Toward a Strategic Plan for U.S. Continental Scientific Drilling: Into the New Decade


DOSECC WORKSHOP PUBLICATION 3
Front cover: DEM of the Snake River Plain, showing the Kimama, Kimberly, and Mountain Home drilling sites. The eastern Snake River Plain has subsided under the weight of a mafic sill at depth, while the western portion is a tectonic basin. Above: drilling at Mountain Home Air Force base, where temperatures of 160°C were encountered at 1821.5 m, suggesting geothermal resources at depth.

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TOWARD A STRATEGIC PLAN FOR U.S. CONTINENTAL SCIENTIFIC DRILLING: INTO A NEW DECADE

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EXECUTIVE SUMMARY

As societies around the world seek an economic balance between environmental and energy demands while planning for a wide range of natural hazards, the need for subsurface information about our planet has never been greater (NRC, 2011, 2012). DOSECC\(^1\) annual workshops in 2009 and 2010 produced the background narrative to justify a new interdisciplinary consortium of research scientists who could leverage funds more effectively across national and international interests in the geosciences. The DOSECC workshop held May 23–24, 2011 in Arlington, Virginia, described here, focused on the next phase: producing a vision of how the United States, under the auspices of the National Science Foundation and other federal agencies, could recapture its leadership role in promoting scientific drilling as a critical tool for Earth scientists as they grapple with major societal issues. To that end, the workshop laid out the initial architecture for a U.S. Continental Scientific Drilling (US CSD) initiative that would be guided by a revitalized Interagency Coordinating Group (ICG) linking federal and academic stakeholders.

Justification for a US CSD program is solidly buttressed by numerous scientific success stories over the past decade, the impetus for new discoveries, and the challenge of meeting societal needs. The 2011 workshop provided a forum for reports on the recent successes of several projects, including the joint Integrated Ocean Drilling Program (IODP)/International Continental Scientific Drilling Program (ICDP) drilling of the New Jersey margin linking sediment history with patterns of sea level change; new projects in Antarctica under the Antarctic Climate Evolution program (ACE); the ICDP Dead Sea drilling program; and recent HOTSPOT drilling of the Yellowstone-Snake River Plain. Equally impressive were new efforts proposed for shallow drilling targets in the African tropics and new work on a variety of impact structures.

Recent years have seen the rapid expansion of scientific communities interested in CSD. The workshop specifically reached out to involve these emerging communities, including the National Critical Zone Observatory (CZO) Program, the Deep Time Earth-Life Observatory Network (DETELON), Antarctic Subglacial Drilling, and Earth Cube. The workshop also discussed proactive steps that could be taken to achieve international collaborations on targets of global significance.

Critical to the success of a U.S. CSD program would be the development of partnerships to examine such topics as earthquake and volcanic hazard assessment, geothermal activity, and natural resource concerns. Calculating the societal benefits of an increased understanding of these CSD-related issues—on the boundary between fundamental and applied science—highlights the great importance

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\(^1\) DOSECC (Drilling, Observation and Sampling of the Earth’s Continental Crust) is a not-for-profit corporation whose mission is to provide leadership and technical support in subsurface sampling and monitoring technology for addressing topics of scientific and societal importance. Fifty-three research organizations are members of DOSECC.
and potential of renewed collaboration between the various U.S. government agencies already using CSD tools (e.g., USGS, DOE, DOD, NASA, EPA) and NSF-supported science.

The workshop produced themes and future workshop needs for planning future U.S. continental drilling. These ranged from pre-site surveys to facilities and data management, and emphasized the synergies to be developed and coordinated with a broader, stronger US CSD facility. While large challenges exist in the effort to coordinate across mission-based agencies and NSF-program goals, it is clear that the transformative scientific payoffs of such a facility would be far greater and more cost effective than they would be under the current system, which is hindered by structural impediments to leveraging both science and mission.

One outcome of the workshop was the development of four potential funding models for supporting a US CSD initiative. These include an NSF-sponsored CSD program, an NSF-sponsored CSD facility with set-asides, a CSD program that is jointly supported by NSF and other mission-specific government agencies, and a CSD facility that is jointly supported by NSF and other mission-specific government agencies. All of these options could be developed within the auspices of a new Interagency Coordinating Group (ICG).

As symposium conveners and representatives of the U.S. scientific drilling community, we believe the best option would be the establishment of an NSF facility, possibly in collaboration with science mission-oriented government agencies. We think this is the most cost-effective way to reinvigorate U.S. continental scientific drilling, and we recommend moving into an exploratory phase that promises to develop an implementation phase in the near future.
TOWARD A STRATEGIC PLAN FOR U.S. CONTINENTAL SCIENTIFIC DRILLING: INTO A NEW DECADE

Julie Brigham-Grette², Anthony W. Walton³, Andrew Cohen⁴, Frank Rack⁵

INTRODUCTION

A dynamic, ever-changing planet, Earth is home to over 7 billion people who depend on its habitats and resources. The delicate balance of our environment, healthy air, and safe water is increasingly skewed by demands for all types of energy to fuel economies and sustain societies. At the same time, geologic hazards such as floods, drought, earthquakes, tsunamis, volcanic eruptions and sea level rise threaten populations and homelands around the world. Now, more than ever, scientific drilling represents one of the most promising means we have to extract critical information to understand Earth processes in situ, to collect records of Earth’s history, and to provide predictive measures and sound knowledge needed to protect citizens as we also seek sustainable resource practices. Living on Earth requires recognizing risk and minimizing damage through adaptive strategies and policies that are economically feasible in both the short and long term. Because geologic processes do not recognize political boundaries, successful scientific drilling requires a supported mechanism and infrastructure that fosters both national and international partnerships in the geosciences.

This report lays out a vision as to how the United States, under the auspices of the National Science Foundation and other federal agencies, could recapture its leadership role in by promoting scientific drilling as a critical tool for Earth scientists attempting to solve the major societal problems mentioned above. Academic continental drilling is now at a crossroad, given the critical need for scientific drilling infrastructure as a core activity in support of diverse scientific goals. Needs are currently being met in some fields such as as seismology and geodesy, but the United States presently risks losing the ability to conduct more broadly based drilling related science in a coordinated fashion for the generation to come. On a positive note, the latest NRC (2011, 2012) reports for the Earth Sciences emphasized continental drilling as a fundamental means to reach national science goals over the coming decade.

With NSF funding, DOSECC produced a major workshop report in 2010 that outlined the impetus for developing a new U.S. initiative in continental drilling (Walton et. al, 2010). The 2010 report was an outgrowth of a 2009 report in which representatives of the science community identified a wide array of disciplines benefiting from the fundamental information and significant, societally relevant advances that scientific drilling provides (Walton et. al, 2009). Both reports also contained recommendations for building a US CSD program that would emphasize global and environmental change (high resolution time series and deep time records, evolution of the Earth’s critical zone, and deep biosphere); geodynamics (crustal evolution, fault zone and volcano hazards, and ice sheets); and natural resource systems and concerns (geothermal energy, ground water, hydrocarbons, and CO₂ sequestration). Scientists and representatives of government funding agencies explored sustainable funding models, and the meeting generated considerable excitement for the concept of resurrecting a modernized version of the Interagency Coordinating Group (ICG), first established by the Continental Scientific Drilling and Exploration Act of 1988 (Public Law 100-441).

This report summarizes the recommendations of the May 2011 DOSECC workshop, which focused on the implementation strategies for a new U.S. continental scientific drilling (US CSD) initiative. The workshop was designed, first, to celebrate the scientific successes of recent drilling projects, then to explore the exciting, emerging scientific opportunities in CSD in the next decade, and finally, to provide a forum for exploring the synergistic needs of both emerging drilling programs and drilling traditionally performed under the aegis of mission-based agencies within the federal government (NASA, DOE, USGS, etc.). The most critical outcome of the workshop came during discussion groups whose task was to put forward options for funding and man-

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ing a multi-agency US CSD program based within
the NSF. The charge to participants was laid out by
Robert Detrick, Director of the NSF Division of Earth
Sciences, who proposed the following three possible
future directions for CSD:

- **CSD program option (NSF alone)**, in which,
in addition to NSF/EAR support for U.S. mem-
  bership in ICDP, EAR would establish a CSD
  program (like IODP) with a full time operator,
a number of drilling projects per year, and full
  support for everything from site surveys and key
  support facilities (logging, core and sample stor-
age, data management) to science.

