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Scientific Drilling

Reports on Deep Earth Sampling and Monitoring

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Editorial Preface

Dear Reader:

Scientific drilling in Antarctica (p. 29) provided significant achievements within the International Polar Year (IPY). Coring from a floating ice shelf into the underlying seabed is—even with the assistance of penguins—not a trivial accomplishment. The data gained from this endeavor promise excellent records of past glaciations and sea-level changes that will complement ODP and IODP records from below the deep oceans.

During her first IODP drilling, the Japanese drillship *Chikyu* recently prepared for deep and riser-assisted drilling into the seismogenic zone off-shore Japan (p. 38). In late 2008, the totally remodeled and U.S.-sponsored platform *JOIDES Resolution* will resume IODP operations following years of shipyard work. Her schedule (back page) includes another contribution to the IPY through drilling near Antarctica. ICDP will commence coring the unique archive of three million years of Arctic climate records from below the frozen Lake El′gygytgyn in northeastern Siberia. One poorly known effect of global warming is the response by the polar ice shields and related sea-level change. ANDRILL, IODP, and ICDP contributions to the IPY will help us better constrain the long-term effects of global warming on polar ice sheets and the effect on global sea level. Changes in sea level and its impact on sedimentary stratigraphy were extensively discussed at a joint academic–industry funded workshop (p. 19). Another report (p. 32) presents the first continental European large-scale test bed for recycling of carbon dioxide into deep reservoirs in order to mitigate global warming.

While mankind is largely considered the culprit of global warming, nature is responsible for the formation of Large Igneous Provinces (LIPs) that likely severely impacted the global environment in the geological past. A recent workshop (p. 4) addressed causes and effects of these enigmatic and geologically discrete events. Another meeting (p. 55) discussed the environmental effects of a large marine impact in the Barents Sea. Plans to core the Colorado Plateau in order to recover a continuous record of the early to mid-Mesozoic Era not present within the ocean basins (plate tectonics stole it!) is presented on p. 62.

A special issue of *Scientific Drilling*—Fault Zone Drilling—was published online in late 2007, providing a total of three issues of the journal in 2007. However, the protracted drilling hiatus in IODP has temporarily reduced contributions of scientific reports and caused a publication delay of this issue. Nevertheless, we hope our readers will appreciate the many diverse reports presented in this volume. A new development, an editorial board, is now providing peer-review of the major scientific and technical articles in *Scientific Drilling*. In a final note, we regret to report that our managing editor Emanuel Soeding has departed IODP for new duties. We wish him well and thank him for his help establishing *Scientific Drilling*.

Hans Christian Larsen
Editor-in-Chief

Ulrich Harms
Editor

Front Cover: The ANDRILL drill rig in Southern McMurdo Sound, Antarctica. Mount Erebus, an active volcano is visible in the background right. Photo by Simon Nielsen.
Left inset: Visitors (Emperor penguins) to the ANDRILL Program's Southern McMurdo Sound Project site in late 2007. Photo by Cristina Millan. (See page 29)

Scientific Drilling

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IODP is an international marine research drilling program dedicated to advancing scientific understanding of the Earth by monitoring and sampling subsea-floor environments. Through multiple drilling platforms, IODP scientists explore the program's principal themes: the deep biosphere, environmental change, and solid earth cycles.

ICDP is a multi-national program designed to promote and coordinate continental drilling projects with a variety of scientific targets at drilling sites of global significance.

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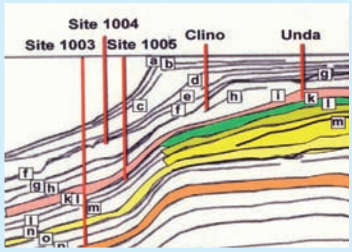

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Investigating Large Igneous Province Formation and Associated Paleoenvironmental Events: A White Paper for Scientific Drilling

by Clive R. Neal, Millard F. Coffin, Nicholas T. Arndt, Robert A. Duncan, Olav Eldholm, Elisabetta Erba, Cinzia Farnetani, J. Godfrey Fitton, Stephanie P. Ingle, Nao Ohkouchi, Michael R. Rampino, Marc K. Reichow, Stephen Self, and Yoshiyuki Tatsumi

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Introduction

Earth's history has been punctuated over at least the last 3.5 billion years by massive volcanism on a scale unknown in the recent geological past. Largely unknown mechanical and dynamic processes, with unclear relationships to seafloor spreading and subduction, generated voluminous, predominately mafic magmas that were emplaced into the Earth's lithosphere. The resultant large igneous provinces (LIPs; Coffin and Eldholm, 1994; Ernst and Buchan, 2001; Bryan and Ernst, 2008) were at times accompanied by catastrophic environmental changes. The interaction of the LIP-associated mantle processes with the Earth's crust have produced a variety of surface expressions (Fig. 1a and 1b); the most common present-day examples are oceanic plateaus (e.g., Kerguelen/Broken Ridge, Ontong Java, Manihiki, Hikurangi, Shatsky), ocean basin flood basalts (e.g., Caribbean, Nauru), magma-dominated divergent continental margins (e.g., the North Atlantic), and continental flood basalts (e.g., Columbia River, Deccan Traps, Siberian Traps). Environmental effects associated with LIP formation include climate changes, mass and other extinctions, variations in ocean and atmospheric chemistry, and Oceanic Anoxic Events (OAEs). Therefore, the geodynamic processes in the mantle that produce LIPs have potentially profoundly affected the Earth's environment, particularly the biosphere and climate. The Integrated Ocean Drilling Program (IODP) affords unique opportunities to investigate LIPs and associated environmental effects, building upon results from the Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP) (Coffin et al., 2006). To this end, a workshop on LIPs, sponsored by IODP Management International (IODP-MI) and the Consortium for Ocean Leadership, was held at the University of Ulster in Coleraine, Northern Ireland, U.K. on 22–25 July 2007 (Coffin et al., 2007).

A multi-disciplinary group of eighty scientists representing academia, government, and industry from sixteen countries discussed strategies for advancing understanding of LIPs and associated environmental events using the three different IODP platforms and related technologies. During the workshop, which began with an examination of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) World Heritage "Giant's Causeway" exposure of the North Atlantic LIP (Fig. 2), scientists investigating LIPs through field, laboratory, and modeling approaches shared their expertise. Specifically, outstanding problems related to LIP origin, emplacement, and environmental impacts were discussed in plenary and breakout sessions. The workshop achieved the following:

- Identified multidisciplinary, synergistic approaches to addressing outstanding Earth system problems associated with LIP science.
- Brought together scientists from widely different areas of expertise (e.g., petrology, paleontology, geodynamics, oceanography, geophysics, logging, volcanology, geochemistry, stratigraphy, tectonics, paleoceanography, paleomagnetics) to focus on how ocean drilling can address unresolved issues associated with the origin,

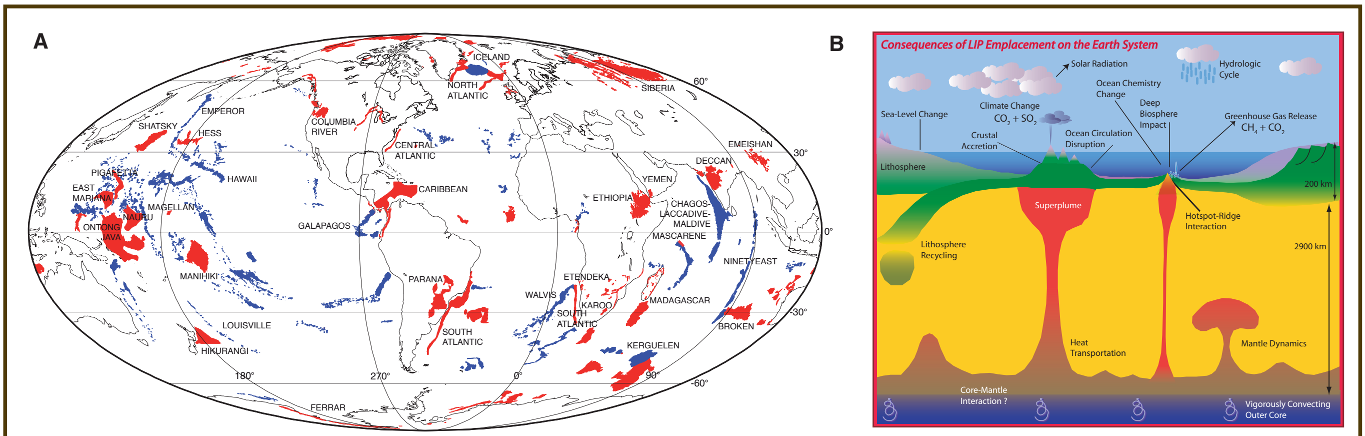

Figure 1. [A] Phanerozoic global LIP distribution. Red = LIPs (or portions thereof) generated by a transient "plume head"; Blue = LIPs (or portions thereof) generated by a persistent "plume tail". Taken from Coffin (2006). [B] A holistic representation of the process of LIP emplacement and associated environmental effects.

emplacement, and evolution of LIPs, as well as their impact on the environment.

- Exposed new scientists to the IODP and nurtured early career scientists, specifically with respect to how scientific drilling can advance understanding of LIPs.
- Enhanced cooperation between the IODP and the International Continental Scientific Drilling Program (ICDP).
- Explored partnerships among IODP, government, and industry.

One of the major outcomes of the workshop was to define multiple pathways to enhance our knowledge of LIPs through scientific drilling. These ranged from ancillary project letters, through individual expedition proposals, to a mission proposal.

This white paper highlights the major problems associated with LIPs that can be addressed through scientific drilling and related studies. It also highlights multidisciplinary approaches required to address such problems, as studies of LIPs encompass mantle geodynamics, emplacement processes, and environmental events affecting the lithosphere, hydrosphere, atmosphere, and biosphere.

Past Achievements

Scientific drilling has played a vital role in the exploration of LIPs, most importantly by providing the first, and in many cases the only, ground truth from the igneous basement of submarine LIPs. While major advances in LIP research involve holistic observational, experimental, and modeling studies involving a broad array of Earth science expertise, results from scientific drilling have been and will continue to be key components of interdisciplinary work. The first dedicated igneous basement sampling investigations of submarine LIPs, conducted during the ODP, concentrated on three provinces: the Ontong Java Plateau (Pacific Ocean), the Kerguelen Plateau/Broken Ridge (Indian Ocean), and the North Atlantic magma-dominated divergent continental margins (Fig. 1). Below, we highlight the major results of these investigations, which have laid the groundwork for the next major phase of discovery during the IODP.

Drilling results from ~120-Ma Ontong Java Plateau basement rocks are complemented by studies of obducted plateau rocks exposed in the Solomon Islands (Andrews et al., 1975; Kroenke et al., 1991; Berger et al., 1993; Neal et al., 1997; Mahoney et al., 2001; Fitton et al., 2004a, b). All Ontong Java basement rocks recovered to date are remarkably homogeneous tholeiitic basalts with minor variations in elemental and isotopic composition, and they were deposited in a submarine environment. Partial batch melting (≥30%) generated the basalts (Fitton and Godard, 2004; Herzberg, 2004), with melting and fractional crystallization at depths of <6 km (Sano and Yamashita, 2004). The lavas and their overlying sediment indicate relatively minor uplift accompanying emplacement and relatively minor subsidence since emplacement. Primarily on the basis of drilling results, multiple models—plume (e.g., Fitton et al., 2004a), bolide impact (Ingle and Coffin, 2004), and upwelling eclogite (Korenaga, 2005)—have been proposed for the origin of the Ontong Java Plateau.

Figure 2. Giant's Causeway (Ireland), part of the North Atlantic LIP. Note the stepped topography in the background, characteristic of flood basalt provinces.

Uppermost igneous basement of the Kerguelen Plateau/ Broken Ridge is dominantly tholeiitic basalt erupted above sea level (Barron et al., 1989, 1991; Schlich et al., 1989; Wise et al., 1992; Coffin et al., 2000; Frey et al., 2003), and it shows two apparent peaks in magmatism at 119–110 Ma and 105–95 Ma (Coffin et al., 2002). Geochemical differences among tholeiitic basalts erupted at each site are attributable to varying proportions of components from the primary mantle source (plume?), depleted mid-ocean ridge basalt (MORB)-related asthenosphere, and continental lithosphere. Proterozoic-age zircon and monazite in clasts of garnet-biotite gneiss in a conglomerate intercalated with basalt at one drill site demonstrate the presence of fragments of continental crust in the Kerguelen Plateau, as inferred previously from geophysical (e.g., Operto and Charvis, 1995) and geochemical (e.g., Alibert, 1991) data. For the first time from an intra-oceanic LIP, alkalic lavas, rhyolite, and pyroclastic deposits were sampled. Flora and fauna preserved in sediment overlying igneous basement provide a long-term record of the plateau's subsidence, beginning with terrestrial and shallow marine deposition and continuing to deep water deposition.

Seaward-dipping reflector (SDR) wedges of the latest Paleocene-earliest Eocene North Atlantic LIP drilled off the British Isles during DSDP (Roberts et al., 1984), off Norway during ODP (Eldholm et al., 1987, 1989), and off SE Greenland during ODP (Duncan et al., 1996; Larsen et al., 1994, 1999) confirmed them to be thick series of subaerial lava flows covering large areas. Lavas on the landward side of the SDRs show geochemical and petrological evidence of contamination by continental crust, implying that they ascended through continental crust during early rifting,

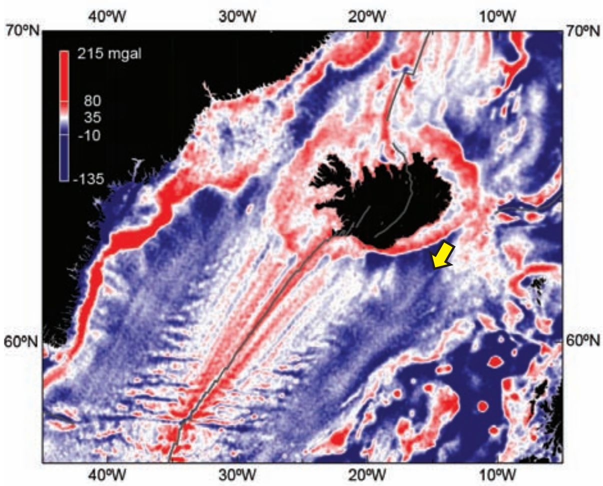

Figure 3. Gravity map of the North Atlantic Ocean showing prominent V-shaped ridges in the basement topography around the Reykjanes Ridge south of Iceland. These represent crustal thickness variations of ~2 km. The yellow arrow shows the location of thick sediment drifts deposited by northern component water flowing southwards over the Iceland-Faeroes ridge. Thinner drifts are present south of the Greenland-Iceland ridge.

whereas oceanward SDR lavas appear to have formed at a seafloor spreading center resembling Iceland. Drilling results from these margins indicate extreme magmatic productivity over a distance of at least 2000 km during continental rifting and breakup, with spatiotemporal influence of the Iceland plume during rifting, breakup, and early seafloor spreading (Saunders et al., 1998).

Mantle Geodynamics

In many respects, LIP magmatism remains quite enigmatic, yet its unique characteristics (e.g., volumes of erupted lava, time duration of volcanism, distinct geochemical composition with respect to MORBs, and frequency over geologic time) unequivocally highlight the importance of understanding the underlying physical, chemical, mechanical, and dynamic processes.

The mantle plume model, in which dynamic instabilities of a thermal boundary layer (e.g., the D'' zone at the base of the Earth's mantle) give rise to a mantle plume with a large head and a long-lived conduit or tail, provides a context for interpreting a wealth of surface observations related to LIPs and hotspot volcanism. And, if plumes do originate in the lowermost mantle, they may be the only way to 'sample' the deepest part of the Earth's mantle. Regardless of the origin of LIPs, studying them and hotspot volcanism provides unique and fundamental information about mantle dynamics, global heat and mass transfer in the mantle, time scales for 'storage' of geochemical heterogeneities and, ultimately, mixing efficiency of mantle convection.

Over the last decade, our views of mantle plumes have evolved considerably; the 'mushroom' shaped plume is certainly possible, but it is not *the* unique plume morphology. By moving beyond the simplistic assumption of a compositionally homogeneous mantle, where density differences are only due to temperature differences, numerical simulations and fluid dynamics laboratory experiments have found an astounding variety of plume sizes and shapes (Tackley, 1998; Davaille, 1999).

Although the nature of compositional heterogeneities in the Earth's mantle is still a matter of debate (e.g., recycled denser, eclogitic crust; early Earth crust; ancient mantle possibly interacting with the metallic core), many lines of seismological and mineral physics evidence suggesting the presence of chemically distinct, denser material in the lowermost mantle. Therefore, thermo-chemical plumes (i.e., their density contrast with respect to the surrounding mantle depends on both excess temperature and intrinsic composition) provide a new and exciting framework to relate deep mantle dynamics to LIP-forming events and pose a variety of new questions that can be addressed through scientific drilling.

Mantle Temperature Versus Mantle Fertility in LIP Formation

A primary question in understanding LIP formation is the extent to which melting anomalies reflect excess fertility in the mantle rather than excess mantle temperature. This issue lies at the heart of the current mantle plume debate. Mantle temperature can be addressed through the major-element composition of primitive LIP basalt via phase equilibria (Herzberg et al., 2007), and studies thereof suggest excess temperatures of <200°C. Mantle fertility is more difficult to investigate because its effects can be mimicked by lower degrees of mantle melting. Diachronous V-shaped ridges around the Reykjanes Ridge south of Iceland (Fig. 3) provide an example of how this problem might be addressed. These ridges reflect fluctuations in crustal thickness of ~2 km, and they are caused by pulses in magma productivity radiating outwards from the Iceland hotspot at ~20 cm yr^{1}. Drilling on the peaks and in the troughs along a transect away from the Reykjanes Ridge will allow basalt composition and hence mantle temperature estimates to be related to crustal thickness. Temperature fluctuations should result in an inverse correlation between gravity (a proxy for crustal thickness) and incompatible-element concentrations in basalt because these concentrations will be lower in larger-degree mantle melts. A direct correlation will indicate fertility pulses. A fluctuation in mantle temperature will cause a correlated fluctuation in water depth along the Greenland–Iceland–Faeroes ridge, affecting the flow of northern component water southwards from the North Atlantic (Wright and Miller, 1996; Jones et al., 2002; Poore et al., 2006). Sediment drifts south of the Iceland–Faeroes ridge (yellow arrow in Fig. 3) should record variations in this flow, and coring these will provide an independent proxy for temperature fluctuations in the Iceland hotspot. This synergy between mantle-dynamic and paleoceanographic objectives will be of considerable mutual benefit.

Thermo-Mechanical Plume-Lithosphere Interaction with Massive Magmatism

The amount of surface dynamic uplift induced by the arrival of a deep mantle plume is being widely debated. Pioneering models (e.g., Farnetani and Richards, 1994) suggested an unrealistically high uplift rate before volcanism, due to the following: (1) the assumption of purely thermal plumes, (2) poor representation of the lithosphere and the overlying crust, and (3) limited numerical resolution.

The plume uplift issue is currently being revisited using thermo-chemical plumes, which show a lower vertical velocity component than purely thermal plumes, and thus induce lower strain rates at the base of the lithosphere. Furthermore, the new generation of numerical models incorporates both a buoyant residual solid in the plume head resulting from partial melting, and surface exchanges of energy and mass between the ascending melts and surrounding rocks. For various plume buoyancy fluxes, lithospheric ages, and geodynamic settings, we can now calculate surface uplift/subsidence as a function of time and distance from the plume center. Model predictions should then be compared with geological observations obtained through drilling. It is important to emphasize that the geologically reconstructed time sequence of surface deformation needs to encompass a time interval extending from a few million years before to a few million years after the main phase of LIP construction.

Coupling of theoretical predictions with observations will lead to a self-consistent and coherent model of mantle plume dynamics and its thermo-mechanical effect on the overlying lithosphere. The periphery of the Ontong-Java Plateau (OJP) away from its convergent margin with the Solomon Islands may be ideal for this type of study. The OJP represents the world's most extensive LIP (equivalent to the size of Greenland or western Europe) that, on the basis of current knowledge, formed in ~5 myr at ~122 Ma. It is divided into a High Plateau containing the bathymetric high and a seismically slow cylindrical mantle root extending to ~300 km depth (Richardson et al., 2000; Klosko et al., 2001; Gomer and Okal, 2003) and an Eastern Salient (Fig. 4), with all drill sites encountering igneous basement being located on the High Plateau. Both isostatic (minimum) and dynamic (maximum) crustal uplift were significantly less for the OJP than for active hotspots today, and total subsidence is also anomalously less (Neal et al., 1997; Ito and Clift, 1998; Ito and Taira, 2000; Ingle and Coffin, 2004; Roberge et al., 2005) than that of any other known oceanic lithosphere (Parsons and Sclater, 1977; Coffin, 1992; Stein and Stein, 1992). However, to complicate this situation, ODP Leg 192 recovered a sequence of volcaniclastic sediments at Site 1184 on the Eastern Salient that represent subaerial eruptions (Thordarson, 2004); this is interesting because this site is not over the mantle root. The sequence was divided into several sub-units separated by wood horizons (Mahoney et al., 2001). Borehole heat flow measurements from the High Plateau and Eastern Salient will establish the thermal or chemical nature of the mantle root, and recovery of basement lava flows from the Eastern Salient will test whether volcanism was extensively subaerial in this area during formation of the OJP (consistent with plume theory), or whether the Site 1184 volcaniclastic sequence was produced by a late-stage volcanic edifice with the bulk of the Eastern Salient being constructed by submarine volcanism.

LIP Internal Architecture

Although drilling typically only scratches the surface of thick igneous basement, it is important to explore the internal structure of a LIP to quantify the relative volumes of extrusive versus intrusive magmatism (Cox 1992; Kerr et al., 1997). Better estimates of total melt volumes and compositions will help to bracket melting rates and to define melt transport/storage mechanisms between subsurface magma chamber(s) and the surface. Moreover, interactions between partial melts and the surrounding rocks determine the length- and time-scales over which LIP magmatism can change the temperature, the internal loads, and the state of stress of the pre-existing lithosphere and crust. LIPs emplaced in oceanic lithosphere (rather than the thicker and more compositionally complex continental lithosphere) are thus better suited to investigate the thermo-mechanical and compositional modifications induced by LIP magmatism in the lithosphere and the uppermost asthenosphere.

