Integrating Ocean Drilling and NASA Science:

A Workshop to Explore Missions to Planet Earth

April 2-4, 2024

Final Report

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Executive Summary

Integrating Ocean Drilling and NASA Science: A Workshop to Explore Missions to Planet Earth was held on April 2–4, 2024 in Washington, D.C., at the Washington Plaza Hotel. This was a strategic workshop designed to lay the foundation for a new partnership between the National Science Foundation (NSF) and NASA focused on scientific ocean drilling. The goal of this workshop was to identify and build on the implicit scientific synergies that NASA's Earth and Planetary Science Divisions within the Science Mission Directorate (SMD) have with scientific ocean drilling. There were 109 people who attended this workshop (77 in person and 32 virtually) and below is the list of findings that were produced.

Interagency Partnership Pathways

<u>3.1.1 NASA-NSF Joint Research Programs</u>. Creation of a trial joint program/strategy/mission for a sustained period of time by NASA-NSF interagency funding to bring different communities together to focus on research topics of mutual interest (highlighted in specific findings in subsequent sections). It is recognized that interagency programs have to be introduced via the decadal survey processes for NASA Earth and Planetary Science as well as NSF Ocean Sciences, and this can be done by the respective communities, but a trial program would demonstrate the validity of such an approach. This trial program could also be a way to broaden questions to be of interest to both agencies. Examples of potential joint programs bridging NASA and NSF Ocean Sciences where scientific ocean drilling could be critical to a major advance in understanding:

- Planetary evolution in our Solar System;
- Rapid/extreme physical and chemical exchanges between planetary surfaces and interiors.

<u>3.1.2 Combining Data Sets</u>. NASA observes surfaces using orbital space craft and occasionally rovers. Sampling of the subsurface is rare for the agency. NSF ocean drilling observes and directly samples the subsurface. In a combined NSF-NASA (Earth Science) research program, integration of ocean drilling data with Earth observing data would enhance both datasets. This could be started by initiating a program that pairs graduate students working with ocean drilling data and core with others working on related NASA Earth and planetary science data to foster collaboration between different groups/institutions. In addition, applying some spectroscopy techniques common to space missions as standard IODP measurements at planetary analog locations would help build up a database that allows better interpretation of extraterrestrial signatures.

<u>3.1.3 Missions to Planet Earth</u>. The meeting participants encouraged NASA and NSF personnel to explore the joint use of the *JOIDES Resolution* (*JR*) ocean drilling vessel to explore co-funded "Missions to Planet Earth" expeditions to further research topics of mutual interest, noting the *JR* could be available through 2028. *<u>Mission to Planet Earth</u>* expeditions could also occur on a future US scientific drilling platform. This initiative could be used to mature NASA & NSF technology developments by increasing technology readiness levels. The costs would be much less than launching spacecraft for NASA, and at the behest of congressional appropriations NSF has ongoing modest funding for ocean drilling.

Earth's Climate

4.1.1.1 Interagency Partnership Pathway: Synergistic Climate Research-1. Three essential science areas fall within an overarching priority highlighted in the 2024 NASEM Decadal Survey of Ocean Sciences Priorities for Future Scientific Ocean Drilling and is a NASA's Flagship Initiative: Ground Truthing Global Climate Change;

- High Latitude Focus on Future Sea Level Rise: How much, how fast, where? Ice proximal records of past ice sheet behavior
- Changing Equilibrium Climate Sensitivity: Past warm climates
- Habitability/Marine ecosystem productivity response during past warm climates

4.1.1.2 Interagency Partnership Pathway: Synergistic Climate Research-2. Other areas that could foster synergies between Scientific Ocean Drilling and NASA scientists are:

- Proxy Development
- Improved Age models
- Extreme Environment Technology Development

4.1.1.3 Interagency Partnership Pathway: Integration of Past & Modern Climate Data. Paleoclimate data can be used to evaluate structural uncertainty within the predictive climate models (i.e., paleoclimate data can be used to assess how the emergent properties of the models match the real world, and use the results to constrain projections).

4.1.1.4 Mission to Planet Earth: Climate Predictions. Scientific ocean drilling has provided critical insights into how Earth's climate has changed in the past, which is critical to understanding how our climate may change in response to both natural and anthropogenic inputs now and in the future. Future investigations may include finding means of linking future and past scientific ocean drilling data with satellite observations of sea surface temperatures, greenhouse gases, and other climate parameters to provide better predictions of how Earth's climate is changing and how that will impact macroscopic life on Earth.

Astrobiology/Habitability

4.2.1.1 Interagency Partnership Pathway: Limits on Life. Understanding where life does not exist (and perhaps cannot exist) is equally important to understanding how to detect life in extreme environments. For example, limits on life can be explored through ocean drilling in extreme environments (e.g., Expedition 376 Brothers Arc Flux). Future drilling combined with ongoing biological technology developments will enable us to better understand the boundary conditions for life, which will provide insight into the origin and evolution of life on Earth as well as an understanding of the potential limits of life on other planetary bodies. Technology developments required to determine these limits in seafloor sediments and rocks will also aid in the development of instrumentation necessary to search for life elsewhere.

4.2.1.2 Interagency Partnership Pathway: Preservation of Organic Signatures. Legacy IODP cores known to contain organic signatures can be used to:

- Evaluate how well organic signatures are preserved in returned samples (e.g., OSIRIS REx, Mars) particularly those stored for an extended period of time
- Enable our understanding of why some organics are preserved rather than consumed by life over geologic time scales, a critical question from the 2050 Science Framework

4.2.1.3 Interagency Partnership Pathway: Recycling & Redox Processes. Recycling of elements that are precursors for the life-form metabolites and redox processes drive exchange of elements (e.g., high flow zones with high porosity and permeability allows more recycling; groundwater exchange zones). A focus on fluid-rock interactions that drive habitability seems timely with specific environments of extraterrestrial interest including impact and volcanic hydrothermal systems.

4.2.1.4 Mission to Planet Earth: How this Ocean World can inform about other Ocean Worlds-1. Future investigations evaluating hydrothermal alteration processes in diffuse, off-axis vent fields will likely yield new and directly applicable insights into alteration of Ocean World seafloors and cores, as seafloors in other Ocean Worlds are unlikely to display plate tectonics.

4.2.1.5 Mission to Planet Earth: How this Ocean World can inform about other Ocean Worlds-2. Future investigations at both on-axis and off-axis active hydrothermal systems can provide insight into prebiotic chemical synthesis pathways that can enable a better understanding of organic chemical evolution, which may be an important habitability marker for other Ocean Worlds.

Impact Processes, Geohazards, and Geodynamics

4.3.1.1 Interagency Partnership Pathway: Onset of Plate Tectonics. Plate tectonics on Earth dictates the structures and life on Earth, so pinpointing the onset of plate tectonics throughout the deep geologic timescales can help to compare to other planets. This knowledge gap currently limits our ability to explain how tectonics modify Earth systems.

4.3.1.2 Interagency Partnership Pathway: Effects of Impacts. Study of impact structures on Earth informs us about flexure & elastic thickness of the lithosphere, gravity effects, and long-term response of Earth to loading from impacts. This has implications for other terrestrial planetary bodies.

4.3.1.3 Interagency Partnership Pathway: Geohazard Prediction. Better predictive tools are needed for geohazards so a clear future investigation could be a coupled monitoring for earthquake and landslide hazards using borehole installed sensors with high resolution (temporal and spatial) satellite observation of tectonically active areas (e.g., coupling the temporal resolution of pore pressure changes in advance of, during and after events with structure for motion studies, InSAR, and GNSS observations of permanent deformation).

4.3.1.4 Mission to Planet Earth: Habitability Implications of Impacts. Understanding the role impacts play in habitability is essential for Mars and some Ocean Worlds where impacts may play a significant role in reshaping surface and subsurface habitability. Drilling multiple sites in impact structures on Earth would yield important information to address this. Drilling into the central basin at the Chicxulub impact structure could illuminate the geobiology and thermal history of a recent impact hydrothermal system.

Plume Volcanism

4.4.1.1 Interagency Partnership Pathway: Origin of Large Low Shear Velocity Provinces (LLSVPs). Many hotspots on Earth are sourced from the edges of the Pacific and African LLSVPs. It has been proposed that LLSVPs represent the remnants of subducted oceanic crust that have sunk to near the core-mantle boundary, or they may represent relics of Theia, the primordial impactor which collided with Earth and led to the formation of the Moon. Geochemical studies of plume-derived basalts to search for impactor contributions (versus solely terrestrial origin components) and compositional comparisons between volcanic rocks from the Pacific LLSVP, African LLSVP, and plume-derived volcanics not associated with LLSVPs may enable discriminating between the aforementioned hypotheses.

4.4.1.2 Interagency Partnership Pathway: Felsic Crusts and Magmatism: The formation of massive felsic crust on Earth is thought to require recycling hydrated basaltic crust into the mantle, remelting of these materials, and the resulting magmatism. Felsic magmatism may have occurred within wider basaltic terranes on both Mars and Venus early in the histories of these planets. Scientific ocean drilling expeditions aimed at understanding the formation mechanisms of these and similar regions (e.g., intra-oceanic arc magmatism) may bear lessons for the origins of similar features on other worlds (e.g., the Iceland rift zone the Caribbean Plateau, the Izu-Bonin-Mariana forearc, and the Ontong Java Plateau).

4.4.1.3 Interagency Partnership Pathway: Spectroscopic Examination of Legacy LIP and Hotspot Legacy Cores. New spectroscopic methods should be used on existing cores and new drilling can use these new methods.

- The core from the Hawaiian Scientific Drilling Project (HSDP), as well as ocean drilling legacy cores (e.g., Emperor Seamounts, Louisville Seamounts, Ontong Java Plateau, Kerguelen Plateau, Caribbean Plateau) could also be used to gather spectral data to compare with orbital data from Mars, the Moon, and Mercury to examine compositional variations.
- Mars – examination of alteration processes on Mars; on Earth volcanic material weathers quickly. Look at the spectroscopic signatures on altered volcanic cores recovered by ocean drilling to better interpret the data from Mars.

4.4.1.4 Interagency Partnership Pathway: Study of Hydrothermally Altered Basalts. The production and hydrothermal alteration of basaltic seafloor along mid-ocean ridges as well as oceanic islands and plateaus (particularly tholeiitic basalts) may be a good analog for understanding alteration of the ancient basaltic crust of Mars or at the seafloors, of ocean worlds such as Europa and Enceladus.

4.4.1.5 Mission to Planet Earth: Understanding Large Igneous Provinces (LIPs): Understanding LIPs is important for understanding planetary volcanism and tectonics. On planetary bodies we will be lucky to get to 2 m or 10 m. We need to learn more about the origin(s), timing, and evolution of LIPs.

