CLOSING THE GAP BETWEEN STATE OF THE ART AND STATE OF THE PRACTICE IN SUBSURFACE CHARACTERIZATION AND MONITORING

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ABSTRACT

The Idaho National Engineering and Environmental Laboratory and the Lawrence Berkeley National Laboratory are launching the Consortium for Research on the Earth's Subsurface (CORES), intended to provide solutions to society's critical problems associated with the Earth's subsurface. The product of CORES is a significantly funded, sustained, nationally integrated program of subsurface science research that addresses critical national problems and is supported by the science and engineering community, industry, policy-makers, regulators, and stakeholders. The research agenda is a consortium-based effort to (1) integrate, accelerate, and stage currently funded, as well as proposed, subsurface research, (2) focus on new aspects of what is needed to produce step, rather than incremental, changes to the current level of understanding with respect to the Earth's subsurface, (3) involve interdisciplinary teams of researchers through a continuous, sustained investment in subsurface research, and (4) target the research toward solving critical national problems. This white paper builds upon the ideas presented at the first two workshops in the CORES series—the Coupled Processes Meeting held on July 30 and 31, 2003 at Lawrence Berkeley National Laboratory in Berkeley, California and the Challenges in Subsurface Characterization, Imaging, and Monitoring Workshop held on September 24–26, 2003 in Salt Lake City, Utah. The motivation and approach for moving forward with these ideas is provided herein.

MOTIVATION FOR CORES

The future health and economic welfare of Earth's population depends upon a continuing supply of uncontaminated water, clean air, and available energy resources. Yet throughout the 20th Century, environmental damage outpaced scientific understanding of Earth processes. By 2020, one-third of the world's population may lack access to safe and clean water, air, and energy. Without a concerted effort to improve understanding, our society may lack sufficient solutions for:

- Contaminant transport
- Oil and gas exploration
- CO_2 sequestration
- Precision agriculture
- Ecohydrology
- Engineering applications.

Unfortunately, the nation is underinvesting in research in the physical sciences and engineering. Adequate understanding and management of subsurface resources and processes are key to ensuring the sustainability of human life on Earth, but presently there is:

- A limited understanding of subsurface properties, processes, parameters and the coupling among processes,

- Inadequate technology for characterizing subsurface properties and heterogeneities,
- A lack of comprehensive data sets for model calibration and validation, and
- An incomplete understanding of how to apply laboratory data to field-scale problems.

The Consortium for Research on the Earth's Subsurface (CORES) is a multi-disciplinary, multi-agency research initiative launched by the Idaho National Engineering and Environmental Laboratory (INEEL) and the Lawrence Berkeley National Laboratory (LBNL) to strengthen research and find solutions to the critical problems associated with the Earth's subsurface. The mission of CORES is to ensure energy security and environmental protection by improving the understanding of subsurface processes applicable to:

1. Water resources management
2. Environmental remediation
3. Sustainable agriculture
4. Energy production
5. Climate change
6. National security
7. Planetary exploration.

To achieve this mission, a coordinated, sustained, and sufficiently funded research effort is required to make timely and noteworthy advances on national problems in these areas.

Water Resources Management

Protecting our aquifers from contamination and developing a sound basis for the management and protection of water resources is necessary to ensure the availability of clean water supplies. Among the issues on which CORES will focus is the contamination of ground and surface water from past industrial, defense, mining, and agricultural practices. Many former mining communities no longer receive the economic benefit of extractive industries, but they are responsible for cleaning up hazardous substances from closed or abandoned mines. Dairies and livestock feeding operations near suburban areas could impact the quality of drinking water. A resurgence of fossil fuel exploration, including drilling for coal bed methane gas, will necessitate new methods of managing low-quality groundwater brought to the surface in the production process. State and local agencies are requesting improved tools, methods, and analytical support for conducting environmental assessments, engineering system analyses, advanced remediation and treatment technologies, and low-cost monitoring techniques. Understanding the interrelation between contaminants and subsurface structures, properties, and processes is necessary to be able to predict, control, and mitigate transport and migration of contaminants into our aquifers. Given the present state of knowledge, we cannot guarantee that subsurface contamination will not end up in our water supplies.

