Core-log-seismic integration in scientific drilling: Generating age-calibrated 3-D views of the crust.

Scientific drilling provides detailed, high-resolution, direct observations of the Earth's crust. Ocean drilling science has a long-running history, starting with the Deep Sea Drilling Project (DSDP, 1968-1983) and running through the Ocean Drilling Program (ODP, 1985-2003), continuing as the Integrated Ocean Drilling Program (IODP, 2003-present), and with growing ties to the International Continental Drilling Project (ICDP, 1996-present). Over the course of these drilling programs, intensive analysis of a wide array of global geological and geophysical systems has been accomplished, including:

- oceanic crustal architecture,
- tectonics and fluid flow along convergent and divergent plate margins,
- oceanic plateau composition, structure, age, and genesis,
- volcanic and non-volcanic rifted margin tectonics, structure, and evolution,
- sedimentary records of ocean circulation, climate change, and evolution,
- fault-zone geometry and dynamics.

As scientific drilling efforts expand in terms of technological capability, geographical reach, and scientific scope, new themes that arise out of past discoveries and research are driving the efforts of the scientific drilling community:

(1) physical and chemical processes that drive earthquakes and volcanic eruptions,
(2) global climate change and its driving forces,
(3) planetary-scale impacts and their effects on climate and mass extinction,
(4) the deep biosphere and relationships to geologic processes,
(5) the physics of plate tectonics and heat, mass, and fluid transfer in the lithosphere.

Recent achievements related to these oceanic and continental drilling programs (Arctic drilling and coring, fault zone drilling and coring, downhole monitoring) have set the stage for developing an integrated understanding of the complex linkages between diverse components of the Earth system.

One major aspect of integrating various data into comprehensive, synoptic perspectives of global geological systems involves extending and incorporating the detailed but 1D-view of the borehole with a complete 3D-view of the surrounding geological and geophysical data, and combining that 3D-geometry with age data obtained from cores. Bridging the scale gap between these diverse data relies on the acquisition of downhole logs that record formation properties on an intermediate scale between laboratory measurements on core samples and geophysical surveys. This procedure, core-log-seismic integration, relies on the following relationships: (1) complementary log and core data that can be interpreted jointly, (2) logging data that provide in-situ ground truth for core data, and (3) logs allow calibration of geophysical survey data (e.g. through synthetic seismograms). These relationships provide the basis for linkage of the depth domain (cores) and the time domain (seismic data). Scientific drilling, coring, and logging projects that take place in locations determined using 2D and/or 3D seismic site surveys provide an excellent opportunity to develop new methods for visualizing and better understanding the various components of the Earth system.

An international workshop addressing the scientific and technical challenges associated with core-log-seismic integration was held on October 3-4, 2005 in Tokyo, Japan, and was organized by the Center for Deep Earth Exploration - Japan Agency for Marine-Earth Science and Technology (CDEX-JAMSTEC) and the Japan Drilling Earth-Science Consortium (J-

DESC). This workshop was intended to promote discussions between scientists who use core, log and seismic data to address academic or industrial problems, and the main objective was to review and explore extant data processing, analysis, and integration methods. Emphasis was placed upon recognizing and addressing the interdependence between scientific targets and the methodology used for data collection, analysis, and integration. The workshop program, proceedings and most of the presentations can be accessed at http://www.jamstec.go.jp/chikyu/jp/news/nw_050712.html.