- **CSD program option (NSF plus other agen-
cies)**, in which NSF/EAR would continue to
  support U.S. membership in ICDP. However,
in this option NSF would work in collaboration
  with other government agencies, such as USGS,
  NASA, and DOE, to establish a CSD
  program (like IODP) with a full time operator, a
  number of drilling projects per year and full
  support for everything from site surveys and key
  support facilities (logging, core and sample storage, data
  management) to science.

- **CSD facility option**, in which, in addition to
  NSF/EAR support for U.S. membership in
  ICDP, EAR would continue to provide base sup-
  port for DOSECC or a DOSECC-like
  organization. Additionally, EAR
  would support drilling operations
  and key facilities (logging, core and
  sample storage, data management)
  with funding separate from the core
  science programs, although the core
  programs would still support post-
  drilling science costs. This option
  might also be coupled with support
  from other government agencies.

Further discussions during the workshop ex-
expanded upon the pros
and cons of these ideas when considered alongside the
value-added complexity of partnering academic sci-
ence objectives with mission-based agencies such as
DOE, USGS, and NASA, when appropriate. This pair-
ing has the most potential if it is addressed strategi-
cally as a transformative shift away from the business-
as-usual fragmented mode of uncoordinated programs
at both national (interagency) and internationals (e.g.,
ICDP) levels.

**THE SCIENCE THAT DRIVES CONTINENTAL DRILLING**

Justification for a US CSD program is solidly but-
tressed by numerous scientific success stories over the
past decade, the impetus for new discoveries, and the
challenge of meeting societal needs. Many of the ap-
plications of continental drilling to science were re-
viewed and celebrated at workshops in 2009 and 2010
(see Walton et al., 2009, 2010). By the 2011 workshop,
even more new and exciting discoveries had been
made as drilling and emerging research themes contin-
ued to come online in the CSD community. The 2011
workshop provided an opportunity for participants to
hear summaries of these exciting developments from
projects across the globe, which clearly illustrated the
extraordinary reach of CSD across the Earth and life
sciences.

<table>
<thead>
<tr>
<th>Project</th>
<th>Total Funds, US$</th>
<th>ICDP Funds, US$</th>
<th>ICDP%</th>
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<tbody>
<tr>
<td>Malawi</td>
<td>1,840,000</td>
<td>760,000</td>
<td>41</td>
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<td>Qinghai</td>
<td>1,550,000</td>
<td>550,000</td>
<td>36</td>
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<td>Peten Itza</td>
<td>950,000</td>
<td>500,000</td>
<td>53</td>
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<td>Chesapeake</td>
<td>1,750,000</td>
<td>970,000</td>
<td>55</td>
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<td>SAFOD</td>
<td>22,000,000</td>
<td>2,200,000</td>
<td>10</td>
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<tr>
<td>FAR DEEP</td>
<td>970,000</td>
<td>550,000</td>
<td>57</td>
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<tr>
<td>Iceland</td>
<td>3,000,000</td>
<td>150,000</td>
<td>5</td>
</tr>
<tr>
<td>Potrok Aike</td>
<td>2,300,000</td>
<td>1,300,000</td>
<td>57</td>
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<tr>
<td>El’gygytgyn</td>
<td>10,200,000</td>
<td>2,200,000</td>
<td>25</td>
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<tr>
<td>New Jersey</td>
<td>8,700,000</td>
<td>500,000</td>
<td>6</td>
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<tr>
<td>Lake Van</td>
<td>1,400,000</td>
<td>870,000</td>
<td>62</td>
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<td>Snake River</td>
<td>5,640,000</td>
<td>1,000,000</td>
<td>18</td>
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<tr>
<td>Dead Sea</td>
<td>2,500,000</td>
<td>920,000</td>
<td>37</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>62,800,000</strong></td>
<td><strong>12,470,000</strong></td>
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Ulrich Harms (ICDP) discussed the structure of ICDP, briefly noting the numerous projects it had financed in recent years and its plans for the near future. The breadth of ICDP project areas is emblematic of the reach of CSD today. They encompass active faulting and earthquake processes (3 projects completed, 8 in various stages of development), climate dynamics and global environments (12 completed, 15 in development), volcanism and geothermal development (4 completed, 3 in development), geobiosphere and early life (8 completed, 5 in development), impacts and impact structures (4 completed, 4 in development), mantle plumes and large igneous provinces (3 completed, 2 in development), convergent plate boundaries and collision zones (2 completed, 3 in development), and natural resource and industry-coupled projects (3 completed, 4 in development). However, the scale of international CSD support by ICDP belies the disturbing trend that fewer and fewer of these important projects are occurring under U.S. scientific leadership because matching funds for CSD efforts in the United States have not kept pace with CSD investments in other key ICDP member countries.

Recently Completed Drilling Projects

Greg Mountain (Rutgers University) discussed how our understanding of sea level controls on continental shelf sediment architecture is evolving as a result of collaborative onshore and offshore drilling and seismic research on the New Jersey continental margin. Relatively simplistic models linking patterns of sea level fluctuations and sediment delivery to sequence stratigraphy, which have been the standards of academic and industrial research, are undergoing revision as a result of this work. Drilling by DOSECC on the challenging shallow continental shelf environment, which was critical to this project’s success, is allowing us to much more accurately understand the significance of seismic stratigraphic variability across the continental shelf.

For the past 15 years, the Antarctic Climate Evolution (ACE) project has also integrated scientific results from various platforms (ocean, land, and ice) to compile data on Antarctica’s history. Frank Rack (University of Nebraska) synthesized the results, which are informing us about the scale and rapidity of ice-sheet and sea-ice responses to climate forcing, sea level changes, and changes in heat sinks and insulators. Future advances in reconstructing paleotopography and palaeoenvironments of Antarctica will rely heavily on CSD approaches.

John Shervais (Utah State University) explained the scientific rationale and early findings of HOTSPOT, the Snake River Scientific Drilling Project. For the
Toward a Strategic Plan for a U.S. Continental Scientific Drilling Program

DOSECC drilled a transect of drill holes across the Snake River Plain in 2011. The project’s major scientific goals are to test whether the Yellowstone-Snake River volcanic system results from a deep mantle plume, to document the nature of this plume, if it exists, and more broadly, to understand how mantle plumes interact with continental lithosphere. As with many emerging scientific drilling projects, HOTSPOT also aims to address key applied, societal concerns related to geothermal resources on the Snake River Plain.

Steve Goldstein (LDEO) reviewed the preliminary results of the Dead Sea Drilling Project, for which drilling was completed just before the workshop. This project is documenting the extraordinary environmental fluctuations that have buffeted the Middle East over, approximately, the last 200,000 years and have been recorded in the Dead Sea’s sediments. One of the most striking early findings is the discovery that the Dead Sea either nearly or completely dried up during the last interglacial, an event that was previously considered—based on modeling approaches—to be extremely unlikely, and which has profound societal implications for modern water resources in this arid and turbulent region.

Lake drilling, done primarily to improve our understanding of the continent’s paleoclimatic history, has had numerous successes over the past decade. For example, one project documented the heretofore unrecognized existence of extraordinary episodes of prolonged drought in the African tropics during the early Late Pleistocene. The implications of this and similar findings in other lakes for continental climate dynamics are immense. James Russell (Brown University) discussed the results of these recent lake CSD project and the trajectory lake drilling is likely to take over the next ten years. Vast improvements in our ability to quantitatively reconstruct climate from drill cores,
coupled with strong synergies between the lake drilling and climate modeling communities, are transforming this science in ways unimaginable only a decade ago when the global lakes drilling program got underway.

Christian Koeberl (University of Vienna) explained the science behind impact-crater drilling, drawing on examples from three structures that have already been drilled (Lake Bosumtwi, Chesapeake Bay, and Lake El’gygytgyn) and many others in various stages of planning. Core samples derived from drilling are essential for resolving scientific debates about the 3D structure of impacts and crater-formation processes.

Brian Huber (Smithsonian Institution, National Museum of Natural History), discussed results from the Cretaceous Tanzania Drilling Project, which is establishing a stratigraphic and tectonic history for the continental margin of Africa in southeastern Tanzania through the critical supergreenhouse world interval. The exceptional preservation of foraminifera (only available through drill core samples) is allowing Huber and his colleagues to quantitatively reconstruct temperature variability and the evolutionary record of shelf ecosystems through this time period at a very high resolution.