Analogues

4.5.1.1 Interagency Partnership Pathway: Analogue Sites for Tectonics Associated with Plume Volcanism. On Earth's seafloor, analogue settings to explore complex tectonic settings that explore plume evolution, rifting (both initiation and failure), plume-ridge interactions, and plume-driven subduction processes include the Magellan Rise oceanic plateau (DSDP Legs 7 and 61), the North Fiji and Lau back-arc basin (ODP Legs 134 and 135), the Caribbean and offshore northwest South America, the Cascadia subduction zone, the Walvis Ridge, and the South China Sea.

4.5.1.2 Interagency Partnership Pathway: Ground-truthing NASA Earth Science Orbital Data. Legacy scientific drill cores from the last 50 years of NSF and its partners funded expeditions are an opportunity for ground truth of NASA's Earth Science division funded remote sensing data and models as well as NASA's Planetary Science Division studies of specific volcanic, impact, and hydrothermal processes including the search for life.

4.5.1.3 Interagency Partnership Pathway: Definition of "Analogue Site". Earth is not a good analogue for some planets we want to study - Venus is a great example. Therefore, in addition to field analogue sites, laboratory analogues need to be considered, with the caveat that experiments cannot be run for "geologic" amounts of time, so modeling becomes important.

4.5.1.4 Interagency Partnership Pathway: Analogue Site Opportunities. Analogue site studies should incorporate interdisciplinary/multidisciplinary opportunities. For example, impact craters inform about the impact process, lithospheric composition and flexibility, melt-sheet differentiation, habitability, and hydrothermal systems.

4.5.1.5 Mission to Planet Earth: Best Analogue Sites.

- *Mars*: ocean island basalts are probably the best (plume-related, no continental crust signature), but on Earth these are young when compared to Mars. Also, Svalbard for habitability, life detection, and planetary protection studies.
- *Astrobiology-1*: try to understand where life can exist on Earth and then try to understand what the extremes do for life so that we can figure out where are the boundaries that life can exist on Earth. That will give us a framework for where it can live in other places. But the more we understand about it here (and how it responds to its extremes) can help us in that search.
- *Astrobiology-2*: It is interesting and important to find places on Earth that host unique life that only exists there. This is the case for one island in the Canary Islands. There are two places on that island that host a specific life only for that geology. So, what does that geology look like for that environment? What are the conditions for hosting that kind of life only at that particular point on the planet? Can then extrapolate to Mars and beyond.
- *Volcanism*: Plume volcanics in oceans to avoid contamination via the Earth's felsic crust
- *Impact craters* are all over the Solar System. And there have been valid points that maybe we can only compare an Earth crater to a Mars crater because you've got the water involved. But if you're looking for a place on Earth where you know there isn't life, it's immediately after an impact. And so, looking at the development of life within that once uninhabitable situation, we can then look at the drill cores and the recovery of life afterward.

4.5.1.6 Mission to Planet Earth: New Ocean Drilling Expeditions. New scientific drilling, logging, and borehole monitoring to answer critical questions in hazards, impact processes, volcanism, and habitability at the appropriate analogue sites. For example:

- Drilling into the Chicxulub impact structure would allow recovery of an intact, impact melt sheet providing insights into melt differentiation, planetary crustal evolution, and hydrothermal habitats;
- Drilling in other terrestrial impacts serve as analogs for understanding the evolution of Mars, the Moon, and other worlds through insights into shock processes and development of impact generated structures, stratigraphy, and morphology that dominates most planetary surfaces, as well in the search for extraterrestrial life.

Other

4.6.1.1 Interagency Partnership Pathway: Jointly Funded Proposals. There are mechanisms in place to facilitate inter-agency transfer of funds and have inter-agency funded proposals. The meeting participants encourage NASA and NSF to explore these possibilities in light of the research synergies discussed at this workshop. For example, the next Astrobiology Research Coordination Network CAN could contain an ocean drilling component.

4.6.1.2 Interagency Partnership Pathway: Early Career Opportunities. It is important to continue early career funding and training opportunities in ocean drilling, especially with LEAPS proposals.

4.6.1.3 Interagency Partnership Pathway: Integrating Data Sets. Connecting technologies/instrumentation used to characterize cores with those used for satellite measurements could be a way of integrating NASA and ocean drilling data (e.g., same spectral measurements, etc.).

4.6.1.4 Interagency Partnership Pathway: Maximizing Ocean Drilling Legacy Data. Tools need to be generated for exploration of existing legacy collection to maximize their use (e.g., Google Earth of IODP holes that is interactive with site/drilling data).

1. Introduction

Integrating Ocean Drilling and NASA Science: A Workshop to Explore Missions to Planet Earth was held on April 2–4, 2024 in Washington, D.C., at the Washington Plaza Hotel. This was a strategic workshop designed to lay the foundation for a new partnership between the National Science Foundation (NSF) and NASA focused on scientific ocean drilling, which is aligned with the recent memorandum of understanding between the two federal agencies (Potter, 2021). The goal of this workshop was to identify and build on the implicit scientific synergies that NASA's Earth and Planetary Science Divisions within the Science Mission Directorate (SMD) have with scientific ocean drilling and to explore using the United States scientific ocean drilling vessel, *JOIDES Resolution*, its replacement, and allied international and commercial drilling assets for joint research ventures. There were 109 people who attended this workshop (77 in person and 32 virtually).

The audiences for this workshop are the NSF (Ocean and Earth Sciences) and NASA (Earth and Planetary Sciences) division directors, program managers, and the United State Science Support Program for Scientific Ocean Drilling (USSSP). The findings presented herein represent a distillation of broad community input that was comprised of almost 50% early career scientists.

The workshop goal was developed in response to the synergies between the 2050 Science Framework (2020; from the scientific ocean drilling community) and the Explore Science 2020-2024: A Vision for Scientific Excellence (2020; from NASA's Science Mission Directorate). In both of these documents, collaborations with other agencies are welcomed and encouraged. Specifically, in the 2050 Science Framework (2020), connections and collaborations between scientific ocean drilling and space agencies are highlighted as an *Enabling Element* (Terrestrial to Extraterrestrial) in the period 2024-2050. NASA's Science Mission Directorate has also highlighted "Interconnectivity and Partnerships" as one of its priorities for science in the period 2020–2024 (Science 2020–2024, pages 20–22). Five strategies are outlined to enable this, and strategies 3.2 (Actively seek collaborations with international partners based on their unique capabilities and mutual scientific goals) and 3.3 (Actively engage with other federal agencies to make more informed decisions, cooperate in scientific research, and pursue partnerships that further national interests) are particularly pertinent to forging linkages with scientific ocean drilling, which is international in nature.

Table 1: Summary of workshop attendees and travel support.

Attendee Category	I-P	V	TS
Graduate Student	16	5	15
Post-Doctoral Fellow	11	1	11
Assistant Prof.	7	4	5
Early Career	3	1	3
Associate Professor	4	3	1
Professor	12	4	12
Research Faculty/Scientist	16	7	4
Gov Employee	4	2	0
E&O	1	1	0
Manager	2	2	0
Industry	1	1	0
Lecturer	0	1	0
TOTAL	**77**	**32**	**51**

I-P = In-Person; V = Virtual; TS: Travel Support

Eary Career Participants in red

Funding was sought and obtained from the United States Science Support Program (funded by the NSF) and from NASA via the Topical Workshops, Symposia and Conferences ROSES call of 2023. Both NASA and USSSP are thanked for their support, which allowed for a focused workshop, including breakfast and lunch for each of the three session days. This allowed for important networking and discussions that could not have happened if the participants had to disperse for meals. Funds allowed 51 of the 77 in-person participants (67%) to receive travel support up to $2,100, with relevant receipts (Table 1). Also, one of the strategies for this workshop was to emphasize the early career participation (e.g., graduate students, post-doctoral researchers, assistant professors, and those who identified as "early career on the registration form, meaning they were within 6 years of their Ph.D.). These researchers made up almost 50% of the in-person attendees, 34% of the virtual attendees, and 67% of those receiving travel support (Table 1).

2. Synergistic Research Opportunities

This strategic workshop was stimulated by the recent memorandum of understanding between NSF and NASA (Potter, 2021) and intended to highlight new collaborations between the two federal agencies. Prior to the workshop, the Steering Committee identified a number of complementary and synergistic research areas that NASA Earth and Planetary Science Divisions have with scientific ocean drilling and by extension NSF Ocean Science aligned research foci. It is important to note that scientific ocean drilling research has been conducted in the United States for 50+ years (e.g., Koppers et al., 2019) so a wealth of material and data are available to integrate with NASA datasets and opportunities (and vice versa). Areas for collaboration are amplified below, but are defined in important documents such as the NASA Earth Science Decadal Survey (2018), the NASA Planetary Science Decadal Survey (2023), the 2050 Science Framework (2020) [from the international scientific ocean drilling community], and the *Science 2020-2024: A Vision for Scientific Excellence* (2020) [from NASA's Science Mission Directorate – NASA-SMD (2020)], as well as the current NASA Strategic Plan (NASA, 2022). These documents articulate that collaborations with other agencies are welcomed and encouraged as indicated by the following examples:

- NASA Earth Science Decadal Survey (2018). **Recommendation 2.1**: *Earth science and applications are a key part of the nation's information infrastructure, warranting a U.S. program of Earth observations from space that is robust, resilient, and appropriately balanced.* ***NASA, NOAA, and USGS, in collaboration with other interested U.S. agencies, should ensure efficient and effective use of U.S. resources by strategically coordinating and advancing this program at the national level****, as also recommended in the 2007 Earth Science and Applications from Space (ESAS) decadal survey*.
- NASA Planetary Science Decadal Survey (2023). This contains a section entitled *Intra-Agency, Interagency, and International Collaborations* [on page 531] that produced the following finding: ***Already established, and newly emerging, mechanisms for facility and data collaborations across other federal science agencies can serve as a good model for future NASA collaborations****. Such partnerships ought to span from theoretical modeling and simulations to data ecosystems to data analysis, laboratory experiments, and field investigations across multiple entities*.
- 2050 Science Framework (2020). Connections between scientific ocean drilling and space agencies are specifically highlighted as an "Enabling Element" (*Terrestrial to Extraterrestrial*) in the period 2024-2050, a summary of which is given here: ***Future collaboration between international space agencies and scientific ocean drilling will benefit efforts to better understand planetary evolution, evaluate the potential for indigenous life elsewhere in the universe, and assess the risks posed by extraterrestrial impacts.*** *Through space exploration, humankind aspires to discover the fundamental physical laws of the universe, decipher the conditions required to promote planetary formation and evolution, and ultimately, unravel the origin of the universe and life. Scientific ocean drilling's investigations into Earth's structure, magnetic field, and volcanism and the requirements for planetary habitability have similar goals. Earth's ocean basins provide a reference frame for exploring challenging environments and offer a natural laboratory for testing remote and space exploration robotic technologies. Integration of modern satellite data with historic records from scientific ocean drilling will be a powerful new approach to*

understanding Earth's interconnected processes today and climate evolution into the future. Synergies with NASA's Earth Science Division are shown in Table 2.