Environmental remediation

Subsurface geoscience directly supports environmental cleanup and long-term stewardship needs by providing the scientific underpinnings necessary to:

- Characterize the subsurface geology and buried waste
- Accurately locate and identify subsurface fluids and contaminants, including phase and partitioning [DNAPL (dense nonaqueous phase liquid), water, gas, metals, rads, etc.], relative quantities, transport mechanisms, etc.
- Formulate and test computational models of subsurface processes

- Reliably predict the fate and transport of nuclear, chemical, and biological agents in soil and groundwater
- Improve our understanding of subsurface processes applicable to predicting the behavior and enabling cost-effective, safe management, and treatment of contaminants in the subsurface
- Safely contain hazardous materials and remove buried waste that poses an unacceptable risk
- Manipulate physical, chemical, and microbial conditions to remediate or destroy mobile contaminants
- Validate and verify system performance and cleanup levels for regulators and stakeholders.

Understanding the fate and transport of subsurface contaminants will help us design engineered solutions and systems to protect the ecosystems and the public in a timely and cost-effective way. Current methods for providing long-term stewardship are neither cost-effective nor reliable. Residual contamination remaining after cleanup will require management strategies beyond the capability of current technologies. Advances in science and technology are required to eliminate or otherwise mitigate the hazards associated with long-lived substances in the subsurface.

Sustainable Agriculture

Sustaining a high level of agricultural productivity while protecting the quality of soil and water is essential to our survival. Our agricultural industry relies upon the use of fertilizers, pesticides, and herbicides that can contaminate the soil and migrate into the water table. The ability to measure, predict, and quantify the effects of biological, chemical, and physical properties will enable us to optimize utilization and assess impacts of these chemicals. A proposed interdisciplinary research team might consist of an agricultural scientist, a groundwater biologist, a geologist, an ecologist, and an ecosystem scientist, with participation from a local farmer.

Energy Production

Our population requires access to inexpensive, reliable energy supplies to maintain our standard of living. There is a need to develop and deploy efficient and clean energy technologies that meet our nation's energy needs, enhance our environment, and strengthen our national competitiveness. A portfolio of different energy sources (fossil, hydropower, renewables, nuclear, etc.) is necessary to ensure an adequate supply of safe, reliable energy. Of these, the geoscience-based energy resources include nuclear, coal, oil, gas, geothermal, and gas hydrates. There is a role for nuclear energy in electricity and hydrogen production. Subsurface issues play a role in power plant siting, waste heat rejection, and radioactive waste disposal. New science can aid in the identification and characterization of subsurface reservoirs and also yield improvements in extraction efficiency. Identification, characterization, and recovery of new fossil fuel reserves is essential, since much of our fossil fuel supplies are purchased from countries with unstable political situations. Natural gas hydrate contains highly concentrated methane, which is a promising energy resource. Gas hydrate is found in suboceanic sediments in the polar regions (shallow water) and in continental slope sediments (deep water), where pressure and temperature conditions combine to make it stable. The worldwide amount of methane in gas hydrates is about twice the amount of carbon held in all fossil fuels on Earth.

Climate Change

Efforts to mitigate climate change rely on accurate interpretation and prediction of processes controlling carbon cycling and sequestration. Data is needed that will enable an objective assessment of the potential for, and the consequences of, climate change at global and regional scales. Such data feeds into quantitative models and enable predictions of the net exchange of CO_2 between the atmosphere, land, and oceans. Mitigation options to prevent human-caused climate change rely on understanding the basic physical, chemical, and biological processes of the Earth's atmosphere, land, and oceans and how these processes may be affected by energy production and use. Environmental implications of sequestering excess atmospheric carbon dioxide in terrestrial ecosystems and the ocean must be assessed. Also, once CO_2 is sequestered, the challenge is how to ensure that it remains locked up.