Moreover, we note that the current debate on the role of plumes in the formation of thick, *subduction-resisting* lithosphere in the Archean will benefit from a better characterization of the density and viscosity structure resulting from LIP volcanism. This may be difficult to achieve directly through scientific drilling, even with riser capability, although direct

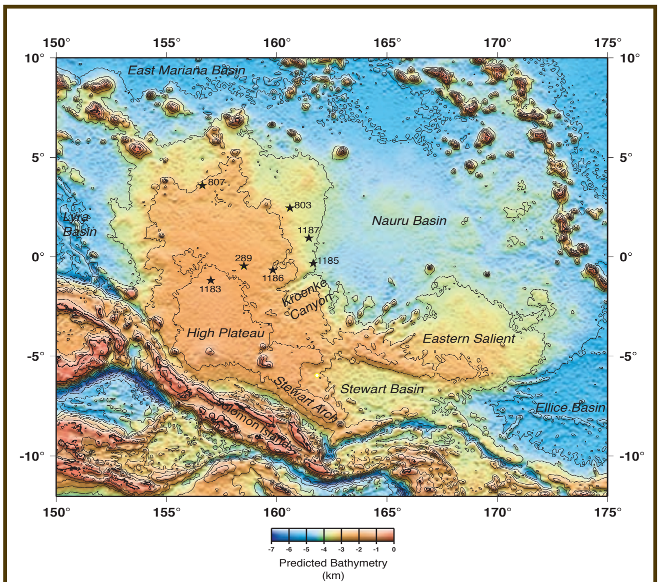

Figure 4. Bathymetry of the western Pacific Ocean including features of the Ontong Java Plateau and surrounding basins. Numbered stars represent DSDP Leg 30, ODP Leg 130, and ODP Leg 192 drill sites that penetrated and recovered igneous basement.

results of site survey work, done in preparation for drilling, can directly bear on this question.

Plumes and Superplumes: Exploring Interactions with Slabs and the Earth's Core

Although we generally consider plumes to be isolated 'bodies', they are part of mantle convection and are likely to interact with subduction processes and deep Earth dynamics. Plumes upwelling from the thermal boundary layer at the base of the Earth's mantle could enhance flushing of stagnant slabs into the lower mantle, and vice versa (Nakagawa and Tackley, 2005). During Cretaceous time, LIP and arc magmatism—which are surface manifestations of mantle upwelling and downwelling, respectively—occurred simultaneously (Reymer and Schubert, 1984; Larson, 1991; Eldholm and Coffin, 2000). Decoding the time relation between magmatism at LIPs and at convergent margins is, therefore, key to understanding the primary cause of mantle convection.

Recently, Burke and Torsvik (2004) restored twenty-five LIPs of the past 200 myr to their eruption sites using a new global paleomagnetic reference model. Ninety percent of the LIPs, when erupted, lay above low-velocity seismic-shear-wave regions of the D'' zone, as indicated in current tomographic models, suggesting that the deep mantle beneath the Central Pacific and Africa may represent a long-lived source region for plumes. Better characterization of LIPs will therefore help to understand the nature of 'superplumes', their stability over time (≥200 myr?), and their potential to sample distinct geochemical reservoirs. By using 2-D numerical simulations, Farnetani and Samuel (2005) have shown the complex internal dynamics of thermo-chemical plumes, leading to the possible coexistence of different types of plumes and superplumes (Fig. 5).

Finally, the accumulation of cold slabs and the upwelling of hot material induce spatial and temporal variations in heat flow at the core-mantle boundary, affecting the outer core convection and the frequency of polarity reversals (e.g., low (high) core heat flux, infrequent (frequent) polarity reversals). Courtillot and Olson (2007) showed that three magnetic superchrons preceded the largest Phanerozoic mass extinctions (Cretaceous-Tertiary, Triassic-Jurassic, Permo-Triassic), which are associated with major flood basalt events. These authors suggest that thermal instabilities in the D'' layer may increase heat flow from the core and trigger the end of a magnetic superchron. Documenting the timing of LIP magmatism and superchron events will provide key information on dynamic linkages between the core and mantle.

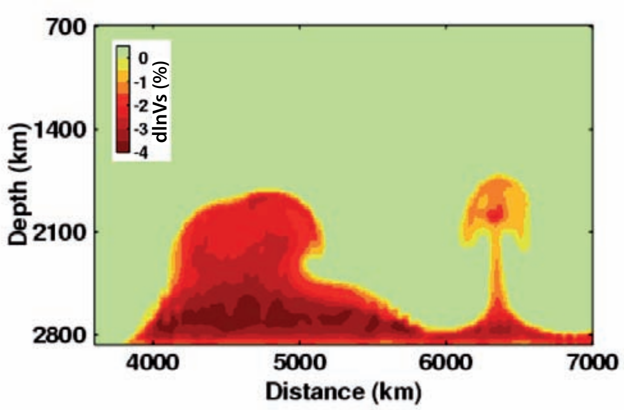

Figure 5. 2-D model showing the coexistence of plumes and superplumes in time and space (Farnetani and Samuel, 2005). Colors correspond to calculated seismic velocity anomalies (see inset key for quantitation).

Geodynamics and Tectonic Setting

LIPs are emplaced along active plate boundaries (e.g., magma-dominated divergent continental margins) and in intraplate settings (e.g., continental flood basalts). The tectonic setting of emplacement for most oceanic plateaus and ocean basin flood basalts, however, is not completely understood. A key question is whether upwelling mantle can erode the lithosphere sufficiently to instigate formation of a divergent plate boundary (Hill, 1991; Davies, 1994). While this appears to be the case for the North Atlantic volcanic province, where extension and seafloor spreading relocated from the Labrador Sea to the incipient northernmost North Atlantic coincident with massive North Atlantic volcanic province magmatism (Srivastava and Tapscott, 1986), the situation is significantly less clear for other magma-dominated divergent continental margins (e.g., Northwest Australia and Kerguelen/Antarctica/India/Australia). To gain a thorough understanding of relationships among mantle geodynamics, tectonics, and basaltic magmatism, we need to investigate more than a single example of magma-dominated divergent margins by scientific ocean drilling.

In marked contrast to the North Atlantic example, the Northwest Australian margin is segmented, and igneous rock volumes vary considerably along strike, without clear evidence for a related mantle plume (Mutter et al., 1988; Hopper et al., 1992; Symonds et al., 1998; Planke et al., 2000). This makes the margin a strong candidate to test the edge-driven/small-scale convection hypothesis (Mutter et al., 1988; King and Anderson, 1998; Korenaga, 2004) for generating excessive magma by drilling a margin transect across multiple seaward-dipping reflection wedges, the Wallaby Plateau, and normal oceanic crust. The geochemistry, petrology, and geochronology of the recovered rocks will yield melting conditions, mantle reservoir type, extent of continental contamination, and the spatiotemporal evolution of the magma source.

The Kerguelen Plateau/Broken Ridge appears to have begun forming in the nascent eastern Indian Ocean at least 10 myr after breakup among Antarctica, India, and southwestern Australia (Coffin et al., 2002; Gaina et al., 2007). Despite these conjugate continental margins exhibiting some characteristics of excessive magmatism during breakup (e.g., SDR wedges; Stagg et al., 2007) and contemporaneous continental basaltic volcanism (Storey et al., 1992; Frey et al., 1996), the lack of physical and therefore geochronological continuity between these margins and the Kerguelen Plateau/Broken Ridge reveals yet another variation from the North Atlantic example of simultaneous continental breakup and LIP formation. Drilling the Early Cretaceous SDR wedges of the conjugate southwest Indian Ocean margins and the oldest portions of the Kerguelen Plateau to determine geochemistry, petrology, and geochronology will address critical questions involving relationships between geodynamics and tectonic setting.

Emplacement

Unravelling the emplacement of LIPs is pivotal in understanding their significance in the formation of the Earth's crust as well as any potential environmental consequences. Our understanding of these processes remains quite limited, and basic questions—such as whether or not the centers of these eruptions occur along fissures—are still matters for debate. Onset of volcanism can be determined for most continental LIPs, although cessation of activity is more problematic to determine due to erosion of uppermost lavas. Oceanic LIPs provide a unique opportunity to address these issues as they are generally better preserved, and consequently can provide a more complete picture of LIP formation. The major issue concerns timing of LIP generation and emplacement (i.e., whether the event was short- or long-lived). We observe examples of both in almost wholly submarine LIPs and in subaerially emplaced LIPs that have been partly rifted and submerged. This overarching question encompasses several missing links in our present understanding that are immediately addressable by scientific drilling.

Duration of Emplacement

Many LIPs appear to have at least one major pulse of volcanism when the most voluminous lava sequence was erupted. Identifying the duration of the full sequence of lavas enables identification of the most voluminous intervals. Knowing the time span of the most voluminous interval(s) for each LIP is crucial for determining the mechanism of emplacement and the potential environmental impact. Furthermore, sampling and dating the lavas allow questions concerning episodicity (about which we know little in major LIPs) to be addressed. For example, was there more than one interval of voluminous volcanism associated with the LIP's formation? As well as from direct sampling of LIP lavas, much can be learned about the onset and cessation of LIP volcanism from environmental indicators contained in sedimentary sections in older basins adjacent to the LIPs and (potentially) worldwide. These include shifts in isotopic and trace metal content of the sediment that can be linked to the arrival of the first LIP lavas onto the seafloor and/or (perhaps) volcanic degassing to the atmosphere. If the sedimentary sequence yields a high-resolution record, this can provide a highly sensitive time indicator of the onset and cessation of LIP activity, directly correlating the LIP with any contemporaneous environmental events.

Style and Timing of LIP Eruptions

Many eruptions occur during the lifespan of a LIP. For almost all LIPs, the total volumes of lavas are not accurately known, let alone those contained in each eruptive package (or other volcanic deposits such as hyaloclastites). What is also unknown is whether each package was produced by short, intense eruptive episodes, or more pulse-like and protracted ones. Critical for addressing environmental recovery is accurate determination of intervals between eruptions. Drilling into LIPs will provide samples of sediment between lavas to address this (e.g., ODP sites 642 and possibly 807; Larson and Erba, 1999). The probability of finding chronological and environmental markers (e.g., carbonaceous or siliceous sediment deposition) between flow units is much higher in the oceanic environment than on the continents. Erosion during emplacement of submarine LIPs is expected to be minimal; hence, it is more likely to recover flows erupted in sequence. Furthermore, the final (uppermost) lavas are commonly not preserved in continental flood basalts, but truly submarine LIPs offer a much greater chance of obtaining the full sequence of lava products, or at least the last erupted lavas.

If these two fundamental problems can be addressed, we will be able to answer questions such as:

1) When was the big pulse or biggest pulses of volcanism during a LIP's lifespan?
2) Does this time correlate globally with sudden environmental events?
3) What possible role(s) does LIP emplacement have on these sudden events?

Timing of emplacement is critical for determining magma fluxes and, ultimately, the mantle processes controlling magma production. Is magma production in plume heads controlled by 'bottom-up' or 'top-down' processes? To better understand the possible effects of LIP volcanism being causal for brief but severe environmental crises, it is necessary to determine eruption rates, and this, in turn, will be useful to model the transport and emplacement distances of lava flows.

Consequences of Shallow Intrusions

Another topical and critical question concerns LIP-related sill emplacement into sediments leading to gas release into the ambient environment; this has occurred on land and on the ocean floor (Svensen et al., 2004). Would submarine gas or fluid release directly affect the oceanic environment (Fig. 6)? To better examine relationships between sills and lava flows, drilling in specific areas can address the timing of the intrusion of the sills, whether they were the feeders for the flood lavas (see section Duration of Emplacement above) and plumbing systems for LIPs. If the sills and their interactions with sediment cause environmental changes, then it is vital to establish the timing of sill and LIP lava emplacement. Further to the consideration of sills, we know little about magma reservoirs for LIPs, including their locations and dimensions. Are the chambers deep or shallow? Perhaps in oceanic crust, more primitive magmatic material can be erupted at the surface that would otherwise be stalled in continental crust, and a study of this may provide clues to the nature of the initial magmatism related to LIPs.

Relationships Between Subaerial and Submarine LIP Emplacement

What are the differences between subaerial and submarine emplacement of LIP lavas, and thus the similarities or differences in LIP architecture between the continental and oceanic realms? In the ocean, very large flow fields may be possible underwater, and perhaps few barriers halt the spread of lava flows. We might thus predict widespread lava fields covering whole provinces, but is this realistic? What do LIP super-eruption products look like when they are emplaced under water? Are the component lava bodies of oceanic flow fields similar in dimension to those in continental flood basalt provinces, with flow unit thicknesses of 100 m or greater? What is the overall architecture of an oceanic plateau sequence? It appears that their dominantly shallow dipping, low angle slopes would favor the inflation of lava flows (Self et al., 1998).

Lava age distributions are also needed to assess how LIPs are constructed. Even though younger, post-major pulse lavas cover most oceanic LIPs, it may be possible to find widespread main-pulse lavas at the edges of LIPs. Using the architecture of better-known subaerial LIPs (Fig. 7), we can assess where best to drill to intersect long lava flows in submarine LIPs.

An important aspect of subaerial versus submarine emplacement of LIPs is the nature of seaward-dipping reflectors (SDRs). These are highly significant components of several LIPs (such as the North Atlantic and Kerguelen) and not observed in continental LIPs. They are most likely related to the tectono-magmatic setting, but what do they represent? Are they exclusively subaerially emplaced, but subsided parts of a LIP, or might they also form in marine environments? Some geophysical observations suggest the latter, but confirmation by ocean drilling is required. To understand the nature of SDRs, it is crucial to drill full sequences to determine if these were emplaced as deep marine sheet flows, perhaps infilling a subsiding rift basin.

LIP-Generated Felsic Magmas

Felsic volcanic rocks are typically much higher in potassium than their mafic counterparts and thus contain ideal minerals for Ar-Ar dating. Drilling on the Kerguelen

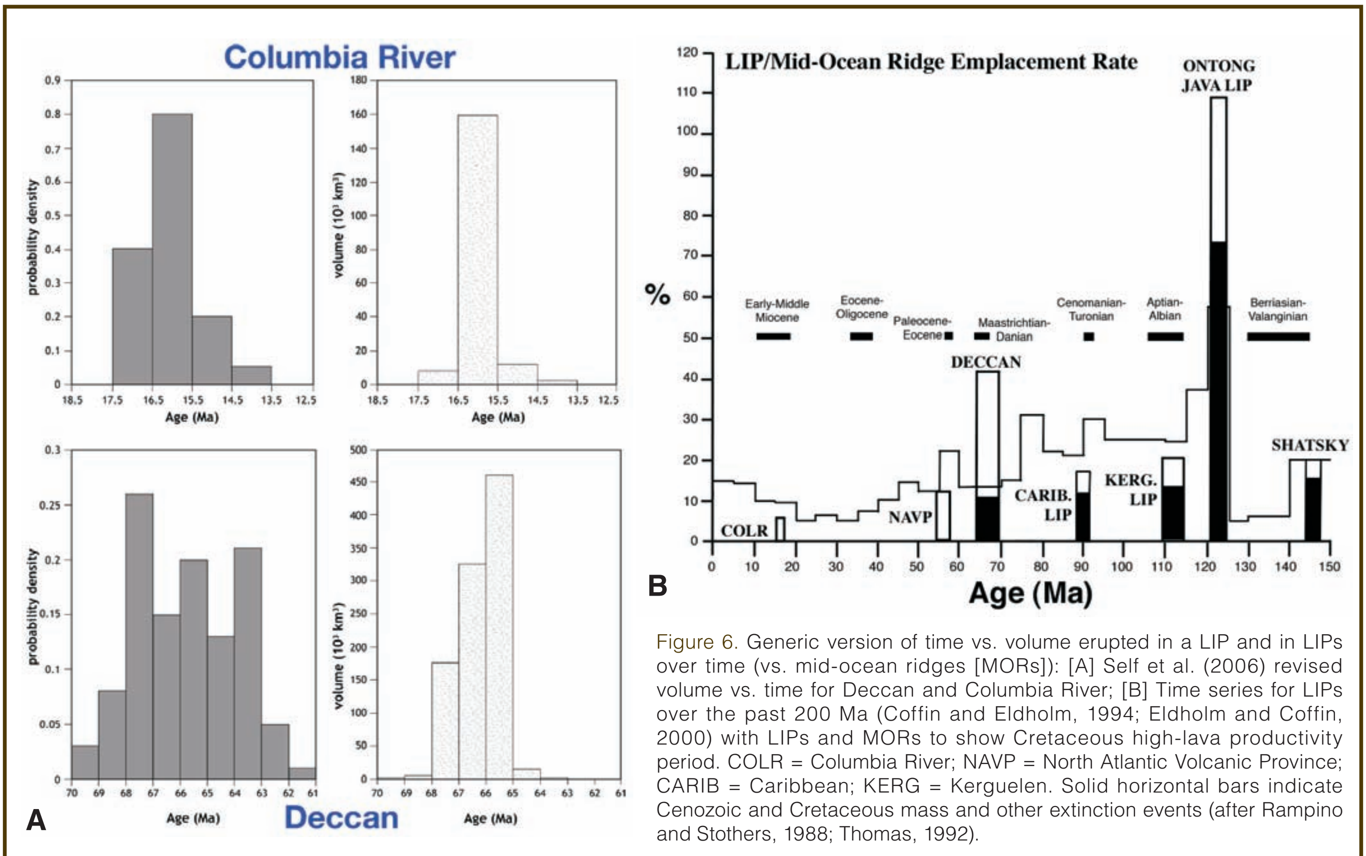

Figure 6. Generic version of time vs. volume erupted in a LIP and in LIPs over time (vs. mid-ocean ridges [MORs]): [A] Self et al. (2006) revised volume vs. time for Deccan and Columbia River; [B] Time series for LIPs over the past 200 Ma (Coffin and Eldholm, 1994; Eldholm and Coffin, 2000) with LIPs and MORs to show Cretaceous high-lava productivity period. COLR = Columbia River; NAVP = North Atlantic Volcanic Province; CARIB = Caribbean; KERG = Kerguelen. Solid horizontal bars indicate Cenozoic and Cretaceous mass and other extinction events (after Rampino and Stothers, 1988; Thomas, 1992).

Plateau (ODP Leg 183) recovered significant amounts of a wide variety of felsic volcaniclastics and lavas (Coffin et al., 2000). Other oceanic LIPs, such as Hess Rise in the Pacific (DSDP Leg 62), contain discrete intervals of felsic lavas. Many, if not all, continental LIPs contain felsic components in the main-series lavas (Bryan et al., 2002), but not from the Deccan and the Columbia River provinces. Eruptions of these evolved magmas can be explosive (e.g., the Ethiopian ignimbrites) and represent valuable stratigraphic and geochronologic markers if they can be correlated to felsic ash fall deposits in deep sea sediment (Peate et al., 2003). Drilling into felsic volcanic products of LIP volcanism, on both the LIP proper and in neighboring sedimentary sections, will help anchor the timing of eruptions via chronostratigraphy.

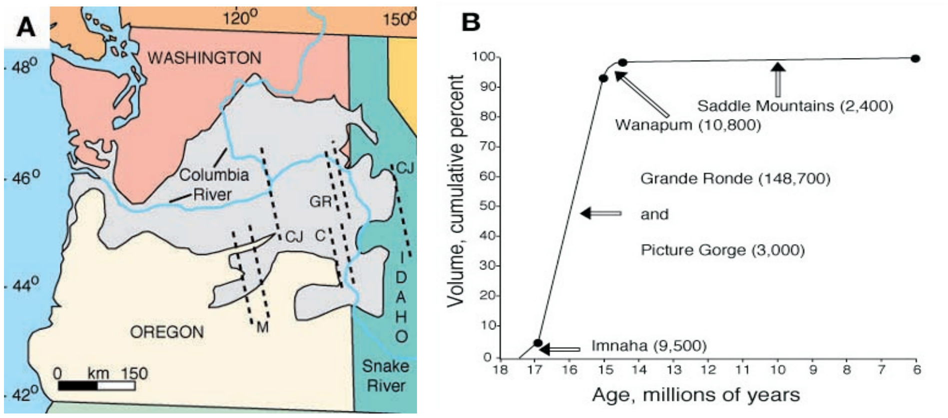

Figure 7. [A] Map of the Columbia Plateau, showing the limits of the Columbia River flood basalts and the feeder dike systems (dashed lines). CJ indicates the longitudinal boundaries of the Chief Joseph dike swarms that fed the Clarkston (Imnaha, Grande Ronde, and Wanapum) and Saddle Mountain basalts. The Grande Ronde (GR) and Cornucopia (C) swarms are concentrations within the CJ. M indicates the Monument dike swarm that fed the Picture Gorge basalt. [B] Ages and estimated volumes of the major eruptive units of the Columbia River basalts. This figure illustrates that surficial sampling of a LIP can yield information on its history of formation.

Environmental Consequences

Connections between large historic basaltic eruptions and perturbations of the global environment are well documented. Classic examples include the eruptions of Laki, Iceland in 1783, and Eldgjá, Iceland in 934, both of which were followed in subsequent years by historically cold summers in the northern hemisphere (Stothers, 1998). In contrast, LIPs represent much larger outpourings of basaltic magmas over much longer time scales, and recent data (Coffin and Eldholm, 1994; Kerr, 1998; Larson and Erba, 1999; Leckie et al., 2002; Snow et al., 2005; Kuroda et al., 2007) increasingly suggest temporal correlations between LIP formation and significant oceanographic, biotic, and climatic events, the most severe of which are OAEs. Greenhouse gases released from LIP magmas, as well as sediment-magma interactions and ocean chemistry changes associated with the LIP emplacement, may have had major effects on the global environment (Fig. 1b). Critical in understanding the impact LIP magmatism may have had on the environment is determining LIP volume and, more importantly, magma eruption rates. Scientific drilling has a vital role to play in identifying the mechanisms and quantifying the timescale and magnitude of effects, and interdisciplinary, synergistic collaborations among scientists from a variety of disciplines are required.

Atmospheric Impacts of LIP Emplacement

LIPs may impact the atmosphere, oceans, and biosphere by rapidly releasing huge amounts of magmatic volatiles (CO_2, SO_2, etc.) or volatiles (CO_2, CH_4) from intruded sediments (e.g., carbonates, organic-rich shales, evaporites) (Fig. 8). Directly or indirectly, they may cause changes in the atmosphere/ocean system that lead to perturbations of atmosphere/ocean chemistry, circulation, ecology, and biological productivity (Self et al., 2006). This was especially true in Cretaceous and Early Tertiary time, when the atmospheric CO_2 content of the atmosphere was three to seven times higher than that of today (Fig. 9), and perhaps more susceptible to short-term perturbations in ocean/atmosphere dynamics and their ensuing effects on life. Furthermore, recent compilations suggest that a sudden sea level rise (~60 m; Miller et al., 2005) was associated with the Paleocene-Eocene Thermal Maximum (PETM) event (Kennett and Stott, 1991; Bains et al., 1999; Svensen et al., 2004), which in turn was concurrent with the formation of the North Atlantic Volcanic Province (Eldholm and Thomas, 1993).

