Scientific Ocean Drilling Beyond 2023

Science Framework Working Group

Columbia University, New York, U.S.A.

July 23-24, 2019

Delegates (19)

Anthony Koppers **(Chair)**	Oregon State University	U.S.
Cristiano Chiessi	University of São Paulo	Brazil
Gail Christeson	University of Texas at Austin	U.S.
Mike Coffin	University of Tasmania	Australia (ANZIC)
Rosalind Coggon	University of Southampton	U.K. (ECORD)
Stuart Henrys	GNS Science	N.Z. (ANZIC)
Yoon-Mi Kim	KIGAM	Korea
Iona McIntosh	JAMSTEC	Japan
Katsuyoshi Michibayashi	Nagoya University	Japan
Yuki Morono	KCC, JAMSTEC	Japan
Antony Morris	University of Plymouth	U.K. (ECORD)
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Dhananjai Pandey	NCPOR	India
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Others (7)

Jamie Allan	National Science Foundation	NSF IODP
Carl Brenner	Lamont-Doherty Earth Obs.	USSSP
Beth Christensen	Rowan University	U.S.
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Maureen Raymo	Lamont-Doherty Earth Obs.	USSSP
Sanny Saito	$MarE^3$, JAMSTEC	J-DESC
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Scientific Ocean Drilling Beyond 2023
NEW SCIENCE FRAMEWORK and ROADMAP

July 23-24, 2019
Columbia University, New York, USA

Preamble on Planning Process

Six international planning workshops were organized in September 2018, and April-May and August 2019 by IODP-India, J-DESC, ECORD, ANZIC, USSSP, and IODP-China. More than 650 scientific ocean drilling scientists participated, including about 30% female and 40% early- to mid-career scientists. The results from those workshops were presented and discussed on July 23-24 during the first meeting of the *Science Framework Working Group* at Columbia University. In this document, the 19 scientist delegates, representing all IODP member countries and consortia, including IODP-Brazil and IODP-Korea, are providing a consensus proposal for a new science framework in support of future *Scientific Ocean Drilling Beyond 2023*. From August 6-26, a draft of this proposal was posted on IODP.org for commenting by the IODP community, and based on constructive community input, a revised proposal was presented to and endorsed by the IODP Forum during its September 2019 meeting in Osaka, Japan.

Framework for Scientific Ocean Drilling through 2050

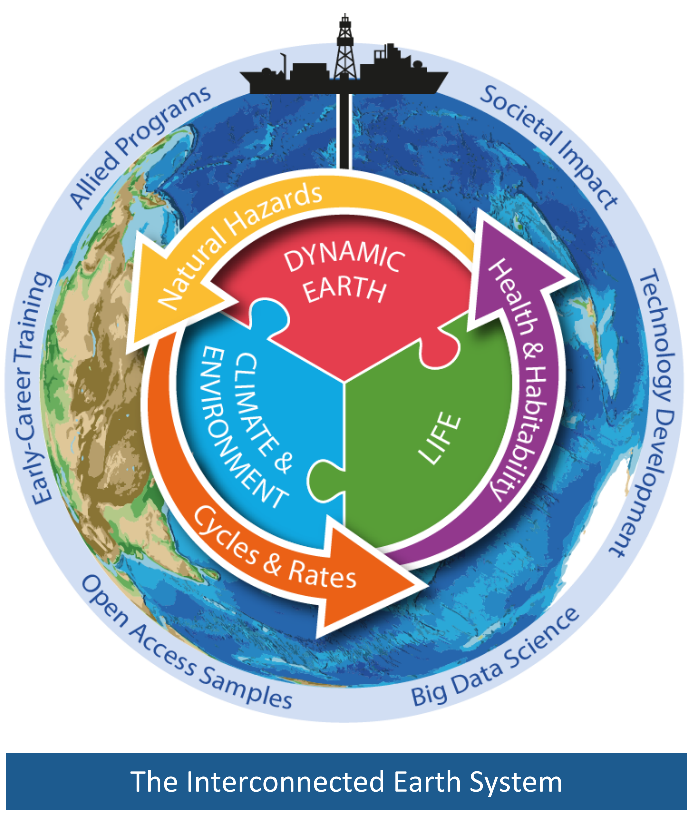
A. Science Framework Title and Vision Statement

Exploring Earth by Scientific Ocean Drilling

To explore Earth system processes and feedbacks through geological time with scientific ocean drilling.