National Security

The events of September 11, 2001 were a wake-up call to our nation. Knowledge advances in the subsurface sciences can play a role in strengthening our national security. Effective ways of detecting radioactive, biological, and chemical agents (including buried landmines) in the subsurface are needed. Underground siting of defense installations and nuclear power plants to defend against enemy/terrorist attacks are being proposed. Improvements in subsurface sensing technology could allow detection of illusive and buried targets.

Planetary Exploration

The search for subsurface water has become a primary focus of planetary exploration. Its abundance and distribution (both as ground ice and groundwater) have important implications for understanding the geologic, hydrologic, and climatic evolution of the planet, the potential origin and continued survival of life, and the accessibility of a critical in situ resource for sustaining future human explorers. Any exploration activity (such as deep drilling) whose success is contingent on the assumed presence of subsurface water must be preceded by a comprehensive high-resolution geophysical survey capable of assessing whether local reservoirs of water and ice actually exist. A principal goal of the Mars science, astrobiology, and human exploration programs is to determine the three-dimensional distribution and state of subsurface water at a sufficient resolution.[1] Objectives of subsurface exploration of Europa (a satellite of Jupiter) is to provide scientific access to the hypothesized subglacial ocean. Images of Europa's surface strongly resemble images of sea ice on Earth. It is possible that beneath Europa's surface ice there is a layer of liquid water, perhaps as much as 50 km deep, kept liquid by tidally generated heat. If so, it would be the only place in the solar system besides Earth where liquid water exists in significant quantities.[2] Terrestrial experience has shown the the accurate interpretation of such data is likely to require the application of multiple geophysical techniques.[3]

FUNCTIONS OF THE RESEARCH AGENDA

The functions of the national subsurface science research agenda proposed by CORES are to (1) integrate, accelerate, and stage currently funded, as well as proposed, subsurface research, (2) focus on new aspects of what is needed to produce step, rather than incremental, changes to the current level of understanding with respect to the Earth's subsurface, (3) involve interdisciplinary teams of researchers through a continuous, sustained investment in subsurface research, and (4) target the research toward solving end-user problems. A consortium-based, rather than an individual-investigator driven approach will ensure efficient and effective discovery and lead to the transformation of new knowledge into results. CORES research will aim to produce breakthrough solutions that will reduce risk and cost, address technology needs and gaps, and strengthen science capabilities. CORES participants will collaborate across institutional boundaries to ensure that the best solutions are achieved and that diverse, multidisciplinary capabilities are utilized in a focused national collaboration.

Integrate and Coordinate Research

This effort should integrate the individual pieces of research currently being performed at various institutions and identify the missing pieces that tie together lines of existing research. By pulling the topics together and orchestrating them, rather than just ramping up the funding, the impact can be magnified. Much of the fundamental subsurface environmental research traditionally funded by the federal government consists of individual investigator-initiated projects. Although individual projects may provide outstanding research results, the full benefit of the collection of projects is not realized because the synergism among projects is not well developed. New knowledge can be integrated through a coordinated mix of theory, experiments (bench and laboratory-scale), intermediate scale testing, field scale work, simulation, and modeling.

Tie to Other Programs

The research to be performed can be directly linked to research programs, such as the Department of Energy's (DOE's) Genomes to Life (GTL) program. The GTL program is researching various microbes to carry out DOE's mission of energy security, environmental cleanup, and climate change. CORES will produce new knowledge of the subsurface conditions important for microbes, such as (1) Methanococcus jannaschii, which produces methane, an important energy source, (2) Deinococcus radiodurans, which can survive high levels of radiation and holds promise for radioactive waste cleanup, and (3) Thalassiosira pseudonana, an ocean diatom that participates in the biological pumping of carbon to ocean depths and has the potential for mitigating global climate change.[4] Research at the interface between life science and physical science can yield new insight into subsurface processes. The Ocean Observatories Initiative [5,6] represents an effort parallel to CORES, but in a different medium.