Oceanic Anoxic Events

Episodes of complete depletion of oxygen below surface levels in the Earth's oceans, known as OAEs (Schlanger and Jenkyns, 1976), represent the most momentous environmental changes in the ocean of the past 250 million years, and bear some similarities to the less impactive PETM event. Examples of linked LIP emplacement and major environmental/biological crises include (Fig. 10): Oceanic Anoxic Event (OAE)-1a in the early Aptian (~122 Ma) and the Ontong Java Plateau (~120 Ma), Manihiki Plateau (~120 Ma) and the Kerguelen Plateau (~119 Ma); OAE-2 around the Cenomanian-Turonian boundary (~94 Ma) and the Caribbean-Colombian flood basalts (~92–94 Ma); and the PETM (55 Ma) and the North Atlantic Volcanic Province (~55 Ma).

There are two possible causal relationships between LIPs and OAEs: 1) the instigation of oceanic anoxia through global warming by greenhouse gases (e.g., CO_2, CH_4) that leads to ocean stagnation, which in turn induces anoxia in deep/intermediate depths of the ocean; and 2) submarine volcanic eruptions and associated massive hydrothermal release of trace metals into the global ocean instigating black shale events (Snow et al., 2005). Furthermore, the connection between LIPs and marine biotic changes (including some extinctions) has been ascribed to acidification of seawater by adding CO_2 and SO_2 (Coffin and Eldholm, 1994; Kerr, 1998). However, these ideas require critical evaluation.

Exploring Linkages between LIP Emplacements and Environmental Events

To evaluate linkages between LIP emplacements and environmental events requires information on multiple topics:

1) Accurate and precise timing, duration, and magnitude of LIP magmatic activity and environmental/biotic perturbations;
2) Volatile fluxes related to LIP emplacement events (i.e., LIP magma degassing as well as those potentially derived from magma-sediment interactions) and the extent of gas release into the ocean/atmosphere environment;
3) Hydrothermal fluid compositions (especially trace metals) and fluxes related to LIP emplacement events, and the extent of their release into the ocean environment;
4) Eruptive environments (e.g., deep/shallow submarine; subaerial) and sediment-magma interactions, as well as the overall tectonic settings, of LIP events;

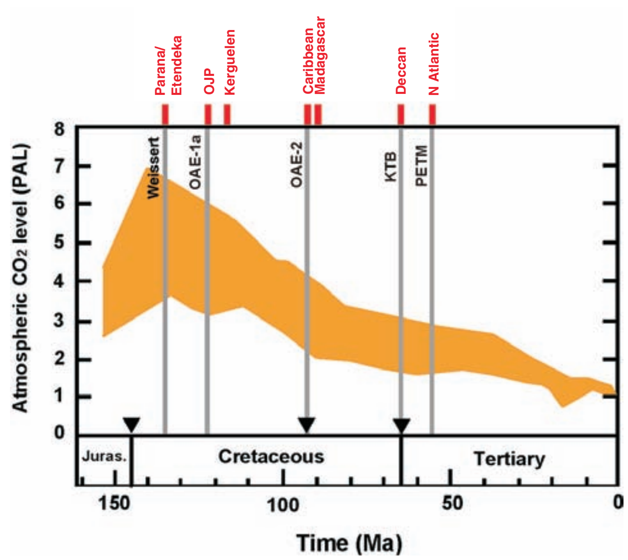

Figure 9. Estimated atmospheric CO_2 concentrations during the last 150 myr (Berner and Kothavala, 2001; Tajika, 1998). Shaded areas indicate global oceanic anoxic events (OAE-1a and OAE-2), Cretaceous-Tertiary boundary (KTB), and Paleocene-Eocene Thermal Maximum (PETM). Mass extinctions events (Sepkoski, 1996) are shown as black inverted triangles.

5) Specific paleoenvironmental conditions prior to, at the onset of, and during times of LIP emplacements (i.e., to define changes in atmospheric and oceanic physical and chemical properties and circulation).

Temporal coincidence between LIPs and environmental crises is clear for a few examples (e.g., North Atlantic LIP, Deccan Traps, Siberian Traps), but temporal correlations between others need further evaluation.

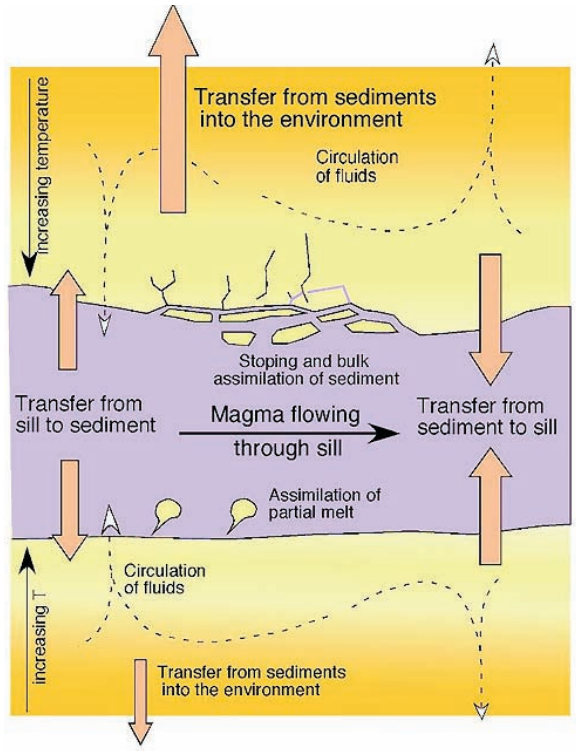

Figure 8. Hypothetical representation of sill-sediment interaction and the release of gases liberated from the sedimentary wallrock.

Sediment and volcanic rock recovered by the IODP in various oceanic basins and at different paleolatitudes will provide opportunities to resolve these issues in the following ways:

- Obtaining complete, high-resolution sedimentary records from critical ocean environments (e.g., the Mesozoic pelagic/deep, shallow, and atoll; sediment from the Pacific, Indian, Arctic, and Southern oceans; and high paleo-latitudinal sites are critically required).
- Obtaining syn-sedimentary sections within or adjacent to individual LIPs to estimate the potential hydrothermal fluid release and gas release through sediment-magma interactions.
- Targeted drilling to bracket the duration, peak, and volume of magmatic activity (e.g., tectonic windows and feather edges of LIP basement, and syn-sedimentary sections).
- Bracketing the chronology/duration of the environmental events through recovery of sedimentary sections containing carbonates at locations permanently above the carbonate compensation depth, or CCD (e.g., Magellan Rise).

New Approaches to Drilling of LIPs

Global understanding of LIPs will benefit greatly from new approaches, with drilling as a key investigative tool. Such new approaches, detailed below, include strengthening collaboration with industry; more integrative, multidisciplinary studies; development and deployment of new technologies; and coordinated IODP-ICDP investigations.

Industry Connections to Drill LIPs

Drilling of LIPs is of interest to the hydrocarbon industry to understand the fundamental processes, in time and space, involved in LIP development and evolution. In particular, interest focuses on how these processes influence the thermal, structural, depositional, and vertical motion histories of adjacent sedimentary basins (i.e., how LIPs influence the generation, maturation, and migration of hydrocarbons). Among the various LIP categories, the primary industry interest is magma-dominated divergent continental margins and, to a lesser degree, oceanic plateaus underlain, in whole or in part, by continental crust. Specific LIPs (e.g., the Norwegian, northwest Australian, and South Atlantic margins) are in regions of interest to the hydrocarbon industry, and ties with industry should be developed to the maximum extent possible.

Collaborative IODP–industry LIP investigations could take the form of industry–academia consortia established to address topics of interest to both industry and members of the IODP community using any of the three IODP platforms. Industry contributions to such consortia could include site surveying and seismic processing/reprocessing of existing seismic data using sophisticated techniques, as well as financial support for planning, execution, and interpretation phases of drilling programs.

Joint IODP–industry drilling ventures should address highly ranked scientific objectives, and the resulting data should be public domain, or offered to the community after a brief participant-exclusive period. Joint, dedicated LIP scientific drilling ventures provide a means to expand opportunities for scientific drilling while maintaining IODP scientific integrity.

An Integrated Approach to Drilling LIPs

LIP science will be advanced in five key areas by drilling, with objectives and potential drilling sites outlined below.

Obtaining deep sections within multiple LIPs to examine magmatic (and therefore mantle source) variability through time. This will require offset drilling along a rifted LIP margin or into a deep erosional feature within a LIP. Potential locations include (a) conjugate rifted margins of the Kerguelen Plateau and Broken Ridge, Indian Ocean; (b) conjugate rifted margins of the Hikurangi and Manihiki plateaus, Pacific Ocean; (c) Danger Islands Troughs of the Manihiki Plateau, Pacific Ocean; (d) proposed conjugate rifted margins of the Ontong Java Plateau bordering the Stewart Basin, Pacific Ocean; (d) Kroenke Canyon of the Ontong Java Plateau, Pacific Ocean; and (e) flanks of the TAMU Massif on the Shatsky Rise, Pacific Ocean. Note that as one of the oldest oceanic plateaus, Shatsky Rise is an important drilling target for increasing our understanding of the processes that form LIPs as well as how they evolve over time (e.g., subsidence history, secondary volcanism), although basalts from the feature are characterized by MORB-type isotopic signatures (Mahoney et al., 2005).

Defining the nature of melting anomalies (i.e., compositional vs. thermal) that produce LIPs. Understanding the underlying mechanics and dynamics of melting anomalies can be tested where basalt composition can be related to crustal thickness or where there is evidence for anomalous mantle beneath a LIP, such as (a) diachronous V-shaped ridges around the Reykjanes Ridge south of Iceland (Fig. 3) in the North Atlantic (see section Mantle Geodynamics above for rationale); and (b) Ontong Java's High Plateau, underlain by a 300-km-deep "root" of seismically anomalous mantle that has been

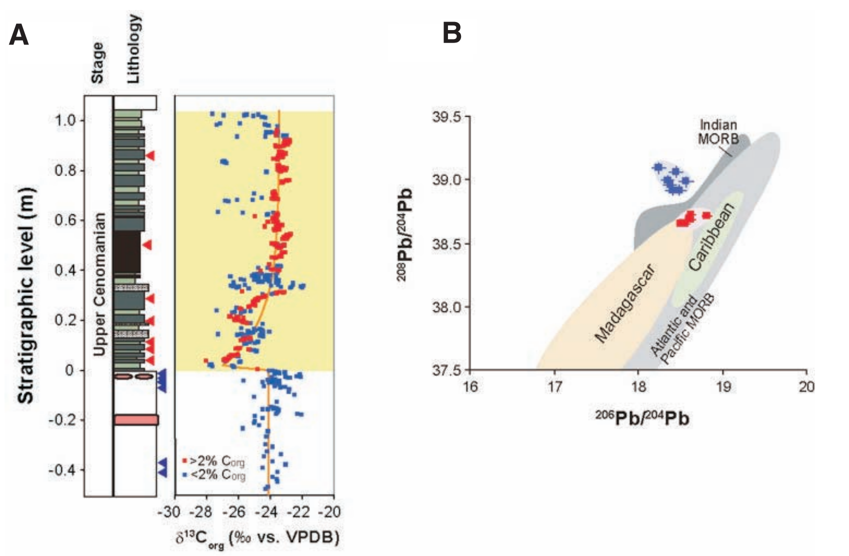

Figure 10. [A] A high-resolution profile of carbon isotopic composition of total organic matter from OAE-2 section from central Italy (Bonarelli Event, colored interval). Data from organic-rich (>2% total organic carbon content) and -poor (<2%) sediment are indicated by red and blue symbols, respectively. The profile indicates negative excursion at the base of the OAE-2. [B] A cross-plot of $^{206}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$ in the Bonarelli (red symbols) and underlying Cenomanian limestone (blue symbols). For comparison, Pb isotopic compositions of basaltic rock from Caribbean (88–95 Ma), Madagascar flood basalts (88 Ma), and from MORB (present) from the Atlantic, Pacific, and Indian oceans are also shown. Both figures are referred from Kuroda et al. (2007).

postulated to represent the fossil plume head of the OJP (Richardson et al., 2000; Klosko et al., 2001; Gomer and Okal, 2003). By determining heat flow from drill holes above the interpreted fossil plume head as well as away from it, the nature of the melting anomaly can be tested, as numerical models suggest that it should retain a detectable thermal signature.

Defining precise durations of oceanic LIP events. Two obvious ways to bracket LIP events are to (a) drill through the oldest and youngest eruptive sequences of a LIP, and (b) core a syn-LIP sedimentary sequence in an older proximal basin. Pursuing option (a) is not feasible by drilling through the entire eruptive sequence of a LIP, but if the age final eruption can be determined, the age of the start of LIP formation can be approximated by drilling through the lava flow sequence at the feather (distal) edge of a LIP. Option (b) will be pursued by drilling syn-LIP sedimentary sequences and analyzing for both age-dateable ash layers and chemical anomalies that are related to LIP formation and/or ash layers (taking into account the varying residence times in ocean water of different elements). Ideally, both options will be pursued. The feather edge of most oceanic LIPs may be drilled providing that it is distal to any volcanic vents and is not tectonic in nature. Examples of syn-LIP sedimentary sections in proximal basins include the following:

Kerguelen Plateau: Perth Basin off SW Australia, Enderby Basin and Princess Elizabeth Trough between Kerguelen and Antarctica;

Deccan Traps: Western and Northern Somali Basin west of Seychelles, where Deccan basalts crop out;

Agulhas Plateau: Transkei Basin between the Agulhas and Mozambique plateaus;

North Atlantic Volcanic Province: central and northern North Atlantic, ideally recovering sections through the Paleocene-Eocene Thermal Maximum event;

Shatsky Rise: Northwest Pacific Basin west of Shatsky Rise;

Ontong Java Plateau: Nauru Basin west of, and East Mariana and Pigafetta basins north of, the Ontong Java Plateau.

Moreover, the ~145-Ma Magellan Rise has a carbonate, chert, and black shale (OAE) section (Winterer et al., 1973) encompassing the formations of the Ontong Java, Manihiki, and Hikurangi plateaus. Similarly, the crests of Late Jurassic and Early Cretaceous seamounts in the western Pacific preserve syn-sedimentary sections deposited above the CCD (i.e., carbonate sediments).

Defining modes of eruption-constant effusion over several million years or several large pulse events over the same time interval. This will be achieved by a) age dating of discrete ash layers in syn-sedimentary sections, b) drilling through the feather edge of a LIP reached by only the largest flows—test for age progression, and c) drilling through basement reflections interpreted to represent alternating thin and thick flows (Inoue et al., 2008).

Establishing relationships among oceanic LIPs, OAEs, and other major environmental changes (e.g., ocean acidification and fertilization). Late Jurassic and Cretaceous OAEs are known to be approximately synchronous with LIP events (Jones and Jenkyns, 2001). Syn-sedimentary sections containing OAE, and bounding intervals are critical for analyses of elemental and isotopic variations associated with OAEs. These data can be compared with similar data from synchronous LIPs. Recovery of OAE intervals at multiple locations around an oceanic LIP allows directionality of fluxes to be evaluated. Knowledge of the duration of the LIP event is required for these studies (see above).

Technology and LIP Drilling

Advances in drilling technology will improve our understanding of LIP origin, emplacement, and environmental impacts dramatically. Specifically, technologies that should either be developed or implemented by the IODP that will advance our understanding of LIPs significantly include the following:

Enhanced recovery of syn-sedimentary sections, especially those with alternating hard-soft (e.g., chert-chalk) layers. To date, recovery of intercalated hard/soft sediment from the Pacific and Indian oceans has been exceedingly difficult during the DSDP, ODP, and IODP, and poor core recovery precludes recovery of important syn-sedimentary sections.

Sidewall coring, important for recovering soft sediment from alternating hard-soft layers. OAEs encompass a maximum of 150 cm of vertical section, although recovery of underlying and overlying sediment is necessary as well for biostratigraphic dating each OAE.

Oriented cores. Linking hotspots to LIPs, especially in the Pacific, is hampered because unoriented cores yield only paleolatitude information. Oriented cores are critical for determining sediment magnetostratigraphy in low latitudes, investigating geomagnetic field behavior, studying plate motions, and establishing flow directions of lavas.

Riser drilling in >2500 m of water. This will open opportunities for drilling through the feather edges of LIPs to the basement or sediment beneath, thereby bracketing the durations of LIP events.

Collaborations between IODP and ICDP

LIPs are equally well manifested in the oceans as on land. Questions such as the nature of the mantle source of volcanic plateaus, the ascent of magma from source to surface, magma fluxes through the life of a plateau, and the impact of LIP emplacement on global climate are best treated by a joint IODP/ICDP approach. The lessons learned from drilling on variably well exposed continental flood basalts can then be applied to the study of their more spectacular, but less accessible, oceanic counterparts. Proxies of climate change, measured in oceanic and continental sequences, provide information on the contrasting impact of the wholly submarine emplacement of an oceanic plateau and the open-to-the-atmosphere impact of continental volcanism. A key target of ICDP drilling should be the sill complexes that presumably underlie most LIPs. These complexes, relatively inaccessible in ocean basins, are important for four reasons. 1) They are an important element in the magmatic plumbing of each LIP. 2) Volatile-release at sill-sediment contacts contributes greatly to climate impact. 3) Valuable deposits of Ni, Cu, and Pt-group elements are located in these sills. 4) Intrusions in sedimentary basins influence the maturation of petroleum deposits and complicate exploration for such deposits. An understanding of the sill complexes, therefore, has important economic implications, in both continental and oceanic settings. Most importantly, unique and promising opportunities exist for combined IODP/ICDP drilling of the same LIP (e.g., onshore and offshore sections of the North Atlantic Volcanic Province; the Parana-Etendeka flood basalts (South Atlantic); the Deccan Traps-Seychelles Bank dikes (Indian Ocean); *in situ* and obducted (Caribbean, Central and South America) Caribbean flood basalts; Alpha Ridge and the High Arctic LIP; and the Ontong Java Plateau and obducted sections thereof in the Solomon Islands (Pacific Ocean).

Conclusions

The LIPs workshop was highly successful in showing that studying LIPs requires an integrated approach involving mantle geodynamics, plume modeling, petrology, environmental impacts, paleoceanography, physical volcanology, micropaleontology, geophysics, and tectonics. The workshop also concluded that oceanic LIPs must be studied in concert with their continental counterparts to better understand emplacement mechanism and environmental effects of their emplacement. A number of conceptual drilling targets and prospective regions were identified. In addition, areas where technology development was needed were highlighted, as were potential LIP-focused IODP-industry and ICDP/IODP collaborations. The result of this workshop will allow focused IODP LIP drilling proposals to be developed.

Acknowledgements

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Drilling to Decipher Long-Term Sea-Level Changes and Effects—A Joint Consortium for Ocean Leadership, ICDP, IODP, DOSECC, and Chevron Workshop

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Introduction

One of the most societally relevant objectives of the Earth sciences is to understand the history and impact of global sea-level (eustatic) fluctuations at different timescales. Over a third of the world's population lives within 100 km of a coastline. One-tenth of the global population and thirteen percent of the world's urban population live in coastal areas that lie within just 10 m above sea level (the Low Elevation Coastal Zone or LECZ), which covers only two percent of the world's land area (McGranahan et al., 2007). Reconstruction of global mean sea level since 1870 indicates a twentieth century rate of sea-level rise of 1.7 ± 0.3 mm yr^{-1} and a significant acceleration of sea-level rise of 0.013 ± 0.006 mm yr^{-2} (Church and White, 2006), in part due to anthropogenic influences. Satellite observations in the last decade show that the rates have increased since 1993 to 3.3 ± 0.4 mm yr^{-1} (Cazenave and Nerem, 2004). Remote-sensing data suggest that ice sheets currently contribute little to sea-level rise. Best estimates are that sea level could rise by as much as 50 cm in the next 100 years (IPCC, 2007). However, dynamical instabilities in response to climate warming may cause faster ice-mass loss (Cazenave, 2006). Rahmstorf et al (2007) show that sea-level observations are tracking at the high end of the IPCC estimates and conclude that 80 cm, and perhaps >1 m, is the most likely global rise by 2100. In some of the most heavily populated areas (e.g., the U.S. Atlantic seaboard) relative sea-level rise exceeds 4 mm yr^{-1} (Psuty and Collins, 1996) due to combined effects of global sea-level rise and subsidence. While such rates are gradual on a human timescale, the geological record shows that they can increase rapidly and dramatically (e.g., >2 m in a century; Fairbanks, 1989; Bard et al., 1990); in addition, the retreat of shorelines can be erratic and rapid even under conditions of moderate global rises of sea level.

The geologic record provides an opportunity to quantify the timing, amplitudes, rates, mechanisms/controls, and effects (stratigraphic response) of eustatic change (Figs. 1 and 2). This information, in turn, provides a baseline for predicting future global sea-level changes and assessing anthropogenic influences. In order to understand the effects of potential future eustatic trends, it is vital to document how the Earth system has operated during past abrupt climate changes (e.g., the last and penultimate deglaciations) and under past conditions of extreme climate forcing, and to constrain the eustatic response to elevated CO_2 levels. For example, determining how sea level varied in response to past intervals of global warming—e.g., marine isotope chrons 5e (Thompson and Goldstein, 2005), 11 (Droxler et al., 2003), 31 (Scherer et al., 2008); "mid " Pliocene warmth (Draut et al., 2003), the middle Miocene climate optimum, the early Eocene (Zachos et al., 2001), and the Late Cretaceous (Abreu et al., 1998; Miller et al., 2005 a, b; Bornemann et al., 2008)—will provide a means to evaluate the eustatic impact of future climate trends. Understanding how processes/mechanisms yield specific eustatic responses will therefore improve our understanding of the societal impact of the resulting sea-level changes. Furthermore, understanding how process interactions produce the preserved stratigraphy of beds and sequences is fundamental to deciphering the long-term geologic and climatic history recorded by sediments in a variety of marine sedimentary basins. These environments are also economically and strategically important—testing predictive sequence models has a proven potential for identifying oil and gas resources and for ground water/pollution remediation issues. Such research also helps to achieve the long-sought goal of predicting margin lithologies in the absence of drilling, a concept pioneered by the Exxon group (Vail and Mitchum, 1977). Finally, constraining the history of sea-level change provides data of direct use to researchers in other disciplines because of the relationships between

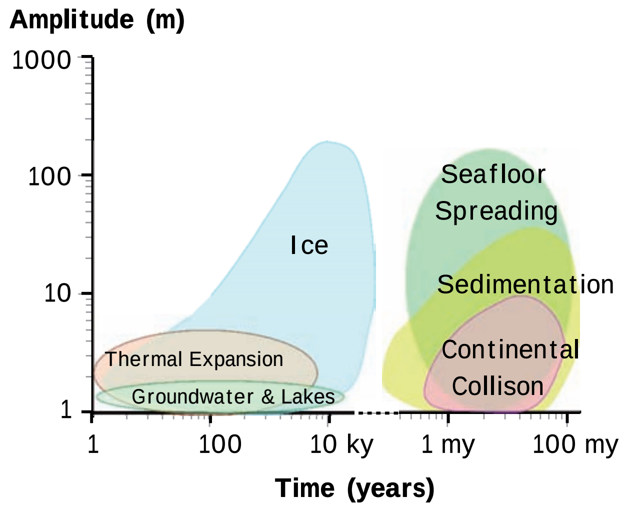

Figure 1. The mechanisms that generate eustatic change operate on different timescales and generate different magnitudes of sea-level change. These variations in conjunction with proxy data may be used to determine the causal mechanisms of eustatic change. (Modified from Miller et al., 2005a.)

eustasy and ice-sheet growth and decay, nutrients and ocean productivity, carbon storage, and ocean chemistry.

