000 3-component seismographs) that are currently the frontier of geophysical sensing.

A broader range of instrumentation is a necessity for world-class research institutions. Campaign GPS instruments, earthquake seismometers for campaign-style monitoring, intermediate-to-broad-band seismometers, short-period ocean bottom seismometers, seafloor geodesy, and a functional portable seismic streamer are all current techniques that UTIG can lead the way in their maintenance and deployment. This field-based instrumentation should be complemented by analytical and experimental facilities at UTIG, including laboratories for deformation experiments and rock and sediment properties.

Autonomous underwater vehicles are approaching "off the shelf" access. Near-bottom and shallow subsurface imaging are cornerstones of many UTIG research efforts. Expanding into AUV technology is widely recognized as a frontier area, and many UTIG efforts already capitalize on this approach, including polar and planetary programs.

4. Energy Geosciences

4.1. Strategic opportunities in the oil and gas industry

The oil and gas industry has experienced yet another downturn in commodity prices that have typified its existence since the days of the Drake Well. Workforce reductions through layoffs and voluntary or forced retirements are dramatically impacting petroleum exploration/production companies, seismic vendors, and oil field service firms. Talented individuals with deep energy experience are departing the field and fundamental research is being curtailed.

This creates an opportunity for UTIG to expand the breadth and impact of its energy research to fill the gap left by a contracting industry and to greet the enormous and exciting challenge of transitioning our energy economy. We will focus on long term, strategic and fundamental research programs. The timelines for this type of research are longer and more appropriate to the academic approach, allowing for non-traditional methods and collaborative, multi-disciplinary efforts that can lead to step change advances.

We identify four research directions that address first-order geological questions and that UTIG is uniquely positioned to address: 1) Frontier exploration and field programs, 2) Unconventional resources and induced seismicity, 3) Dealing with energy big data and 4) Simulation. While UTIG has a strong foundation, collaboration with other research units, UT colleges, and other universities will be critical to our success. A key goal should be to look for internal synergy with ongoing efforts at UTIG in geophysical expertise and field acquisition. In particular, a distinctive combination of physical and numerical experimentation, microstructural observation, and understanding of tectonic processes give UTIG scientists the ability to confront many of Energy Science's greatest problems.

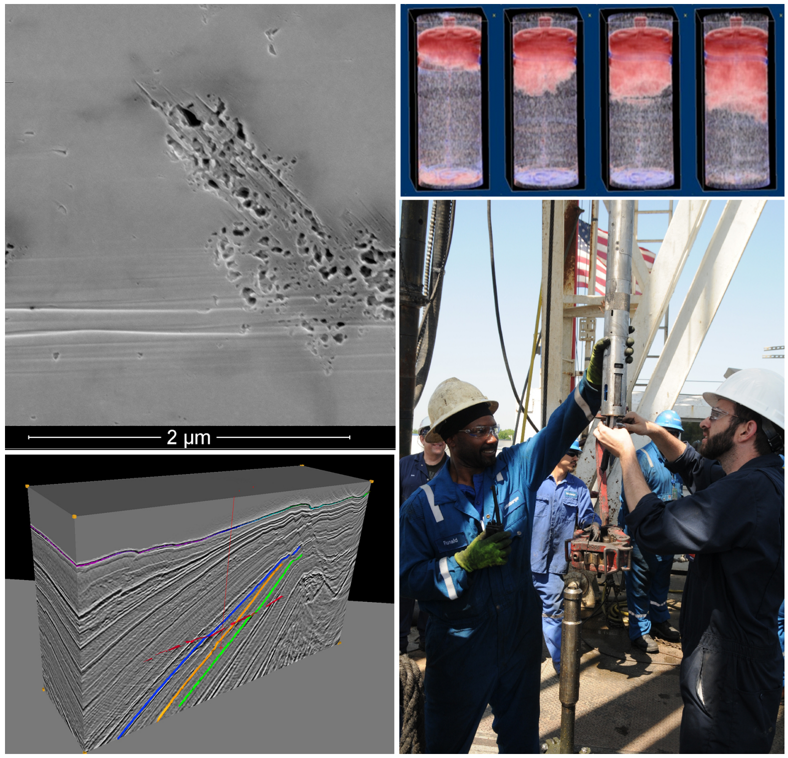

Figure 6 – Energy Research at UTIG spans the pore to the plate scale. Active projects relate to nano-pore systems (Barnett Shale sample; upper left), laboratory simulations of gas hydrate formation (upper right), analysis of three dimensional seismic data (bottom left; Gulf of Mexico depositional systems). As well as the design and development of new downhole measurement tools (bottom right).

4.2. UTIG approach and strengths

Our research is trans-disciplinary and includes the development of geologic models, theoretical advances in imaging and simulation, integration of disparate data types, and exploration of new regions via field geophysical and geological data acquisition and analysis, and computational and physical modeling and experimentation. We have foundational strength in numerical simulation (wave propagation, imaging, seismic reservoir characterization, and seismic inversion). Our Gulf Basin Depositional Synthesis Project (GBDS) has made longstanding contributions to our understanding of the Gulf of Mexico and it provides a platform for new collaborative studies in the Gulf. For decades we have worked to understand the methane hydrate system and its implications for energy and climate. Through our GeoFluids consortium we are exploring the role fluids play in the evolution of sedimentary basins and the migration and entrapment of hydrocarbons.