Emerging Projects: Expanding Partnerships Within CSD

One of the highlights of the 2011 workshop was the opportunity to hear about the rapid expansion of scientific communities interested in collecting data through CSD. Some groups represent traditional components of the Earth sciences who are just now becoming aware of the potential that subsurface sampling and monitoring through drilling can provide. Others, from outside the Earth sciences, are interested in using the drill to access information relevant to fields as disparate as microbiology and anthropology.

A critical societal problem throughout the world is the lack of understanding about the migration and geochemical evolution of arsenic in aquifers over short time spans. Unfortunately, sampling As-bearing unconsolidated sands in ways that allow hypotheses to be adequately tested has remained elusive when using traditional hydrological methods. Lex Van Geen (LDEO) discussed a novel partnership between DOSECC and a large number of research institutions to develop new freeze sampling coring tools that would allow such work to be done. Tests of this breakthrough technology are planned for the next few years.

Paleoclimate research that involves studying sediment cores collected from lake deposits is a relatively mature field. However, lake cores are now also being used to address a whole range of new questions, which is bringing a wide reach of new communities into CSD. For example, drill cores from a series of paleolakes in the African rift, to be collected in the near future, can potentially be used to test various hypotheses about human ancestor speciation and geographic dispersal, which will require collaborations between Earth scientists and anthropologists.

Many groups not previously connected to the CSD community were represented at the 2011 workshop.
They included the National Critical Zone Observatory (CZO) Program, an NSF-funded initiative that is currently investigating six CZO study areas situated in different climate and bedrock regimes throughout the United States. Cliff Riebe (University of Wyoming) explained that CZO studies are designed to investigate the interconnections between energy and materials influx and dissipation, weathering, erosion, and landscape evolution in the soil-forming outermost portion of the solid Earth as well as the terrestrial biosphere. Although CZO instrumentation, monitoring, and modeling studies have been underway for several years, little attention has been paid to the “deeper” portions of the critical zone—areas only accessible by drill-core-based investigation. Previously conducted geophysical studies within the critical zone suggest much greater spatial heterogeneity than researchers had previously realized. This raises many questions about weathering depth, mineralogical composition, and fracture networks, all with important implications for terrestrial ecosystem feedbacks.

Thomas Olszewski (Texas A&M) discussed the critical role that CSD must play in the developing Deep Time Earth-Life Observatory Network (DETELON). DETELON’s mission is to use knowledge of Earth’s deep past to understand and forecast the consequences of ongoing environmental change for living systems and human society. It aims to study issues such as the nature and timing of abrupt transitions across tipping points into a warmer world, and ecosystem thresholds and resilience in a warming world.

The Broader Message

Several common themes emerged from the workshop presentations on CSD. The first was a clear need for continued technological innovation in scientific drilling, coring, and downhole instrumentation methods. The scientific community is clamoring for new and better ways to retrieve undisturbed samples, to instrument boreholes in ways that take advantage of cutting-edge technologies, and to address increasingly complex and interdisciplinary research questions. Moving forward with such approaches will require both concerted leadership in technology development and financial resources.

Secondly, broadening of the CSD community will require an expanded set of drilling platforms from which to collect critical samples. The success of the multi-platform approach is evident in such projects as the New Jersey continental margin transect, which combined wireline diamond coring with lift-boat operations on the shallow inner shelf to provide a synergy of drill-core data unobtainable from a single drilling method. The New Jersey project also highlights the scientific benefits of close cooperation between the continental and ocean scientific drilling communities. Similarly, Ross Powell (Northern Illinois University) discussed the potential for scientific exploration synergies between the ice drilling, Antarctic Drilling, and CSD communities. CSD techniques will ultimately be critical for adequate sampling of sediments that lie below Antarctica’s glacial ice caps and to address questions about ice dynamics (especially in a warm-
ing world), glacial history, and preglacial stratigraphic and tectonic history.

At the other end of the spectrum, there is clearly a need for very small, lightweight, and portable drilling rigs that can be deployed for the many times when only shallow drilling is required. Having this type of equipment pool would also satisfy the need to make drilling a practical tool for early career PIs and where budgets and research time frames are limited. Technology development would be critical in this area because high-precision tools for sampling sediment, rock, and water would need to be downsized to make them useable with smaller drill rigs than is now possible.

There is broad consensus that we need to extend our ability to retrieve highly resolved temporal records of environmental change into the deep geological past. Events such as the Paleocene/Eocene Thermal Maximum (PETM) serve as models for Earth/life system interactions in rapidly warming environments, a topic that is highly relevant today. Although marine records from ocean drilling certainly provide part of the story about what occurred during these events, the continents hold important evidence that is particularly pertinent to present terrestrial species. Drill cores are unquestionably the most important source for uncontaminated, unweathered, continuous records of proxies, such as organic molecules, that are essential for reconstructing past worlds.

Nurturing international partnerships is an increasingly important task for CSD. Even for projects conducted wholly within the United States, the costs of drilling related activities, coupled with the need for U.S. scientists to tap into expertise not always available in U.S. laboratories, makes international collaboration essential. Early career investigators, in particular, must learn how to navigate through the complexities of research partnerships with international scientists in order to compete on the global scientific stage. CSD projects are often ideal for international collaboration and learning because they typically target scientific objectives of global significance.

Finally, CSD will be used to address critical societal issues in years to come. From its inception, CSD has been used to examine such topics as earthquake and volcanic hazard assessment, geothermal activity, and natural resource concerns. However, as many of the workshop presentations made clear, CSD also has a vital role to play when it comes to understanding emerging scientific issues that will affect all of us in the near future. It could be an immeasurable resource, for example, in projects that require shallow drilling in the critical zone; quantifying biogeochemical processes, material flux transfer rates, and contaminants affecting the habitable part of our biosphere; and deeper drilling to determine the potential for carbon sequestration.

Figure 5. Foliated fault gouge at 10490 ft measured depth (at black line) from the Southwest deforming zone in cored interval 2 of Hole G of SAFOD Phase 3. Coring provides samples of the active zones of faults for studies of deformation mechanisms and effects as well as allowing for sampling of fluids and placement of instruments for short- or long-term measurements. Understanding the structure of fault zones at the hand specimen to microscopic level is a key to understanding the mechanisms and conditions of faulting. http://www.earthscope.org/es_doc/data/safod/Core%20Photo%20Atlas%20v4.pdf, downloaded 1/7/2012.
These CSD-related issues, on the boundary between fundamental and applied science, highlight the great potential for renewed collaboration between the various U.S. government agencies already using CSD tools (USGS, DOE, DOD, NASA, EPA) and NSF-supported science. John Eichelberger (USGS) reviewed the USGS’s long history of interest in CSD, which spans many of the topics that were under consideration at the workshop and involves numerous collaborative success stories with academic scientists. (Recent examples include the San Andreas Fault Observatory at Depth and the Chesapeake Bay Impact Structure Deep Drilling Project.) Eichelberger noted that the USGS would continue to have a strong interest in drilling fault zone, volcanoes, geothermal and hydrologic systems, potential carbon sequestration targets, and paleoclimate records. Similar needs of DOE (e.g. Project HOTSPOT) and other government agencies demonstrate the great potential value in revitalizing the interagency agreement on continental drilling. Joint efforts to understand the dynamic processes of the Earth’s outer crust through CSD have an important role to play in meeting the challenge of building a more disaster-resistant America in the decades to come.