The challenge is considerable because eustatic effects are complexly intertwined with processes of basin subsidence and sediment supply (Cloetingh et al., 1985; Karner, 1986; Posamentier et al., 1988; Christie-Blick et al., 1990; Reynolds et al., 1991; Christie-Blick and Driscoll, 1995; Kominz et al., 1998; Kominz and Pekar, 2001). Extracting the eustatic signal requires integrated onshore/offshore drilling transects involving global retrieval of cores representing multiple timeframes and depositional settings, including siliciclastic, carbonate, and mixed systems (Fig. 3). Fundamental to the approaches recommended by our workshop are as follows: 1) to enhance our understanding of eustatic timing, amplitudes, rates, and stratigraphic response during the icehouse period, when glacioeustasy is known to be the principal eustatic mechanism, and; 2) to begin an aggressive program to understand the mechanisms responsible for greenhouse eustasy and how they relate to climatic trends and stratigraphic response.

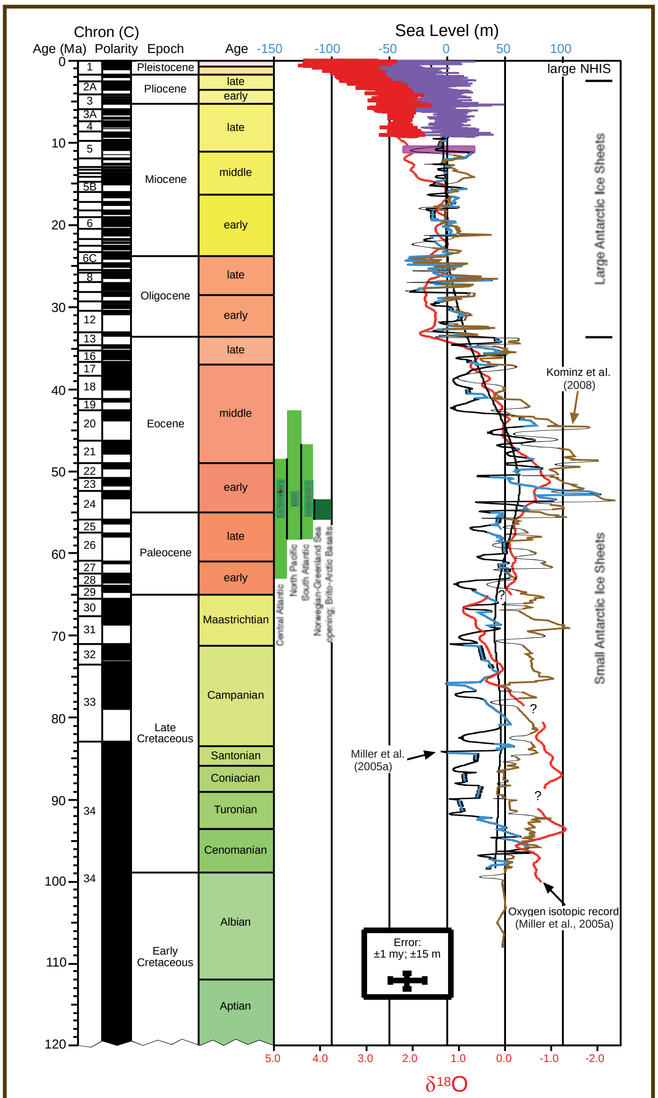

Figure 2. Global sea level (light blue) for the interval 7–100 Ma derived by back-stripping five New Jersey coastal plain core holes (Miller et al., 2005a). Revised back-stripped sea-level curve (brown) based on a total of eleven New Jersey core holes (Kominz et al., 2008). Global sea level (purple) for the interval 0–7 Ma derived from $\delta^{18}O$, shown in red for a benthic foraminiferal $\delta^{18}O$ synthesis from 0–100 Ma with the scale on the bottom axis (in parts per thousand, Miller et al., 2005a). The Miller et al. (2005a) back-stripped sea-level curve was smoothed with a 21-point Gaussian convolution filter to generate the smooth black curve. The pink box at 11 Ma is a sea-level estimate derived from the Marion Plateau (John et al., 2004). Light green boxes indicate times of spreading rate increases on various ocean ridges (Cande and Kent, 1992). Dark green box indicates the opening of the Norwegian-Greenland Sea and concomitant extrusion of basalts (Modified from Browning et al., 2008).

Salt Lake City Workshop

Various groups related to the Ocean Drilling Program (ODP) have developed strategies for studying eustasy on orbital (>19 kyr) and longer timescales (Imbrie et al., 1987; Watkins and Mountain, 1990; JOIDES, 1992). These strategies have begun to be implemented with drilling transects across the New Jersey margin (ODP Legs 150, 150X, 174A, and 174AX), the Bahamas (Leg 166 and mission-specific platform sites) and a targeted sea-level amplitude experiment on the Marion Plateau, Northeast Australia (Leg 194). However, an effective, coordinated strategy requires that additional margin transects be drilled. In addition, it has been fifteen years since the last of these groups; the Sea-Level Working Group (JOIDES, 1992), discussed goals and strategies of sea-level research. Recent drilling advances, including the use of mission-specific platforms (MSP) offshore and joint onshore-offshore drilling (e.g., IODP Expedition 313), together with new views on the roles of tectonics and sediment dynamics, required that the scientific community re-evaluate the fundamental assumptions of sea-level studies.

As a follow-up to the SEALAIX Symposium ("Sea-Level Changes: Records, Processes and Modeling", September 2006, Presqu'île de Giens, France), an international workshop of more than fifty participants was held in Salt Lake City, Utah (8–10 October 2007) sponsored by Consortium for Ocean Leadership (formerly Joint Oceanographic Institutions), the International Continental Scientific Drilling Program (ICDP), the Integrated Ocean Drilling Program (IODP), Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC), and Chevron. The purposes of the workshop were 1) to review results of ODP and early IODP drilling for sea-level objectives; 2) to reevaluate principles and strategies for constraining genetic links between eustatic change and Earth system processes and for defining the relative roles of eustasy versus local processes in building the stratigraphic record; and 3) to identify possible geographical areas and time-intervals for future IODP drilling transects. Presentations about IODP, ICDP, and DOSECC were followed by keynote scientific talks and a series of short, three-minute presentations by participants. Breakout groups subsequently focused on the relationship between recorded sea-level cyclicity and eustatic mechanisms through time, and on deciphering the stratigraphic response to eustasy through a sedimentary process approach in both

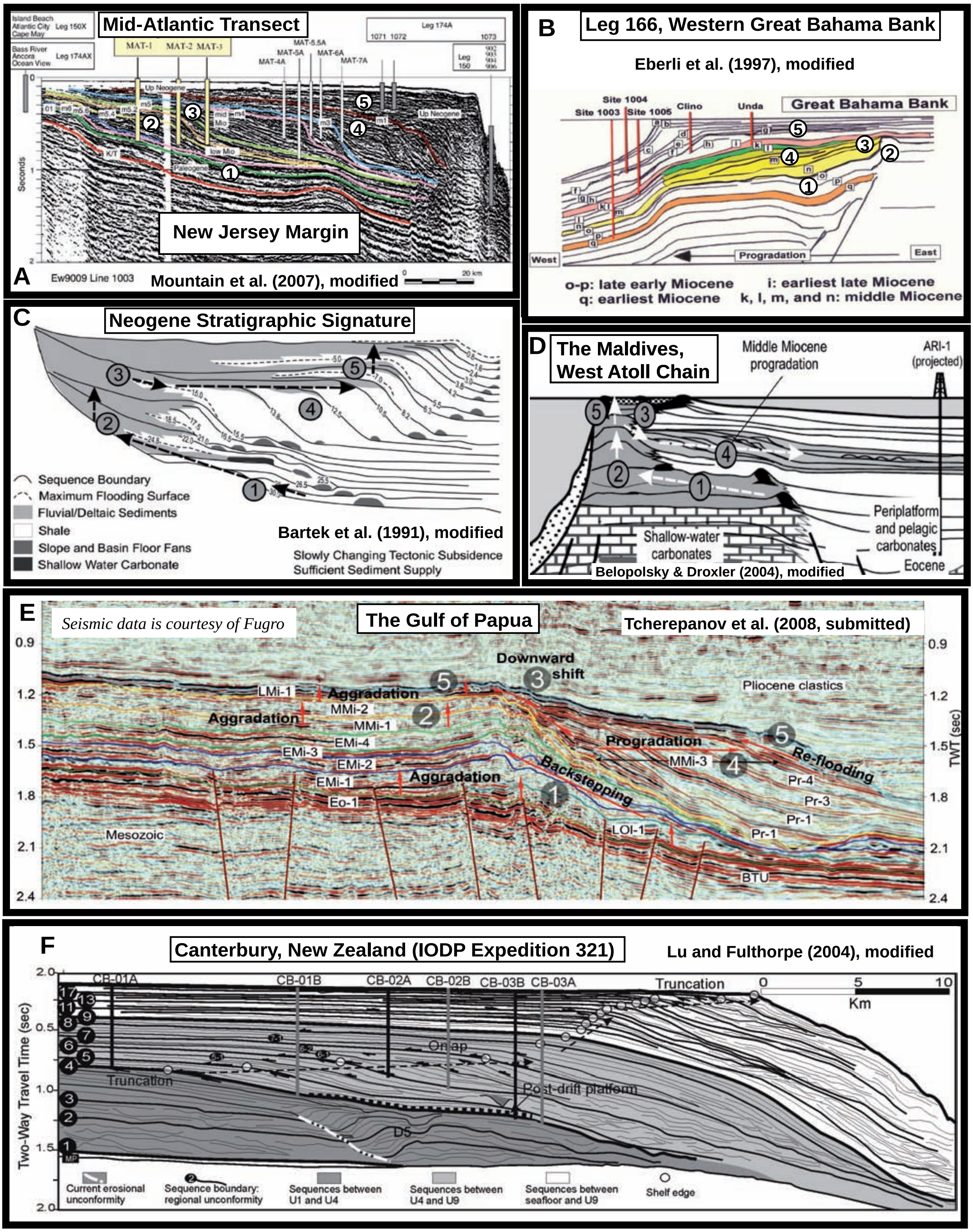

Figure 3. [A] Middle Atlantic Transect (MAT) off New Jersey, showing drillsites targeting a Paleogene-Pleistocene prograding clinoform succession. MAT has been drilled on the slope (ODP Leg 150; sites not shown) and shelf (Leg 174A; sites 1071–1073 along strike from this profile), as well as on the Coastal Plain (Legs 150X and 174AX). Inner shelf drilling (MAT 1-3) is planned as a Mission-Specific Platform IODP Expedition 213. [B] Line drawing of interpreted Great Bahama Bank sequences drilled during ODP Leg 166 (Sites 1003–1005) and the Bahamas Drilling Project (sites Clino and Unda). [C] The stratigraphic signature of the Neogene represented by: 1) late Oligocene-early Miocene aggradation, backstepping and partial drowning; 2) late early Miocene-early middle Miocene vertical growth or aggradation; 3) earliest middle Miocene downward shift of deposition; 4) late middle Miocene systematic lateral growth (progradation); and 5) late Miocene-early Pliocene re-flooding and aggradation (Bartek et al., 1991; Tcherepanov et al., 2008). [D] The Neogene stratigraphic signature along the West Maldives Inner Sea carbonate margin. [E] Neogene stratigraphic signature in the Gulf of Papua. [F] A future sea-level transect: line drawing of interpreted sequences, offshore Canterbury Basin, New Zealand, showing proposed IODP sites, scheduled for drilling as IODP Expedition 317.

icehouse and greenhouse worlds. Breakout Group Two was further subdivided into siliciclastic and carbonate groups. In addition to identifying scientific questions and objectives, the groups were also asked to consider drilling program design, potential target areas, and technology requirements (onshore and offshore).

Objective 1: Determining Eustatic Mechanisms

Understanding the mechanisms that drive eustatic change requires knowledge of the timing, amplitudes, and rates of global sea-level change (Fig. 1). It also requires information on climate and paleoceanography, mainly derived from proxy records (Fig. 4), and tectonic mechanisms that control the volume of the oceans. In turn, such quantification of eustatic change will contribute to other areas of the Earth sciences by helping to constrain such processes as ice-sheet growth and decay, ocean temperatures, carbon burial, and inorganic carbon precipitation in carbonates (Fig. 4) as well as global tectonism (Harrison, 1990). Sea level is important for the study of tectonic processes, because it is the datum against which vertical tectonic movements are measured.

1) Refining timing, amplitudes, and mechanisms of icehouse (Oligocene-Recent) eustatic change. ODP results to date have demonstrated that global sea-level changes over the past 42 myr can be explained, in part, by growth and decay of continental ice sheets (glacioeustasy; Miller et al., 1996; Eberli et al., 1997; Eberli, 2000). Such drilling has principally addressed the timing of sea-level change and has also determined that sequence boundaries indeed represent timelines as predicted in the sequence stratigraphic model (Eberli et al., 1997; Betzler et al., 2000).

However, our understanding of how climate change influences sea level, even during this “icehouse” period of large ice sheets, is incomplete. In particular, there are still uncertainties surrounding the hierarchy of eustatic and sequence periodicities, and particularly the origins of sequences with durations of >1 myr, which do not appear to conform to long-period (1.2 myr and 2.4 myr) astronomical variations (Miller et al., 2005a). It is surprising that modulation by the 1.2-myr-long tilt cycle is not a dominant periodicity in icehouse sea-level records, because it has been shown that the short 41-kyr tilt cycle dominates the ice-volume record of the past 34+ my (Zachos et al., 2001). The 2.4-myr very long eccentricity cycle dominates carbon isotopic records throughout the Cretaceous to Cenozoic through its effects on the carbon system, which might be expected to be influenced by sea-level changes. Spectral analysis of the Miller et al. (2005a) sea-level records shows that variations occur with an as-yet-unexplained, persistent 3-myr beat that may be either an interference between the 1.2 myr and 2.4 myr cycles or be an artifact of an undersampled sea-level signal. This intriguing relationship bears investigation because the million-year-scale sea-level signal can be shown to be a composite of 41-kyr tilt cycles, at least for the icehouse world (Miller et al., 2005a).

Moreover, sea-level amplitudes during this period have not yet

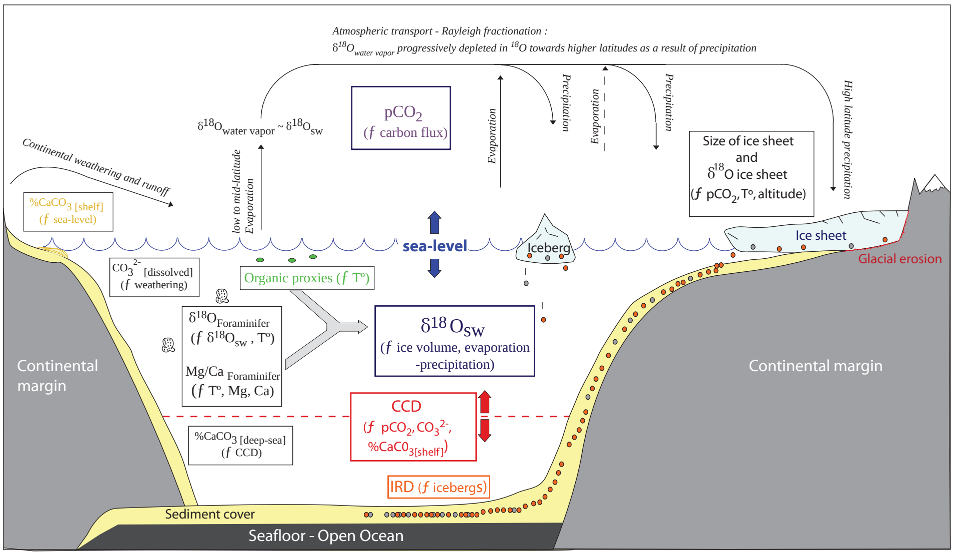

Figure 4. Details are given below.

Schematic figure illustrating how deep-sea geochemical records can be used to understand mechanisms of past eustatic changes by analogy to the modern ocean. During atmospheric transport from low to high latitudes water vapor becomes progressively more depleted in $\delta^{18}O$, and ice sheets have a very negative $\delta^{18}O$ signature. The isotopic composition of high latitude ice sheets is a function of the magnitude of isotopic fractionation within the hydrological cycle, which in turn is dependent on pCO_2 and temperature, and could vary over geological timescales. Consequently, the $\delta^{18}O$ composition of seawater ($\delta^{18}O_{sw}$) is largely a function (f) of ice volume and regional evaporation and precipitation processes. Reconstructing $\delta^{18}O_{s}w$ in different ocean basins will highlight times of eustatic changes due to ice-volume fluctuations, as well as provide a record of the timing and amplitude of these changes. $\delta^{18}O_{sw}$ can be derived by combining the isotopic composition of foraminiferal calcite (“$\delta^{18}O_{Foraminifer}$”) with independent temperature proxies (e.g., Mg/Ca for deep-water temperature, and TEX86 and alkenones for surface water temperatures). Subsequently, correlation of excursions in $\delta^{18}O_{sw}$ to more positive values with independent evidence of sea-level change can be taken as support for the operation of a glacio-eustatic mechanism. Open ocean sites can also provide more indirect evidences of the relative role of glacio-eustasy through geological time. The presence of ice rafted debris (IRD) in open ocean sediments indicates iceberg transport, and thus a significant volume of ice at sea level along continental margins. The waxing and waning of ice sheets is a function of high-latitude temperatures and atmospheric pCO2, which also impact the position of the carbonate compensation depth (CCD). Fluctuations in the CCD are recorded as variable carbonate contents ($\%CaCO_3$) within deep-sea sediments and could be used as indirect evidence of glacial/interglacial alternations, as CCD is sensitive to changes in carbonate burial on the shelf. Finally, eustatic variations control the area of shelf submerged, thus indirectly impacting the type of rocks subjected to continental weathering, the amount of nutrients and carbonate ions delivered to the coastal ocean, and the area available for carbon burial on continental margins. Some isotope systems (Os, Nd, and Sr) are available as proxies of continental weathering. The weathering processes ultimately have feedbacks on the carbon cycle, climate, and glacioeustasy.

been adequately constrained. One approach for determining eustatic amplitudes that has been applied with success to the New Jersey margin involves combining sequence stratigraphic and back-stripping analyses (Fig. 5; Kominz and Pekar, 2001; 2002; Pekar and Kominz, 2001). The resulting sea-level curve (Fig. 2; Browning et al., 2008) represents the best current estimate, but it is still incomplete because lowstand sediments were not recovered, introducing uncertainty to estimated amplitudes. Possibly as a result, the Miocene part of the New Jersey sea-level curve does not appear to correspond as well to the globally recognized stratigraphic signature of the Neogene as other eustatic curves (Fig. 6; Bartek et al., 1991). Furthermore, the New Jersey curve also differs from δ18O records that have been corrected for paleotemperature and are therefore an improved record of ice-volume fluctuations (Billups and Schrag, 2002; Lear et al., 2004), and which do correspond well to the stratigraphic signature of the Neogene (Fig. 6).

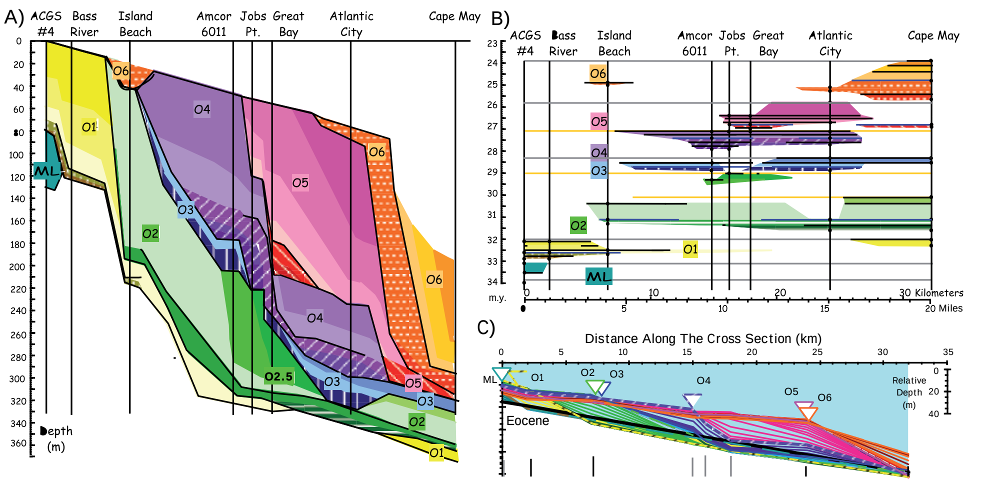

Figure 5. In order to determine sea-level change from a marginal marine setting, we recommend at least two-dimensional sequence stratigraphic back-stripping. An example of some of the data required for two-dimensional sequence stratigraphic back-stripping from Kominz and Pekar (2001, 2002) is shown for illustration. [A] Chronostratigraphic chart for New Jersey coastal plain Oligocene sequences. Solid colors represent highstand systems tracts, while lowstand systems tracts are depicted by patterned colors. Vertical lines show well control. [B] Sequence model for New Jersey coastal plain Oligocene sequences. Patterns and lines as described above. [C] Geometry of horizons identified in A and B after performing geohistory analysis. Sequences may be identified by colors, which reflect those in A and B, and the labeled offlap break points (inverted triangles) of the final horizon of each sequence. (Modified from Kominz and Pekar, 2002.)

Finally, estimates of the amplitudes of eustatic change from one-dimensional back-stripping at one location (e.g., New Jersey; Miller et al., 2005a; Kominz et al., 2008; Browning et al., 2008) requires supplemental application of this procedure to strata on distant continents (e.g., Carter et al., 1991). Future scientific drilling must therefore include additional drilling for icehouse eustatic objectives. Ideally, two- and three-dimensional back-stripping procedures would improve amplitude estimates (Kominz and Pekar, 2001). These approaches require good regional seismic coverage and a well-constrained, regional, sequence stratigraphic framework, including data that can only be obtained from cores.