B. Who We Are and What We Do

- We are an international scientific community pioneering large-scale, interdisciplinary research in the subseafloor of the world's oceans.
- We explore Earth systems in places that can only be accessed and understood through scientific ocean drilling.
- We probe past time to reveal the interactions among the oceans, Earth, life, climate, and society.
- We communicate the results of our research and their societal impact to the public.



Infographic illustrating the interconnected nature of the Earth System that we seek to understand through scientific ocean drilling.

C. Overall Framework Structure and Review Cycle

The new science framework has a long-term, greater than 25-year outlook, ending in 2050. This allows for new foundational approaches ranging our research efforts far into the mid-21st century. The major objective of scientific ocean drilling through 2050 is to advance our understanding of Earth as an interconnected system through societally relevant long-term research endeavors.

The new framework centers around eight core ***Strategic Objectives*** and five ***Flagship Initiatives***. The *Strategic Objectives* are foundational research areas that are open-ended to encourage innovation and new discoveries through the mid-21st century. This distant time horizon of the science framework allows for the implementation of *Flagship Initiatives,* which comprise coordinated, sustained scientific ocean drilling endeavors that cross-cut multiple *Strategic Objectives* and require interdisciplinary efforts over several decades to address specific societal challenges. Successes in future scientific ocean drilling are intrinsically linked with: effective communication of our results to the public and policy makers; capacity building within the international scientific community; training the next generation of researchers; access to big data science; open access to samples and data; and new developments in technology. This new framework will demand an even stronger interdisciplinarity in scientific ocean drilling, enhanced by advanced collaborations with external partner organizations. It will also show how our science informs society, while addressing foundational Earth system research questions.

All *Strategic Objectives* and *Flagship Initiatives* will evolve through bottom-up proposal submission between now and 2050. Progress toward the new science framework will be assessed with a periodic five-year programmatic review cycle. This allows for intermediate adjustments or additions to the *Strategic Objectives* and *Flagship Initiatives*.

D. Strategic Objectives

The new science framework emphasizes interconnected research that links science disciplines in order to address societally critical paradigms. Through this approach, scientific ocean drilling will make new discoveries and deepen our understanding of Earth's ***Natural Hazards***, ***Cycles and Rates of Change***, and ***Health and Habitability***, each of which can only be addressed by researching the cross-cutting pathways among the broad research areas of the ***Dynamic Earth***, ***Climate and Environment***, and ***Life***.

Strategic Objectives form the core of scientific ocean drilling through 2050, and are described on the next two pages with descriptive tag lines and example research topics that resonated across all six international planning meetings. Note that these examples are sub-bulleted here to illustrate the scope and multidisciplinary nature of the *Strategic Objectives* and may serve as topics in the text of the final Science Framework. The *Strategic Objectives* listed have been designed to be open-ended, to encourage innovation and new discoveries and allow new Earth system science to emerge through the bottom-up proposal writing and review process.

- **Habitability on Earth**
  Defining the conditions for and role of life in the sub-seafloor
  - How organisms live, interact, and die beneath the seafloor
  - How microbes interact with rocks and fluids
  - Rules of life and how these both govern and are affected by Earth processes
  - Explore the origins of life on Earth
- **Feedbacks in the Earth System**
  Constraining the processes that operate between oceans, Earth, life, and climate
  - Feedbacks among life, the rock cycle, crustal properties, mantle dynamics, and the core
  - Active tectonics and their impact on oceanic and atmospheric circulation and chemistry
  - Solar, climate, and tectonic factors that govern ocean circulation and global ecosystems
  - How subseafloor life and Earth's environment shape the cycling of energy and mass
  - Controls on the biogeography of microbial communities within the oceanic crust
- **Earth's Climate Factory**
  Examining the ice sheets, global ocean circulation, the monsoon, and sea level under different climate states
  - How mechanisms and rates of sea level change vary through time
  - Earth events and processes that initiate ice sheet mass loss and growth
  - Evolution of polar and sub-polar land and ocean systems under different climate states
  - Shifting oceanic circulation patterns as a major climate change trigger
  - Climate teleconnections between different regions and circulation systems
  - How the overall cryosphere, including sea ice, permafrost and marine gas hydrates, responded to climate change in the past
- **Earth's Past as a Spotlight on the Future**
  Elucidating our future climate and environment using marine records of Earth's history
  - Marine and terrestrial ecosystem dynamics in the greenhouse worlds
  - The climatic, biological, and chemical characteristics of an ice-free planet
  - Records of human impacts on the Earth system
  - Evolution of ocean health over geologic time in the lead up to the Anthropocene
- **Tipping Points in Earth's History**
  Identifying the causes, scales, and consequences of climatic and environmental perturbations
  - Timescales and patterns of ecosystem recovery after major disturbances
  - Effects of catastrophic environmental perturbations that shaped the history of life