**STRUCTURING A US CSD PROGRAM: BUILDING ON MOMENTUM AND SYNERGY**

One of the many goals of the 2011 workshop was to gather input from the participants representing the science community on key issues essential to framing a powerful vision for a US CSD. Continental scientific drilling encompasses four major themes (Walton et al., 2009) for which drilling provides vital information and samples (Table 2). Each of these themes includes a number of topics; participants in the 2009 workshop thought the progress of each topic was worth following through periodic workshops that would summa-

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<tr>
<th>Themes</th>
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<td>Global Environmental and ecological change</td>
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<td>(Antarctic deep time records)</td>
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<td>CO2 sequestration</td>
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Table 2. Themes and topics for continental scientific drilling (Walton et al., 2009).
TOWARD A STRATEGIC PLAN FOR A U.S. CONTINENTAL SCIENTIFIC DRILLING PROGRAM

Drilling into Volcanoes
(modified from John Eichelberger, USGS)

Past efforts:
Sampling magma (some accidental)
Kilauea Iki lava lake
Puna (Kilauea)
Iceland Deep Drilling Project
Geothermal energy, including supercritical zone
Kikkonda geothermal field
Iceland Deep Drilling Project
Structure of volcanoes.
Inyo Domes Scientific Drilling Project
Long Valley Exploratory Well
Unzen Scientific Drilling Project
Hawaii Scientific Drilling Project

Ideal future effort:
Objectives
- Structure and mechanisms of volcanoes
- Nature and configuration of magma
- Geothermal energy & mineral deposits
- Volcanic hazards
- Volatile flux

Target
- Active, well-instrumented volcano
- Multiple holes of increasing depth
- Ultimate target: explore the magma itself.

Specific possibilities: Newberry, Akutan, Makushin. Also Mutnovsky in Russia, various Japanese volcanoes.
Funding: NSF, USGS, DOE, Industry

rize the science to date, identify the major themes for further investigation, and develop a program to implement them. These topics provide ample scope for exciting and likely transformative science. Some of the more exciting opportunities include the following:

- Drilling into sediments of long-lived lakes to provide detailed records of Plio-Pleistocene climate unavailable from other sources. This alone will help understand the dynamics of the Earth’s climate.

- Exploring Deep-Time through continental drilling. The Earth now has conditions of CO₂ concentration and experience effects that lie outside the range of those during the Plio-Pleistocene. Atmospheric levels of CO₂ are now at levels not seen since the Oligocene and are heading higher. Earth scientists have identified several episodes of greenhouse and ice-house climates, several sharp excursions of atmospheric composition or temperature, and sedimentary accumulations for which no modern analog exists. Full understanding of the climatic and marine response to those conditions requires the kind of unweathered and stratigraphically complete records that only drill cores can provide. Further information on past climates, especially from isotopes and other geochemical analyses, would constrain the physics of the Earth’s climate more rigorously and more completely over the range of geologically documented conditions than is possible from recent record.

- Investigating the Earth’s deep continental biosphere. Studies of the ocean crust, oceanic islands, deep mines, and a small number of continental drilling sites have explored the realm of the deep biosphere. While biology has studied many of the niches occupied by organisms at the surface, in the hydrosphere, and in the atmosphere, recent explorations of the subsurface suggest a huge standing crop of organisms that may increase the total known volume of living organisms by several 10s of percent. Exploration of the deep biosphere beneath the continents is a subject that should excite many scientists across disciplines, just as the discovery of chemosynthetic organisms at submarine vents and methane seeps has done. Only drilling can access the habitat of such deep-dwelling organisms.

- Drilling in active fault zones and volcanoes. The Tohoku earthquake and tsunami of March 11, 2011, is just the latest of a series of devastating earthquakes; earthquakes and volcanic eruptions pose special hazards around the world. A full understanding of earthquake processes requires drilling of active or recently active faults to understand the initiation and fracturing of such events. Exploration of the structure and plumbing system of volcanoes should lead to a greater comprehension of the eruption process and of the many volcanic hazards.

- Investigating the subsurface science associated with carbon sequestration. Sequestration in deep aquifers appears to be a useful option for removing CO₂ from the atmosphere as well as recovering additional oil from otherwise depleted fields. DOE is funding investigation of CO₂ sequestration. While many such projects have a single purpose, adding on additional scientific objectives could be an economical way to provide more researchers with vital, and otherwise unattainable, data at a low cost-benefit ratio.

- Examining the history of Earth magmatism. The Hawaii Scientific Drilling Project demonstrated that long records of unweathered samples, used in studies of the formation of hotspot magma in
Figure 6. The Department of Energy funds research on carbon utilization and sequestration in which drilling is an important source of samples and drill holes are used for subsequent geophysical and petrophysical measurements. A grant to the Kansas Geological Survey and Berexco, LLC of Wichita, Kansas, has permitted investigation of dolomite of the Ordovician Arbuckle Group in Sumner County, Kansas, as a possible site for CO₂ sequestration and of the overlying Mississippian oil reservoirs as sites of enhanced oil production by CO₂ injection. View is from the southwest. Elevations in feet. 
the subsurface and its interactions as it rises to the surface, led to an understanding of a fundamental Earth process. The ongoing HOTSPOT Project is currently examining the interaction of hotspot magmas with continental crust in the Snake River Plain of Idaho. Few comparable studies of other volcanic environments have been undertaken.

- Understanding planetary impacts. On planets other than Earth, impact of meteorites is the most common surficial process. Only through drilling of terrestrial impact craters can critical earthly subsurface samples be obtained to constrain the various models of impact and help us better understand the dynamics of impacts elsewhere in our solar system.

The 2009 report, however, did not anticipate, or only marginally foresaw, several key issues, discussed below, that should be addressed through drilling.

- Disaster preparation has come into focus in the wake of numerous recent destructive natural disasters worldwide. In its 2012 budget request to Congress, NSF has requested funding for its CaMRA (Creating a More Disaster Resistant America) program, an initiative within GEO to “catalyze basic research efforts at NSF in hazard-related science to improve forecasting and prediction of natural and man-made hazardous events” (NSF, 2011a). CSD-based research provides a critical platform for developing this capacity—for example, through the installation of borehole instrumentation in active faults and volcanoes.

- Development of long-lateral horizontal wells completed with staged hydrofracing has opened immense new resources of natural gas and is leading to increases in U.S. oil reserves for the first time in decades. However, controversy has developed over the potential hazards that the fracturing process and the chemicals used in that process might pose to potable ground-water supplies. Furthermore, the process of fracturing rock—important for optimizing exploration and recovery efforts—is not well understood. Drilling could provide real samples of fractured rock for study and also verify seismic models designed to predict the extent of induced fractures and their possible interaction with ground water.

- Understanding the critical zone—where the solid Earth, the hydrosphere, the atmosphere, and

Figure 7. Impact breccias from the Lake El’gygytgyn Drilling Project, 2009. This project combined interests in paleoclimatology from lakes with investigation of impact structures and processes to exemplify the synergism possible in CSD projects. It also demonstrated DOSECC’s capability for innovation to meet project demands and for planning, logistics, and operations under difficult conditions. Illustration courtesy Christian Koeberl, University of Vienna
the biosphere interact—requires fresh samples that illustrate the weathering process and biological interactions. Because the critical zone lies close to the Earth’s surface, shallow holes must be drilled so that the appropriate samples can be collected. Current critical-zone observatories (CZO) have been developed in upland areas distinct from the sedimentary basins in which ancient rocks have accumulated. A program of shallow drilling to support the objectives of the critical-zone observatories, and provide undisturbed and uncontaminated samples of these environments and their biological communities, would be most informative.

- Arsenic levels in ground water render the water toxic to long-term users in many areas of Southeast Asia. Projects now exist to develop the means to sample rock and fluids from As-contaminated aquifers by freezing them in situ before recovery. Only such sampling can provide insight into this significant health hazard.

- As the atmospheric levels of CO\textsubscript{2} increase beyond those last present during the \textit{Oligocene} and head toward Eocene levels by the 22nd Century, investigations of Earth and life systems under greenhouse conditions are drawing increased interest. The DETELOON Science Plan proposes a network of observatories to investigate condi-

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Figure 8. Shallow resistivity (A) and seismic structure (B) at the Southern Sierra CZO, with inferred porosity (C). Differences in geophysical properties between meadow and forest areas may reflect soil properties or water retention. Inset shows that soil porosity matches geophysical values near the CZ tree. Shallow cores can resolve any ambiguity while providing information on mineral assemblages, composition of fluids, and the biota. Image courtesy Cliff Riebe, University of Wyoming, from Holbrook et al. in prep.
tions and processes during greenhouse episodes. Perhaps more relevant is investigation of physical processes and feedbacks, and their interaction with the biota, during periods of transition from icehouse to greenhouse conditions, similar to what is occurring now. As rigorous investigation of atmospheric and oceanic composition requires fresh, stratigraphically controlled samples, a program to drill shallow to moderate-depth holes is a necessary aspect of such projects.