- NASA-SMD (2020). "Interconnectivity and Partnerships" is highlighted as one of its priorities for science in the period 2020-2024 (pages 20-22). Five strategies are outlined to enable this in strategies 3.2 (*Actively seek collaborations with international partners based on their unique capabilities and mutual scientific goals*) and 3.3 (*Actively engage with other federal agencies to make more informed decisions, cooperate in scientific research, and pursue partnerships that further national interests*) are particularly pertinent to forging linkages between scientific ocean drilling and NASA science.
- NASA (2022). Partnerships with other federal agencies is specifically called out in this document [page 15: *NASA will extend partnerships domestically and internationally*], and Strategic Goal 1 contains Strategic Objectives 1.1 (Understand the Earth system and its climate) and 1.2 (Understand the Sun, solar system, and universe) that lend to collaborations between NASA science and scientific ocean drilling (see Table 2).

Table 2, prepared for this workshop, highlights the synergies between scientific ocean drilling as presented in the 2050 Science Framework and research emphases within NASA Earth Science and Planetary Science divisions..

Table 2:

	Division	**Research Emphasis**	**Ocean Drilling Research: 2050 Science Framework**
NASA Science Mission Directorate	Earth Science	Climate Variability & Change	FI: Ground Truthing Future Climate Change; SO: Earth's Climate System
		Carbon Cycle & Ecosystems	SO: Global Cycles of Energy & Matter
		Earth Surface and Interior (including natural hazards)	FI: Probing the Deep Earth; FI: Assessing EQ & Tsunami Hazards; SO: Natural Hazards Affecting Society
	Planetary Science	Origin & Evolution of Life	FI: Exploring Life & it's Origin; SO: Habitability & Life on Earth
		Origin & Evolution of Planetary Bodies	FI: Probing the Deep Earth; EE Terrestrial to Extraterrestrial
FI = Flagship Initiative; SO = Strategic Objective; EE = Enabling Element			

The workshop was organized to augment these synergies and facilitate discussion around potential future joint research activities. Over the course of three days, sessions were crafted to highlight the value of coordinating synergistic research efforts between NASA and NSF focused on using scientific ocean drilling to explore planetary habitability and limits on life, Earth's changing climate, tectonics & volcanism in the Solar System, planetary analogue studies, impact processes and extraterrestrial threats, and geohazards. Discussion also focused on exchange of technology and technological development as a potential collaborative opportunity. Each oral session was comprised of invited and contributed presentations, supported by a vibrant poster session on the second day, with each session culminating in a lively discussion period facilitated by members of the steering committee. The workshop culminated in a number of focused breakout sessions. The full workshop agenda is included in Appendix A.

This report presents major outstanding questions of interest to NASA (Earth and Planetary Science communities) and the NSF and international ocean drilling science communities. The major findings are highlighted, and individual summaries of each in-person breakout session are also included in the Appendix B. One of the goals of the workshop was to highlight potential synergistic proposals that could be developed by the NASA and Ocean Drilling communities.

The report is divided into 5 potentially collaborative science themes plus the catch-all - Other:

1. Earth's Climate
2. Astrobiology/Habitability
3. Impact Processes & Geohazards
4. Plume Volcanism & Tectonics
5. Analogues
6. Other

3. Focus Questions and Findings

In order to set the scene for discussions, focus questions were discussed throughout the workshop.

1. **How can proposals be crafted with integrated NASA and ocean drilling objectives?**
2. **How do we integrate ocean drilling data with NASA data?**
3. **Is it possible for NASA-NSF to co-fund a drilling expedition on the U.S. drill ship *JOIDES Resolution* or other platforms?**

Discussion throughout the workshop kept coming back to these questions and three specific findings from these discussions are listed below as potential interagency partnership pathways.

3.1 Interagency Partnership Pathways

3.1.1 NASA-NSF Joint Research Programs. Creation of a trial joint program/strategy/mission for a sustained period of time by NASA-NSF interagency funding to bring different communities together to focus on research topics of mutual interest (highlighted in specific findings in subsequent sections). It is recognized that interagency programs have to be introduced via the decadal survey processes for NASA Earth and Planetary Science as well as NSF Ocean Sciences, and this can be done by the respective communities, but a trial program would demonstrate the validity of such an approach. This trial program could also be a way to broaden questions to be of interest to both agencies. Examples of potential joint programs bridging NASA and NSF Ocean Sciences where scientific ocean drilling could be critical to a major advance in understanding:

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4. Outstanding Research Questions and Findings

4.1 Earth's Climate

Major Research Questions

- **What are the meridional thermal gradients (temperature gradients between tropics and poles) during past warm climate intervals?**
  - What mechanisms allow for polar amplification of warmth?
  - What are the maximum temperatures possible in the tropics?
  - Are temperature proxies reliable? If not, what should be done to improve calibrations/reliability?
  - What new data are required to generate reliable meridional thermal gradient estimates (e.g., time intervals, locations)?
  - What is the origin of existing data/model mismatches (e.g., Cretaceous "cool tropics paradox" was the result of poor proxy data quality)?
- **What climate tipping points are key for better predicting near-term climate and ocean change?**
  - How might meridional overturning circulation change with continued high-latitude warming and freshening? What implications will these changes have on regional climate?

  - How sensitive are ice sheets to oceanic vs atmospheric heat? How will Antarctic ice mass loss due to oceanic forcing be offset by ice mass gain due to atmospheric warming, which increases precipitation?
- **How much and how fast will sea levels rise with continued warming?**
  - How do different ice catchments respond to oceanic and atmospheric warming?
  - How did ice catchments presently responding to ongoing warming respond during past warm climate intervals?
  - How fast did ice retreat in these catchments during the last deglaciation? What factors forced deglaciation in each catchment?
  - How does understanding of catchment scale ice mass loss improve estimates of both eustatic and relative sea level rise? How does the solid earth respond to ice mass loss in specific catchments?

- **How do we integrate the modern and paleoclimate records to better predict future climate regimes?**
- **How has Earth's climate sensitivity to greenhouse gas forcing evolved over the last 66 million years?**
- **Earth's climate system has been shown to respond non-linearly to changes in Earth's orbital parameters. What climate feedbacks act to amplify changes in Earth's orbital configuration?**
  - Why is eccentricity pacing of climate only observed at certain times in the last 65 Ma? What feedbacks amplify changes in Earth's eccentricity?
  - Why aren't changes in Earth's precession a dominant signal in paleoclimate records?
- **What is the biotic response to past and ongoing climate warming? How does climate warming impact marine biodiversity?**

4.1.1 Findings

4.1.1.1 Interagency Partnership Pathway: Synergistic Climate Research-1. Three essential science areas fall within an overarching priority highlighted in the 2024 NASEM Decadal Survey of Ocean Sciences Priorities for Future Scientific Ocean Drilling and is a NASA's Flagship Initiative: Ground Truthing Global Climate Change;

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- Extreme Environment Technology Development

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4.2. Astrobiology/Habitability

Major Research Questions

- **What are the limits of life and are there environments where no life exists?**
  - What environments on Earth are not habitable? For example, identifying where lipid structures are no longer stable.
- **How do different lithologies that have different fluid/rock interactions provide nutrients for life? What is the interaction between lithology and biochemistry?**
- **When we sample the subsurface of other worlds (ocean worlds or rocky), what technologies are required to select targets in 3D (including depth) and determine how deep we need to drill?**
- **How much work with astrobiology/habitability can be done with legacy cores?**
  - How much do biomarkers degrade?
  - How does mold growth on legacy cores impact biomarker proxies?
- **What are the differences between biotic and abiotic processes under dramatically different conditions from standard temperatures and pressures?**
- **How can we biogeochemically characterize the Anthropocene and how can those ideas be applied to detecting life signatures in rocks?**
- **Can chirality of amino acids in carbonaceous chondrites (enantiomeric excess) survive impact events and impact temperatures?**

4.2.1 Findings

4.2.1.1 Interagency Partnership Pathway: Limits on Life. Understanding where life does not exist (and perhaps cannot exist) is equally important to understanding how to detect life in extreme environments. For example, limits on life can be explored through ocean drilling in extreme environments (e.g., Expedition 376 Brothers Arc Flux). Future drilling combined with ongoing biological technology developments will enable us to better understand the boundary conditions for life, which will provide insight into the origin and evolution of life on Earth as well as an understanding of the potential limits of life on other planetary bodies. Technology developments required to determine these limits in seafloor sediments and rocks will also aid in the development of instrumentation necessary to search for life elsewhere.

4.2.1.2 Interagency Partnership Pathway: Preservation of Organic Signatures. Legacy IODP cores known to contain organic signatures can be used to:

- Evaluate how well organic signatures are preserved in returned samples (e.g., OSIRIS REx, Mars) particularly those stored for an extended period of time
- Enable our understanding of why some organics are preserved rather than consumed by life over geologic time scales, a critical question from the 2050 Science Framework

4.2.1.3 Interagency Partnership Pathway: Recycling & Redox Processes. Recycling of elements that are precursors for the life-form metabolites and redox processes drive exchange of elements (e.g., high flow zones with high porosity and permeability allows more recycling; groundwater exchange zones). A focus on fluid-rock interactions that drive habitability seems timely with specific environments of extraterrestrial interest including impact and volcanic hydrothermal systems.

4.2.1.4 Mission to Planet Earth: How this Ocean World can inform about other Ocean Worlds-1. Future investigations evaluating hydrothermal alteration processes in diffuse, off-axis vent fields will likely yield new and directly applicable insights into alteration of Ocean World seafloors and cores, as seafloors in other Ocean Worlds are unlikely to display plate tectonics.

4.2.1.5 Mission to Planet Earth: How this Ocean World can inform about other Ocean Worlds-2. Future investigations at both on-axis and off-axis active hydrothermal systems can provide insight into prebiotic chemical synthesis pathways that can enable a better understanding of organic chemical evolution, which may be an important habitability marker for other Ocean Worlds.