  - Formation of large igneous provinces and their environmental and biosphere impacts
  - Evolution of rainfall and aridity patterns and their causes
  - Consequences of reaching different tipping points in the climate system

- **The Life Cycle of Earth's Tectonic Plates**
  Investigating the generation, aging, and death of lithospheric plates and their impacts on the Earth system
  - Causes and processes of plate boundary formation and destruction, their temporal evolution, and implications for geohazards
  - Impact of spreading rate, tectonic setting, intra-plate volcanism, and hydrothermal aging on lithosphere architecture
  - Hydrothermal and microbiological interactions among plates and the mantle, oceans, and atmosphere, with impacts on geochemical cycles, resources, and life
  - Mechanisms of back-arc formation, ophiolite emplacement, and continental growth
  - Influences of tectonic events in the evolution of the oceanographic patterns
  - Relationship of the lithospheric cycle to the formation of Earth's deep interior large low shear-wave velocity provinces and the formation of mantle plumes

- **Global Cycles of Water, Energy and Matter**
  Determining the nature, magnitude and impacts of water, energy and matter transfer in the Earth system
  - Processes that influence the occurrence, timing, and magnitude of volcanism
  - Origin and impacts of geomagnetic reversals, secular variation, and large-scale anomaly features such as the South Atlantic Anomaly on the Earth system
  - Evolution of subsurface fluids and influences on life, climate, and geochemical cycles
  - Deep carbon storage in the subseafloor and mantle
  - Understanding metal budgets and cycles in the subseafloor environment
  - Evaporitic ocean basins and their role in Earth history
  - Fresh water under the ocean floor

- **Natural Hazards Impacting Society**
  Researching and monitoring natural hazards in the marine environment
  - Rates and amplitudes of natural hazards in the past
  - Impacts of natural hazards on the climate, environment, and society, including earthquakes, tsunami, explosive volcanism, hydrate destabilization, submarine landslides, asteroid impacts, draughts, and storm surges
  - Feedbacks among sea level, climate, volcanism, and tectonics
  - Physical processes controlling slip behavior at the subduction interface
  - Improving hazard assessment guided by monitoring

E. Flagship Initiatives

The next scientific ocean drilling science framework will have a distant time horizon in the mid-21st century to allow for the implementation of *Flagship Initiatives* requiring sustained, long-term research efforts. These *Flagship Initiatives* are expected to comprise multi-expedition foundational scientific ocean drilling endeavors that cross-cut multiple *Strategic Objectives* and require interdisciplinary efforts over 10-20-year time periods. These *Flagship Initiatives* may in particular help address societal challenges.

- **Ground-truthing Future Climate Change**

Climate change is one of the greatest challenges confronting modern society. State-of-the art computer models allow future climate projection, but these models are imperfect and require independent validation. Climate records from across the globe, capturing recent and deep geological time, are essential to understand the global feedbacks that operate in both warmer and colder climate states than present. This information is needed to test, train, and improve global Earth system models, the outputs of which guide international agreements on tackling climate change. Scientific ocean drilling is uniquely positioned to provide these critical ground-truthing data sets over the next decades. In particular, drilling can directly show us the dynamics of past ice-free poles, the consequences of large magnitude injection of greenhouse gases into the biosphere, and behavior of marine and terrestrial environments before the large-scale erosion and geochemical perturbations of humans on Earth systems. With high-resolution, complete recovery coring, we can also assess the importance of tipping points in the Earth system that can affect society, and assess their rates and magnitude of potential impact. To accomplish the goals of this *Flagship Initiative*, science community members may for example propose future coordinated approaches aimed at collecting such high-resolution, complete-recovery cores along transects and grids. North-south transects across the ocean basins, from the poles to the tropics, and high-density grids in the polar regions, will provide a fundamental contribution in positioning society for future climate change.

- **Probing the Deep Earth**

The quest to achieve a complete penetration of Earth’s oceanic crust through the Moho discontinuity has been a long-term aspiration and compelling motivation for scientific ocean drilling, but has been challenging and elusive due to technological limitations and long-range scheduling constraints. Deep drilling is required to understand the formation and evolution of two-thirds of our planet’s surface, the fundamental nature of Earth’s deep interior and its geodynamic behaviour, and the interrelationships between geological, biogeochemical and climate cycles in the wider Earth system. The greater than 25-year outlook of the new science framework will allow the scientific ocean drilling community to adopt a staged approach to reaching the Earth's upper mantle, via a series of interconnected, ambitious expeditions that will take full advantage of emerging 21st century drilling technologies.