THE PLANNING PROCESS: THEME-BASED WORKSHOPS

Other geoscience consortia, such as the Incorporated Research Institutions for Seismology (IRIS) and the IODP, have developed coherent scientific plans for advancing their science. The CSD community, both in the United States and internationally, is different from these organizations in two ways. First, the CSD community is relatively diverse in terms of its scientific interests, as described above. Second, while there is no such thing as an inexpensive IODP hole because of the concentration on particular facilities—such as the need to deploy ships efficiently in view of their high fixed costs—the equipment requirements and costs of continental drilling can be scaled to a project’s needs. While costs of CSD projects may seem high to individual investigators, such projects are less dependent upon pieces of equipment or facilities dedicated to just one project. More than one CSD project can be conducted in distant places, either sequentially or simultaneously, with shared equipment. For example, in late 2009 DOSECC deployed a project at Lake Potrok Aike in southern Patagonia and in early 2010 began operations at Lake El’gygytgyn in eastern Siberia.

Based on the unique needs of CSD projects, a strategy for continental scientific drilling should include a series of topical plans in conjunction with a unifying plan for the necessary facilities, equipment, and technological development as well as plans for community building, outreach, and education.

Participants in the 2009 workshop (Walton, et al., 2009) considered the PAGES Lakes Drilling plan (Colman, 1996) to be a good model for identifying a unifying program for advancement and one that the entire lakes paleoclimate community could support. The 2009 report recommended a series of N-S transects of lake sediment coring projects. These transects were to extend through the Americas, Europe and Africa, and East Asia and Australia. Worldwide models of the Plio-Pleistocene climate history were to be developed from climate records and proxies from the cores, and from complementary oceanic cores. Lakes were recommended because they provide decadal-scale precision not found in bioturbated oceanic sediments. The lakes plan identified the technological tools necessary for its implementation; this need was partially met by the GLAD 800 system that DOSECC developed and by DOSECC’s more recent Deep Lakes Drilling System. Recent drilling into Lake Van, Turkey, and the Dead Sea illustrates continuing efforts to get key data for climate modeling. The LacCore facility at University of Minnesota, Twin Cities, provides key facilities...
for study and curation of lake cores. The Human Origins subgroup conducted workshops that have led to a sound and widely supported plan for drilling in Pleistocene lake sediments in East Africa. Implementation awaits further funding. None of the other topics for scientific drilling has such a compelling plan, at present.

The 2009 participants (Walton et al., 2009) envisioned a series of topical workshops catalyzed by members of the CSD community but open to members of overlapping communities and parallel entities with international participation. A key feature of such topical planning workshops would be the participation of members from other segments of the CSD community, who might have overlapping interest in some of the plans that emerge. Conveners of such workshops could be U.S. or internationally based, and funding could come from national scientific funding agencies or the ICDP. Having members of the US CSD community in key positions would provide U.S. leadership in areas where it is currently lacking and help to ensure U.S. participation in future projects; U.S. participation in CSD projects, not to mention leadership, has declined over the past several years (Walton et al., 2010).

The 2011 workshop recommends that the US CSD community develop a series of topic-based workshops to plan for advancing the science of its several components.

The DOSECC Science Planning Committee (SPC) has been charged with identifying knowledgeable and energetic scientists who can take the lead in organizing conceptual workshops for the various topics. In response to recommendations of the 2009 workshop (Walton et al., 2009), the SPC has recently been enlarged to include scientists from institutions that are not members of the consortium as well as to enhance international participation in its deliberations. Where-as the current DOSECC cooperative agreement includes funding for some workshops, that funding is mainly for community-wide gatherings. Funding for topic-specific workshops must come from other sources, such as NSF, other national science funding agencies, or international entities.

SYNERGIES

The US CSD community encompasses specialists with a wide range of interests, from paleoclimate and sea-level history to impacts and igneous processes to earthquakes and environmental hazards. The unifying leitmotif is the need to drill to get vital subsamples and data. This leitmotif exists on all levels, from the need for basic infrastructure and preservation of results to participation in particular drilling projects. Many projects, undertaken for whatever reason, might serve more than one purpose. For example, the Chesapeake project researchers sampled the subsurface biota in addition to investigating an impact structure and providing information on Cenozoic sea-level history. The Bosumtwi and El’gygytgyn projects combined paleoclimate studies of lake records with the examination of impact structures.

This marriage of convenience among various disciplines could be a strength of a US CSD program because it brings together scientific interests and potential at relatively low cost and broadens support for individual projects. Connections made through the drilling process also may create unanticipated intellectual synergies as intelligent, creative individuals of differing backgrounds establish working relationships.

As an example, drilling the Hawaiian Scientific Drilling Project (HSDP) required DOSECC to develop an innovative, large, top-drive rig that set records for deep continuous coring. In another instance, the lakes drilling program needed a suitable and portable platform to carry out its investigation; this need led to the GLAD 800 system and the newer Deep Lakes Drilling System, developed by DOSECC. Because the nature of lake sediments requires special tools for sampling and coring, DOSECC developed the appropriate hardware, which has been very successful with a high degree of core recovery from all kinds of sediment. DOSECC also developed a heave-compensation system for drilling on large lakes and marine shelves and successfully demonstrated its utility. Current efforts involve developing a freeze-shoe coring tool to preserve fluids in recovered samples. Future projects will require similar advances. Because of the synergistic nature of the drilling community, it is possible to justify the cost of development of such tools and spread that cost over many research groups and projects. Through open workshops involving participants from within and outside the CSD community, as endorsed above, the community can identify needs for technology advances and immediate applications for the equipment.

Educational Opportunities

New initiatives in the community offer significant opportunity for expanding interest in scientific drilling. Scientists and educators with needs for shallow cores will be able to use the highly portable Winkie© drill rig that is to be purchased under DOSECC’s current cooperative agreement. For educational purposes,
this equipment will offer field camps and other field-based educational efforts the opportunity to add the third dimension to outcrop studies and to educate both instructors and students about the advantages cores provide. For researchers, the Winkie® system could be a key tool in studies such as those of the critical zone, where numerous shallow holes are required instead of one or a few deeper ones. Some investigators need drilling equipment for sampling remote lakes, where vehicles cannot go. Highly portable drilling system like the Winkie®, but with lake coring or fluid sampling capabilities, would be ideal for those situations. Availability of the Winkie® system at low cost will greatly broaden the access to and application of drilling for gathering key data and samples. It will also offer opportunities for educating the public about the science that can arise from subsurface studies using drilling.

Several drilling projects, notably SAFOD, have provided undergraduate students with the opportunity to participate in on-site tasks. Many undergraduates have been involved with the description of core and the analysis of samples, which has often led helped direct them to their undergraduate theses projects. However, without a broader program, opportunities have mostly been accessible only to undergraduate students at the limited number of institutions who participate directly in the drilling projects. One program that does provide invaluable experience is the NSF’s Research Experience for Undergraduates (REU), which engages beginning Earth scientists in drilling projects during their college years.

This workshop recommends that the DOSECC office, or other members of the CSD community, should develop an REU program with actual drill-site experience or demonstrations followed by deployment to drill sites or laboratories where the students could gain analytical research experience.

A NECESSARY STEP: REVIVE THE ICG TO COORDINATE AMONG FEDERAL CONTRIBUTING AGENCIES

In 1988 Congress established the Continental Scientific Drilling and Exploration Act (Public Law 100-441; http://thomas.loc.gov/cgi-bin/query/z?c101:S.1943.1S), which mandated an Interagency Coordinating Group (ICG) consisting of representatives from NSF, USGS, and DOE. This Act recognized that drilling provided samples vital to scientists who were employed or funded by a number of agencies in the Federal Government and were essential to aspects of the

Figure 10. Project Hotspot, the Snake River plain drilling project explores geothermal potential as well as petrologic and paleoclimatological questions. Upper: outcrop of pillow basalt where a lava flowed into a stream. In the eastern Snake River Plain, rhyolite in caldera fills and ignimbrite outflow sheets underlies the basalt. Here the project seeks to investigate the geochemical signature of hotspot volcanism in a continental realm to understand the processes that create and modify the magma as well as investigating the potential for geothermal resources. Lower: In the western Snake River plain, basalt is common at the surface, but the underlying rocks are diatomites and other sediments of Pleocene Lake Idaho, which provide a fine paleoclimatological record. Much of the funding for the western Snake River plain phase of the project came from the US Air Force, which is seeking hot water to provide green energy for Mountain Home Air Force Base. The project was funded by the Department of Energy and ICDP in addition to the Air Force, showing the broad interest in drilling in disparate entities of the Federal Government. Photos courtesy Tony Walton, University of Kansas, John Shervais, Utah State University.
missions of the agencies themselves. Although the ICG functioned for several years, it withered when the funding trajectory did not encourage new initiatives. A low point in proposal pressure reflected a paradigm shift from single deep holes that required expensive operations to projects centered around shallow holes, where the scientific effort was a larger fraction of the cost and the payoffs came to more disciplines. Unfortunately, as drilling activity ramped up again with the Long Valley Project, HSDP, and lake-drilling initiatives, the ICG did not revive.