Enable High Throughput

The pace of current research must be accelerated in order to produce step changes to the current level of understanding with respect to the Earth's subsurface. High-throughput approaches, technologies and user facilities would enable the research community to obtain results more rapidly, and in turn transfer the results to end users for timely implementation.

Stage the Research

Different technologies needed at different times may enable the research to be staged for optimum efficiency. Some problems can be broken down into subproblems that can be solved independently and the results combined.

Focus on New Aspects

CORES must focus on new aspects of what we need to move forward in order to advance our understanding of the subsurface. We need to redefine the ways that subsurface geoscience research is conducted and, ultimately, how research leads to improvements in understanding and prediction. New approaches and new facilities offer the potential of overcoming scientific barriers. Novel experiments can produce data that will revolutionize our perspective of the subsurface. Innovations in approach, tools, and technology that will significantly advance our ability to characterize and model subsurface processes must be identified. Development of new experimental and computational methods, tools, and capabilities are required to assimilate, understand, and model the data at the appropriate scales and levels of complexity. Comprehensive simulation and new modeling tools must be able to incorporate diverse data sets. Advanced analytical techniques to understand chemical and biological processes at the molecular level are needed to provide insight into the microbial "machines" being tapped for their biochemical capabilities.

Use Interdisciplinary Teams

Subsurface environmental research needs are by their nature interdisciplinary, since natural systems do not function neatly within individual scientific disciplines. Researchers must therefore work across the boundaries of traditional scientific disciplines to make progress.[7] Traditional funding resources are typically not adequate to support sustained the research and/or exploration of large interdisciplinary teams. Individual investigators generally lack the breadth of experience to understand all aspects of the problem; thus, a wide range of expertise is required, involving knowledge of geological, biological, hydrological, geochemical, and thermal processes. To significantly advance scientific discovery, integrated interdisciplinary teams are required. This effort will link the research being performed at various institutions (i.e., national laboratories, federal agencies, universities, and private companies), since no single institution has all the required expertise or facilities to address all subsurface environmental research needs.

Provide Continuous, Sustained Funding

All the stages along the path from inception through deployment need a continuous, sustained investment in order for promising approaches to develop into breakthroughs. Without the government's involvement and funding commitment, market forces alone are insufficient to drive the necessary advances in this field. Uncertainties in policy and funding levels have been impediments to making rapid progress. The infrastructure needed to implement the research agenda transcends the budget of a single university or national laboratory. Ample funding must be allocated to create and improve existing facilities to carry out cutting-edge research.

PATH FORWARD

To establish the consortium, we envision a multiyear effort—in the first year, defining the initiative, the participants, and establishing an Advisory Committee; in the second (and most critical) year, defining the crosscutting science behind the research agenda and writing proposals; and in the third year, commencing research. The Advisory Committee is comprised of nationally recognized experts that will provide strategic direction to CORES, as well as champion, guide peer review and coordinate proposals. With the assistance of the Advisory Committee, the goals, priorities, and scope of the CORES effort will be clearly defined. These clearly stated goals will guide the development of the research agenda and ensure that CORES addresses the most critical subsurface issues. These goals will enable prioritization of the proposed research outlined in the research agenda. Specification of a compelling, limited set of priorities is essential to accelerate progress across the spectrum of the subsurface geosciences.

CORES should be structured according to the nation's environmental, national security, and economic challenges. The national problems to be solved will be defined by representatives from government, industry, and the science community. An example of such a national problem is the need to increase the extraction efficiency of energy resources. The agencies that will be a part of CORES and the champions within each agency to support CORES must be identified. The concept of a national research agenda in subsurface science needs to be presented to the various Federal agencies and their participation solicited. A challenge will be to overcome the cultural dynamics of the different organizations and pull them together under a common framework. Early involvement of stakeholders and regulators is essential to the success of CORES.