- **Diagnosing Ocean Health**

Through scientific ocean drilling, we can explore past interactions between life and Earth's environment leading up to the Anthropocene. The health of our oceans is currently seeing growing impacts of long-lasting human-made materials, gases, and industrial pollutants that contribute to anthropogenic climate change, global ocean acidification, and the expansion of oxygen minimum and dead zones. Still, very little is known about the impact of these contaminants on our oceans and its ecosystem. Geologically-induced perturbations, such as past global warming and cooling, increased global volcanism, oceanic anoxic events, asteroid impacts, and mass extinction events, provide vital instances in the history of our planet when the entire interconnected system of the oceans, Earth, and life underwent a significant readjustment. A concerted effort in future scientific ocean drilling should provide access to comprehensive marine records that contain the pre-Anthropocene baselines and analogs to ocean acidification, deoxygenation, nutrient inputs, and rapid temperature change that could be used to inform the impact of today's ongoing environmental changes and perturbations.

- **Exploring Life and Its Origin**

Scientific ocean drilling has revealed that microbial organisms are present and metabolically-active at multi-kilometer depths in both sediment and ocean crust. Deep biosphere research on these newly discovered lines of Archaea, Bacteria, Eukarya, and viruses remains in its infancy, and most of the deep biosphere is yet to be explored and understood. Scientific ocean drilling through 2050 will allow us to capitalize on new and emerging techniques in this rapidly developing field to explore the fundamentals of life, and its persistence, resilience, interactions and diversity through time. A systematic study of life in the subseafloor throughout the world's ocean basins can provide a powerful approach to unraveling species origin, evolution and extinction, to understanding life on the early Earth, and to characterizing and searching for habitable environments in the universe.

- **Assessing Tsunami and Earthquake Hazards to Society**

The most catastrophic event in recent history was the magnitude 9.1 Sumatra 2004 Boxing Day earthquake and tsunami that killed more than 230,000 people. Natural hazards, including such mega-scale earthquakes, are prominent targets for scientific ocean drilling, because it remains the only tool capable of directly accessing the source regions of these devastating sub-seafloor events. Revolutions in instrument development are enabling us to detect and monitor such natural hazards in novel ways and ever-greater detail. The time is ripe for ambitious, long-term drilling strategies to investigate seismic slip in a range of global fault environments, and through complete earthquake cycles, in order to aid future earthquake and tsunami risk assessments and projections.

F. Relation to Allied Programs

The *Strategic Objectives* and *Flagship Initiatives* that underpin scientific ocean drilling through 2050 aim to study Earth as an integrated and interconnected system of processes and feedbacks. The science priorities laid out in this new science framework strongly align and complement research initiatives in allied research programs, such as the International Continental Scientific Drilling Program (ICDP) and the National Aeronautics and Space Administration (NASA) and other space agencies around the world (ESA, JAXA, CNSA, ISRO, ASA).

The strong alignment is evident in the five science themes of the current ICDP science plan, which comprises ***Active Faults and Earthquakes***, ***Heat and Mass Transfer***, ***Global Cycles and Environmental Change***, the ***Hidden Biosphere***, and ***Cataclysmic Events***, and, for example, is expressed under NASA's Strategic Objective 1.1 ***Under-stand the Sun, Earth, Solar System, and Universe***, which includes the goal of ***Searching for Life Elsewhere***. Within the new era of scientific ocean drilling we will capitalize on new opportunities afforded by parallel coordinated research efforts within ICDP and the various national space agencies. This will allow for critical new science growth in those related research areas.

G. Data Science and Analytics

Progress toward addressing the eight *Strategic Objectives* and the five *Flagship Initiatives* increasingly and critically depends on the integration of data sciences in scientific ocean drilling. For example, ground-truthing future climate change based on IPCC climate projections will require data aggregation from hundreds of globally-distributed sites acquired over many scientific ocean drilling expeditions. These analyses are unique, as only scientific ocean drilling is able to acquire data covering large-scale geographic areas with information going back deep into geological time, providing comprehensive baseline data from time intervals under various global climate states. In a similar fashion, exploring life and its origin on Earth would require the building of a subseafloor microbial databank to allow for methodical progress in this *Flagship Initiative*. By focusing on FAIR (Findable, Accessible, Interoperable, Reusable) data practices, future scientific ocean drilling will allow scientists to focus on the linkages among data types that are critical for meeting our *Strategic Objectives*.