The 2009 and 2010 workshops recognized that drilling projects over the past 15 years have seen collaborative efforts among not only the defined ICG agencies but also NOAA and the Department of Defense. Many of them were international collaborations (Walton et al., 2009, 2010). The Long Valley Project was supported by the USGS and, as geothermal exploration, was of interest to DOE. NASA funded drilling to recover fresh material from Archean and Proterozoic rocks that recorded the history of life and the atmosphere—a topic of broad interest to geology and biology. The USGS, with NASA, joined the ICDP in supporting the Chesapeake Bay Drilling Project, which, while centered on meteorite impact processes, also produced compelling results on the deep biosphere and insight into sea-level history. This current workshop, in particular, has recognized that multiple divisions within NSF support science that would benefit from findings of drilling projects and, therefore, should participate in supporting CSD efforts. Examples of other cases where this has been done are the Polar Programs’ support for drilling in Antarctica and in Lake El’gygytgyn and support by DOE, USGS, and NASA of diverse research activities that require drilling. Internal coordination was necessary in those agencies as well.

A major recommendation of this workshop, carried over from previous workshops, is to revive the ICG and expand it to reflect the diverse interests in samples and data from drilling projects. This would allow various federal agencies to participate in science planning, project execution, and operational and scientific funding as their interests dictate.

A revived ICG would offer a broader scientific community the opportunity to participate in CSD projects and share funding for the necessary infrastructure and community support. In short, an effective ICG would improve a vast array of subsurface sciences and spread the cost among interested parties. There is a precedent for resurrecting a coordinating group; after the Interagency Arctic Research Policy Committee (IARPC) had been suspended or nearly inactive for years, it recently became more active, with coordination from the Office of Science and Technology Policy (OSTP). IARPC has drawn special attention because of the likely prospect of an ice-free Arctic Ocean. The advantage of such a coordinating group is its ability to focus on a mission and justify that mission over a decadal time scale with a large constituency.

Within a revived ICG, each agency would have multiple divisions interested in samples and data from drilling projects. NSF might find that drilling interests cross boundaries between directorates. Clearly, EAR in GEO will maintain a leading interest. However, the Social, Behavioral, and Economic Sciences Directorate could support drilling to answer questions concerning the course of human evolution, while other programs could become engaged in supporting studies of fossil endemic biota preserved in lake sequences, as in the Lake Ohrid project. Both types of studies bear on more general questions linking the GEO and BIO Directorates concerning the rates and triggers of evolution. Moreover, access to the deep biosphere via drilling is expected to provide a vast new window on the activities of organisms. This theme is also of interest to NASA, which is involved in the study of extreme environments and early life. For the USGS, drilling active faults and volcanoes is an important part of its mission to create a more disaster-resistant America. The USGS core repository and its extensive laboratories show that it is also concerned with infrastructure arrangements. Within the ICG, the USGS might be more oriented toward providing in-kind or personnel contributions than the other agencies. Finally, DOE’s interests in carbon capture, utilization, and sequestration (CCUS) and in geothermal resources require drilling and may have substantial ancillary scientific payoff.

Although within the framework of the ICG there will naturally be concerns about how to allocate responsibility for particular initiatives, discussions about those

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6 The Interagency Arctic Research Policy Committee (IARPC) includes representatives of the following Federal agencies or offices:
National Science Foundation; Department of Commerce; Department of Defense; Department of State; Department of Health and Human Services; Department of Homeland Security Office of Science and Technology Policy; Department of Agriculture; Department of Energy; Department of the Interior; Department of Transportation; National Aeronautics and Space Administration; Environmental Protection Agency; Smithsonian Institution; National Endowment for the Humanities.

The National Science Foundation (NSF) is the lead agency responsible for implementing Arctic research policy, and the NSF chairs the IARPC.
responsibilities might be healthy in the long run. Introducing a large group of agencies and scientists into the process will broaden the constituency for drilling in general and individual projects on particular. In the greater sense, bringing various agencies into the fold will increase the resources available, the diversity of the investigations, and, most importantly the scientific potential.

Because the interests within agencies are diverse, a revived ICG should be structured to function effectively. It should consist of a representative from each agency to serve as a single point of contact as well as a functional executive director, or chief of staff, to coordinate the group’s activities. To ensure that each agency is fairly represented, appropriate program managers from each agency must participate in overall planning processes and CSD-wide initiatives (e.g. data management, sample curation and storage) and ad hoc participants should be chosen for specific issues, such as particular areas of investigation or individual projects. The executive director, or chief of staff, would probably come from NSF because that agency has the broadest mandate of the participants, and would likely be the NSF program manager for the CSD initiative and perhaps NSF’s representative to ICDP.

Federal law mandates an ICG. Re-implementing the ICG requires that NSF, specifically the leadership of EAR and the relevant program directors, take the initiative to bring agencies together.

IMPEDIMENTS

This report has identified the strength that the CSD community derives from its topical diversity. Unfortunately, this diversity also impedes advancement of a strong, U.S.-based drilling program because it makes it harder for the US CSD community to speak with a single voice. This workshop, as well as those in 2009 and 2010, has attempted to connect the various elements of the community to focus on the infrastructure, both tangible and intangible, necessary for a dynamic U.S. program. Specific recommendations for developing that infrastructure are presented in the 2009 and 2010 workshop reports (Walton et al, 2009, 2010).

One impediment to a dynamic US CSD program is the lack of understanding among some Earth scientists of the advantages of drilling as a means to collect high quality samples and data. This can only be overcome through organized planning efforts, preferably focused on individual coherent topics that emphasize the scientific advances that can be achieved only through drilling. This problem can also partially be solved by educating potential investigators, beginning with early career investigators and students, who should be involve in open topical planning efforts.

Two additional operational challenges facing the CSD community are the cost and complexity of major drilling projects and the lack of necessary resources for drilling operations. Overcoming these obstacles requires a central organizing facility that promotes the community while providing the expertise in management and operations. The DOSECC facility in Salt Lake City, or a similar facility, could provide the necessary expertise, management, equipment, and personnel. This would allow scientists more time to focus on the scientific aspects of projects and eliminate the need for investigators to master the engineering operations and management details associated with drilling.

Unavailability of funding is perhaps the largest impediment. National science budgets, including that of NSF, are flat or slowly rising. The ICDP is working to gradually grow its assets with incremental increases in country contributions of its members. When selecting projects to fund, some agencies impose difficult conditions; DOE, for example, requires significant cost-share from non-federal sources for its projects.

Geoscience education generally does not include training in the advantages of drilling for gathering samples and data, and U.S. geoscientists have not universally embraced drilling as a key component of their research. This state of affairs and the perception that drilling costs are high have led to a lack of understanding in many instances, at best, and hostility, at worst, among those who review proposals for funding. The CSD community needs to do a better job of educating the scientific community and of imbuing students with an appreciation of the utility of subsurface samples. DOSECC has made a considerable effort to work with students through its internship or small grants program. In the past, that program has been funded from DOSECC’s own resources, but the current DOSECC cooperative agreement with NSF includes funding for additional interns.

Due to the high cost of drilling, it is important to preserve as much of the samples and other data from each project as possible. Current initiatives are directed at retaining data and making them available to all comers. LacCore provides facilities for study and sampling of cores from lake projects and stores the cores for future use. However, no such single facility exists to curate, store, and study hard rock cores, such as the 10 km or more from the Newark Basin Project or...
the 3+ k of HSDP core. While these cores are in fact safely stored, they are in different facilities and can be difficult to track down. Storage of cores and other samples from drilling projects should be addressed in a straightforward fashion, and ongoing efforts to catalog data and make it available should be monitored and strengthened as necessary.