4.3 Impact Processes, Geohazards, and Geodynamics

Major Research Questions

- **Do impact melt sheets differentiate and on what timescale?**
    - Interpretation of gravity/magnetic/compositional signatures of extraterrestrial melt sheets
    - Differentiated melt sheets could produce economic mineral deposits (e.g., Sudbury)
- **What is the heterogeneity of impact hydrothermal systems and the range of fluid-rock interactions?**
- **How do microbial ecosystems evolve within impact hydrothermal systems?**

- **Can we use impact crater observations and models to investigate rheology and physical properties of planetary interiors?**
- **How transferable are impact cratering processes on Earth to other planetary bodies due to the abundance of water/hydration?**
  - Mars can still be a good comparison due to the presence of ice
- **How can we use the surface expression of different lithologies/mineralogies of impact craters on Earth to piece together subsurface stratigraphy that we can't access on other planetary bodies?**
  - We need high-resolution (<100 m/pixel) spectral data from the Moon and Mars
- **Is there evidence of organic synthesis from impact events? Can organics survive impacts?**
  - Experiments to explore this require funding – programs that enable this will need to be identified
- **What changes in habitability occur after impact and how long do those changes last?**

4.3.1 Findings

4.3.1.1 Interagency Partnership Pathway: Onset of Plate Tectonics. Plate tectonics on Earth dictates the structures and life on Earth, so pinpointing the onset of plate tectonics throughout the deep geologic timescales can help to compare to other planets. This knowledge gap currently limits our ability to explain how tectonics modify Earth systems.

4.3.1.2 Interagency Partnership Pathway: Effects of Impacts. Study of impact structures on Earth informs us about flexure & elastic thickness of the lithosphere, gravity effects, and long-term response of Earth to loading from impacts. This has implications for other terrestrial planetary bodies.

4.3.1.3 Interagency Partnership Pathway: Geohazard Prediction. Better predictive tools are needed for geohazards so a clear future investigation could be a coupled monitoring for earthquake and landslide hazards using borehole installed sensors with high resolution (temporal and spatial) satellite observation of tectonically active areas (e.g., coupling the temporal resolution of pore pressure changes in advance of, during and after events with structure for motion studies, InSAR, and GNSS observations of permanent deformation).

4.3.1.4 Mission to Planet Earth: Habitability Implications of Impacts. Understanding the role impacts play in habitability is essential for Mars and some Ocean Worlds where impacts may play a significant role in reshaping surface and subsurface habitability. Drilling multiple sites in impact structures on Earth would yield important information to address this. Drilling into the central basin at the Chicxulub impact structure could illuminate the geobiology and thermal history of a recent impact hydrothermal system.

4.4 Plume Volcanism

Major Research Questions

- **Why are there large volcanic events on other planets, but no tectonics?**
  - On Earth, plume volcanism can drive tectonics, but we don't see corresponding tectonics on any other planetary bodies.
  - Underwater plumes on Earth are very altered, we need to drill through the altered rocks and only deep drilling can do that
  - Plume volcanics help us understand the thermal evolution of planetary bodies
    - Connections to Venus, Mars, the Moon and Mercury
- **How can jointly funded analogue studies of terrestrial plume volcanics be established to further knowledge of the process across the Solar System?**
  - Old seamount drilling to see how long the mantle plume existed. Seamount drilling enables tracking of hotspots through paleomagnetism, geochemistry, and geochronology, which makes it possible to study how mantle plumes existed over a long geologic time period, which can then be compared to other planetary bodies. This can also be tied to habitability of old seamount and volcanism related systems.
  - Plume-ridge interactions and relationships with rifting. Understanding how plumes can be geochemically diverse, and mixing of reservoirs affect the chemical diversity that we see on other planetary systems.
  - Areas where we can get hydrous high silica volcanoes, non-subduction related. Caribbean Plateau – Aruba.
  - If we know what we are looking for specifically, we can use the spectral characteristics/signature, classification, and clustering algorithms to look for specific places. Using the power of remote sensing data will help, without necessarily having to go there.
- **Can ocean drilling address the record of large eruptions?**

4.4.1 Findings

4.4.1.1 Interagency Partnership Pathway: Origin of Large Low Shear Velocity Provinces (LLSVPs). Many hotspots on Earth are sourced from the edges of the Pacific and African LLSVPs. It has been proposed that LLSVPs represent the remnants of subducted oceanic crust that have sunk to near the core-mantle boundary, or they may represent relics of Theia, the primordial impactor which collided with Earth and led to the formation of the Moon. Geochemical studies of plume-derived basalts to search for impactor contributions (versus solely terrestrial origin components) and compositional comparisons between volcanic rocks from the Pacific LLSVP, African LLSVP, and plume-derived volcanics not associated with LLSVPs may enable discriminating between the aforementioned hypotheses.

4.4.1.2 Interagency Partnership Pathway: Felsic Crusts and Magmatism: The formation of massive felsic crust on Earth is thought to require recycling hydrated basaltic crust into the mantle, remelting of these materials, and the resulting magmatism. Felsic magmatism may have occurred within wider basaltic terranes on both Mars and Venus early in the histories of these planets. Scientific ocean drilling expeditions aimed at understanding the formation mechanisms of these and similar regions (e.g., intra-oceanic arc magmatism) may bear lessons for the origins of similar features on other worlds (e.g., the Iceland rift zone the Caribbean Plateau, the Izu-Bonin-Mariana forearc, and the Ontong Java Plateau).

4.4.1.3 Interagency Partnership Pathway: Spectroscopic Examination of Legacy LIP and Hotspot Legacy Cores. New spectroscopic methods should be used on existing cores and new drilling can use these new methods.

- The core from the Hawaiian Scientific Drilling Project (HSDP), as well as ocean drilling legacy cores (e.g., Emperor Seamounts, Louisville Seamounts, Ontong Java Plateau, Kerguelen Plateau, Caribbean Plateau) could also be used to gather spectral data to compare with orbital data from Mars, the Moon, and Mercury to examine compositional variations.
- Mars – examination of alteration processes on Mars; on Earth volcanic material weathers quickly. Look at the spectroscopic signatures on altered volcanic cores recovered by ocean drilling to better interpret the data from Mars.

4.4.1.4 Interagency Partnership Pathway: Study of Hydrothermally Altered Basalts. The production and hydrothermal alteration of basaltic seafloor along mid-ocean ridges as well as oceanic islands and plateaus (particularly tholeiitic basalts) may be a good analog for understanding alteration of the ancient basaltic crust of Mars or at the seafloors, of ocean worlds such as Europa and Enceladus.

4.4.1.5 Mission to Planet Earth: Understanding Large Igneous Provinces (LIPs): Understanding LIPs is important for understanding planetary volcanism and tectonics. On planetary bodies we will be lucky to get to 2 m or 10 m. We need to learn more about the origin(s), timing, and evolution of LIPs.

4.5 Analogues

Major Research Questions

- **What Questions about planetary volcanism can be answered on Earth, and where is the best place to study it?**
- **How can tectonic processes and earthquakes on Earth inform interior and surface processes elsewhere, using our tectonic-rich planet to inform key specific processes on other planets?**
- **How can terrestrial chemosynthetic habitats inform us about astrobiological potential?**

    - Recycling of elements that are precursors for the life-form metabolites, how does global tectonics processes inform chemosynthetic habitats? Sulfur, for example, is important. Recycling of elements. How does this dictate how life will form on other planets? Maybe where permeability allows more recycling (e.g., groundwater exchange zones. Redox processes drive exchange of elements.
    - The advantage of Earth is that there are easily accessible analogues, but relevant environments in the subsurface ranging from cm to km to study microbial communities need to be identified.
- **How can tectonic processes and earthquakes inform interior and surface processes on other worlds?**
    - Plate tectonics on Earth dictates the structures and life on Earth, pinpointing those changes throughout the deep geologic timescales can help to compare to other planets.
    - Understanding how much gas comes out of faults during earthquakes will help us understand our planet, and by extension other planets. Helium is a great example. Surface processes, temperature and chemical condition of alterations determine chemosynthetic environments. Systematic understanding of the factors, and kinetics of such processes (tectonics) will be essential.
    - In terms of characterizing analogues, in order for us to be able to understand how tectonics differs between planets that have global tectonics, and those that do not, we need to be able to explain the "when" and "how" of plate tectonics on Earth. This knowledge gap currently limits our ability to explain how tectonics modify everything else (tectonics interacts with everything). We should use the strong tectonic signal we have on Earth to inform our understanding of other planets. Also, most of the preserved earliest volcanic samples are felsic, therefore, we need to understand how the Earth tectonics evolved through time, from a time when tectonics wasn't global to the present-day planet with the entire range of volcanism.
    - Intra-plate felsic volcanism, Venus Tessera might be a felsic volcano, and that might be a good analogue for Earth before plate tectonics.
    - We have different causes of quakes on Earth (and the Moon) so this also true for other planets. Need to understand on Earth (and the Moon) in order to extrapolate toother planets.
    - What we can learn after an impact- the flexure of the lithosphere, the elastic thickness, the gravity, long term response of Earth to loading from impacts. We can do the same for Mars.

4.5.1 Findings

4.5.1.1 Interagency Partnership Pathway: Analogue Sites for Tectonics Associated with Plume Volcanism. On Earth's seafloor, analogue settings to explore complex tectonic settings that explore plume evolution, rifting (both initiation and failure), plume-ridge interactions, and plume-driven subduction processes include the Magellan Rise oceanic plateau (DSDP Legs 7 and 61), the North Fiji and Lau back-arc basin (ODP Legs 134 and 135), the Caribbean and offshore northwest South America, the Cascadia subduction zone, the Walvis Ridge, and the South China Sea.

4.5.1.2 Interagency Partnership Pathway: Ground-truthing NASA Earth Science Orbital Data. Legacy scientific drill cores from the last 50 years of NSF and its partners funded expeditions are an opportunity for ground truth of NASA's Earth Science division funded remote sensing data and models as well as NASA's Planetary Science Division studies of specific volcanic, impact, and hydrothermal processes including the search for life.

4.5.1.3 Interagency Partnership Pathway: Definition of "Analogue Site". Earth is not a good analogue for some planets we want to study - Venus is a great example. Therefore, in addition to field analogue sites, laboratory analogues need to be considered, with the caveat that experiments cannot be run for "geologic" amounts of time, so modeling becomes important.

4.5.1.4 Interagency Partnership Pathway: Analogue Site Opportunities. Analogue site studies should incorporate interdisciplinary/multidisciplinary opportunities. For example, impact craters inform about the impact process, lithospheric composition and flexibility, melt-sheet differentiation, habitability, and hydrothermal systems.