The topics discussed included (1) different approaches to core-log and core-log-seismic integration from theoretical (scaling, modeling, petrophysics) and technological (engineering, IT) points of view, (2) method testing using individual case-studies, and most importantly, (3) comparison and exchange of methods and techniques between researchers and engineers working in related or complementary fields. The workshop provided a platform for discussion and comparison of state-of-the-art core-log-seismic integration practices in both academic and industrial case studies. These included reviews of integrated approaches for improved oil exploration and oil recovery as well as site characterization for CO_2 sequestration (industrial focus), and integrated approaches in oceanic, coastal and continental environments (academic focus). Examples of scientific questions and targets included the nature of the seismogenic zone (Nankai Trough, San Andreas Fault Observatory at Depth (SAFOD), Taiwan Chelungpu-fault Drilling Project (TCDP)), salt-water intrusion in coastal aquifers (ALIANCE project), as well as long- and short-term climate change, paleoceanographic and paleoenvironmental investigations (glacial eustatic cycles and sedimentary responses to sea level change, teleconnection between land and sea with respect to the monsoon cycle; origin and evolution of carbonate mounds in the Porcupine basin).

Most of the discussions underlined two main issues related to core-log-seismic integration: problems associated with depth and depth calibration, and problems associated with measurement scales and ambient conditions during measurement. As a result, a series of new technical and educational challenges were identified as critical issues for further exploration.

Depth issues

Standardizing the depth positioning and accuracy of collected data sets, including: drilling and engineering parameters, cores, log data sets, mud-logging and cuttings in riser-drilling operations (where applicable) remains a critical problem across academic and industrial operations. The generation and calibration of synthetic seismograms, and the attendant problems associated with time-depth conversion of seismic data (either using velocity models from refraction data or reflection coefficients computed from logs) generated an extensive discussion and debate centered around the contribution of vertical seismic profiling techniques and tools. Broad consensus was reached regarding the need for standard definitions and processing procedures for generating a common depth framework in drilling and logging operations.

Scale and measurements under in-situ conditions

Measurements acquired at various scales, often using a wide array of instruments with different theoretical or methodological foundations, pose a significant challenge to core-log-seismic integration. This situation is highlighted by examples such as porosity data where (1) weight and volume are measured using both wet and dry samples, (2) neutron-porosity logging tools calibrated for limestone are used in a wide array of geological settings to estimate porosity data, (3) assumed grain densities are used to derive porosity data from density logs, (4) assumed slowness values for both fluid and rock are used to derive porosity values from acoustic logs, or (5) Archie's law is used to derive porosity values from resistivity logs. As a result, porosity as measured at core/sample scales (often with depressurization and expansion effects) is significantly different from the in-situ porosity as measured by downhole tools (which incorporate the contribution of vugs, voids, or fractures into porosity data). The importance of temperature- and pressure-controlled and calibrated physical properties measurements (acoustic velocity and velocity anisotropy, density, porosity, electrical resistivity, and etc.) has been widely emphasized, and clearly underlines the need for in-situ measurements of pressure and temperature. Recommendations were devised for a review of available core and downhole logging equipment and expertise (specifications vs. needs), and adoption of an optimal strategy (sample selection, on-site vs. delayed investigations) to achieve these scientific objectives.

Technical and educational challenges

Presentations and discussions of new technological developments focused on depth issues, data acquisition in extreme environments and integration of a wide array of new methods. Examples of such developments include (1) the contribution of downhole imagery tools to bridge the scale gap between core and log measurements, (2) the intensive feasibility testing of logging while coring systems potentially equipped with geophones (for check-shot surveys while coring), and (3) the development of new downhole probes for microbiology and geochemical investigations in order to meet the scientific needs of the deep biosphere research community. Finally, participants recognized that major efforts are needed (1) to promote better documentation of methods, assumptions, tools, resolution, and limitations inherent in each newly acquired data set, (2) to widely disseminate the results of successful core-log-seismic integration efforts, and (3) to make full use of the existing data collected by major scientific programs. A proposal was put forward to advocate the adoption of well-characterized test sites encompassing a wide variety of geological settings that would be dedicated to experiments, calibration and testing of new methods and tools, and developing references for comparison to ongoing or new investigations. The consensus of workshop participants was that these issues and initiatives provide a basis for community-wide consideration and discussion, and that collaboration and continued cross-disciplinary communication will set a solid foundation for continued progress toward developing comprehensive and integrated solutions to these complex problems.

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