2) Challenging the paradigm of a stable, ice-free "greenhouse" climate. Though we are beginning to unlock the mysteries of icehouse sea-level changes, our understanding of eustatic change during the preceding "greenhouse" world of the Triassic to early Eocene is controversial. For example, the Late Cretaceous has been reconstructed as a greenhouse world with warm polar climates (Bice et al., 2006), and most studies have assumed the absence of polar ice sheets (e.g., Huber et al., 1995). However, the work of Exxon Production Research Company (Vail and Mitchum, 1977; Haq et al., 1987) and more recent publications (Van Sickel et al., 2004; Miller et al., 2003, 2005a, b; Bornemann et al., 2008) have indicated large (tens of meters), short-period (<1 myr) Late Cretaceous global sea-level (eustatic) fluctuations (Fig. 2). In addi-

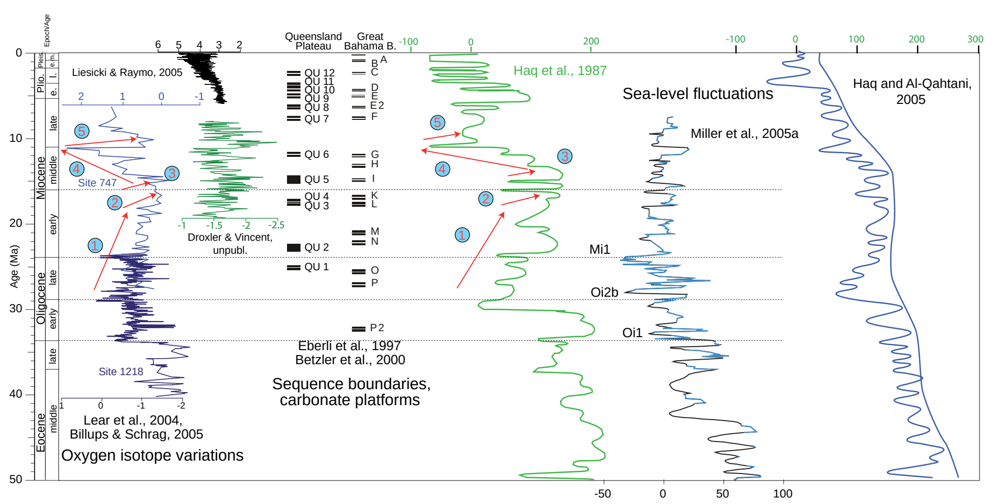

Figure 6. Oxygen isotopic and eustatic curves showing correspondence to the stratigraphic signature of the Neogene (red arrows and numbers 1–5; see Figure 3). The Miller et al. (2005a) eustatic curve from the New Jersey margin does not conform precisely to the global signature, particularly in the middle and late Miocene.

tion, second- (~10 my), third- (1–5 my) and fourth- (~0.5 my) order sequences can apparently be correlated widely between tectonically active and passive regions (e.g., Western Interior Seaway, Europe and India; Gale et al., 2002) suggesting eustatic control. Glacioeustasy is the only known mechanism for producing such large, rapid eustatic changes (Donovan and Jones, 1979; Fig. 1).

There are two solutions to this enigma: eustatic mechanisms are not fully understood, or there were ice sheets throughout much of the Triassic to early Eocene (Stoll and Schrag, 1996, 2000; Abreu et al., 1998; Miller et al., 2003, 2005a,b; Bornemann et al., 2008). ODP and ICDP drilling onshore New Jersey (Leg 174AX) have provided a detailed record of Cretaceous to early Eocene sequences. This record quantifies high amplitudes and rates of eustatic change (>25 m in <1 myr) in the Late Cretaceous to Eocene greenhouse world. Based on this sea-level history, Miller et al. (2003, 2005a, b) have proposed that ice sheets existed for geologically short intervals (i.e., lasting ~100 ky) during the Late Cretaceous-Eocene. This view can be reconciled with previous assumptions of an ice-free Greenhouse World. Eustatic changes on the 10^6 yr scale were typically ~15–30 m in the Late Cretaceous-Eocene (ca. 100–33.8 Ma), suggesting growth and decay of small- to medium-sized (10–15 x 10^6 km^3) ephemeral Antarctic ice sheets (Miller et al., 2005a, b).

However, although such indirect evidence for ephemeral ice sheets is growing, there is, as yet, no physical evidence for Late Cretaceous to early Eocene ice sheets. A particular difficulty is that other data indicate warm global temperatures for much of this interval—for example, very warm Albian-Santonian sea surface temperatures in the tropical Atlantic (Forster et al., 2007). There is therefore a need for additional high-resolution stratigraphic records from the greenhouse period.

Objective 2: Defining Stratigraphic Responses

The stratal geometries that define sedimentary sequences worldwide (Mitchum et al., 1977; Haq et al., 1987) result from a complex interplay of processes acting in three dimensions. Eustasy competes with climatic and paleoceanographic variations, tectonism, rates and modes of sediment supply, and submarine current activity to influence base level and shoreline position and, hence, stratal formation and preservation. Understanding margin sedimentation, therefore, requires evaluation of multiple processes (including eustasy) at various temporal and spatial scales (Nittrouer and Kravitz, 1995). However, predictive models of the distribution of sediments within unconformity-bounded sequences are based on assumptions about the importance of relative sea-level change (Posamentier et al., 1988; Vail et al., 1991) that have yet to be adequately tested.

Nevertheless, various industry and academic studies have established that unconformity-bounded sequences are indeed the building blocks of the stratigraphic record (see summary in Christie-Blick and Driscoll, 1995), as first proposed by Vail and Mitchum (1977), and that they can occur in predictable patterns (Fig. 3). For example, the geometric signature of stratigraphic sequences along continental margins for the last 30 Ma involves (Fig. 3C–E) (1) late Oligocene (Chattian) and early Miocene (Aquitanian) aggradation, back-stepping and drowning; (2) late early Miocene (Burdigalian) and earliest middle Miocene (early Langhian) aggradation; (3) earliest middle Miocene (late Langhian) downward shift of deposition; (4) middle Miocene (Serravallian) progradation; and (5) two stacked flooding and aggradational episodes in the late Miocene (Tortonian) and early Pliocene (Zanclean) separated by a late Miocene (Messinian) downward shift of deposition (Bartek et al., 1991, Tcherepanov et al., 2008a and b). Although this pattern is widespread and is observed globally in both siliciclastics and carbonates (Fig. 3; Bartek et al., 1991; Tcherepanov et al., 2008a and b), the heart of this section, the early and middle Miocene, has not yet been ground-truthed by drilling. The fundamental assumptions and predictive capabilities of sequence models can only be tested by drilling on shallow continental shelves where (3-D) sedimentary geometries are constrained by seismic data (e.g., Kominz and Pekar, 2002).

Siliciclastic Margins. Because of the complex interplay of forcing mechanisms responsible for the stratigraphic record, stratigraphic response must be defined in a diversity of time periods and settings, both tectonic and sedimentary. Siliciclastic sediments are excellent sea-level markers because both highly sensitive indicators of shoreline position, and they are globally widespread. However, it is essential to define the specific sedimentary processes (depositional, transportational, and erosional) responsible for the stratigraphic record and to distinguish the responses of these processes to eustasy from their responses to local forcing. This process-based approach must be a component of future drilling-based sea-level research.

The stratigraphic record comprises both surfaces and intervening sedimentary units. In offshore work, surfaces are often defined initially using seismic reflection profiles and later calibrated by coring (Fig. 3). However, only coring can provide the lithofacies and biofacies of the intervening units. Sequence stratigraphic models of such units (Posamentier et al., 1988; Van Wagoner et al., 1988; Vail et al., 1991) are based on simple assumptions about how facies respond to relative sea-level changes. However, the real world is rendered more complex by the additional influence of local forcing and the three-dimensionality of sequence architectures. Future drilling to investigate the stratigraphic response to eustasy must therefore evaluate the contributions of tectonism and sediment supply. In addition, geometrical variations must be constrained by pre-drilling seismic surveys.

Carbonate Platforms and Margins. Carbonates are excellent sea-level markers because carbonate facies are depth-dependent owing to the importance of sunlight to many carbonate-secreting organisms (Eberli et al., 1997; Camoin et al., 2007a). The relationship of these systems to the carbon cycle allows direct correlation of climatic and eustatic signals (Lear et al., 2004). In addition, multiple dating techniques are available for carbonates (including ^{14}C, U/Th, Sr, U/Pb, biostratigraphy, and magnetostratigraphy). These enable examination of a wide range of frequencies of sea-level change, from millennial scale to tens of millions of years.

Continental margin transects (Fig. 3) have the advantage that their stratigraphic architectures are well constrained by seismic data. However, they are complemented by tropical reefs and atolls, which provide the most reliable geological estimates of relative sea level by dating "fossil sunshine" (e.g., shallow dwelling corals). The study of coral reefs is of crucial importance in attempts to resolve the rates of millennial-scale changes in sea level, to clarify the mechanisms that drive glacial-interglacial cycles, and to constrain geophysical models. Coral reefs provide unparalleled records of sea-level amplitudes, particularly for the middle to late Pleistocene. For example, drilling reefs in Barbados has provided a precise estimate for the last eustatic lowstand (120 ± 5 m below present at 18 ka; Fairbanks, 1989; Bard et al., 1990; Peltier and Fairbanks, 2006). Shallow-water drilling of coral reefs remains challenging due to recovery problems, but is necessary to allow study of recent high-resolution climate changes, and it contributes to estimates of the future behavior of the Earth system on societal timescales. This approach was employed during IODP Expedition 310 off Tahiti (Camoin et al., 2007a, b).

Strategies

1) *A focus on both icehouse and greenhouse objectives.*

2) *Drilling transect approach.* This approach, which was tried and tested on the New Jersey Margin and Great Bahama Bank, with additional IODP drilling planned off New Zealand (Fig. 3), must be enhanced and extended by:

- Integration of onshore (e.g., ICDP, DOSECC) and offshore (IODP, DOSECC) drilling. The record of icehouse eustasy is best preserved offshore (e.g., on continental margins), but the older, greenhouse, record tends to be preserved and drillable beneath coastal plains or in onshore basins (e.g., the Western Interior Seaway). Onshore drilling is therefore expected to play an increasingly important role in sea-level studies.

- Drilling of sufficient boreholes, including multiple transects where necessary, and incorporation of sufficient seismic control to constrain three-dimensional stratigraphic architecture.

- Maximizing core recovery by using appropriate drilling technology (e.g., casing, mud) and platforms (e.g., Mission Specific Platforms [MSPs]), and by adapting coring strategies as needed, e.g., by using diamond coring or short advances of the XCB.

3) *Recognizing the value of addressing tectonically active settings.* For example, the stratigraphic expression of sea-level change in active foreland basins in the U.S. and Canadian western interior basins is superlative, though the stratigraphic records incorporate the effects of both eustasy and tectonism.

4) *Incorporating a focus on high-resolution (10^3–10^5 yr) glacial-interglacial cycles* (e.g., the last 130 kyr). Examination of margins with high stratigraphic resolution will allow evaluation of the interaction of eustasy and other processes (e.g., Papua New Guinea; Jorry et al., 2008), and integration with process-oriented modeling (e.g., physical and mathematical modeling done as part of the Margins and Intermargins Initiatives).

5) *Coordination with drilling operations designed to address other objectives.* Sea-level studies can benefit greatly from the results of research into, for example, paleoclimate, carbon cycling, and ice-sheet dynamics (Fig. 4). Conversely, these research programs will also gain necessary insights from a well constrained eustatic history.

Future Work

Future IODP drilling for sea-level objectives includes IODP Expedition 313, New Jersey inner shelf drilling scheduled for summer 2009 and IODP Expedition 317, Canterbury Basin, New Zealand, scheduled for November 2008–January 2009. Great Barrier Reef drilling is tentatively planned for 2009. These planned expeditions, and existing IODP proposals (e.g., Maldives, North West Australian Shelf, Gulf of Mexico - Southern Bank, Belize margin, Gulf of Papua), all address icehouse objectives. Such drilling is indeed vital, in particular to constrain icehouse eustatic amplitudes and to calibrate the stratigraphic signature of the Neogene (Bartek et al., 1991). However, the next phase of sea-level studies must include greenhouse objectives. We therefore encourage proponents to prepare and submit sea-level proposals for both offshore and onshore drilling focusing on the greenhouse world.

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ANDRILL's Success During the 4th International Polar Year

by Fabio Florindo, David Harwood, Richard Levy, and SMS Project Science Team

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Introduction

One of the scientific programs of the Fourth International Polar Year (Allison et al., 2007; www.ipy.org), the ANDRILL (ANtarctic geological DRILLing) Program demonstrated ability to recover high quality marine and glacimarine sedimentary drill cores from high latitude ice-covered areas. ANDRILL's inaugural 2006 and 2007 drilling seasons resulted in the two deepest drill holes on the Antarctic continental margin, recovering 2,400 meters of high-quality and nearly continuous sediment core. A chief scientific objective of this collaborative effort of scientists, engineers, technicians, students, educators, drillers, and support personnel from Germany, Italy, New Zealand, and the United States is the recovery of sedimentary archives from which past climatic and environmental changes in the southern high latitudes can be reconstructed. More than 120 individuals have been involved in each of the two drilling projects, eighty of whom worked in Antarctica during each austral summer season.

Two Successful Antarctic Seasons

Completed in early December 2007, the AND-2A drillcore of the Southern McMurdo Sound (SMS) Project (Figs. 1 and 2) recovered 98% of the 1138.54 m of sedimentary rock penetrated, demonstrating that the ANDRILL drilling system (Figs. 1, 3, 4, and 5) is capable of consistently recovering high quality cores. The AND-2A drillcore is exceeded in depth only by ANDRILL's first drill hole AND-1B of the McMurdo Ice Shelf (MIS) Project (Fig. 2), which reached a total depth of 1284.87 m with similar success of high core recovery. Capable of operating in a range of environmental settings, the MIS Project drilled from an 84-m-thick ice shelf platform in 943 meters of water, and the SMS Project operated on the surface of 8.4 m of multi-year sea-ice over a 384-m water column. Alex Pyne, the Drilling Science Manager, merits recognition for the concept, design, and successful integration of elements of the ANDRILL drilling system.

Both of the ANDRILL projects reached their scientific targets. The MIS Project, led by Tim Naish (NZ) and Ross Powell (U.S.), recovered a record of a dynamic cryosphere of the last 13 million years of glacial and climatic variation of the West Antarctic Ice Sheet and Ross Sea region. The SMS Project (led by the authors of this report) completed drilling operations in late 2007 after recovering an expanded 600-m-thick section of the target interval that recorded a history of ice-proximal, shallow marine paleoenvironmental variation during the middle Miocene. This interval has long been held as a fundamental step in development of the Cenozoic cryosphere—interpretations of deep-sea oxygen isotope records suggest the middle Miocene encompassed a change from a period of warm climatic optima, approximately 17.5 Ma to 14.5 Ma, to the onset of major cooling between c. 14 Ma to 13 Ma, and the formation of a quasi-permanent ice sheet on East Antarctica.

In addition to the 600-m-thick middle Miocene interval (800–223 mbsf), the AND-2A drill core also recovered an expanded lower Miocene section (1138.54 up to c. 800 mbsf) through an interval previously recovered during the Cape Roberts Project and an upper Pliocene to Recent interval (223 mbsf to 0.0 mbsf) that is thinner but correlative to parts of the Upper Neogene section recovered by the ANDRILL MIS Project in drill core AND-1B. Abundant volcanic clasts and tephra layers in the core, also provide the materials to document the 20-million-year evolution of the McMurdo Volcanic Province including several previously unknown explosive volcanic events.

Figure 1. Panoramic image of the ANDRILL drilling rig and science laboratories in Southern McMurdo Sound during late 2007, operating from a 8.4-meter-thick sea-ice platform. Transantarctic Mountains are visible in the background.

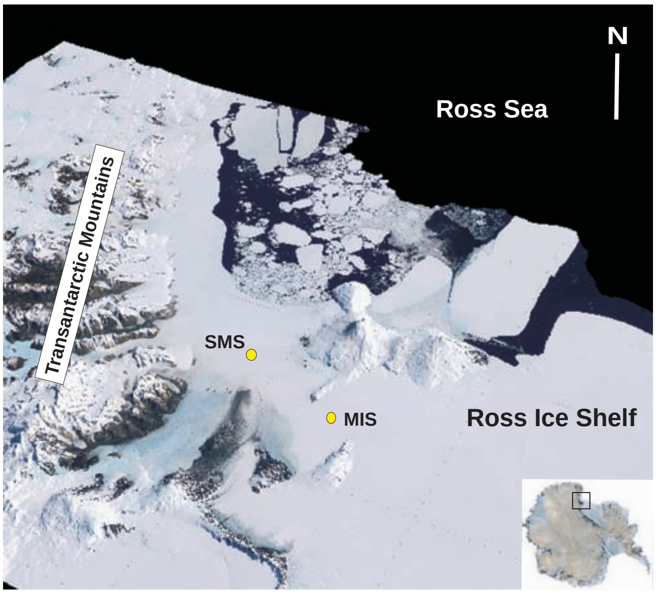

Figure 2. Satellite image of the McMurdo Sound region, including location of the Southern McMurdo Sound (SMS) and McMurdo Ice Shelf (MIS) drill sites.

Other results of the SMS Project include (1) a nearly continuous downhole logging operation, including deployment of a range of tools and a borehole televiewer, to match the excellent core physical (MSCL) and chemical (XRF scanning) properties data collected on-ice; (2) the first Antarctic *in situ* stress measurements from hydrofracture experiments conducted near the bottom of the borehole; (3) successful reconstruction and orientation of the core, using physical features, borehole tele-imaging, and a core orienting tool; (4) a robust chronostratigraphic framework, developed through integrated diatom biostratigraphy, magnetostratigraphy, and radiometric dating of volcanic materials, which now provides age control for the drill hole and the network of seismic lines in the western Ross Sea; (5) a vertical seismic profile study with three-component data; (6) the richest Cenozoic macropaleontological resource in East Antarctica, with more than fifty productive marine horizons; and (7) a record of terrestrial and marine temperature variations from a variety of climate proxies.

Future Activities and Planning

Programs like ANDRILL can help constraining uncertainties about the future behavior of Antarctic ice sheets and resultant sea-level change. These stratigraphic records will be used to determine the behavior of ancient ice sheets and to better understand the factors driving past ice sheet, ice shelf, and sea-ice growth and decay. This knowledge will enhance our understanding of Antarctica's potential responses to future global climate change. With this in mind, the ANDRILL scientific and operations teams continue to plan for future scientific progress using the ANDRILL system through field-based site surveys, scientific planning, and technological developments. ANDRILL's capabilities are expanding to operate from an ice shelf platform several hundred meters thick and moving at a rate of more than two meters per day. The ANDRILL teams are also assessing the feasibility of reentering a drill hole, following relocation of the drilling rig and drill site science facilities. In the meantime, the science team members involved in the MIS and SMS projects are actively studying the drill cores and reporting initial results (Harwood et al., 2006, 2008; Naish, et al., 2007a, 2007b, 2008). These results are vital to SCAR's (Scientific Committee on Antarctic Research) ACE (Antarctic Climate Evolution) program (www.ace.scar.org), whose objectives are to integrate geological and paleoclimatic data into climate and ice sheet models to constrain estimates of Cenozoic ice volume variability, and terrestrial and marine paleotemperatures.

In support of the 4th IPY's focus on education and outreach objectives (http://www.ipy.org), ANDRILL is also engaging and training the next generation of Antarctic geoscientists and educators through exciting and collaborative international research and is taking polar science adventure into classrooms and homes through a stimulating and diverse education and outreach program (http://andrill.org/iceberg).

Acknowledgements

The ANDRILL project is a multinational collaboration between the Antarctic Programs of Germany, Italy, New Zealand, and the United States. Antarctica New Zealand is the project operator, and developed the drilling system in collaboration with Alex Pyne at Victoria University of Wellington and Webster Drilling and Exploration Ltd. Antarctica New Zealand supported the drilling team at Scott Base, and Raytheon Polar Services supported the Science team at McMurdo Station and the Crary Science and Engineering Center. Scientific support was provided by the ANDRILL Science Management Office, University of

Figure 3. ANDRILL sediment cores were flown by helicopter daily from the drillsite to the Crary Science and Engineering Center at McMurdo Station. Photo by Lucia Simion.

Figure 4. Diamond-impregnated drilling bits enable the ANDRILL drilling system to recover high-quality core, with up to 98% core recovery through glacial and glacimarine sediments.

Figure 5. Drilling operations under the ANDRILL drill-rig canopy.

Nebraska-Lincoln. Scientific studies are jointly supported by the U.S. National Science Foundation, NZ Foundation for Research, the Italian Antarctic Research Program, the German Science Foundation, and the Alfred Wegener Institute. For more information, please visit the ANDRILL website at http://andrill.org.

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Related Web Links

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Fig. 4: Photo courtesy of ANDRILL
Figs. 3 and 5: Photo by Lucia Simion

The CO_2SINK Boreholes for Geological Storage Testing

by Bernhard Prevedel, Lothar Wohlgemuth, Jan Henninges, Kai Krüger, Ben Norden, Andrea Förster, and the CO_2SINK Drilling Group

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Introduction

Europe's first onshore scientific carbon dioxide storage testing project CO_2SINK (CO_2 Storage by Injection into a Natural saline aquifer at Ketzin) is performed in a saline aquifer in NE Germany. The major objectives of CO_2SINK are the advancement of the science and practical processes for underground storage of carbon dioxide, and the provision of operational field results to aid in the development of standards for CO_2 geological storage. Three boreholes (one injection well and two observation wells) have been drilled in 2007, each to a depth of about 800 m. The wells are completed as "smart" wells containing a variety of permanent downhole sensing equipment, which has proven its functionality during its baseline surveys. The injection of CO_2 is scheduled for spring 2008 and is intended to last up to two years to allow for monitoring of migration and fate of the injected gas through a combination of downhole monitoring with surface geophysical surveys. This report summarizes well design, drilling, coring, and completion operations.

Since the publication of the Intergovernmental Panel on Climate Change Report (IPCC, 2005), carbon dioxide capture and storage, including the underground injection of CO_2 through boreholes, became a viable option to mitigate atmospheric CO_2 release. One of the major goals for the immediate future is to investigate the operational aspects of CO_2 storage and whether the risks of storage can be successfully managed.

CO_2SINK is the first European research and development project on *in situ* testing of geological storage of CO_2 in an onshore saline aquifer (Förster et al., 2006). Key objectives of the project are to advance understanding of and develop practical processes for underground storage of CO_2, gain operational field experience to aid in developing a harmonized regulatory framework and standards for CO_2 geological storage, and build confidence towards future set in "projects of that kind".

The CO_2SINK site is located near the town Ketzin to the west of Berlin, Germany (Fig. 1). The plan is to inject into a saline aquifer over a period of two years a volume of approximately 60,000 t of CO_2. For this purpose, one vertical injection well (Ktzi-201) and two vertical observation wells (Ktzi-200 and Ktzi-202) were drilled at a distance of 50 m to 100 m from each other (Fig. 1). All three wells are equipped with downhole instrumentation to monitor the migration of the injected CO_2 and to complement the planned surface geophysical surveys. The injection of CO_2 will be interrupted at times for repeated downhole seismics (VSP, MSP), cross-hole seismic experiments, and downhole geoelectrics.