4.5.1.5 Mission to Planet Earth: Best Analogue Sites.

- *Mars*: ocean island basalts are probably the best (plume-related, no continental crust signature), but on Earth these are young when compared to Mars. Also, Svalbard for habitability, life detection, and planetary protection studies.
- *Astrobiology-1*: try to understand where life can exist on Earth and then try to understand what the extremes do for life so that we can figure out where are the boundaries that life can exist on Earth. That will give us a framework for where it can live in other places. But the more we understand about it here (and how it responds to its extremes) can help us in that search.
- *Astrobiology-2*: It is interesting and important to find places on Earth that host unique life that only exists there. This is the case for one island in the Canary Islands. There are two places on that island that host a specific life only for that geology. So, what does that geology look like for that environment? What are the conditions for hosting that kind of life only at that particular point on the planet? Can then extrapolate to Mars and beyond.
- *Volcanism*: Plume volcanics in oceans to avoid contamination via the Earth's felsic crust
- *Impact craters* are all over the Solar System. And there have been valid points that maybe we can only compare an Earth crater to a Mars crater because you've got the water involved. But if you're looking for a place on Earth where you know there isn't life, it's immediately after an impact. And so, looking at the development of life within that once uninhabitable situation, we can then look at the drill cores and the recovery of life afterward.

4.5.1.6 Mission to Planet Earth: New Ocean Drilling Expeditions. New scientific drilling, logging, and borehole monitoring to answer critical questions in hazards, impact processes, volcanism, and habitability at the appropriate analogue sites. For example:

- Drilling into the Chicxulub impact structure would allow recovery of an intact, impact melt sheet providing insights into melt differentiation, planetary crustal evolution, and hydrothermal habitats;
- Drilling in other terrestrial impacts serve as analogs for understanding the evolution of Mars, the Moon, and other worlds through insights into shock processes and development of impact generated structures, stratigraphy, and morphology that dominates most planetary surfaces, as well in the search for extraterrestrial life.

4.6. Other

Major Research Questions

- **How do we make the results of IODP and other drilling expeditions more discoverable?**
    - Legacy Asset Projects (LEAPs) will need to use and integrate these data
- **Are there available age models for all of the legacy drilling sites in order for people to access and look for sites to work on?**
    - Could NSF/NASA support staff paleontologists to refine age models for legacy cores?
- **For LEAPs, what database/repository will improvements to legacy core age models (for example) be placed in? How will we ensure it is not spread out between too many databases to reasonably check?**
    - Will need to develop a common data repository
    - Going forward, NSF needs to support the core repositories as much as possible for enhanced measurement capabilities and legacy data management
- **How can NASA technology development be integrated with ocean science technology development?**
- **What cores are understudied relative to how much information these could contain?**
    - Develop procedures for characterizing legacy cores using modern techniques
        - 60% of samples requested from repositories in last year were from only 30 sites, many cores have not been worked on beyond initial shipboard descriptions
- **What would joint research projects look like?**
    - NASA-TWSC and USSSP co-sponsored this workshop, with an awkward funding structure that took almost four years to navigate. Two parallel proposals submission makes funding awkward, so having a single body review the proposal will make it easier, having just one reaction to the proposal.

- NSF has explored joint proposals with other funding agencies outside the U.S. (i.e., the Natural Environment Research Council in the U.K.). U.S. scientists need to be encouraged to collaborate internationally on legacy cores or other programs. For example, the NSF-NERC style where the proposal is reviewed once by either NERC or NSF. Could something like this can be made for NASA and NSF proposals? Or a joint review board that meets once?
- Within the U.S. there is a mechanism for inter-agency transfer of funds, which was historically done through the *Life In Extreme Environments* (NASA-NSF funded) program. Program managers would need to identify and remove the barriers. However, the federal government updated the guide for inter-agency operations. It seems once a project is approved, funding between agencies might be easier. The National Oceanographic Partnership Program helps to facilitate inter-agency funding, and NASA, NSF, NOAA, etc., seems to be part of this program. This mechanism could be explored.
- IODP ends this year, the future will be in a different framework. But there is a precedent in the recent past, where additional money can come in from a different program to fund drilling projects with particular goals that match the goals of the funding entities and the drilling project objectives. Sort of supplemental funding. It allows NSF to stretch their budget.

- **How can proposals be crafted with integrated NASA and scientific ocean drilling objectives and is it possible to get interagency funding by NSF and NASA ROSES through collaborative proposals?**

4.6.1 Findings

4.6.1.1 Interagency Partnership Pathway: Jointly Funded Proposals. There are mechanisms in place to facilitate inter-agency transfer of funds and have inter-agency funded proposals. The meeting participants encourage NASA and NSF to explore these possibilities in light of the research synergies discussed at this workshop. For example, the next Astrobiology Research Coordination Network CAN could contain an ocean drilling component.

4.6.1.2 Interagency Partnership Pathway: Early Career Opportunities. It is important to continue early career funding and training opportunities in ocean drilling, especially with LEAPS proposals.

4.6.1.3 Interagency Partnership Pathway: Integrating Data Sets. Connecting technologies/instrumentation used to characterize cores with those used for satellite measurements could be a way of integrating NASA and ocean drilling data (e.g., same spectral measurements, etc.).

4.6.1.4 Interagency Partnership Pathway: Maximizing Ocean Drilling Legacy Data. Tools need to be generated for exploration of existing legacy collection to maximize their use (e.g., Google Earth of IODP holes that is interactive with site/drilling data).

5.1 APPENDIX A: Workshop Agenda

Integrating Ocean Drilling and NASA Science: A Workshop to Explore Missions to Planet Earth

Washington Plaza Hotel, National Ballroom
April 2-4, 2024

April 2, 2024	DAY 1
8:00-9:00 am	Continental breakfast
8:30-10:30 am	**Introduction and Value of Coordination (Clive Neal, session chair)**
8:30-8:55 am	Introduction to synergies between NASA and Scientific Ocean Drilling, highlighted by volcanism on Earth and other worlds plus intro to topics below (Clive Neal – Notre Dame) (25 min)
8:55-9:15 am	NASA Science – Understanding modern climate - Laura Lorenzoni (NASA Earth Science Division) (20 mins)
9:15-9:30 am	Habitability and Limits of Life on Earth and elsewhere (Charity Phillips-Lander - SwRI) (15 mins)
9:30-9:45 am	Impact Processes and Extraterrestrial Threats (Sean Gulick – UT Austin) (15 mins)
9:45-10:00 am	Crewed Exploration, including development of astronaut tools and exploration (Ryan Watkins - NASA) (15 mins)
10:00-10:15 am	Studying ocean worlds – including Earth (Steve Vance – NASA) (15 mins, virtual)
10:15-10:30 am	**Q&A Discussion—**Potential Research Synergies (15 mins) Clive Neal (moderator), Gryphen Goss (note taker)
10:30-10:45 am	**BREAK (15 mins)**
10:45-11:00 am	Introduction to NASA Research Programs (Mitch Schulte - NASA) (15 mins)
11:00-11:15 am	Beyond IODP: The changing landscape of scientific ocean drilling (Clive Neal – Notre Dame) (15 mins)
11:15-11:30 am	IODP cores and data & post expedition science (Kevin Johnson - NSF) (15 mins)
11:30-11:45 am	Results of the NASA Decadal Survey (Sonia Tikoo, Stanford) (15 mins)

11:45 am-12:00 pm	**Q&A and discussion** about funding mechanisms and potential linkages (20 mins) Clive Neal (moderator), Libby Ives (note taker)
12:00-1:30 pm	**LUNCH (90 mins)**
1:30-3:00 pm	**Habitability and Limits on Life (Charity Phillips-Lander, session chair)**
1:30-1:45 pm	Invited talk (Melody Lindsay - Bigelow): Overview of Scientific Ocean Drilling to understanding habitability and limits on life (15 mins)
1:45-2:00 pm	Invited talk (Lindsay Hays – NASA Headquarters): Overview of NASA science to understanding habitability and limits on life (15 mins)
2:00-2:10 pm	6023 Osinski - The Role of Meteorite Impacts in Creating Habitable Planetary Bodies
2:10-2:20 pm	6015 Kring - Ocean Drilling to Test the Impact Origin of Life Hypothesis for Earth and its Application to Other Planetary Bodies
2:20-2:30 pm	6001 Bray - The Importance of Drill Cores for Impact Cratering and Astrobiology Studies
2:30-2:40 pm	6013 Teece - Organic Alteration Processes Confound Biosignature Detection in Hydrothermal Environments: The Need for Subsurface Studies
2:40-3:00 pm	**Q&A and Discussion -** Potential Research Synergies within the subjects of Astrobiology, Habitability, and Limits on Life (20 mins) Charity Phillips-Lander (moderator), Jordyn Robare (note taker)
3:00-3:30pm	**BREAK (30 mins)**
3:30-5:00 pm	Plenary Discussion (90 mins): Sean Gulick (moderator), Jared Nirenberg (note taker)

What are the major outstanding questions that need to be addressed from the NASA and ocean drilling perspectives?

- Earth Climate Science
- Astrobiology/Habitability
- Impact Processes and Hazards
- Plume Volcanism

Guiding questions to focus discussion:

- How can proposals be crafted with integrated NASA and ocean drilling objectives?
- Can orbital data be used as site survey data for ocean drilling proposals?
- How do we integrate ocean drilling data with NASA data?