SUMMARY

For certain kinds of scientific investigations, there is no substitute for samples obtained through drilling. Several Federal agencies, including NSF, DOE, USGS, and NASA, have strong interests in science based on drilling samples and data. The success of drilling in the United States, and on U.S.-involved international projects, is dependent on the efforts of a U.S. drilling community whose strengths and weaknesses lie in its diversity. On one hand, the community is so diverse that it is drawn in different directions intellectually and has not yet spoken with an effective single voice. This diversity can limit the community’s ability to agree on an overall CSD science plan needed to identify new capabilities; to establish the planning process, necessary facilities, and equipment; and to create a structure to oversee the community and its activities, including educational and outreach activities. On the other hand, diversity can lead to collaborations between individual projects that span many disciplines. While scientific planning should focus on individual topics, it also should be an open process that deeply involves parallel entities and overlapping communities as well as participation of members of other interested topical groups within the CSD community. The key to a successful US CSD is finding the right balance between competing interests.

PROGRAM VS. FACILITY OPTIONS

The current funding model for continental drilling by the U.S. academic community presents many problems. Science proposals with drilling requirements compete in interdisciplinary programs with drilling costs included in the overall science costs. DOSECC drilling costs are excluded from the Instrumentation and Facilities funding pool. As a result, the cost is born by the program supporting the science. Because drilling is inherently expensive and risky, such programs are less likely to be funded given that, for example, four to five other science proposals might be funded for the equivalent cost of one scientific drilling project. Pressure on program managers to maintain a balanced portfolio of funded projects places limits on drilling ventures. Most scientists who use drilling as a tool for research would agree that U.S. science projects have a hard time getting off the ground not because of a lack of competitive ideas but because of the lack of initial and matching funding. It is simply difficult for U.S. scientists to access a fair share of the significant contribution NSF makes to ICDP because of the structural impediments they face in getting the additional matching funds from NSF that ICDP requires. This is undoubtedly the major reason U.S. scientists are falling behind their peers in other countries like Germany, and perhaps Switzerland, who have access to dedicated CSD programs (so called “priority programs” of about 1.7 to 2.0 M Euro in Germany) that are working—without structural impediments—in concert with ICDP. While no one disputes the merits of our peer review system, there is a growing history of projects approved by ICDP that lack U.S. participation because scientists could not acquire NSF support in a timely fashion (e.g., Laguna Potrok Aike). Retaining NSF’s status quo system of funding CSD projects and infrastructure is likely to foster the long-term decline and eventual demise of CSD-based research in the United States. This should not be considered a viable option as long as international scientific leadership is a goal of NSF.

Therefore, the charge to the U.S. drilling community under the leadership of DOSECC is to develop a viable model for a U.S. CSD facility that matches stable resources to common goals. The scope of these common goals, at both national and international levels, ultimately will dictate the path of CSD. Unless a robust partnership can be solidified that leverages science funding (NSF) with mission-agency funding (e.g., USGS, NASA, DOE), NSF and these agencies will continue to go it alone. There are challenges to both the partnership and independent options up for consideration. Four possible strategies can be imagined for future support of a viable US CSD initiative, which we have outline below:

1. CSD program option—with this option, NSF-EAR would establish a CSD program analogous to IODP, with a fulltime operator supporting a number of drilling projects per year. This program would provide full planning and community support, from site surveys to key support facilities (logging, core and sample storage, data management) and science. Membership in ICDP would continue to be supported by NSF.
   
   Pros:
   
   An advantage of this option is that it would furnish the community with virtual “one stop shopping” for carrying a drilling project from the exploratory phase to completion. This option also
would provide important continuity for key supporting infrastructure and would facilitate the development of a programmatic-driven science plan (under some circumstances, this may be considered a con).

**Cons:**

A disadvantage of this option is that potentially it may be too costly if not nourished by new resources from NSF. Moreover, it is possible that the goals of a science-driven drilling program might not be easily tied to the needs and priorities of core programs elsewhere in NSF.

2. **CSD facility option with set asides**—With this option NSF would continue base support for DOSECC or a DOSECC-like organization, and NSF alone would support site survey costs and drilling operations along with key drilling support facilities (logging, core and sample storage, data management) separate from the science programs. Science costs for post-drilling analysis and borehole instrumentation would still be supported separately by core programs within NSF and compete with other science goals for funding. ICDP membership would continue to be supported by NSF.

**Pros:**

The advantage of this option is that funding is directed to drilling with funds set aside to match demand driven by the community. This would allow for some year-to-year flexibility and would make it easier for core programs to support drilling projects. This option would, in theory, provide more continuity of funding to CSD for key supporting infrastructure.

**Cons:**

This option would probably become more costly than the status quo (see beginning of section), but less than the CSD program option above (how much is not clear); for projects to go forward under this option, they would be dependent on core programs and NSF EAGR-type grants for science/site survey funding.

3. **CSD program option with joint science and mission agency collaboration**—Following this model, NSF, USGS, NASA, and DOE would jointly establish a CSD program analogous to IODP, with set asides, a full time operator and support for a number of drilling projects per year. The program would collectively provide full planning and community support, from site surveys to key support facilities (logging, core and sample storage, data management) and science. U.S. membership in the mission of ICDP would continue to be supported by NSF. This would leverage shared costs across the federal government.

**Pros:**

The “one stop shopping” aspect of this proposal provides continuity of provisions for key supporting infrastructure to drilling. It potentially enables the development of a programmatic-driven science plan. Most important is the concept of potentially shared costs, i.e., leveraging, in which science might be tied to needs/priorities of core programs and missions across the federal government.

**Cons:**

Coordination and shared objectives may be very difficult to manage. Science plans might be too restrictive to maintain the support of agency partnerships that would have periodic changes in executive branch priorities.

4. **CSD facility option with joint science and mission agency collaboration**—In this model NSF, USGS, NASA, and DOE would support U.S. membership in ICDP, NSF, USGS, NASA, and DOE would provide the base support for DOSECC or a DOSECC-like organization. EAR would lead the coordination of drilling operations and key facilities (logging, core and sample storage, data management), with funds separate from science programs; However, science costs would still be supported by core programs.

**Pros:**

Drilling and science targets would be demand driven and flexible; access to set asides would make it easier for core programs to support drilling projects, resulting in more continuity of funding for key supporting infrastructure.

**Cons:**

This option would likely be more costly than status quo, but less than the CSD program option above (how much is not clear); projects would remain dependent on core programs for science/site survey funding.

**CREATING A PATH TO SELECTING AN OPTION**

Selection among the US CSD options laid out above would commence with strategic decision as to whether to chose a facility or program support strategy and who should lead the initiative. Beyond these fundamental choices, the U.S. drilling community and fund-
ing agencies must be prepared to consider a number of key matters that were raised during the breakout group discussions. These include:

- Management Issues: How would a US CSD program be administered?
- Interagency collaboration: What would be the role and protocols of the ICG if NSF were to take on the management role?
- Future Science Objectives: Would annual theme-based workshops or one large community workshop suffice to both match and sustain scientific vs. mission-based agency drilling needs with proposal deadline anniversaries?
- Emerging Challenges
  - Data and metadata management, e.g., “Earth Cube” and IODP-like Drilling Leg reports
  - Cross-platform proposals: How would proposal reviews and panel administration be handled?
  - Cuts in federal programs: The known unknowns within federal budgets and competing program needs.
- International Concerns
  - By what means can the U.S. community and a new US CSD be better leaders and collaborators while developing stronger partnerships?

Many of the concerns here can only be articulated into a management framework after NSF and other federal agencies have determined how much they are willing to share in facilitating and promoting the success of a US CSD program or facility. It is clearly the opinion of the workshop participants that this new program needs to be transformative and assertive within the scope of federal mandates.

The preference of the workshop participants was multi-agency support for a US CSD facility with DOSECC or a DOSECC-like company as the implementing organization.