The preparatory phase for CO_2 injection started in April 2004 with a comprehensive geological site characterization and a baseline fluid monitoring (Förster et al., 2006). This was followed by a baseline 3-D seismic survey (Juhlin et al., 2007) and the development of a drilling and completion concept (Fig. 2) allowing for monitoring during CO_2 injection and storage observation.

Geological Background

The CO_2SINK site is located in the Northeast German Basin (NEGB), a subbasin of the Central European Basin System. The sedimentary succession in the NEGB is several kilometers thick containing geological formations of Permian to Quaternary age, comprising abundant deep saline aquifers. The CO_2 will be injected into the Stuttgart Formation (lower portion, Fig. 3) of Triassic (Middle Keuper) age, into the southern flank of a gently dipping double anticline.

The 80-m-thick target formation rests at about 630–710 m depth at a temperature of about 38°C. The formation is made up of siltstones and sandstones interbedded by mudstones deposited in a fluvial environment. The reservoir is in sandstone channels as well as levee and crevasse splay deposits. These channel-(string)-facies rocks alternate with muddy

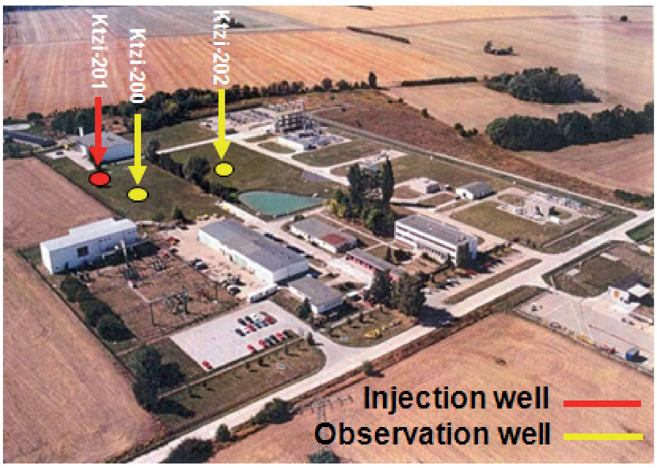

Figure 1. Location of boreholes at Ketzin industrial park.

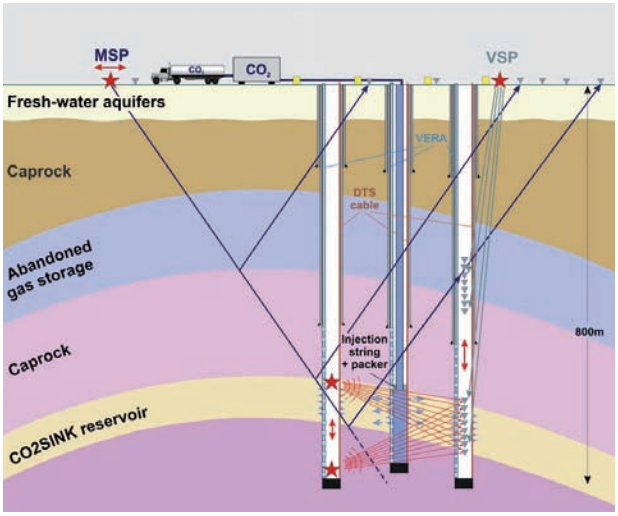

Figure 2. Schematic concept of Ketzin geology, drilling, and geophysical monitoring including moving source seismic profiling (MSP), vertical seismic profiling (VSP), cross-hole seismics, surface 3-D seismics, and surface and cross-hole geoelectrics using a permanently installed Vertical Electrical Resistivity Array (VERA), and Distributed Temperature Sensing (DTS) (from Förster et al., 2006).

flood-plain-facies rocks of poor reservoir quality. A geostatistical approach applied to the reservoir architecture (Frykman et al., 2006) pointed towards variable dimensions of the sandstone bodies and was supported by continuous wavelet transforms on 3-D seismic data (Kazemeini et al., 2008).

The Stuttgart Formation is underlain by the Grabfeld Formation (Middle Keuper), which is a thin-bedded mudstone succession with interbedded marlstone, marly dolomite and thin anhydrite or gypsum beds deposited in a clay/mud-sulfate playa depositional environment (Fig. 3; Beutler and Nitsch, 2005). The immediate caprock of the Stuttgart Formation, the Weser Formation (Middle Keuper), also is of continental playa type, consisting mainly of fine-grained clastics such as clayey and sandy siltstone that alternate with thin-bedded lacustrine sediments, like carbonates, and evaporites (Beutler and Nitsch, 2005). The high clay-mineral content and the observed pore-space geometry of these rocks attest sealing properties appropriate for CO_2 capture (Förster et al., 2007). The Weser Formation is overlain by the Arnstadt Formation (Middle Keuper), again of lacustrine character (mud/clay-carbonate playa; Beutler and Nitsch, 2005) with similar sealing properties. The two caprock formations immediately overlying the Stuttgart Formation are about 210 m thick (Fig. 3).

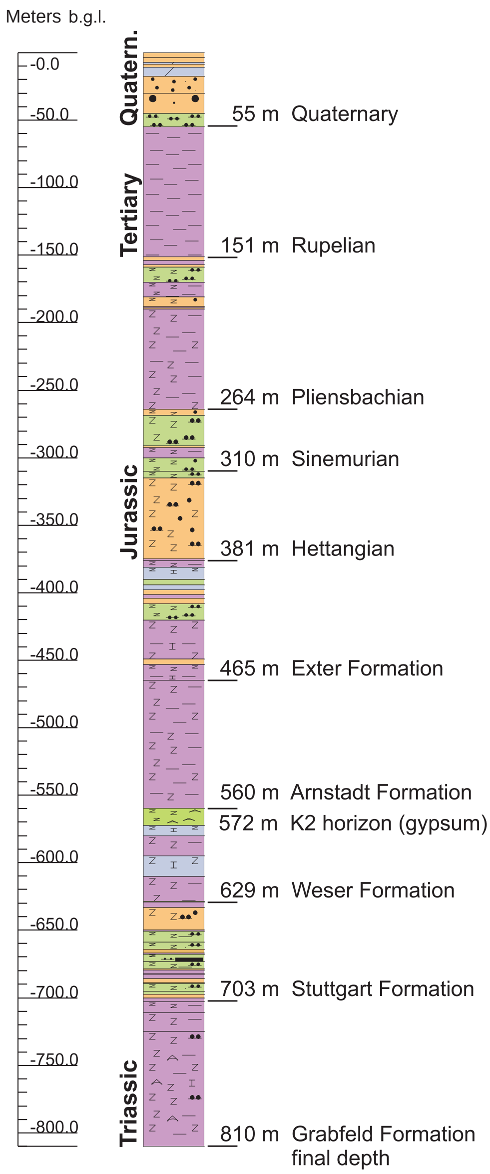

Figure 3. Condensed geological profile of the Ktzi 200/2007 borehole. Lithological color code: mudstone (magenta), siltstone (green), sandstone (yellow), anhydrite (light blue).

Borehole Design

All three wells were designed with the same casing layout, including stainless production casings equipped with pre-perforated sand filters in the reservoir section and wired on the outside with a fiber-optical cable, a multi-conductor copper cable, and a PU-heating cable to surface (Table 1). The reservoir casing section is externally coated with a fiber-

Table 1. Casing Schemes

	Depth [m]	Diameter [inch]	[mm]	[lb/ft]	Quality	Connection
Stand pipe	30	24	610	125.5	4140	welded
Conductor	150	18 5/8	473	87.5	X56	Buttress-BTC
Reserve Casing	ca.340	13 3/8	340	54.5	K-55	Buttress-BTC
Intermediate	590	9 5/8	244	36	K-55	Buttress-BTC
Production String	800	5 1/2	140	20	13Cr80 (outside coating)	VAM Top
Injection String	680	3 1/2	89	9.3	C-95 (inside coating)	TS-8

glass resin wrap for electrical insulation. A staged cementation program was planned around the application of newly developed swellable elastomer packer and stage cementation downhole tools. This technology was preferred over perforation work that would have caused unmanageable risks of potential damage of the outside casing cables.

The 200-m core sections for detailed reservoir and sealing property investigations were recovered with a 6" x 4" wire-line coring system using polycrystalline diamond compact (PDC) core bits. The 6 1/4" core hole sections were enlarged to 8 1/2", and the wells finally deepened below the reservoir zone to accommodate sufficient sensor spacing for installation of behind-casing sensor arrays.

Drilling and Completion Operations

Constructing three wells close to each other and with such a dense sensor and cable population requires detailed planning. For this purpose, high-end oilfield QHSE (Quality, Health, Safety, Environment) management tools were applied, such as "drill well on paper" (DWOP), hazardous operation identification, repeated incident reporting, post job analysis, and risk management.

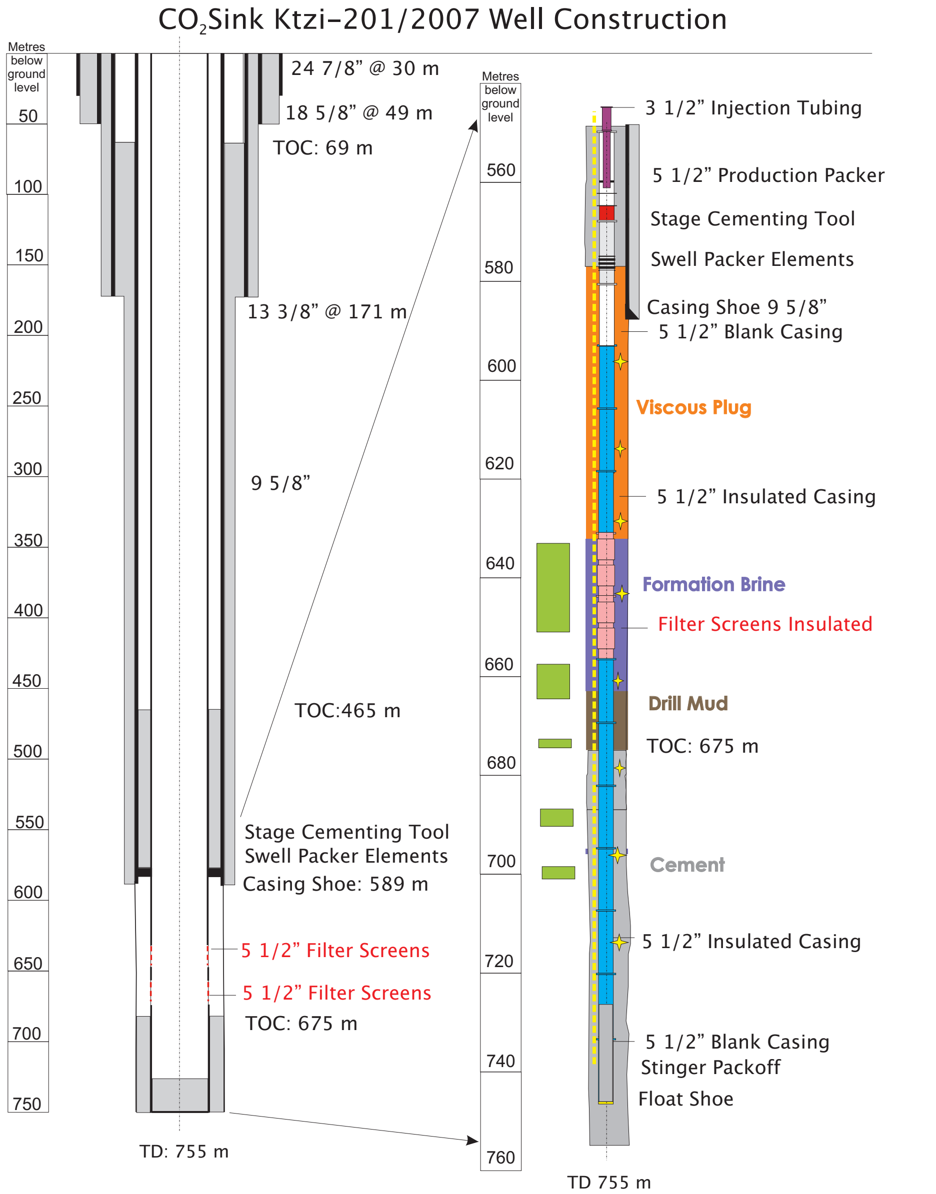

Figure 4. Drilling design and well completion of the Ktzi 201/2007 borehole. Yellow line indicates DTS and ERT cables with location of ERT electrodes (yellow pluses). Sandstone reservoir intervals are shown in green.

Drill site construction started in December 2006, and the drilling operation commenced on 13 March 2007 with the mobilization of a truck-mounted and top-drive equipped rotary drill rig. All the Ketzin wells were drilled with a shale inhibited KCl-water-based mud system, with the exception of the top-hole section in the fresh-water aquifers, where a K_2CO_3-water-based system was required by the authorities. Both drill muds were conditioned at 1.05–1.16 gcm^{-3} density. In order to avoid potential risks from environmental hazards, the project further implemented a "shallow gas" procedure in this well section to avoid spills when the wells would encounter high pressurized shallow gas from the past gas storage activity. For this purpose, the top-hole section of the first borehole was pre-drilled with a blow-out preventer/ diverter/gas-flare installation on the rig to capture and control unexpected and sudden shallow gas influxes. As no stranded shallow gas was encountered during drilling (as also confirmed by reconnaissance wire-line logging and surface seismic processing), this pilot drilling was consequently skipped for the second and third well. Casing (18 5/8") running and cementation with stinger to surface were performed in all three wells without problems.

In the following 12 1/4" sections, the wells penetrated the Jurassic aquifer systems in which under-balanced pressure regimes were supposed. All wells encountered a minimum of three loss circulation zones between 366 m and 591 m with cumulative mud losses of 550 m^3. The addition of medium- to coarse-grained shell grit to the mud cured the loss of circulation and brought the wells safe to the 9 5/8" casing depth between 588 m and 600 m.

The lower part of Weser Formation and the entire Stuttgart reservoir section were cored with a specially designed $CaCO_3$-water/polymer drilling mud (1.1 g cm^{-3}). In the first well, a total of 100 m core was drilled in thirty-nine core runs, and an average recovery of 97% was achieved. In the second well 80 meters of core was retrieved in thirty-one runs (100% recovery). In the third well only the top 18 m of the Stuttgart Formation was cored with the same excellent performance. The 6 1/4" core hole section was then enlarged to 8 1/2", and the wells finally deepened below the reservoir into the Grabfeld Formation.

Stainless steel 5 1/2" production casings (Fig. 4) were installed and cemented in all wells with sensors and cables on the outside. The cables were terminated and fed pressure tight at the wellhead to the outside through the drilling spool below the casing slips. The cement selected in all casing cementations was standard class-G with fresh water and no additives (SG = 1.98 kg L^{-1}), with the exception of the plug cementation, for which a specially designed CO_2-resistant class-G salt cement was selected.

The CO_2 injection well was completed with a gas-tight and internally coated production tubing, including a permanent production packer above the injection horizon, a fiber-optic pressure and temperature mandrel/gauge arrangement above the packer and a wire-line-retrievable subsurface safety valve at 50 m depth below the well head. The optical cables and hydraulic safety valve actuation lines were clamped to the outside of the production tubing and fed pressure tight to the outside at the tubing hanger adaptor below the Christmas tree gate valves.

Permanent Downhole Sensors for Monitoring of CO_2

Geophysical monitoring techniques are applied in CO_2SINK to delineate the migration and saturation of injected CO_2 (Fig. 2). The injection well and the two observation wells are equipped with state-of-the-art as well as newly developed geophysical sensors. The data from this permanent downhole monitoring will be interpreted in combination with data from periodic seismic monitoring (VSP, MSP, and cross-hole seismics) and periodic fluid sampling and well logging (Reservoir Saturation Tool).

The following permanent components were installed in the boreholes for scientific monitoring:

- a fiber-optic-sensor cable loop for Distributed Temperature Sensing (DTS; all wells)
- a two-line electrical heater cable (Ktzi 201/2007, Ktzi 202/2007)
- a Vertical Electrical Resistivity Array (VERA) consisting of fifteen toroidal steel electrodes, 15-line surface connection cable (all wells)
- fiber-optic pressure/temperature (P/T) sensor, fiber-optic surface connection cable (at injection string only).

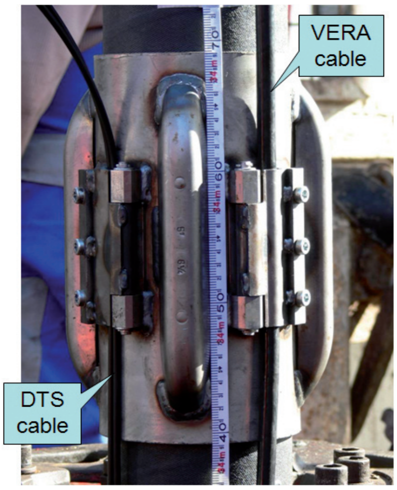

Figure 5. Centralizer attached to casing string with DTS (left) and VERA cables (right).

Using the DTS technology, quasi-continuous temperature profiles can be measured on-line along the entire length of the wells with high temporal and spatial resolution (Förster et al., 1997; Büttner and Huenges, 2003). The permanent installation of DTS sensors behind the casing (Hancock et al., 2005; Henninges et al., 2005) offers the advantage of full access to the well during technical operations, which, for example, allows control of the process of casing cementation (Henninges and Brandt, 2007). The borehole temperature data will primarily serve in the delineation of physical properties and of the state of the injected CO_2. To enhance the thermal signal and improve the monitoring of brine and CO_2 transport, successive thermal perturbation experiments (Freifeld et al., 2006) will be performed, using the electrical heater cable installed adjacent to the DTS cables. VERA provides data on the CO_2 saturation employing the Electrical Resistivity Tomography (ERT) method. Each of the VERA arrays covers an interval of about 140 m centered in the injection horizon and consisting of fifteen electrodes spaced at about 10-m intervals. The P/T-sensor installed at the bottom of the injection string above the packer system will continuously monitor the downhole pressure and temperature changes during injection. Data will be transferred via optical fiber attached to the injection string.

The inclusion of the permanent downhole sensors into the well completion required a selection of suitable completion components and procedures. Custom-made casing centralizers were used for outside-casing installation of sensor cables, for centralization of the casing inside the borehole, and for protection of cables from mechanical damage during installation (Fig. 5). The 8 1/2" borehole diameter in the lower reservoir sections allowed for sufficient clearance within the annular space between casing and borehole wall and thus for a safe installation of the downhole sensors. Within the 140-m zone, where the VERA electrodes are placed, the steel casing was electrically insulated outside using a fiberglass coating.

After an on-site installation test had been conducted, the installation of the DTS and VERA cables (Fig. 5) and electrodes in the Ktzi 200, 201, and 202 wells was performed on 5 May, 5 July, and 18 August 2007. After careful installation operations of up to 18–24 h duration, the cables were guided into the substructure of the drill rig, and the casing was cemented.

The DTS monitoring allowed online monitoring and control of the cementing operations and provided valuable information about the positions of the cemented sections during the setting of the cement. This information was verified by subsequent industry-standard cement-bond logs. The installation of monitoring tools was finished by feeding the cables into the casing spool at the wellhead, which was subsequently pressure-sealed using a stuffing box. Preliminary tests of VERA have shown that all electrodes and cables are fully functional.

Field Laboratory

The CO_2SINK field laboratory comprised core-cleaning and core-sealing facilities, a full core imager, and a Geotek gamma-ray density core logger. The field lab was designed to record and describe a high core-run volume within a short handling time to quickly generate the litholog for the drilled boreholes and to identify the reservoir section. This procedure was necessary in order to proceed rapidly with decision making on the selection of the borehole intervals completed with filter casings through which the CO_2 would be injected into the formation or monitored.

In the preparation for unconsolidated sandstone in the Stuttgart Formation, coring was performed with PVC liners in 3-m liner intervals. At the drill rig, liners were cut after orientation marking into 1-m sections, and the cut surface geologically described was sealed before being transferred to the field lab for analyses. Sections containing sandstone were shipped preserved in liners to a commercial laboratory for "hot-shot" poro-perm analysis. Reservoir sandstone intervals (Fig. 6) with porosities on the order of 20%–25%, together with requirements for permanent ERT sensor arrangement on the casing, guided the depths at which the wells were completed with filter screens for CO_2 injection and monitoring.

Figure 6. Core image of reservoir sandstone showing cross-bedding.

The geological description of core started with the sections of well-cemented mudstone after its cleaning with synthetic formation water, reorientation, and scanning unrolled using an optical core scanner. Later, the "hot-shot" reservoir sections were included. From the geological core and cutting descriptions and interpreted petrophysical well logs, stratigraphic-lithologic logs (Fig. 3) were finally generated for all three CO_2SINK wells to refine the geological model. For example, the stratigraphic-lithologic logs were used to calibrate the 3-D seismic time sections (Juhlin et al., 2007). Petrographical and mineralogical studies and geochemical analyses from reservoir and caprock were performed to characterize the Ketzin site on micro-scale as a basis for fluid-rock-alteration modeling.

Outlook

CO_2SINK is the first project that extensively uses behind-casing installations for a study of the CO_2 injection and storage process in a geological medium. In this regard, CO_2SINK differs from other scientific projects of CO_2 test storage, such as the Frio experiment in Texas (Hovorka et al., 2006), the Nagaoka experiment in Japan (Kikuta et al., 2004), the field test in the West Pearl Queen Reservoir in New Mexico (Pawar et al., 2006), and the Otway Basin pilot project in Australia (Dodds et al., 2006).

It is envisaged that the extensive set of data generated by cross-correlation of seismic surface monitoring, well-logging and monitoring, and simulations, will allow for verification of *a priori* scenarios of storage/migration of fluids. Emphasis, for example, will be given to the observation of non-isothermal effects in the storage formation during injection as described by Kopp et al. (2006). This type of effect also can occur during leakage from a storage reservoir along a fracture zone as numerically investigated by Pruess (2005). Thus, the observations in progress will contribute to a sound understanding of the thermodynamic processes of CO_2 injection at well-scale as well as in the short and longer term the processes during CO_2 storage at larger scale.

Acknowledgements

We would like to thank all partners of the CO_2SINK project for their continued support and contributions that helped to finish the three wells in a healthy and environmentally safe manner. Special thanks go to Shell International and StatoilHydro for their most valuable advice and operational support during the planning and drilling phase in Ketzin. Furthermore, thanks go to VNG AG for letting us use their site at Ketzin and for their local logistical support on site. The CO_2SINK project receives its funding from the European Commission (Sixth Framework Program, FP6) and two German ministries, the Federal Ministry of Economics and Technology (CO_2-Reduction-Technologies for fossil fuelled power plants, COORETEC Program), and the Federal Ministry of Education and Research (Geotechnologien Program).