5:00-7:00 pm	**Welcome Reception - Thomas Circle Suite**

April 3, 2024	DAY 2
8:00-9:00 am	Continental breakfast
8:30-10:15 am	**Earth's Changing Climate (Sean Gulick, session chair)**
8:30-8:45 am	Invited talk (Amelia Shevenell - University of South Florida): Overview of Scientific Ocean Drilling to understanding Earth's Past Climate (15 mins)
8:45-9:00 am	Invited talk (Kaustubh Thirumalai - University of Arizona): Combining NASA and IODP Climate Datasets (15 mins)
9:00-9:10 am	6016 Kim - Bolstering Sea Ice Models through Multiple Sea Ice Proxy Reconstructions during Past Global Warm Periods
9:10-9:20 am	6017 Weber - Antarctic Ice-sheet and Sea-Level History in the Weddell Sea
9:20-9:30 am	6040 Castillo - A Tale of Two Cycles: Methane on Earth and Titan Ocean Worlds
9:30-9:40 am	6028 Burton - Global Signals of Cretaceous-Cenozoic Climate Change and Catastrophe in the Deep-Marine Clastic Sedimentary Basin Record
9:40-9:50 am	6038 Guerra - Sediment Record of Climate Change in the Arctic (Kongsfjorden, Svalbard Archipelago)
9:50-10:15 am	**Q&A and Discussion**—Synergies (including suggestions from the participants) (25 mins) Sean Gulick (moderator), Dustin Harper (note taker)
10:15-10:45 am	**BREAK (30 mins)**
10:45 am-12:00 pm	**Volcanism in the Solar System (Clive Neal, session chair)**
10:45-11:00 am	Invited talk (Kevin Konrad– University of Nevada, Las Vegas): Overview of Scientific Ocean Drilling to understanding plume volcanism (15 mins)
11:00-11:15 am	Invited talk (Jim Garvin – Goddard Space Flight Center): Overview of NASA science to understanding volcanism in the Solar System (15 mins)
11:15-11:25 am	6027 McCanta - Identification and Characterization of Volcanic Tephra Deposits in Drill Cores Using VSWIR Spectroscopy

11:25-11:35 am	6025 Greenberger - Contiguous Mineralogic Composition at Sub-mm Scale with Micro-Imaging Spectroscopy of Earth's Ocean Crust and Upper Mantle: New Insights from the Oman Drilling Project for Fluid-Rock Reactions on this Planet and Beyond
11:35 am-12:00 pm	**Q&A and Discussion**—Synergies (25 mins) Clive Neal (moderator), Geoff Wheat (note taker)
12:00-1:30 pm	**LUNCH (90 mins)**
1:30-3:15 pm	**Planetary Analog Studies (Sonia Tikoo, session chair)**
1:30-1:50 pm	Invited talk (Gordon Osinski – University of Western Ontario): Role of terrestrial analog studies in studying other planetary bodies (20 mins)
1:50-2:00 pm	6004 Thorpe - Drilling Icelandic Lakes to Unravel the Sedimentary History of Mars
2:00-2:10 pm	6011 Sheevam - Exploring Subsurface Analog Environments: Insights from Hawaiian Drill Cores for Martian Analog Studies
2:10-2:20 pm	6012 Liu - Methane Clumped Isotopes Reveal Anaerobic Methane Metabolism in the Deep Biosphere
2:20-2:30 pm	6034 Martos - Understanding the History of the Solar System by IODP-like Drilling on Mars
2:30-2:40 pm	6033 Stoner - Causes and Consequences of our Planet's Dynamic Magnetic Field: A Proposed Ocean Drilling and Combined Stakeholder Program (GeoMag50k) to Understand a Variable Field and its Impact on Earth and Other Planetary Systems
2:40-2:50 pm	6031 Lopes (Virtual) - What a 1.2km Section of Serpentinized Oceanic Rocks from the Atlantis Massif (IODP Expedition 399) Can Tell Us About Martian Magnetic Anomalies
2:50-3:15 pm	**Q&A and Discussion**— Types of analog studies ocean drilling can facilitate (25 mins) Sonia Tikoo (moderator), Md Golam Kibria (note taker)
3:15-3:30 pm	**BREAK (15 mins)**
3:30-4:15 pm	Plenary Discussion: (45 minutes) Clive Neal (moderator), John Ajayi note taker)

- How can this ocean world inform us about other ocean worlds?

- How can tectonic processes and earthquakes inform interior and surface processes on other worlds?
- How does volcanism on Earth inform us about volcanism on other planetary bodies?
- How can terrestrial chemosynthetic habitats inform us about astrobiological potential?

Overarching questions:
- What would joint research projects look like?
- How could they be funded?

4:15-5:00 pm Poster Presenters Lightning Talks (3 mins each, 3 slides max)

6002 Tsang - Migration of a Deep, Hot Fluid in the Nankai Subduction Margin and Sulfate Dating (IODP Exp. 370, Site C0023)

6003 Luzzi - Brine Pools in the Gulf of Mexico: A Proxy for Habitability on Enceladus

6006 Liu - How to Let General Public and Educators Easily Access IODP Data and Results

6014 Davis - Investigating Stable Potassium ($^{41}K/^{39}K$) Isotope Fractionation Associated with Microbial Illitization

6019 Wiersberg - Land-to-Sea Drilling: A Means of Learning More About the Origin and Evolution of Life

6021 Sibert - Fish as an Indicator of Marine Ecosystem Structure, Function, and Evolution in Deep Time

6029 Sawicki - Examination of Banded Iron Formations with Mossbauer Spectroscopy

6030 Mannam - Exploring the Depths: Underwater Mapping of Extraterrestrial Planets Using Side Scan Sonar

6032 Huang - Gravitational Influence on Life's Genesis: The Role of Hypervelocity Impacts in Prebiotic Chemistry

6035 Espe - TRIPLE-IceCraft: A New Platform for Transport of Scientific Payloads for in-situ Measurements in the Ice, Under the Ice, and Beyond

6036 Cook - Understanding Carbon Cycling in Gas Hydrate Systems Requires Scientific Ocean Drilling

6039 Castillo - To the Subsurface and Beyond: Future Coupling of Planetary Geology, Remote Sensing, and Scientific Ocean Drilling

6042 Indyk - Technology Development for Accessing Ocean Worlds

5:00-7:00 pm Poster Session and Reception - Thomas Circle Suite

April 4, 2024	**DAY 3**
8:00-9:00 am	Continental breakfast
8:30-10:00 am	**Impact Processes and Extraterrestrial Threats (Clive Neal, session chair)**
8:30-8:45 am	Invited talk (Sean Gulick – UT Austin): Overview of Scientific Ocean Drilling to understanding impact processes and their role in habitability of Planet Earth (15 mins)
8:45-9:00 am	Invited talk (James Walker – DART): Overview of NASA science to understanding impact processes and extraterrestrial threats to Planet Earth (15 mins)
9:00-9:10 am	6010 Anghel - Probing the Mass of Meteoroids Based on Well-Known Impacts with the Earth
9:10-9:20 am	6041 Gulick - Return to Chicxulub: Proposal to Drill the Center of the Earth's Best Preserved Large Impact Basin
9:20-10:00 am	**Q&A and Discussion**—Synergies (including suggestions from the group) (40 mins) Clive Neal (moderator), Anne Joseph (note taker)
10:00-10:15 am	**BREAK (15 mins)**
10:15 am-12:00 pm	**Geohazards (Sonia Tikoo, session chair)**
10:15-10:45 am	Invited talk (Robert Emberson – NASA Headquarters) Studying modern geohazards from orbit (30 mins)
10:45-11:00 am	Invited talk (Demian Saffer, UT Austin) The historical perspective – the role of ocean drilling data (15 mins)
11:00-11:15 am	6005 Hourston - Automated InSAR Time-Series Analysis Tool for Geological Interpretations in Near-Real Time
11:15 am-12:00 pm	**Q&A and Discussion—**Synergies (45 mins) Sonia Tikoo (moderator), Ruth Aronoff (note taker)
12:00-1:30 pm	**LUNCH (90 mins)**
1:30-3:00 pm	**Breakout Groups Challenges (90 mins) – Development of synergistic research initiatives (13:30)**
1:30-1:40 pm	Plenary: Instructions for Breakout Groups (Clive Neal)

Breakout 1	Develop initiatives to include past & present climate observations (Amelia Shevenell lead, Jasmin Naher note taker). Location: National Ballroom
Breakout 2	Develop initiatives that include analogue sites for astrobiological applications for defining the limits on and existence of life (Phillips-Lander lead; Anastasia Yanchilina note taker) Location: Thomas Circle Salon A
Breakout 3	Develop initiatives that use terrestrial analogues studied or to be studied by ocean drilling to yield information on extraterrestrial volcanism (Tikoo lead; Luan Heywood note taker) Location: Thomas Circle Salon B
Breakout 4	Develop initiatives that use terrestrial analogues that should be studied by ocean drilling to yield information on the impact cratering processes and hazards (Gulick lead; Morteza Safari note taker). Location: Thomas Circle Salon C
Breakout 5	Virtual Only (TBD)
3:00-3:15 pm	**BREAK (15 mins)**
3:15-3:35 pm	Plenary Report from Breakout Groups & Discussion (5 mins each
group) 3:35-4:15 pm	Discussion of the Workshop Findings (40 mins)
4:15-4:30 pm	Next Steps and Closing Remarks (15 mins)
4:30 pm	**ADJOURN**

5.2 APPENDIX B: Breakout Group Summaries

Breakout 1: Develop initiatives to include past & present climate observations

Background

A wide-ranging discussion of climate-associated science questions occurred during the NASA-IODP workshop climate breakout group. Three essential science areas emerged that fall within an overarching priority highlighted in the 2024 NASEM Decadal Survey of Ocean Sciences Priorities for Future Scientific Ocean Drilling and is a NASA's Flagship Initiative: Ground Truthing Global Climate Change. These science areas are:

1. High Latitude Focus on Future Sea Level Rise: How much, how fast, where? Ice proximal records of past ice sheet behavior

NASA's cryospheric sciences uses satellite and airborne remote sensing to understand changes in ice mass balance, with implications for future sea levels as well as changes in sea ice extent, which influence Earth's albedo. These data are used to improve ice-related processes in climate models. IODP scientists use NASA generated data to test the hypothesis that today's climatically sensitive catchments were also sensitive in the past. IODP has prioritized recovering sediments and generating paleoclimate records from both deep-sea and climatically sensitive ice-proximal locations to determine past changes in ice sheet behavior, ocean temperatures proximal to ice sheets, polar amplification, and global patterns of sea level rise.

Antarctica is the largest unknown in projected sea level rise timing and rates. In the last several decades, NASA data has revealed: **1)** variable behavior of ice sheets across different regions of Antarctica, and **2)** that large portions of East Antarctica may be more sensitive to warm climate conditions than previously thought. Thus, there is a need for additional ice-proximal paleoclimate data from East Antarctica's multiple catchments, which contains 53 meters of sea level equivalent ice. A comprehensive sampling of deep sediment records from the continental shelves offshore of major catchments is required to determine which regions responded (and how) during past warm climate intervals, and the climate tipping points associated with past changes. *Such records are the only way to extend NASA's time series of ice sheet observation, with the understanding that these records will vary in resolution farther back in time, but will provide important boundary conditions for modelling past climate.*

2. Changing Equilibrium Climate Sensitivity: Past warm climates

NASA has an active paleoclimate modelling group that requires data routinely generated by the scientific ocean drilling community. Specifically, they are interested in understanding the climate system during past warm climate intervals, including the Eocene, Early to Middle Miocene, and less so, the Pliocene. Such data are critical for testing how well global circulation models can reproduce the climate system's sensitivity to greenhouse gas forcing, and if equilibrium climate sensitivity changed over time, under different boundary conditions (e.g., continental configurations, greenhouse gas concentrations). Scientific ocean drilling scientists routinely generate data useful to climate modelers (e.g., time slice temperature records), but typically not at the spatial resolution needed to avoid extensive interpolation. Such data would be useful for reconstructing past meridional thermal gradients, ocean and atmospheric circulation changes. There is particular interest in understanding past hydrologic system changes in the tropics, where anthropogenic climate impacts are likely to impact a majority of Earth's human population.