4.3. Priorities and opportunities in the energy geosciences

Fundamental research on both unconventional and conventional reservoirs and associated fluids should be undertaken in the midst of this industry reorganization.

4.3.1. Frontier exploration and field programs

Where is the next conjugate margin play?: Exploration in deepwater has moved beyond traditional passive margins toward divergent and convergent margins, as new deep crustal models are developed. One example is the rapidly evolving conjugate margin play in the Central Atlantic basin where a new play paradigm of deepwater sand fairways on the eastern margin of the Atlantic was developed. This basin in Ghana was, before sea floor spreading, a conjugate with basins in Guyana and adjacent areas. For this reason, companies are now exploring on the western side of the Atlantic. UTIG will build on its strength plate tectonic reconstructions and illuminate the next hydrocarbon-rich conjugate margin play area.

The new Arctic frontier: Global warming is resulting in dramatic reduction in Arctic ice cover which will open a largely unexplored environment to scientific exploration at relatively modest cost. UTIG's experience in seismic acquisition coupled with its knowledge in Antarctic and Greenland terrains provide a foundation to pursue investigation of the earth's polar frontiers. A particularly exciting question at the intersection of the study of climate and energy is the study of sea floor seeps. Questions remain around how seeps form, conditions for migration into the seabed, and sampling bias could be addressed through ongoing and future near surface studies.

The new Gulf of Mexico frontier: UTIG will build on its significant historical understanding of Gulf Basin processes to pursue new field programs concerning the deep crust of the Southern Gulf of Mexico. First, there is enormous opportunity to perform seismic refraction studies in the southern Gulf of Mexico as deepwater exploration advances to these regions. Second, UTIG will maintain its strong position in the study of methane hydrates through field experiments studying hydrates in the Gulf of Mexico to improve our understanding of the genesis and production of methane hydrates.

4.3.2. Unconventional resources and induced seismicity

Energy production from shales has fundamentally changed the energy economy. Shale gas and oil are typically produced by hydraulic fracturing, which causes an increase in the effective permeability of the formation. Despite the remarkable success of this approach, we have a poor understanding of the fundamental process of hydraulic fracturing. During the hydraulic fracture phase of production well completion and in later stages of production during reinjection of fluids to maintain reservoir pressure, there have been a few cases of felt and smaller induced earthquakes. Though the more significant hazard in the midcontinent United States in the last decade has been larger (magnitude ~5) earthquakes associated in time and space with deeper injection of wastewater mostly produced from unconventional shale oil and gas plays. Collaborative efforts with the Bureau of Economic Geology, funded by the State of Texas, to better understand the physical link between earthquakes and wastewater injection are already underway and should continue to be pursued. We will focus on two topics:

What is the stimulated rock volume?

- What does a hydraulic fracture look like and can its effectiveness be predicted?
- What is the flow behavior, the permeability, and the storage capacity of these systems?
- How can we use well instrumentation and seismic data to illuminate this behavior?

How does water-injection induce earthquakes?

- What monitoring approach can illuminate this behavior?
- Can we build coupled geomechanical models to simulate this behavior?

4.3.3. Dealing with energy big data

Seismic surveys, satellite measurements, well logs, and laboratory experiments, and other datasets are inundating scientists with unprecedented amounts of "Big Data". They are eager to employ this data in model creation, forward model runs, uncertainty estimation, and interpretation of results. Much of this data is currently underutilized due to insufficient computational infrastructure, and its incorporation could revolutionize our understanding of subsurface environments. However, its complexity and size pose significant challenges. Moving and storing the data in order to generate large ensembles, running extremely detailed models, and automating the discovery process will require the use of advanced High Performance Computing architectures and the creation of novel algorithms. Exciting energy challenges include:

Real time conventional or unconventional reservoir behavior:

- Understanding how to make sense of disparate data types including surface geology, cores, time-lapse surface seismic, and Vertical Seismic Profiling, distributed acoustic sensors, distributed temperature sensors and microseismic data;
- Understanding fracture growth through both three-dimensional numerical simulations, prediction of seismic response, and seismological observations;
- Optimizing production through the use of diverse continuous downhole measurements (e.g., pressure, water saturation, and temperature)

Real time drilling:

- Optimizing drilling through integration of real time data such as pressure while drilling, rate of penetration, Gas Chromatograph observations, etc.

4.3.4. Simulation

Numerical simulations play an increasing role in providing a fundamental understanding of geophysical processes. The Energy field is facing a step change in its ability to develop fully coupled basin scale models. In summary, our strategy is to couple numerical approaches with rigorous data assimilation. UTIG will build upon its existing strength on computational earth science and enhance the following capabilities:

- Large scale inverse problems and uncertainty quantification.
- Coupled thermo-geo-poro-mechanical modeling of basin evolution.
- Poro-elastic seismic wave numerical simulations to provide insights into fundamental aspects of wave propagation in reservoirs.
- Simulation of genesis and production of unconventional reservoirs (e.g. gas shales and hydrates).