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Related Web Links

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The First *D/V Chikyu* IODP Operations: Successful Logging and Coring During NanTroSEIZE Stage 1 Expeditions

Shin'ichi Kuramoto, Daniel Curewitz, Moe Kyaw Thu, Hideki Masago, and the Exp. 314, 315, and 316 Science Parties

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The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) is a multi-expedition IODP drilling project aimed at drilling, coring, logging, and instrumenting the seismogenic zone of an active subduction margin , in a region thought to generate megathrust earthquakes of magnitude >8.0 on the moment-magnitude scale (Tobin and Kinoshita, 2006). The Nankai Trough, offshore of the Kii Peninsula, Honshu, Japan (Fig. 1) was chosen as the location for this project based on a number of scientific drilling proposals to IODP. These reviewed existing drilling data in the region, the long-term historical and recent record of great earthquakes, the social and societal relevance of the area, and the accessibility of the seismogenic zone to present drilling technology. The first stage of this multi-stage project was intended to accomplish a broad characterization of the shallow geology, geophysics, physical properties, heat flow, and fluid flow in a transect across the downgoing Philippine Sea Plate, the toe of the Nankai accretionary prism, the megasplay fault zone region on the continental slope, and the Kumano Basin that lies between the accretionary prism and the Kii Peninsula, on the continental shelf (Fig. 2).

Between September 2007 and February 2008, IODP Expeditions 314, 315, and 316 were carried out in order to complete Stage 1 of the NanTroSEIZE; operations included Logging While Drilling (LWD), coring, and downhole measurement at eight sites (thirty-three holes) in the Nankai Trough accretionary prism. On 21 September 2007, *Chikyu* left Shingu port, Wakayama Prefecture, Japan, for her first scientific voyage as an IODP drilling platform. The start of NanTroSEIZE operations took place seven years after the first scientific proposals were submitted (see Kimura et al., 2003; Kinoshita et al., 2003; Suyehiro et al., 2003; Underwood et al., 2003; Screaton et al., 2005), and marked the culmination of thousands of hours of preparation and planning by a Project Management Team (PMT), the IODP Science Advisory Structure (SAS), and the CDEX engineers, technicians, and marine workers.

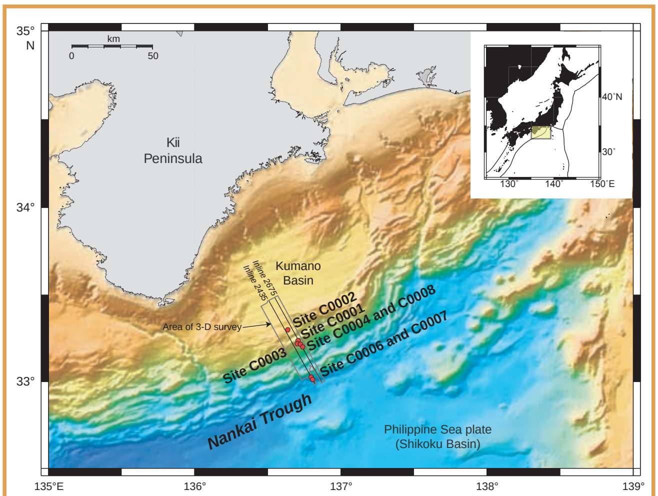


Figure 1. Location of drilled sites during NanTroSEIZE Project Stage 1 in the Nankai Trough off Kumano. Gray box = location of the 2006 three-dimensional seismic survey, black lines = 3-D inlines 2435 and 2675 (see Figure 2), red circles = location of drilling sites. Inset shows location of Nankai Trough.

After 138 days of continuous operations, Stage 1 operations were completed on 5 February 2008. The overviews of each operation as well as the overall accomplishments of Stage 1 are described below. Preliminary reports for each of the expeditions have been published and posted on the Web (http://www.iodp.org/scientific-publications/).

Expedition 314: LWD Transect

Expedition 314, NanTroSEIZE Stage 1 LWD Transect, was planned to obtain a comprehensive suite of geophysical logs and other downhole measurements at six primary sites along a transect: two on the incoming plate, two through major active thrust faults, and two pilot holes for deeper riser drilling that also address scientific targets in the splay fault thrust sheet and the Kumano forearc basin and underlying prism.

Due to the difficulties experienced during attempted wireline logging and relatively higher success during limited LWD operations in previous accretionary prism drilling within ODP, Expedition 314 was entirely dedicated to the LWD effort. LWD tool selection focused on maximizing scientific returns from the tools and the time needed for deployment. The LWD tools used during Expedition 314 were state-of-the-art industrial tools, and this expedition marked the first ODP/IODP use of check shot interval velocity, and sonic velocity, and density/porosity measurements while drilling tools that have only been used on very limited occasions.

The operational plan included one-third of the total days (22.5 days out of 57 days) for contingencies (typhoons, mechanical downtime) and casing operations. Six primary and two contingency sites were planned for the expedition with the drilling order determined by scientific priority and operational difficulty. The location of planned sites and the order of drilling changed after the team faced various challenges. Allotted contingency days were consumed by expected mechanical downtime caused by the strong Kuroshio Current flowing through the area, by difficult drilling conditions, and by unforeseen mechanical and operational events.

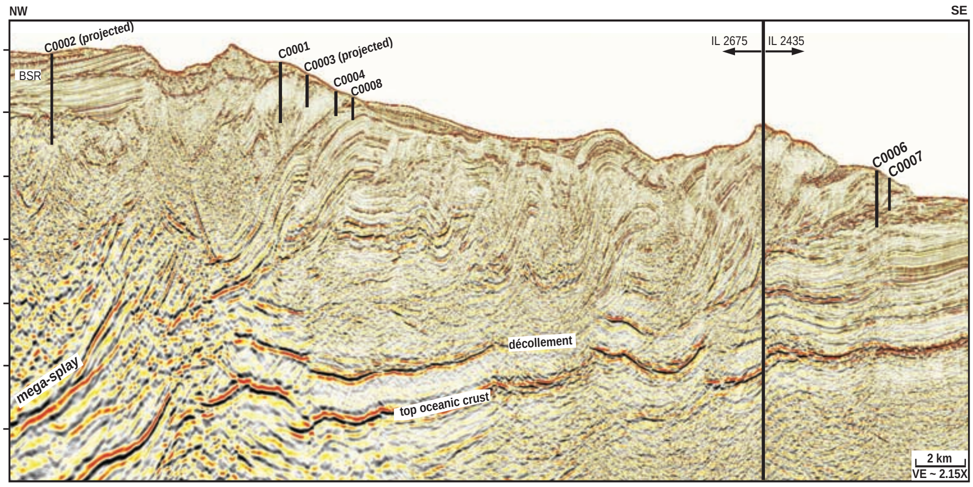


Figure 2. NW-SE slice through the NanTroSEIZE 3-D seismic survey (composite of 3-D Inlines 2435 and 2675) showing the projected locations of the sites, cored and logged during Stage 1. (Moore et al., 2007)

During the eight-week LWD campaign, various measurements were successfully completed at four of the twelve total drilled holes, with LWD data coverage ranging from 400 mbsf to 1400 mbsf (Fig. 3). Tool failure, loss of the Bottom Hole Assembly (BHA) due to borehole collapse, and pilot hole drilling (required for operational safety) consumed the remaining drilling time and accounted for the eight holes not fully logged. Logging data were initially analyzed by the shipboard scientists during the expedition in order to make the LWD data available to the scientific parties of the subsequent NanTroSEIZE Stage 1 coring expeditions (Exp. 315, 316). During the expedition, the shipboard science party worked in four groups: log characterization and lithologic interpretation, physical properties, structural geology and geomechanics, and core-log-seismic integration using various applications for log and seismic data analyses.

The principal results of Expedition 314 reveal a wealth of information about the accretionary prism, and provide a strong foundation for future planning of NanTroSEIZE, analysis of cores, downhole measurements, and observatory monitoring data. Additionally, these data provide a starting point for addressing questions raised about current models of the margin, including the composition and physical characteristics of the stacked thrust sheets comprising the prism, the distribution and character of the faults bounding the structural blocks and thrust sheets, information about the stress state in different areas across the margin, the distribution and occurrence of gas hydrates, and the characteristics of the sediments deposited in both the ancient, transported rocks and the more recent sediments draping the margin. Drilling of Sites C0001 and C0002 will also provide pilot hole information important in preparation for the planned deep-riser sites for later stages of NanTroSEIZE drilling.

Figure 3. LWD drilling operations during Expedition 314. [A] Real time monitoring in the lab area; [B] LWD toolstring on the rig floor; [C] Driller's house operations.

Expedition 315: Megasplay Riser Pilot

IODP Expedition 315 took place between 16 November and 18 December 2007, planned as a geotechnical and scientific pilot study for future riser drilling of the megasplay fault (Fig. 2). Borehole LWD data obtained during Expedition 314 was available for use during Expedition 315; this proved extremely beneficial in planning for drilling, coring, and sampling of the scheduled operations.

The operational plan for the expedition was to drill and core to 1000 mbsf at site C0001, a site considered for future riser drilling, then install riser top-hole casing in the latter half of the expedition. However, the Kuroshio Current was deemed to be running too strong (3–5 knots) to safely install the 36-inch and 20-inch casing strings required for the riser pilot. Drilling and operation plans were changed, and Expedition 315 was devoted to coring and downhole temperature measurement at two sites, C0001 and C0002 (Figs. 1 and 2).

Coring at C0001 was conducted with the foreknowledge that the borehole conditions might deteriorate quickly at or near 500 mbsf, in the same formation that proved so difficult during Expedition 314 and where caving and borehole collapse resulted in the loss of the LWD BHA. Coring commenced with HPCS (hydraulic piston coring system) from the seafloor, and obtained good core recovery down to 230 mbsf, at which point coring was conducted using the ESCS (extended shoe coring system). Core recovery by HPCS was good (75%–90%); however, core quality using the ESCS was quite poor, and RCB (rotary core barrel) coring then commenced. Using the results of LWD, we expected to encounter a zone of drilling difficulty and borehole instability around 450–600 mbsf. Accordingly, the strategy was to wash down to and through this formation and try to core the formations below that. We succeeded in drilling down to the target depth; however, caving and borehole collapse began nearly immediately, precluding attempts to core below the unstable region.

Because riser top-hole casing operations were postponed due to the intense current, Site C0002 in the Kumano Basin was chosen for coring, and it was decided that the deeper section was the most critical target. RCB coring began after drilling down to 475 mbsf, and sixty-six cores were collected from that point down to the total depth. We penetrated the basal unconformity of the Kumano basin at 922 mbsf and continued more than 100 m into accretionary prism materials with moderate recovery. As borehole conditions steadily worsened deeper in the accretionary prism, the hole was abandoned at 1057 mbsf. Two short coring operations using the HPCS system were conducted between the seafloor and 204 mbsf for both geotechnical investigations and for scientific data collection.

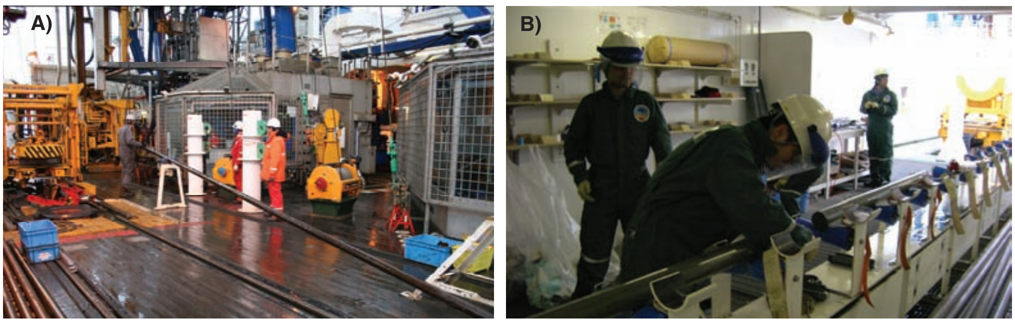
As the first coring expedition for the *Chikyu*, Expedition 315 provided valuable scientific and geotechnical data that will be critical in understanding the Nankai accretionary prism off the Kii Peninsula. In addition, the expedition proved to be invaluable in terms of improving drilling, management, and laboratory performance under harsh weather, strong current, and unfavorable operational conditions. The drilling conditions encountered at intermediate depths at C0001 and C0002 provide important constraints on riserless drilling operations in the fractured and faulted formations that comprise much of the shallow prism, and they will provide data necessary to plan future drilling, coring, and casing operations. Critical scientific data was acquired from the upper part of the accretionary prism at both sites, including geological (lithology, structure, and age), geotechnical (physical properties, temperature) and geochemical information for the accretionary prism materials (Fig. 4). These data will help planning for the engineering and scientific aspects of future riser drilling.

Expedition 316: Shallow Megasplay and Frontal Thrusts

IODP Expedition 316 drilled several sites in a transect across the outer part of the Nankai accretionary prism. The aims of the expedition were to characterize the sedimentology, stratigraphy, and physical properties of the slope sediments, the accretionary prism rocks, and the underthrust material, and to sample and understand the character of fault rocks within fault zones controlling the geometry and evolution of the accretionary prism.

We targeted two major structures: the frontal thrust (sites C0004 and C0008) and the shallow portion of the megasplay fault zone (sites C0006 and C0007) near its intersection with the seafloor (Figs. 1 and 2). Comprehensive sampling and measurement both in boreholes and on core materials were carried out, including downhole temperature measurements, interstitial water sampling, microbiological sampling, gas sampling, and a wide array of sampling for chemistry, mineralogy, and physical properties. More than 1300 meters of core were recovered using HPCS, ESCS, and RCB. More than 5000 samples were taken from the cores for shore-based investigation, and many thousands of continuous and discrete measurements were carried out using the array of laboratory tools on board the *Chikyu*.

We successfully recovered a wide array of fault rocks from fractured rocks to breccia to fault gouge, sedimentary materials ranging from fine clay and mud to siltstone and sand, and we



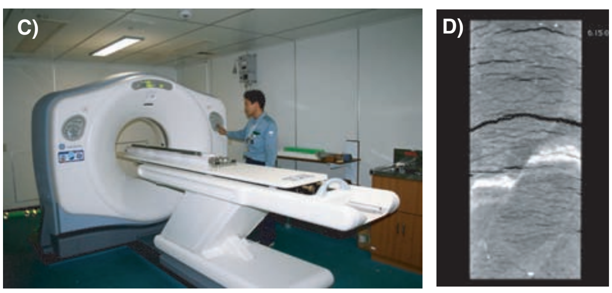


Figure 4. Coring and laboratory operations during Expedition 315. [A] Core barrel being laid out on the drill floor prior to removal of the collected core. [B] Laboratory technicians cutting a core into sections and collecting safety and time-sensitive samples prior to delivery of core section to the core lab. [C] Core section being run through the X-ray CT scanner. [D] X-ray CT image of a small fault zone cutting across interbedded mud (dark areas) and sandy ash (bright areas).

managed to recover extremely coarse grained materials from paleo-trench-axis channels. Materials sampled include recent slope apron/slope basin deposits (including several mass transport complexes that may shed light on the periodicity of slope failure), ancient accretionary prism rocks, and material that has been over-ridden during thrust faulting events (Fig. 5). Analyses of these wide-ranging data sets will shed new light on the evolution, structure, and architecture of the Nankai accretionary prism off the Kii Peninsula.

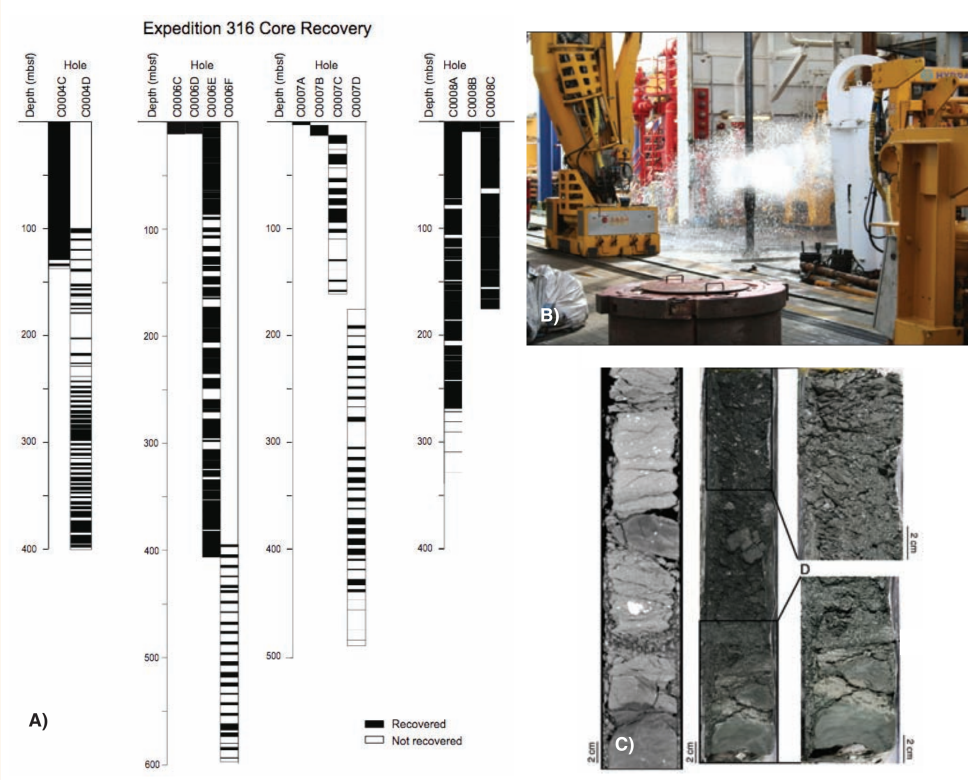


Figure 5. Coring results, coring operations and laboratory work during Expedition 316. [A] Core recovery during Exp. 316. [B] Drill pipe being disconnected immediately prior to removing a core. [C] Composite showing CT image, split core surface, and detail photos of fault zone material.

Overview and Primary Accomplishments

Chikyu accomplished an LWD and two coring expeditions in a transect across the Nankai Trough accretionary prism, gathering large volumes of data, cores, and samples that will help understand the structure and mechanics of the shallow accretionary prism, and that will aid in planning and carrying out future deep drilling to the shallow part of the lying 6–7-km-deep seismogenic zone.

Expedition 314 (LWD Transect) collected 4274 m of LWD logs and conducted 2285.5 m of MWD logs from pilot holes. Expedition 315 (Megasplay Riser Pilot) penetrated 1287 m and recovered 808 m of core. Expedition 316 (Megasplay and Frontal Thrusts) penetrated 2103 m and recovered 1340 m of core. Total drilling length was approximately 12,800 m, and total attempted coring was about 3400 m with an average core recovery rate of about 65%. All cores have been archived for preservation, future description, and sampling at the Kochi Core Center (KCC), one of the three IODP core repositories.

During the course of these expeditions, *Chikyu* was able to test and refine operational techniques and structures that are well-established components of the ODP/IODP operational paradigm, but that are still relatively untested on this newest platform for scientific ocean drilling. These include severe, real-world tests of the Dynamic Positioning system, drilling, coring, and laboratory systems, expedition management, safety monitoring, and onboard operational safety and communications infrastructure. In addition, *Chikyu* was able to pioneer the use of new tools and equipment, including the scientific use of never-before-used LWD tools, testing of new coring systems and techniques, testing of new downhole temperature measurement tools, and extensive use of X-ray Computed Tomography (XCT, Fig. 6) on whole core sections. The use of XCT scanning in particular proved to be an exciting and revolutionary addition to the scientific drilling, as it allows inspection of core before any destructive measurement or sampling is carried out, provides real-time guidelines for sampling and handling before the core is split, and allows the identification of critical intervals for special handling. In addition, the use of XCT imaging to construct pseudo-density logs (using the "CT number" which is a semi-quantitative proxy for bulk density), to measure faults and fractures, and to identify unconformities and fine-scale details provided exciting results on board and opened a new avenue for extensive post-expedition research.

While shipboard and shore-based scientists from the NanTroSEIZE Stage 1 expeditions have already begun analyzing the huge volume of data taken from LWD and core measurements, studies for future deep riser drilling, in terms of geomechanical modeling and borehole stability, are underway in CDEX in collaboration with industry and research specialists.

An immense amount of work has been required to prepare the *Chikyu* for IODP science operations. While it is clear that there is a lot of further effort required to develop the fullest potential of the vessel and its laboratories, when we take into account the successes, problems, and challenges experienced during NanTroSEIZE Stage 1, the results of these three expeditions give us great confidence in the future of IODP operations using the *Chikyu*.

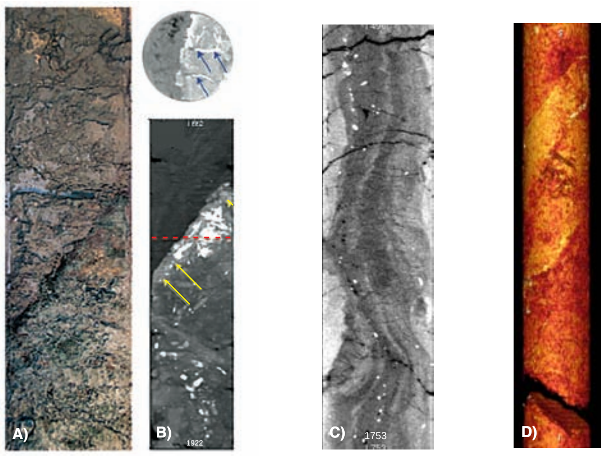


Figure 6. Usage and results from the X-ray computed tomography analyses. [A] Selected X-ray CT images. [B] The relationships that can be seen between the core photos and the CT images; Yellow and blue arrows indicate the position of the clear discontinuity seen in both core and CT image, with bright areas corresponding to mineralized material. The red line in the along-core CT image shows the position of the slice in the upper right. Spatial and angular relationships can be determined with high precision using core orientation. [C] X-ray CT imagery can be used to evaluate coring induced or drilling induced deformation or disruption of the core sample. This image shows flow-in of fluidized mud that occurred during core recovery of a piston core. [D] False color imagery based on CT-number (density contrasts related to pore spaces, water content, and mineral chemistry) can be used to highlight structural features such as this set of normal faults (cutting the core from top right to bottom left in this image). In all cases, cores are 2.5 inches across.

Acknowledgements

We would like to thank the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) for funding *Chikyu*, and to the host of staff, technical workers, managers, and operations personnel in all the various departments and agencies at JAMSTEC, at CDEX, at TAMU, at the ESO, and within the global science community for the work, advice, efforts, and support required to begin this scientific endeavor with such success. Great thanks are owed to the crew of the *Chikyu*, the drilling crew and operational teams, the helicopter pilots, shorebased support staff and supply vessel crews, the technical and design teams who helped construct and test the vessel prior to IODP operations, to the science parties and laboratory staff, and to the enormous number of technicians, scientists, designers, programmers, and engineers who have contributed so much of their time, expertise, and advice to the preparation and execution of the first successful IODP operations of the *Chikyu*.