3. Habitability/Marine ecosystem productivity response during past warm climates

NASA currently collects biogeochemical data with satellites that provide information on carbon cycling and ocean health (e.g., fisheries management, anoxia). Scientific Ocean Drilling routinely extends such records back in time, which enables improved understanding of Earth's deep-time carbon cycle, which in turn may be relevant to modern-day CDR, ocean anoxia, and climate sensitivity discussions. Fisheries management was considered to be more within NOAA's prevue, but long term records of productivity and changes in regional productivity in warmer climate intervals generated in highly productive regions with important fisheries could improve understanding of how conditions might change Furthermore, Scientific Ocean Drilling scientists are asking questions about the evolution of life on earth, which can help us to better understand how life on our planet persists and, how life might evolve on other planets.

In addition to identifying scientific areas that could easily foster collaborations between NASA and Scientific Ocean Drilling scientists, the breakout group discussed the following:

1. Proxy development: Real synergies could be developed between NASA and SOD scientists working towards paleoclimate proxy development. It was noted that NSF does not traditionally fund paleoclimate proxy development, but that in order to extend time series generated by NASA satellites back in time, real work is needed to develop proxies from remote sensing and surface ocean sediments. Once this is done, then we can have more confidence in the proxies we use to reconstruct past climate and ocean change. It was suggested that the NASA ROSES program might be well placed to fund such studies.
2. NASA Climate modelers discussed the need for improved age models so that they could be certain that they were comparing like data with like for a certain time interval. They also expressed the need for improved data repositories that could handle evolving age models and calibrations. Paleoclimate data has been traditionally handled in an ad-hoc way, but a purpose-built database would improve interagency funding and collaboration potential.
3. Extreme environment technological development: There was general discussion about the fact that scientific ocean drilling routinely operated in inhospitable high pressure and low temperature environments. Collaborations between scientific ocean drilling scientists and engineers and NASA scientists/engineers might be fruitful and contribute to both improved seabed drilling on Earth and mars drilling and sample return. Mentions were made of NASA collaborations in Antarctica, including Ice Fin.

Breakout 2: Develop initiatives that include analogue sites for astrobiological applications for defining the limits on and existence of life

Background

The oceanic crust and seafloor hydrothermal systems have provided critical insights into key questions about the origin of life, as well as habitability and the limits of life on Earth and elsewhere. However, the key questions about the origin, evolution, and distribution of life on Earth remain unanswered. Scientific ocean drilling provides a critical window into these questions by enabling us to interrogate the factors that define the limits of life, and therefore habitable conditions, including temperature, pressure, pH, nutrients (CHNOPS), and energy (redox).

Our understanding of life on Earth and its limits is also critical to defining our search parameters for life elsewhere, including both scientific questions and technologies required to answer them. Our discovery of seafloor hydrothermal vents has underpinned much of our understanding of the potential habitability of other Ocean Worlds in the solar system, including Europa, Enceladus, and Titan, as well as potentially moons of Uranus and Neptune.

To address our understanding of our own uniqueness (or not) within the solar system, we require additional insight into the habitability of our own planet. Some of the potential investigations outlined below can use legacy core preserved from past ocean drilling. However, legacy drill core provides limited avenues to continue to explore these questions because only some core has been preserved in a way to preserve seafloor-hosted life, porewaters, and some organics indicative geochemical processes. One resource that may be critical to habitability investigations are cores stored in the Kochi Core Center, which has preserved samples at -20, -80, and -160°C (KCC; https://www.kochi-core.jp/en/iodp-curation/index.html). The KCC will be an important resource for exploring habitability. The rapid evolution of the biogeosciences and astrobiology as fields of study will require us to also pursue future ocean drilling to understand the origin, evolution, and distribution of life on Earth and elsewhere.

Potential Investigations

1) We still do not understand the true limits of life on Earth. Understanding where life does not exist (and perhaps cannot exist) is equally important to understanding how to detect life in extreme environments. Future drilling combined with ongoing biological technology developments will enable us to better understand the boundary conditions for life, which will provide insight into the origin and evolution of life on Earth as well as an understanding of the potential limits of life on other planetary bodies. Technology developments required to determine these limits in seafloor sediments and rocks will also aid in the development of instrumentation necessary to search for life elsewhere.
2) The seafloors of Ocean Worlds may not have focused hydrothermal venting, because these oceanic cores likely do not experience plate tectonics. Therefore, future investigations evaluating hydrothermal alteration processes in diffuse, off-axis vent fields will likely yield new and directly applicable insights into alteration of Ocean World seafloors and cores.
3) Future NASA investigations, including Mars Sample Return will evaluate returned samples to better understand the habitability and astrobiology potential of other worlds. Cores from previous IODP drilling investigations for which organic data exists may be used to evaluate how well organic signatures are preserved in returned samples, particularly those stored for an extended period of time. Moreover, use of these legacy drill cores can enable our understanding of "why some organics are preserved rather than consumed by life over geologic time scales", a critical question from the 2050 Science Framework.
4) Future investigations at both on-axis and off-axis active hydrothermal systems can provide insight into prebiotic chemical synthesis pathways that can enable a better understanding of organic chemical evolution, which may be an important habitability marker for other Ocean Worlds (Davila and Eigenbrode, 2024). This may be accomplished through scientific ocean drilling with a new drill ship or in coordination with NOAA sampling.
5) Spatially co-located cores drilled at different time points may provide insight into both spatial heterogeneity of life and life-related signatures, as well as what factors may

influence these distributions. These data are critical for evaluating both the distribution of life in the subsurface and the factors that influence this distribution. These data will also provide critical insight into how we target subsurface life during drilling missions on other worlds, including the Search For Life on Mars (Exploring Mars Together, 2023-2040).

6) Standard measurements made by NASA during missions and IODP during shipboard investigations do not necessarily align. One area in which new synergies may emerge is in the use of similar technologies and measurements between NASA missions and IODP cores. This would enable cross-divisional investigations and outcomes beyond what has been specifically outlined here. It may also yield new insights into new technologies and instrumentation required to advance the search for life and life-related chemistries in extreme environments on Earth and elsewhere.
7) Past work from the Chicxulub Impact Structure demonstrated that impact-induced geological interfaces are highly habitable environments even if the strata into which the impact occurred would be otherwise less habitable. However, past IODP drilling at the site was limited to the peak ring of the impact structure. Therefore, we do not know how impacts more broadly influence the distribution of habitable conditions. Understanding the role impacts play in habitability is essential for Mars and some Ocean Worlds where impacts may play a significant role in reshaping surface and subsurface habitability.
8) While we commonly think of habitability in terms of the origin, evolution, and distribution of microbial life, all life on Earth is dependent on their own set of habitable conditions, which are often more prescribed than microbial life. Earth's changing climate has implications for changes in large scale geochemical cycles impacting Earth's oceans and land masses. Scientific ocean drilling has provided critical insights into how Earth's climate has changed in the past, which is critical to understanding how our climate may change in response to both natural and anthropogenic inputs now and in the future. Future investigations may include finding means of linking future and past scientific ocean drilling data with satellite observations of sea surface temperatures, greenhouse gases, and other climate parameters to provide better predictions of how Earth's climate is changing and how that will impact macroscopic life on Earth.

Davila, A. and J. Eigenbrode (2024) Organic Chemical Evolution as Roadmap for Life Detection: Implications for Enceladus. AbSciCon Abstract.

Breakout 3: Develop initiatives that use terrestrial analogues studied or to be studied by ocean drilling to yield information on extraterrestrial volcanism

Background

Underpinning the habitability of a terrestrial planet is the geodynamical regime in which it operates. Earth-like planetary bodies that permit vigorous mantle convection and a brittle lithosphere may evolve to develop plate tectonics, which in turn enables climate regulation via carbon and water cycling between the interior of the planet and the surface or atmosphere. The efficient cooling of the Earth's interior that plate tectonics facilitates via extensive globally distributed magmatism (associated with mid-ocean ridges and subduction-related arc volcanism) ultimately helps drive thermochemical core convection that powers a global magnetic field. This field may shield Earth's atmosphere and surface from radiation and water loss over geological timescales.

In contrast, on the other terrestrial planets within our Solar System, the magmatic conduits for heat loss from the interior are largely limited to volcanism driven by the rise of hot and buoyant plumes of material initially sourced from deep within a planet's mantle towards the crust. As a result, the Moon, Mercury, and Mars developed one-plate stagnant lid regimes, while Venus may have evolved into an episodic lid regime that produced periodic catastrophic recycling of the crust on approximately billion-year timescales. Because these worlds lack plate tectonics, they are unable to maintain Earth-like cycling of carbon and water that could serve to stabilize the climate and preserve habitability.

Due to the lack of space missions that have returned samples from the other terrestrial planets within our Solar System, it is difficult to study the processes that shape what tectonic regime a planet eventually evolves into via methods other than theoretical modeling. Analog studies of terrestrial rocks that initially formed in geological settings reminiscent of these other worlds may help bridge this gap. Scientific ocean drilling has the potential to play a salient role in this effort.

Possible Investigations

The production and hydrothermal alteration of basaltic seafloor along mid-ocean ridges as well as oceanic islands and plateaus (particularly tholeiitic basalts) may be a good analog for understanding alteration of the ancient basaltic crust of Mars (McSween et al., 2009) or at the seafloors of ocean worlds such as Europa and Enceladus (Vance and Daswani, 2020). Seafloor hydrothermal environments on Earth support a diversity of microbial life by providing energy sources and nutrients required for chemosynthesis (e.g., Früh-Green et al., 2022). Targets for further exploration of these topics may include the Atlantis Massif (IODP Expeditions 357 and 399), Southwest Indian Ridge (IODP Expedition 360), and the Gakkel Ridge (Arctic Mid-Ocean Ridge Expedition, 2001).

The seafloor preserves an extensive record of over 100 million years of plume volcanism within seamount chains (hotspot tracks). Many hotspots are sourced from the edges of the Pacific and African Large Low Shear Velocity Provinces (LLSVPs), which may represent thermal or compositional anomalies within the deep Earth mantle. The origin of the LLSVPs and, in turn, terrestrial mantle plumes, remains enigmatic. It has been proposed that LLSVPs represent the remnants of subducted oceanic crust that have sunk to near the core-mantle boundary (Niu, 2018). Alternatively, the LLSVPs may represent relics of Theia, the primordial impactor which collided with Earth and led to the formation of the Moon by the coalescence of the debris produced by the impact (Yuan et al., 2023). Geochemical studies of plume-derived basalts to search for impactor contributions (versus solely terrestrial origin components) and compositional comparisons between volcanic rocks from the Pacific LLSVP, African LLSVP, and plume-derived volcanics not associated with LLSVPs may enable discriminating between the aforementioned hypotheses.