H. Technology, Monitoring and Observatories

Future developments in technology, monitoring, and observatory science will underpin our ability to achieve the core *Strategic Objectives* and implement the *Flagship Initiatives*. For example, borehole instrumentation enables investigation and monitoring of the earthquake cycle in locations only accessible through ocean drilling. In addition, deep biosphere exploration, and the discovery of life and its diversity, is only made possible by ongoing developments in coring technologies, sample processing techniques and analytical capabilities. Over the next decades, progress in scientific ocean drilling will continue to be uniquely driven by, and drive, new technology developments.

I. Societal Relevance and Broader Impacts

Societal relevance is integral to all scientific ocean drilling. This is strongly apparent in the five *Flagship Initiatives* that are built upon the eight *Strategic Objectives* in the new science framework. Natural hazards, and the health and habitability of Earth and its oceans, are cross-cutting themes central to the well-being of global society. For example, ground-truthing future climate change will provide critical information to all coastal communities threatened by a projected average sea level rise of one or more meters over the coming centuries. Studies of aridity, rain, and storm patterns; the hazards resulting from earthquakes, tsunamis, volcanoes, landslides, asteroid impacts, and cyclones; and the origin and sustainability of life on our planet, all contribute to the prediction and risk assessment of future global threats to society, as well as a more profound understanding of the Earth system in which we live.

It will be critical to convey the wealth of information gained through scientific ocean drilling to the public across the globe. Outreach and public engagement through education initiatives in member countries and a consistent media presence, that reach and engage a broader audience, will need to capitalize on the extraordinary scientific ocean drilling *Strategic Objectives* and *Flagship Initiatives*. The scientific ocean drilling community must remain deeply dedicated to increasing public awareness and understanding of the Earth we all inhabit. In addition, training of early career scientists and continuing to redress the underrepresentation of women in science, technology, engineering and mathematics (STEM) will be critical aspects in the future scientific ocean drilling program.

Roadmap Until June 2020

The new science framework in support of scientific ocean drilling through 2050 will be published in ***June 2020*** based on agreement amongst the 19 international delegates of this science framework working group and the IODP Forum. This early publication date will allow IODP partners to start to develop a new program for international collaboration in scientific ocean drilling beyond 2032, including planning for the provision of future platforms.

All framework documents will be produced as online-only high-end PDF files and are made available on IODP.org for free access and downloading. The science framework will be a ***living document***, which, under the auspices of the IODP Forum, may be updated based on five-year programmatic reviews.

A. Online Products

- **Full Version of International Science Framework:** ~70-page document, written for the overall scientific ocean drilling community, including a total of 13 chapters to cover each of the *Strategic Objectives* and *Flagship Initiatives*. Each chapter will be two (*Flagship Initiatives*) or four pages (*Strategic Objectives*) long, and will comprise half infographics, half text. In addition, this science framework document will include an executive summary, table of contents, an introduction, and in total four extra contributions summarizing connections to other allied programs, technology development, education and broader impacts, and data.

- **Summary of International Science Framework:** ~4-8-page document, written in layman's language for society at large.
- **Pamphlet of International Science Framework:** 2-page document, written in language appropriate for funding agencies.
- **National Science Framework Versions, Executive Summaries and Pamphlets:** depending on needs, individual Program Member Offices (PMOs) may opt to produce translated versions of the international science framework document, executive summary, and pamphlet, and create derived variations tailored to demands in their countries and consortia.

B. Timeline and Deadlines

DEADLINE	ACTION	DETAILS
11 Sept 2019	IODP Forum discussed and endorsed new science framework and roadmap	• Forum endorsed new science framework and roadmap • Forum selected science framework writing team lead editor **Anthony Koppers** (Oregon State University, USA) and deputy lead editor **Rosalind Coggon** (University of Southampton, United Kingdom) • Forum agreed to number of writers, writer profiles, charge • Forum endorsed online science framework to be produced by June 2020
19 Sept 2019	Invitations go out to writing team and external reviewers	• Science framework writers accept by 26 Sept 2019 • External reviewers accept by 26 Sept 2019
3 Oct 2019	First Zoom meeting science framework writing team	• Laying out charge to science framework writing team • Assignments for writing chapters
1 Nov 2019	First ***internal*** draft due for review by science framework working group and external reviewers on a chapter-by-chapter basis	
1 Dec 2019	Second ***internal*** draft due for review by science framework working group and external reviewers on a chapter-by-chapter basis	
8 Dec 2019	Pre-AGU meeting for science framework working group and writing team	
11 Dec 2019	AGU Townhall	• Presentation of new science framework and roadmap • Introduction of working group and writing team
15 Jan 2020	Final ***internal*** draft due	