One might imagine that a US CSD facility would be somewhat analogous to the University-National Oceanographic Laboratory System (UNOLS). At present, however, the physical facilities and infrastructure are much less established for continental drilling, particularly for certain types of projects and site-survey types of projects. Moreover, it is not clear how a facility might fund pre-site survey and other drilling science that is required for any readiness review of a drilling proposal. The facility would also need to establish a peer-reviewed clearing process—now so commonly lacking—in which non-scientific expenses of pre-site survey and drilling planning would have to be justified. A well-supported facility model in partnership with mission agencies would allow US CSD to facilitate outstanding affordable science within individual NSF programs.

As with the Polar Programs or Ocean Sciences, reviewers of science proposals are not asked to evaluate the base logistical costs lying behind the science. Similarly, in seismology or oceanography, NSF-funded researchers have access to separately financed, but otherwise dedicated sets of instruments (seismometers, active sources and ships). In the case of seismology, investigators can borrow these tools for the cost of shipping. If the operational costs for these NSF-funded activities were evaluated on a proposal-by-proposal basis (as is the case with scientific drilling), they too would suffer significant impediments to research funding. Continental drilling faces similar large-project funding issues to these science programs. While continental drilling has similar potential benefits to science and society, at present it stumbles along with the shackles of having to justify all logistical costs to reviewers in programs with broad interdisciplinary portfolios.

Many European programs can fund both science and drilling operations. The German Geological Survey, for example, sets aside funds for national drilling targets with science that is shared with academic institutions. As is true for many U.S. investigators, success for European investigators with proposed drilling sites outside their own country requires shared multi-national application to the ICDP, and sites must qualify as world-class science targets of international significance. While interactions with ICDP are necessarily required, the German program allows for the leveraging of funds from other nations. A US CSD facility, in any case, would need to accommodate both national and international projects, the latter in partnership with ICDP. Opportunities for commercial and scientific partnerships remain possible via either a US CSD or the ICDP.

To ensure the success of any US CSD vision, there must be a dedicated program/facility manager at NSF who is cognizant that drilling costs are variable and challenging due to variability in fuel, steel, and exchange rates, etc. The program manager would have to...
be someone willing to react to changing ground contingencies. Most importantly, the program manager would have to be a strong advocate at NSF to garner science partnerships from core programs and also be an advocate with the ICG, to help guide and evaluate proposals. Above all, that person would have to be a liaison who could work directly and proactively with the ICG on matters of cross-agency science interests, vision, and evolving priorities. Such a program manager likely would require a knowledge of drilling science and an advisory panel to help sort out projects across disciplines and encourage cross-disciplinary research. ICDP’s Science Advisory Group (SAG) may provide a model for such a panel because it draws expertise from across the Earth sciences yet has been highly successful in providing informed opinions for ICDP’s Executive Committee and Assembly of Governors.

REQUIREMENTS FOR MAINTAINING A STABLE CSD PROGRAM OR FACILITY

Stability in any federal program is realistically an elastic target, more akin to the notion of sustainability than something fixed. Nevertheless, any model, robust program matches stable resources to goals. The NSF Large Facilities Manual (2011b) clearly lays out the necessary policies and requirements for developing a large facility, starting with qualifications, goal setting, and documentation and including downstream requirements for consideration. Mature programs like IRIS serve as models for a US CSD facility. Much of the justification and impetus needed for a facility is articulated in this workshop report and those from 2009 and 2010 (Walton et al 2009; 2010).

The first step in developing any program or facility would be an Exploratory Implementation Phase to define the technical requirements of the US CSD and the roles of NSF and the ICG-member agencies. Looking forward through the next decade, this phase would aim to define the following:

- The appropriate equipment pool for CSD projects
- The costs of different classes of drill rigs (CapEX, OpEX)
- Annual operations & maintenance (O&M) costs
- Rig staffing requirements and modes of operating (e.g., 24/7 vs. something less ambitious)
- Common attributes of similar CSD projects for different types of targets

- Definitions of small, intermediate, and large projects
- Cost, scope, and technical complexity of the US CSD facility

A second step would be to develop a funding model at NSF, with or without leveraged funding from other agencies. Because of its very nature, the collated needs of a US CSD program or facility would include the capacity to fund a range of small, intermediate, and large projects per year. That is, shallow drilling needs of the CZOs and single PI projects, hypothetically, would have to be balanced and sustainable alongside larger, deeper drilling projects with multiple PIs for geothermal, hazards, or lake drilling projects. Visualizing a portfolio of projects over the life of a five to ten year program helps to forecast how this might be achieved.

Tables 3 through 6 (produced by F. Rack,) illustrate hypothetical scenarios that describe the potential funding of individual CSD projects and various versions of a 10 year-long program of CSD. This model establishes a range of funding (from low to high values) for each category and a funding distribution of the duration of each award, but keeps the duration the same for each award category in both the low and high value scenarios. Table 4 illustrates one hypothetical budget scenario using the high values for funding in each category to develop a 10-year-long budget. This budget assumes a base budget of $1,000,000/year for a US CSD facility, but the numbers could also be used for an “almost big” project. Table 5 presents a hypothetical 10-year budget scenario with an emphasis on a large project as part of the mix rather than the facility background funding outlined in Table 2. Table 6 is a similar scenario but skewed toward smaller projects. These tables demonstrate a means of distributing funding over a period of years (up to five years) for each award. As such, the program manager(s) would have a lot of freedom in determining how this distribution actually works for each grant. With experience, there would likely be other options.

RECOMMENDATION OF THE WORKSHOP

The impetus for a new cost effective US CSD facility or program could not be greater than it is now. The energy needs of our cities and towns must be in balance with the knowledge of environmental change as geologic hazards, including floods, drought, earthquakes, tsunamis, volcanic eruptions and sea-level rise threaten populations and homelands around the world. Fundamental knowledge of our Earth’s history
Table 3. Hypothetical model relative to duration and project size.

<table>
<thead>
<tr>
<th>Project Size</th>
<th>Grant Size (Low)</th>
<th>Duration (Years)</th>
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Table 4. Hypothetical scenario for CSD funding including a $1 Million/year facility budget.

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<th>Y3</th>
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<th>Y5</th>
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Total: $15,000,000
Table 5. Hypothetical distribution of CSD projects for a decadal program with focus on larger projects.

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<th>CSD Example Budget</th>
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Table 6. Hypothetical distribution of CSD projects for a decadal program with focus on small projects.

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TOWARD A STRATEGIC PLAN FOR A U.S. CONTINENTAL SCIENTIFIC DRILLING PROGRAM 25
is still unknown. Scientific drilling represents one of the most promising means we have to extract critical information to understanding Earth processes in situ, to collect records of Earth’s history, and to provide predictive measures and sound knowledge that can be used to protect citizens as we also seek sustainable resource practices.

A strong US CSD facility could be built and justified based on the transformative impacts data generated through drilling has on science. The first step requires an exploratory development phase to plan administrative and budgetary procedures and technical drilling requirements as well as to establish a modernized ICG to guide the process. Budgetary planning must go hand in hand with programmatic science development involving stakeholders of the ICG and the wider science community. Theme-based workshops are currently being planned by the DOSECC SPC to foster this process. More importantly, NSF, in partnership with other U.S. governmental agencies interested in US CSD, urgently needs to begin the process of reinvigorating continental scientific drilling through a program of sustainable funding as well as operational and intellectual support.

One outcome of the workshop was the development of four different funding models for supporting a U.S. continental scientific drilling program. These include an NSF-sponsored CSD program, an NSF-sponsored CSD facility with set-asides, a CSD program jointly supported by NSF and other mission-specific government agencies, and a CSD facility jointly supported by NSF and other mission-specific government agencies. All of these options could be developed within the auspices of a new ICG.

As representatives of the U.S. scientific drilling community, we believe that an NSF facility option, possibly in collaboration with science mission-oriented government agencies, offers the best option as a cost-effective way to reinvigorate U.S. continental scientific drilling for years to come. We recommend that plans move into an exploratory phase with the promise to develop an implementation phase in the near future.

**REFERENCES**


**ACKNOWLEDGEMENTS**

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Andy Cohen  University of Arizona
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Back cover:

Center: Drill-site science crew logging core at the Mountain Home site.

Lower: USU Staff Geologist J. R. Hoggan holds a core sample from the Mountain Home site showing the contact between lake sediment below and basalt below at a depth of 2400' (731.7 m).

Upper: Zeolites in the Kimama core at 1402 m depth.