The national subsurface science research agenda will address the scientific problems and knowledge gaps that underlie a range of subsurface problems faced by society today and also in the future. Key questions to guide development of the research agenda are:

- What are the most pressing subsurface science (environmental, energy, and national security) challenges?
- What are the roadblocks to progress, and what must be done to overcome them?
- Which efforts are beyond the mandate of principal investigator-driven research as currently funded by government agencies but could be the responsibilities of a national initiative?
- What step changes in understanding are most needed?

The new knowledge needed to provide solutions to the national problems will be identified at three levels: fundamental science, enabling technology, and engineered systems. The fundamental science level consists of developing the physical and mathematical framework to understand, quantitatively predict, and manipulate subsurface processes. This level provides the science necessary for an enabling technology to rise to the engineered system level where it can be implemented or deployed. Enabling technologies are tools, facilities, or capabilities that can eliminate some of the present barriers to obtaining solutions to identified problems.

Table I Structure for subsurface science strategic research.

Level 1	Fundamental Science	Develop ability to understand, predict, and manage	New physical/mathematical framework
Level 2	Enabling Technology	Use a validated physics-based approach	Testbeds and models to validate framework
Level 3	Engineered System	Apply new knowledge to real-world problems	Systems and solutions for subsurface problems

CROSSCUTTING RESEARCH AREAS

CORES research will focus on unifying topics to leverage the research investment. The knowledge necessary to remove subsurface science roadblocks faced by the national problems specified above can be grouped into crosscutting issues, and workshops will be conducted on each of these crosscutting issues. Research areas which cross cut the national problems include (1) characterization, imaging, visualization, and monitoring of subsurface structures, properties and processes, (2) multi-scale representation of ecosphere parameters and processes, and (3) subsurface coupled processes. We must pool our resources if we are to make progress to remove roadblocks common to these areas.

Characterization, Imaging, Visualization, and Monitoring of Subsurface Structures, Properties, and Processes

The development of advanced imaging and visualization methods can improve our understanding of subsurface fluid flow and distribution. Advanced imaging will not only require better definition and fundamental understanding of how mechanical and electrical energy couples and interacts with Earth materials, but will require new measurement technologies and computational methods to properly analyze and interpret the results, i.e., research in theory coupled with laboratory and field studies, supported by new measurement methods, incorporated into realistic models, and all leading to an accurate representation of the subsurface. Improvements in resolution and data interpretation for geophysical imaging and multi-scale, multi-sensor data integration are needed to identify and characterize subsurface structures, properties and processes. Our ability to see beneath the Earth's surface and image properties and processes taking place therein is extremely limited and wholly inadequate to study the complex processes occurring.[8] For example, there is no known way today to image a specified biotic community that might be degrading hazardous substances just a few meters beneath our feet.

Geophysical, geochemical, and other remote sensing tools must be developed and integrated better, including data fusion, to give us a much better picture of the subsurface. Inversion algorithms are needed to take multiple datasets and invert them to a common model that accurately describes subsurface properties. Links between experimental databases and computational models are needed to maximize our understanding of fate and transport of contaminants. Experimental data can be used to improve codes by enhancing their validity over a wider range of conditions. The design of experiments will rely upon insight provided by computational simulations and, conversely, the experimental data will be used to calibrate computer codes. The coupling of non-intrusive survey geophysical measurements (e.g., electrical surveys) with detailed quantitative precise point-sensor measurements (e.g., lysimeters and vapor-port systems) or borehole (e.g., nuclear magnetic resonance, neutron-based moisture, and geochemical tools) measurements can extend high-precision knowledge away from the borehole.[9] Models of sampling events and instrument response will be necessary to develop instrumentation and controls for remote, in situ sensor networks. Although advantages will undoubtedly accrue from evolutions in geophysics instrumentation, there is a need for a comprehensive investment that would accelerate that evolution.