22 Jan 2020	Posting ***public*** draft ***version 1*** online at IODP.org	• Community gets 3 weeks for commenting • Science framework writing team gets 4 weeks for updating the science framework documents
11 Mar 2020	Posting ***public*** draft ***version 2*** online at IODP.org	• Community gets 2 weeks for commenting • External reviewers get 2 weeks for reviewing the entire version of the science framework • Science framework writing team gets 3 weeks for updating the science framework documents
22 Apr 2020	Final version presented to science framework working group and the IODP Forum for endorsement	
30 Apr 2020	Final version to be produced	
June 2020	Publication of new science framework	

C. Science Framework Writing Team

Charge: The science framework writing team will write the science framework adding details to the structure outlined above and ensuring that the intent of the *Strategic Objectives* and *Flagship Initiatives* is maintained. They will write toward a broad audience resulting in mostly jargon-free chapters, which will be professionally illustrated, to elevate the excitement in our new approaches. They will emphasize where we have excelled in the past by highlighting key science successes and the advances that can be made only through future scientific ocean drilling efforts. They will work effectively together as well as with a team of science writers and illustrators.

Make Up: All authors of the science framework will be selected based on their expertise and active involvement with one or more of the six international planning meetings; this writing team will contain some authors who also are members of the science framework working group. A large number of nominations for the science framework writing team were provided by the science framework working group and the IODP program member offices. The final selection will be based on the skill set and expertise required to fulfill the charge and produce an insightful, visionary science framework. Preference will be given to early- to mid-career scientists where possible. The writing team will be assembled by the appointed lead editors.

Writers: In addition to the lead editors, in total 16 writers will be invited, who will principally work in teams of two on two related *Strategic Objectives* and/or *Flagship Initiatives*. Each writer will be assigned a primary chapter, based on the best-possible expertise fit, and will act as a secondary author on one or more other chapters. The writing assignments are highly focused, whereby each writer will be responsible for creating 4 pages as a primary author only, and he/she would co-write another 4-8 pages as a secondary author. A subset of the writing team will be tasked with acting as authors on the supporting chapters, including outreach and broader impacts. The writers will be named (with affiliation) in the final science framework document.

Lead Editors: The writing team will be coordinated by lead editor **Anthony Koppers** (Oregon State University, USA) and deputy lead editor **Rosalind Coggon** (University of Southampton, United Kingdom). They also are responsible as primary authors for writing the executive summary, the introduction, and all supporting features and boxes.

D. Science Framework Working Group

Charge: The science framework working group has four tasks: (1) providing guidance to the writers as guardians of the science framework vision; (2) reviewing the science framework drafts; (3) endorsing in conjunction with the IODP Forum the final science framework; and (4) acting as liaisons with the IODP science community in their PMO countries and consortia.

Make Up: The science framework working group comprises scientists representing all IODP member countries and consortia. There will be some overlap in the science framework working and writing groups. The chair of the working group also functions as the lead editor of the writing group; the deputy lead editor also is a delegate of the working group; and some of the other delegates may be invited as science framework writers, as indicated above. This will provide efficiencies in communication between both groups, required because of the contracted time line ending in June 2020.

Delegates: The 19 delegates of the science framework working group, who were nominated by their PMOs following the international planning workshops, are listed on the title page of this framework document.

E. Review and Commenting

Community Review: As shown in the timeline table, the wider scientific ocean drilling community will have two opportunities to comment on the science framework, in January and March 2020; earlier drafts will be reviewed by the science framework working group, as well as by a large group of external reviewers who will be involved from the initial draft writing stage until the publication of the science framework.

External Reviewers: For each *Strategic Objective* or *Flagship Initiative* there will be two framework writers, who will be paired with a group of two to three external reviewers. The writers will work closely with their assigned reviewers from the early stages, informally, but also when draft versions are made available to the science framework working group in November and December 2019. In addition, this group of 21 external reviewers will be tasked by reviewing the ***entire version*** of the new science framework in March 2020. The external reviewers will be named (with affiliation) in the final science framework document.