Mantle plumes (sourced from the LLSVPs and otherwise) may have played a role in the initiation of rifting, subduction, and plate tectonics on the early Earth. While the other terrestrial planets in our solar system do not exhibit plate tectonics, there is evidence of rifting and subduction on other worlds. Interaction of mantle plumes with Earth's lithosphere may contribute to the formation of rifts (Brune et al., 2023). Plume-influenced rifting may be responsible for the formation of features such as the ringlike coronae structures on Venus (Gülcher et al., 2020; Smrekar et al., 2023) and the Valles Marineris rift on Mars (Andrews-Hanna, 2012). Reasons for the cessation of rifting on Earth are also enigmatic (Brune et al., 2023). In addition, plumes may have played a role in the onset of subduction and plate tectonics on the early Earth (Gerya et al., 2015). Similar plume-induced subduction appears to have occurred on Venus as well (Davaille et al., 2017), but did not advance to global scale plate tectonics there (Chen et al., 2022). On Earth's seafloor, analog settings to explore complex tectonic settings that explore plume evolution, rifting (both initiation and failure), plume-ridge interactions, and plume-driven subduction processes include the Magellan Rise oceanic plateau (DSDP Legs 7 and 61), the North Fiji and Lau back-arc basin (ODP Legs 134 and 135), the Caribbean and offshore northwest South America (Whattam and Stern, 2015) the Cascadia subduction zone (Stern and Dumitru, 2019), the Walvis Ridge (IODP Expedition 391/397T), and the South China Sea (Li et al., 2020).

Finally, we discuss the origin of crustal differentiation (i.e., the segregation of a planetary crust into lower lying mafic to ultramafic rocks such as those on the Earth's seafloor and higher topography felsic rocks such as those which make up the Earth's continents). The primordial crusts of terrestrial planets were likely of basaltic composition. The formation of massive felsic crust is thought to require recycling hydrated basaltic crust into the Earth's mantle, remelting of these materials, and the resulting magmatism (Arndt, 2013). Felsic magmatism may have occurred within wider basaltic terranes on both Mars and Venus early in the histories of these planets. In the case of Mars, felsic rocks have been observed at (Sautter et al., 2015). On Venus, ancient deformed topographic plateaus called tesserae may be the product of felsic magmatism (Gilmore et al. 2017), though this interpretation is debated. While rare, localized felsic magmatism and resulting volcanism does occur in certain locations on Earth's seafloor, including the Iceland rift zone (Martin and Sigmarsson, 2010), the Caribbean Plateau, the Izu-Bonin-Mariana forearc (IODP Expedition 352), and the Ontong Java Plateau (ODP Leg 192). Scientific ocean drilling expeditions aimed at understanding the formation mechanisms of these and similar regions (e.g., intra-oceanic arc magmatism) may bear lessons for the origins of similar features on other worlds.

Breakout 4: Develop initiatives that use terrestrial analogues that should be studied by ocean drilling to yield information on the impact cratering processes and hazards

Background

Impact cratering is a geologic and biologic process that shapes planetary surfaces, unroofs deeper lithologies, and generate hydrothermal habitats that can sustain chemosynthetic life. Impacts are also a geologic hazard alongside earthquakes and volcanoes. All three can produce tsunami and landslides, and both impact and volcanic processes can perturb atmospheric chemistry and opacity. These active planetary and extraplanetary processes are best understood through record of past events and monitoring of active processes. Planetary exploration off Earth benefits from the remarkable remote sensing resolution and coverage on planets such as Mars and the Moon, whereas research into the geologic record on Earth has the pronounced advantage of deep subsurface images and scientific drill cores and borehole logs at the kilometer scale. Fundamental advances in our understanding of impacts and geological hazards are possible through leveraging the particular advantages of both terrestrial and planetary exploration.

Possible Investigations

There is a clear need for new scientific drilling, logging, and borehole monitoring to answer critical questions in both hazards and impact processes. For instance, drilling into the Chicxulub impact structure in Mexico would allow recovery of an intact, impact melt sheet providing insights into melt differentiation, planetary crustal evolution, and hydrothermal habitats (Gulick, 2024). \In particular, there are links between the search for extraterrestrial life and drilling impact craters on Earth. For instance, both the Chesapeake Bay impact structure and Chicxulub host extant microbial life that are remnant populations of thermophilic organisms still inhabiting impact crater materials 10s of millions year post-impact (Cockell et al., 2021a, 2021b). At Chicxulub, DNA extracted from the International Ocean Discovery Program/International Continental Scientific Drilling Program core immediately after drilling show a remarkably diverse ecosystem existed within the post-impact hydrothermal system (Quraish et al., 2024). Clear research directions are to investigate the fluid-rock interactions through direct sampling investigations of terrestrial craters including Chicxulub that drive these ecosystems to consider likely habitats or even origin of life scenarios for both early Earth and other worlds.

Geohazards can be viewed from space using Earth Observing Systems demonstrating how landscapes change during earthquakes, tsunami, landslides, and volcanic events. However, there is a great need for more predictive tools. Recent experiments and analyses in scientific boreholes have shown the remarkable resolution and sensitivity of installed pressure sensors. Thus, a clear future investigation would be coupled monitoring for earthquake and landslide hazards using borehole installed sensors with high resolution (temporal and spatial) satellite observation of tectonically active areas. Pushing the temporal resolution of pore pressure changes in advance of, during and after events with structure for motion studies, InSAR, and GNSS observations of permanent deformation allow for insight into fundamental physics of hazards on Earth.

Legacy scientific drill cores from the last 50 years of National Science Foundation (and its partners) funded expeditions are an opportunity for ground truth of NASA's Earth Science division funded remote sensing data and models as well as NASA's Planetary Science Division studies of specific volcanic, impact, and hydrothermal processes including the search for life. Some key examples include: 1) cataloging the tephra record for understanding terrestrial volcanic hazards, 2) researching the submarine turbidite records for studying earthquakes and storms, and 3) bringing to bear NASA style instruments on IODP cores such as hyperspectral data collection over terrestrial analogs (e.g., impact crater materials).

Envisioning a NASA and NSF partnership

For many critical scientific challenges, a partnership between NASA and NSF using scientific drilling and cores could be a game changer. For instance, a mission to Earth could be proposed investigating fluid alteration of geologic materials particularly in hydrothermal systems to serve as an analog for potential astrobiologic habitats and to better understand specific planetary datasets like CRISM on Mars. Future scientific ocean drilling expeditions and analyses of existing data could be guided to directly address key NASA questions including determining the role and fingerprints of life in the rock record. In terms of studying geohazards for society, an opportunity exists to use NASA data such as the upcoming global landslide coverage maps to identify key offshore locations to investigate physics of hazards and consider event based studies (paleoseismology, tempestology, etc) to establish probabilities, dependencies, and triggers. For instance, expeditions could target drill locations and leverage legacy cores with extreme pressure and temperature conditions as analogs for metamorphic and biogeochemical processes. As planning for a new U.S. scientific drill ship proceeds there is an opportunity to build in capability to test technology readiness for NASA mission instruments taking advantage of the range of pressures and temperatures encountered in scientific drilling.

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IN PERSON

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Elizabeth	Sibert	Woods Hole Oceanographic Institution	Assistant Professor
Ginger	Sigmon	University of Notre Dame	Other: University Staff
Joann	Stock	California Institute of Technology	Professor
Leonid	Stolov	Honeybee Robotics	Graduate Student
Joseph	Stoner	Oregon State University	Professor
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Kaustubh	Thirumalai	University of Arizona	Assistant Professor
Michael	Thorpe	UMD, NASA GSFC, CRESST	Research Faculty
Sonia	Tikoo	Stanford University	Assistant Professor
Man-Yin	Tsang	University of Washington	Post-Doctoral Fellow
Natalia	Varela	University of Virginia	Post-Doctoral Fellow
Christina	Verhagen	Montclair State University	Post-Doctoral Fellow
James	Walker	Southwest Research Institute	Other: Research
Mike	Weber	University of Bonn	Professor
Charles	Wheat	University of Alaska Fairbanks	Research Faculty
Anastasia	Yanchilina	California Institute of Technology	Post-Doctoral Fellow

Workshop Participants

VIRTUAL

First Name	Last Name	Organization/Institution	Career Stage
Andrea	Adams	Scripps Institution of Oceanography, UCSD	Post-Doctoral Fellow
Barbara	Balestra	American University	Other: Senior Professorial Lecturer
Ruth	Bamford	STFC RAL Space	Other: Senior scientist
Laurie	Barge	NASA JPL	Other: Research Scientist
Chiara	Borrelli	University of Rochester	Assistant Professor
William	Brazelton	University of Utah	Associate Professor
Raquel	Bryant	Wesleyan University	Assistant Professor
Haley	Cabaniss	College of Charleston	Assistant Professor
Saebyul	Choe	Columbia University - LDEO	Other: Early Career
Kristin	Dickerson	UC Santa Cruz	Graduate Student
Catherine	Fischer	BAE Systems, Inc.	Other: Industry
Julie	Huber	WHOI	Professor
Masao	IWAI	KCC/MaCRI, Kochi University	Professor
Alia	Jasim	Jacobs at NASA JSC	Other: Manager
Pamela	Kempton	Kansas State University	Professor
Hiroko	Kitajima	Texas A&M University	Associate Professor
Ethan	Lopes	Stanford University	Graduate Student
Charna	Meth	Scripps Institution of Oceanography	Other: Manager
Sohsuke	Ohno	Chiba Institute of Technology	Research Faculty
Maya	Pincus	U.S. Science Support Program	Other: Education and Outreach
Erika	Rivera	University of Nevada Las Vegas	Graduate Student
Derek	Sawyer	The Ohio State University	Associate Professor
Gavin A.	Schmidt	NASA Goddard Institute (GISS)	Other: Division Chief
Jesse	Scholpp	University of Tennessee	Graduate Student
Jacob	Setera	University of Texas at El Paso - Jacobs JETS - NASA JSC	Research Faculty
Elizabeth	Spiers	University of Texas at Austin	Research Faculty
Steven	Vance	Jet Propulsion Laboratory, California Institute of Technology	Research Faculty
Ryan	Watkins	NASA	Other: Government Employee
Thomas	Wiersberg	ICDP Int. Continental Scientific Drilling Program	Research Faculty
Nanping	Wu	Chinese Academy of Sciences	Professor
Xao	Zhang	University of Science and Technology of China	Graduate Student
Xinyuan	Zheng	University of Minnesota	Assistant Professor