Multi-Scale Representation of Ecosphere Parameters and Processes

Our current ability to predict and optimally manage fluid flow and contaminant transport processes in the subsurface is limited by inadequate understanding of many fundamental biological, geological, chemical, radiological, and physical processes that interact to effect contaminant behavior in the subsurface. Knowledge of contaminant levels and distribution throughout the subsurface is necessary to develop monitoring strategies. This includes investigation of dominant processes and interactions between processes that occur at different spatial scales, and reconciling the different spatial scales associated with measurements, physical processes, and numerical models. We do not understand how to couple non-linear processes that operate at much different length and time scales. For example, bacteria and chemistry operate at scales on the order of 10^{-6} m, whereas transport phenomena are described at scales on the order of 10^{-1} to 10^{-2} m. In addition, subsurface heterogeneities (natural and those created by waste interaction with the porous medium) that may influence the distribution of contaminants in soil and water are difficult to handle with common numerical schemes. The behavior of multiphase fluids in heterogeneous subsurface media and model prediction of processes over various length/time scales and uncertainty estimates are important issues to be addressed. Robust numerical techniques are needed that do not rely upon pre-defined grids and that can handle sharp contrasts. A methodology to assess error and uncertainties in conceptual models, input parameters, and boundary conditions is needed to assess the quality of the predictions. Our ability to predict the behavior of new systems depends on whether the models are built from generalizable knowledge reflected in the concepts and parameters that need to be measured.

Subsurface Coupled Processes

Ecosphere manipulation for sustainable resource usage and environmental remediation will require developing a fundamental understanding of subsurface coupled processes. An example of a CORES research area is the behavior of multiphase fluids in heterogeneous subsurface media. Fundamental to efficient and safe extraction and injection of fluids into the subsurface is accurate prediction not only of fluid phase, composition, and distribution, but also knowledge of flow paths, permeability, and the interaction among the physical, chemical, and microbial processes and properties.

A whole-Earth model to represent and visualize the subsurface system is being considered to integrate computational predictions of relevant processes with subsurface data. This model can be described as a virtual "flight simulator," giving the user a look into the current properties and processes in the subsurface. The ability to perform multiphase contaminant transport simulations at a waste site using a single code is important for evaluating remediation alternatives and estimating life-cycle costs. This model would rely upon a comprehensive subsurface database with information on different geologic environments and aboveground conditions. A robust scientific computing capability would help researchers to enhance understanding of the coupling between transport, driving forces, geology, geochemistry, and biology, effects from basic processes (climate factors, precipitation cycles, humidity) that serve as boundary conditions to the subsurface system.

As models become more realistic and comprehensive, they necessarily become larger and more computationally intensive. This creates two chokepoints. The first is that computers with greater speed and memory are needed. Supercomputers or massively parallel computers are needed to handle the multitude of chemical, physical, microbial, etc., variables and their spatial and temporal variations. Algorithms should be tailored to run efficiently on these computers. The second chokepoint is the visual representation of the output. A large number of parameters must be tracked in four dimensions (three in space plus time), making visualization of the data essential to understanding the physical phenomena being modeled. The Japanese-built Earth Simulator[i] (an NEC-GS40) was designed specifically to support geoscience applications (such as, weather and climate prediction, Earthquake simulations, and Earth mantle dynamics).[10] Certain classes of science can only be investigated on computers in the league of the Earth Simulator. Access to robust computational resources, including algorithms, hardware, networking, data sets, collaborative software, visualization capability, are necessary to significantly advance the current state of the art and practice.

WORKSHOPS

A series of workshops will be conducted to create a research agenda on the crosscutting issues. An agenda will be developed using a systematic approach for each common theme. A question-structured analysis will guide the development of the research agenda for each theme. The questions will be drafted before the workshops and refined at the workshops by the subject matter experts in attendance. The research agenda will be created by reviewing the revised list of questions and identifying critical knowledge gaps. Workshop products will include identification of the fundamental science and enabling technologies needed to ultimately provide engineered systems or solutions to the national problems being addressed by CORES. Proposals to carry out this work will be started at the workshop. CORES research proposals will:

- Address crosscutting technology needs and gaps in subsurface science that underlie critical national problems
- Develop focused lines of research aimed at addressing end-user problems
- Develop integrated, multidisciplinary technical research teams focused on removing crosscutting roadblocks
- Implement technical approaches that will lead to cost savings and accelerated application of the research investment to a myriad of issues
- Include a plan for getting the research results to the problem holders.

Appendix A presents a list of preliminary questions developed at the Challenges in Subsurface Characterization, Imaging, and Monitoring workshop to guide the development of a research agenda for characterization, imaging, and monitoring. Future workshops will be necessary to revise this list of questions and create the research agenda.

COMMUNICATION OF CORES INFORMATION

CORES research will focus on the end use of results and communication of solutions and successes for timely implementation. The new knowledge obtained by CORES research will be shared with policymakers, the scientific and engineering community, end users, technology implementers, regulators, landowners, the public, and other stakeholders. Ideas for effective communication are listed below.

Communication with Policymakers

Policymakers should be briefed on CORES plans and results. High-level commitment from people with good vision and broad representation is needed. CORES should learn from successful programs, such as Genomes to Life, Industries of the Future, etc.

Communication with the Scientific and Engineering Community

Activities to disseminate knowledge within the scientific and engineering community include:

- Holding workshops in conjunction with other national meetings and conferences
- Open panel discussion at a conference, such as the American Geophysical Union, Geological Society of America, or other related meetings
- Publishing the technical elements of the national research agenda in a journal article, such as Eos Transactions
- Researchers publishing findings in the peer-reviewed scientific literature
- Forming a subsurface science society
- Publishing a newsletter with recent research results, future plans, and other information
- Annual CORES investigator meetings held at the research centers.

Communication with End Users, Technology Implementers, and Regulators

Acceptance of new technology by regulators is critical. Activities to transfer new knowledge to the end users, technology implementers, and regulators include:

- Visiting problem holders and exchanging information
- Holding technology transfer meetings.

Communication with Landowners, the Public, and other Stakeholders

CORES must instill a sense of urgency to capture the public's attention and communicate the driving need for this research. A broad segment of the stakeholder community must be involved early. CORES must make the case why science and technology is necessary, i.e., the security of our quality of life, to avert an impending water crisis, and environmental sustainability. Activities to raise public awareness and recruit supporters include:

- Making the community at large aware of this effort by improving outreach and increasing public understanding of these issues (e.g., an ad campaign, science articles for general audiences, educating decision-makers, etc.).
- Disseminating information on the CORES Web site.
- The utilization of real-time data through the Internet could allow students, teachers, and the general public an interactive opportunity to understand and appreciate the relevance of subsurface science to their everyday lives.

- Exciting the public with new knowledge about the Earth's subsurface. NASA sends elaborate probes to investigate new frontiers, provides the data to the scientific community, and then tells the public about it. Geoscientists could capitalize upon this successful strategy by building a mobile laboratory that visits exciting sites on Earth and reports the results to both the scientific community and the public at large. Imagine what could happen if millions of schoolchildren followed the progress of a "RUBBLE" Earth laboratory as it visited Antarctica, Bangladesh, Siberia, South Africa, and Yellowstone National Park.

STATUS OF CORES

Two workshops on Earth science issues have been sponsored by the Idaho National Engineering and Environmental Laboratory and the Lawrence Berkeley National Laboratory. The Coupled Processes Meeting was held on July 30 and 31, 2003 at Lawrence Berkeley National Laboratory in Berkeley, California to discuss the effects of coupled hydrogeological-biological-geochemical-thermal processes, including their recognized and potential impacts on subsurface contaminant transport and remediation, and to address some of the grand challenges with respect to experimentation and modeling. The Challenges in Subsurface Characterization, Imaging, and Monitoring Workshop was held on September 24–26, 2003 in Salt Lake City, Utah. The workshop was composed of subject matter experts in subsurface characterization and monitoring, mainly with a geophysics focus. The purpose of the workshops was to introduce and gain support for CORES and to bring together the subsurface science community to begin formulating a national research agenda in subsurface science. Many of the elements of CORES outlined in this white paper were proposed by the workshop participants.

SUMMARY

We are running out of time! New paradigms must be developed for meeting the challenge of providing clean water, safe and reliable energy, and protecting our country, including the environment, natural resources, economy, and the freedom we enjoy as Americans. CORES proposes to form a critical mass in selected research areas to address major roadblocks, link fundamental research to applied needs, and transfer results to end users of technology. Achieving necessary understanding of the subsurface environment and developing predictive ability requires fundamental advances in basic and applied scientific knowledge, which can most efficiently be achieved from a consortium-based effort focused on the nation's critical environmental, energy, and security challenges.

ACKNOWLEDGMENTS

This work is sponsored by the U.S. Department of Energy under DOE Contract Numbers DE-AC07-99ID13727 and DE-AC03-76SF0098. The authors acknowledge contributions by the participants of the Coupled Processes Meeting held July 30 and 31, 2003 at Lawrence Berkeley National Laboratory in Berkeley, California and the Challenges in Subsurface Characterization, Imaging, and Monitoring Workshop held September 24–26, 2003 in Salt Lake City, Utah. Links to information regarding these workshops can be found on the CORES Web site, at http://www.inel.gov/cores.

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APPENDIX A

QUESTIONS TO GUIDE THE DEVELOPMENT OF A NATIONAL RESEARCH AGENDA FOR SUBSURFACE CHARACTERIZATION, IMAGING, AND MONITORING

Fundamental Science Questions

1. How can we understand the petrophysical relationships in the near surface?
    a. Measuring properties to use in models
    b. Scaling
    c. Spatial and temporal variability
    d. Hydraulic conductivity
2. How can we increase our fundamental understanding of geophysical phenomena in the near-surface environment? Example: seismic wave propagation in unconsolidated media
3. How can we improve our understanding of scaling to use in:
    a. Data integration
    b. Petrophysical relationships
    c. Understand the effect of multi-scale heterogeneity on geophysical response
    d. Is there a way to determine a priori the critical scale of characterization and scale of model development for the process at hand?
    e. Three levels of scale to distinguish are: (1) measurement, (2) physical process, (3) modeling scale.

4. How can we improve data integration, parameter estimation, and joint inversion? Incorporate newfound knowledge in petrophysics, scaling, uncertainty, and multiple sources of error.
5. How can we incorporate advances made in other disciplines?
6. How can we use "unconventional" signal sources? Examples are thunder, microseismics, power lines, muons.

Enabling Technologies

1. How can we make improvements in sensor technology? How to build and deploy sensors? How can we import and modify sensors for use in subsurface science? Ideas for improvement:
    a. Emplacement
    b. Better tracers
    c. Multiple scales
    d. Smaller (nanotechnology)
    e. Contrast enhancers
    f. Network arrays/communication
    g. Self-calibrating, self-healing
    h. Positioning communication (sensor to surface)
    i. Pressure
    j. Tagged tracers (chemical, biological)
2. How do you develop appropriate test beds at different scales for tool development, understanding processes and validating models?
3. How can we develop emerging technologies for use in the subsurface?
    a. How can we make these technologies cost-effective?
    b. Include a cost-benefit analysis
4. Regarding technology transfer, how can we develop approaches/techniques/ protocols to assist moving the state of the science to the state of the practice? How can the most effective protocols, guidelines, and education on deployment be developed for users?
5. How can we improve information management technology and data management/processes?

Engineered Systems

1. What tools are needed for long-term stewardship, regulatory, and waste management site management?
2. What are the end user solutions?
3. How can we develop integrated management and decision-support systems that combine data, predictive models, and visualization?

FOOTNOTES

[i] The Earth Simulator supercomputer is currently the fastest supercomputer in the world with a Linpack benchmark performance of 35.86 Tflop/s ("teraflops" or trillions of calculations per second). It became operational in April 2002 at the Earth Simulator Center in Yokohama, Japan.