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Estimation of Minimum Principal Stress from an Extended Leak-off Test Onboard the *Chikyu* Drilling Vessel and Suggestions for Future Test Procedures

by Weiren Lin, Koji Yamamoto, Hisao Ito, Hideki Masago, and Yoshihisa Kawamura

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Introduction

To understand the physics of faulting and rupture propagation for the great M8-class Nankai earthquakes that recur approximately every 100 years, a comprehensive drilling project is underway: the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE; Tobin and Kinoshita, 2007), which is part of the Integrated Ocean Drilling Program (IODP). Stress levels along seismogenic faults must be known in order to understand processes controlling the timing, energetics, and extent of earthquake ruptures. For scientific drilling projects such as NanTroSEIZE, it is very important to determine the *in situ* stress state at the decollement and the mega splay fault in the Nankai Trough.

Preliminary experiments to determine the orientations and magnitudes of principal stresses in the Nankai Trough were undertaken during the NanTroSEIZE Stage 1 expeditions using borehole image analysis (stress-induced breakouts and tensile fractures; Kinoshita et al., 2008) and indirect, core-based methods such as anelastic strain recovery (ASR; Lin et al. 2006). These experiments will provide necessary and important information about *in situ* stress. However, to improve reliability and reduce experimental uncertainties in these stress determinations, it is necessary to have direct *in situ* measurements of stress magnitudes—in particular, the minimum principal stress—at depth. These direct measurements are best obtained using methods involving the initiation and propagation of hydraulic fractures at depth, such as the traditional hydraulic fracturing test, a leak-off test (LOT), or an extended leak-off test (XLOT, sometimes ELOT) (Zoback et al., 2003). In the present paper, we aim to show that with the advent of the riser drilling vessel *Chikyu*, the XLOT is applicable and effective in deep scientific ocean drilling projects.

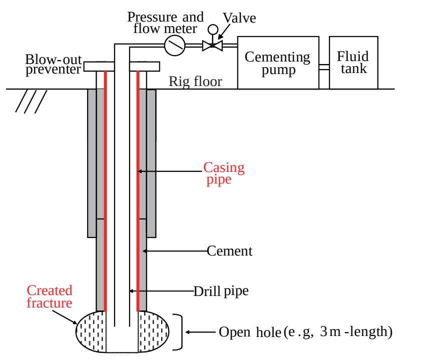

Figure 1. Schematic borehole configuration during a leak-off test (LOT) or extended leak-off test (XLOT; after Yamamoto, 2003)

During previous ODP expeditions and non-riser IODP expeditions, LOT or XLOT (which are sometimes used to determine drilling parameters such as optimal mud density) have not been conducted because the borehole was open to the seafloor. Thus, it has been impossible to pressurize a short interval of open hole below the casing as needed to conduct a LOT or XLOT (see below) without utilizing time-consuming and frequently unreliable drill-pipe-deployed packers. In contrast, the new drilling vessel *Chikyu* provides a riser-drilling capability that allows pressuring the entire casing string with drilling mud immediately after the casing is cemented in place. Therefore, NanTroSEIZE Stage 2 will present the first opportunity for a scientific ocean drilling program to use LOT or XLOT procedures without using a packer, providing direct information on the *in situ* magnitude of the minimum principal stress at minimal cost and risk.

In this study we will demonstrate the feasibility of using LOT and XLOT data acquired during the new riser-drilling program to determine stress magnitude. We will first describe LOT and XLOT procedures, and then use an XLOT data set that was acquired during the 2006 Shimokita shakedown cruise of the *Chikyu* drilling vessel to estimate the magnitude of minimum principal stress. We then recommend what we believe to be the optimum procedures for implementation of LOT–XLOT for determination of stress magnitude during future *Chikyu* riser-drilling programs.

Description of the Tests

A LOT is a pumping pressure test carried out immediately below newly set casing in a borehole (Fig. 1). It is similar to other pumping pressure tests known as the pressure integrity test, formation integrity test, or casing-shoe integrity test. Each of these tests has a different target pumping pressure. The LOT technique was originally developed in the oil industry to assess the “fracture gradient” of the formation (i.e., the maximum borehole pressure that can be applied without mud loss) and to determine optimal drilling parameters such as mud density (Kunze and Steiger, 1991). The LOT procedures are relatively simple. An XLOT is a more complex test with extended pressurizing procedures, as described in detail below. In future riser-drilling by *Chikyu*, it may be possible to regularly implement LOT or XLOT at each casing shoe immediately after casing has been run and cemented.

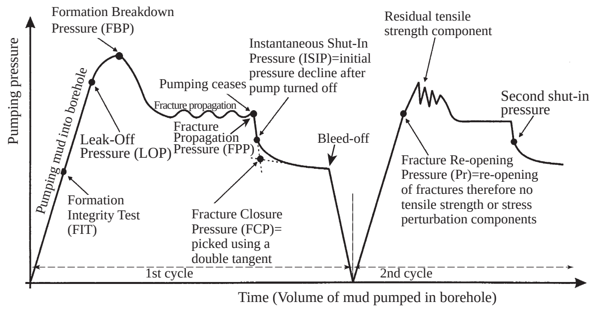

Figure 2. Idealized relationship between pumping pressure and time or volume of injected fluid during an XLOT (after White et al., 2002).

LOT and, in particular, XLOT procedures have been successfully and widely used to estimate the magnitude of minimum *in situ* horizontal stress (Addis et al., 1998; White et al., 2002; Yamamoto, 2003), mainly for the practical purpose of determining borehole stability during drilling operations. These data can be used for another important application—that is, to obtain *in situ* stress information that can be used in scientific objectives. In a similar case in which high borehole temperatures precluded use of a packer Hickman et al. (1998) conducted this kind of test to obtain *in situ* stress magnitude.

To carry out LOT or XLOT after setting casing and cementing, a short length (several meters) of extra open hole is drilled below the casing shoe. The casing shoe is then pressurized by drilling fluid delivered through drill pipe from a cementing pump set on the rig floor of the drilling vessel. The pressure at the casing shoe is equal to the sum of the hydrostatic pressure of the drilling fluid column and the ship-board pumping pressure. Figure 2 shows an idealized pumping pressure curve for XLOT (White et al., 2002).

Initially, pumping fluid into the borehole results in volumetric compression of the drilling mud column and elastic expansion of the casing string plus rock around the borehole. As the pressure in the borehole increases, the leak-off pressure (LOP) is reached when the relationship between pressure increase and volume of fluid pumped deviates from linear. This occurs when fluid begins to diffuse into the formation at a more rapid rate as the rock begins to dilate (Fig. 2). Generally, a LOT is a test that finishes immediately after LOP is reached.

An XLOT is an extended version of a LOT, but it is also similar to the hydraulic fracturing test used for stress measurement. During an XLOT, pumping continues beyond the LOP point until the pressure peaks at formation breakdown pressure (FBP). This creates a new fracture in the borehole wall. Pumping is then continued for a few more minutes, or until several hundred liters of fluid have been injected, to ensure stable fracture propagation into the undisturbed rock formation. The pumping pressure then stabilizes to an approximately constant level, which is called the fracture propagation pressure (FPP). Pumping then ceases (known as "shut-in"). The instantaneous shut-in pressure (ISIP) is defined as the point where the steep pressure decreases after shut-in deviates from a straight line. From our perspective, the most important pressure parameter is the fracture closure pressure (FCP), which occurs when the newly created fractures closes again. FCP is determined by the intersection of two tangents to the pressure versus mud volume curve (Fig. 2). The value of FCP represents the minimum principal stress (Yamamoto, 2003), because the stress in the formation and the pressure of fluid that remains in the fractures have reached a state of mechanical equilibrium. White et al. (2002) collected high-quality XLOT data and showed that both FCP and ISIP provide better estimates of minimum principal stress than LOP, although the difference in the values of LOP and ISIP was small in their study. In addition, ISIP is visually easier to determine than FCP. To end the test, the valve in rig floor is opened, and some of the fluid in the borehole flows back into the fluid tank (known as "bleed-off").

To confirm the pressure values obtained from the initial XLOT, a second pressurization cycle is warranted (Fig. 2). Because a fracture has been created by the first execution of XLOT, in the second cycle the pressure at the time of re-opening of the fracture corresponds approximately to the FPP of the first cycle. In general, it is advisable to conduct additional pressurization cycles beyond the second cycle in order to confirm that stable values of FCP and ISIP have been obtained.

An Extended Leak-off Onboard the *Chikyu*

During the Shimokita shakedown cruise (6 August to 26 October 2006), an XLOT was conducted onboard the *Chikyu*. The test was carried out at a depth of 525 meters below seafloor (mbsf) in 1180 m water depth; fluid density (seawater) was 1.030 g·cm^{-3}, and the injection flow rate was 0.5 bbl·min^{-1} (about 80 L·min^{-1}). Pressure and flow rate were recorded at the surface, using a sample rate of 5 min^{-1}. The resolution of the pressure measurements was 1 psi (about 7kPa) its accuracy is less than ±37 psi (about ±259 kPa). Because the main objectives of the first drilling operation test of the *Chikyu* during the Shimokita shakedown cruise were confirming basic drilling procedures, pure sea water was used, and rough measurement conditions were adopted for the preliminary XLOT. At the Shimokita site, core samples were retrieved only to a depth of 365 mbsf. However, the lithology at the XLOT depth was identified from cuttings analysis as volcanic tuff.

The fluid pumping rate was constant, and pumping was stopped immediately after formation breakdown (Fig. 3). About 400 liters (2.5 bbl) of seawater was injected into a length of about 3 m of uncased borehole for about 6 min, thus creating a fracture in the borehole wall. After shut-in, pressure was monitored for about 14 min and then released (bleed-off). Although two cycles were tried, only a data set of the first cycle was successfully obtained in this test.

The processes of formation breakdown and stable fracture propagation were not clearly evident in this test (compare Figs. 2 and 3). Moreover, the pressure versus time curve was not smooth, owing to the large data sampling interval during the pumping and monitoring processes and the relatively poor accuracy of the rig-floor pressure recorders. Thus, it was hard to pick the FCP with any confidence, as this requires that two tangents be drawn to the pressure decay curve. Instead, we estimate that the magnitude of the minimum principal stress lies between the pressure at the moment the pumps were turned off, which should be a close upper bound to the ISIP since we are conducting the test with low-viscosity sea water, and our estimated value for the FCP, obtained as best we could using a bi-linear tangent approach (Fig. 3). In this manner, we estimate that the magnitude of the minimum principle stress is 18.3–18.5 MPa. For comparison, we estimated the magnitude of vertical stress at the test depth from the density of the formation. An average formation density of 1.5 g·cm^{-3} from 0 mbsf to 365 mbsf was determined from the density profile of core samples retrieved during the Shimokita cruise. We assumed that the average density for the interval 365–525 mbsf was 1.8 g·cm^{-3}; therefore, the vertical stress was estimated to be approximately 20 MPa. Thus, the magnitudes of the minimum principal stress from the XLOT and the vertical stresses are close to one another, suggesting that we either measured the vertical stress with the XLOT or that we measured the minimum horizontal stress and are in a transitional strike-slip to reverse faulting environment. Since we were not able to determine the attitude of the hydraulic fracture in the test interval, we cannot ascertain which of these two possibilities is correct. Considering the many past applications of XLOT, both in continental scientific drilling projects and in industry oil fields (Kunze and Steiger, 1991; Lund and Zoback, 1999), we suggest that, although it is not a perfect and universally used technique, XLOT can provide data that are both valuable and practical for estimating the magnitude of minimum principal stress (Nelson et al., 2007).

XLOT Procedures for Stress Estimation

The XLOT procedure that we suggest for determination of stress magnitudes during future riser-drilling programs conducted onboard *Chikyu* is shown in Fig. 4. This procedure has several advantages over the types of tests often conducted following borehole completion. First, the XLOT procedure is superior to the LOT procedure. It can be difficult to obtain reliable estimates of minimum principal stress by using only the value of LOP, which is the only stress-related parameter obtained by the LOT procedure. Second, we suggest that implementation of multiple XLOT cycles (at least 3 cycles) will provide more reliable results than the LOT or XLOT procedure alone. The first cycle (equivalent to the previously mentioned casing-shoe integrity test) uses a lower maximum injection pressure than the predicted LOP and is designed to estimate the permeability of the formation, determine whether there are pre-existing fracture(s) and weakness(s), and check the effectiveness of cementing. The second cycle is a standard XLOT procedure, and the third cycle is a repetition of the second cycle to confirm the diagnostic pressure values obtained from the previous XLOT.

It is also important to record a high accuracy, closely sampled data set to avoid some of the difficulties in accurately picking test parameters, discussed in the example presented above. Data monitoring and recording details should include pumping pressure, the volume of fluid injected, and the volume of fluid returned to the fluid tank during bleed-off. We think this recording is quite easy. It is also important that the density of the fluid being injected is well known so that the hydrostatic pressure at the casing shoe under ***in situ*** pressure and temperature conditions can be calculated; alternatively, down-hole pressure recording at the casing shoe can be employed (using a wireline or memory tool) to measure directly pressure at the casing shoe.

The procedures that we suggest (Fig. 4) and describe in detail below are similar to those conducted in deep onshore wells (Yamamoto, 2003).

(1) In the first (LOT) cycle, drilling fluid is pumped into the borehole at a constant flow rate (e.g., 0.5 bbl·min^{-1}, or about 80 L·min^{-1}); pumping stops before the expected LOP, and the well is shut-in for 5–10 min. The pressure decline during the very early stage of shut-in reflects the decay of viscous pressure losses in the surface plumbing and drill pipe, and the pressure change during the later stage of shut-in is controlled by the permeability of the formation. If the pressure decline in the late stage of shut-in is large and does not stabilize, the leak-off of fluid might be attributed to the existence of natural fractures or to ineffective cementing. If the casing shoe is too permeable, then the

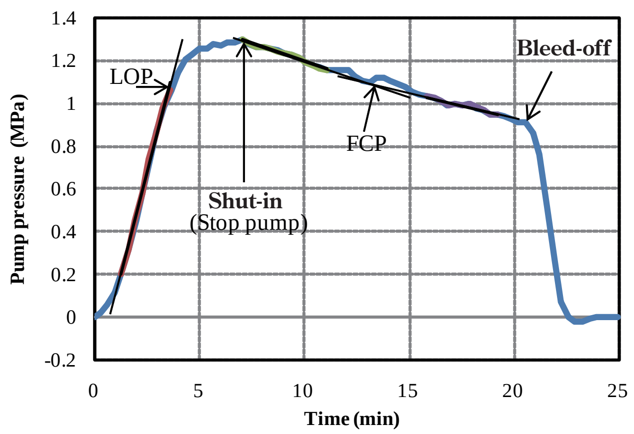

Figure 3. Pumping pressure at drilling rig level versus elapsed time during XLOT carried out on board the riser vessel *Chikyu*.

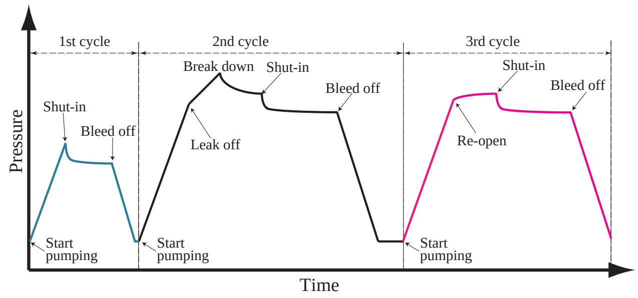

Figure 4. Suggested procedures for conducting XLOT to determine the magnitude of the minimum principal stress.

second and third test cycles are unnecessary, as a reliable measure of the minimum principal stress will not be possible.

(2) In the second injection cycle, pumping continues for at least 1 min beyond formation breakdown, and the well is then shut-in. If formation breakdown is not achieved but pressure decreases during pumping (indicating fracture propagation, perhaps from a pre-existing fracture), then pumping should continue until the volume of fluid injected reaches at least several barrels (e.g., 3 bbl, or about 450 L) and the well is shut in.

(3) The well then remains shut-in while pressure is monitored for at least 10 min or until the pressure ceases to decay. The well is then bled off.

(4) To evaluate the pressure versus volume curve during bleed-off, flow-back volume is monitored with a flow meter. The curve shown in Fig. 5 is an idealized relation between pumping pressure and volume, and it indicates the total amount of fluid lost into the formation (or through other system leaks) during the test. Raane et al. (2006) also mentioned that pump-in/flow-back test appears to give a robust estimate of the minimum principal stress.

(5) The third cycle repeats steps 2–4 and allows comparison of the pressure parameters obtained during the second cycle.

(6) Comparison of the pressure decline curves of the third and second cycles provides information about the state of the borehole. For example, if the pressure decline after shut-in during the third cycle is comparable to that observed in earlier cycles, then the cement bond has not been damaged, and with the test interval permeability has not been significantly affected.

(7) If required, a fourth cycle of pumping can be undertaken to investigate borehole integrity, including the extent of formation permeability during the test. In this case, the casing shoe is again pressurized to the maximum pressure of the first cycle. The well is then shut in, and the pressure and fluid volume monitored. Comparison of the pressure build-up rate (pressure versus volume) during injection and the pressure decline after shut-in during this cycle with those of the first cycle will show whether or not borehole integrity has been compromised.

There may be concern that the new fracture created during the XLOT has affected casing-shoe integrity. In general, casing-shoe integrity is maintained if appropriate drilling fluid (mud) has been used (Morita et al., 1997).

Calculation of minimum principal stress by using LOT–XLOT data depends on the assumption that a new fracture is created in a plane perpendicular to the minimum principal stress by the pumping pressure and that pre-existing fracture(s), weakness(s), anisotropy, and heterogeneity of the formation have no significant influences. Therefore, knowing with certainty the attitude of the new fracture produced is very helpful to determine direction of the minimum principal stress. For this purpose, Fullbore Formation Microimager (FMI) and/or Ultrasonic Borehole Image (UBI) logs or impression packer before and after the test can be conducted to acquire borehole images in cases of hydraulic fracturing which is conducted not at the borehole bottom (casing shoe). However, it should be difficult in case of an XLOT before the test because its test interval is too short to allow installing of FMI- or UBI-type logs. Additionally, in many cases the resolutions of FMI or UBI images are too low to see a hydraulic fracture. Also, given the low probability of success, it is hard to justify the expense and rig time for running a log to image a 1–3 m section of borehole.

The minimum principal stress determinate by an XLOT is equivalent to minimum principal horizontal stress in normal and strike-slip faulting environments; and hydraulic fracture is induced in a vertical plane. In contrast, in reverse faulting environments the minimum principal stress is equivalent to vertical stress; the fracture is formed in a horizontal plane. In general, it is difficult to identify if the minimum principal stress is vertical or horizontal stress without knowing attitude of hydraulic fracture induced. Only in cases where the minimum principal stress from an XLOT is significantly lower in magnitude than the calculated vertical stress, can the minimum principal stress be identified as the minimum horizontal stress.

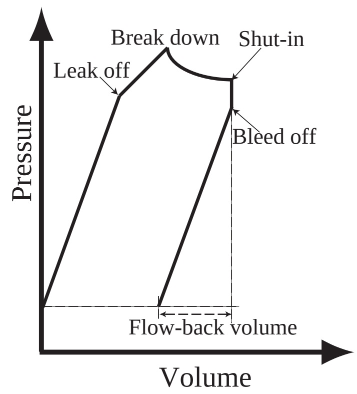

Figure 5. Relationship between pumping pressure and injected volume corresponding to the 2nd cycle in Fig. 4.

A drawback of the XLOT procedure that we have recommended is that it cannot be used to determine the magnitude of maximum principal stress, which is also difficult to determine using the standard hydraulic fracturing test (Ito et al., 2007).

The magnitude of the maximum principal stress in deep wells is best practically determined through an integrated analysis of borehole breakouts and tensile fractures from image logs, rock strength, and the minimum principal horizontal stress from the XLOT, as discussed, for example, in Zoback et al. (2003). However this integrated analysis has several problems which should be solved in the near future, such as rock strength problem (Haimson and Chang, 2002) and the effect of fluid compressibility and compliance of the test system (Raaen et al., 2006). In the near future, it is preferable and hopeful that more reliable and robust *in situ* stress measurements will be developed and applied onboard the *Chikyu*.

Summary

Investigation of *in situ* stress at depth is a necessary and important outcome of IODP drilling programs such as NanTroSEIZE. Fortunately, the availability of the new research vessel *Chikyu* means that LOT and XLOT procedures can be readily undertaken during future riser-drilling programs; these will yield important information about *in situ* stress magnitude as well as providing some of the data needed for drilling operations (e.g., borehole stability analysis). We used data from the 2006 *Chikyu* Shimokita shakedown cruise to demonstrate the feasibility of using XLOT data to determine the magnitude of the *in situ* minimum principal stress at depth. The procedures that we have recommended for the application of XLOT to determine stress magnitude during future riser-drilling programs of the *Chikyu* represent the most important outcome of this work.

Acknowledgements

We thank the *Chikyu* drilling operation team for allowing us to use XLOT data acquired by them during the Shimokita cruise. We gratefully acknowledge Stephen Hickman for his careful reviewing and many constructive comments which greatly improved the manuscript. This work was partly supported by Grant-in-Aid for Scientific Research (C: 19540453) of the Japan Society for the Promotion of Science.

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Ultra-Deepwater Riserless Mud Circulation with Dual Gradient Drilling

by Greg Myers

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Introduction

Drilling deep holes in very deep water presents the offshore drilling community with major wellbore stability challenges that are typically mitigated through the circulation of dense drilling mud to prevent hole collapse and to remove drilling debris ("cuttings"). This is normally accomplished through the application of a riser system (Fig. 1); however, riser lengths are presently limited to use in water depths of around 3047 m. In the scientific ocean drilling realm, we have been very successful in drilling relatively shallow holes (<1500 m) in water depths greater than 3657 m, a range we call "hyper-deep". Drilling in these extreme water depths requires the use of the "riserless" drilling technique (Fig. 1A) which is not constrained by the length limitations of a riser system ("riser").

The new riser-capable drilling vessel *Chikyu* has enabled the Integrated Ocean Drilling Program (IODP) to drill deep holes in water depths up to 2500 m. Scientific objectives in greater water depths with borehole penetrations deeper than 2000 m still remain a major challenge, because IODP does not have effective options for drilling in these environments. A technological solution to improve the drilling of deep holes in ultra-deep water with riserless drilling equipment may now be emerging through a joint effort between IODP-Management International (IODP-MI) and the energy industry. The technology, known as Riserless Mud Recovery (RMR), has been developed and commercialized by the Norwegian firm, AGR Drilling Services (http://www.agr.com/). The RMR system allows for the drilling of the upper section of a borehole using the dual gradient drilling technique (Fig. 1B). The AGR system is presently operating in water depths up to 457 m. This article describes this emerging drilling technology and outlines joint efforts by IODP-MI and the energy industry to modify the system and deploy it in water depths up to 3657 m.

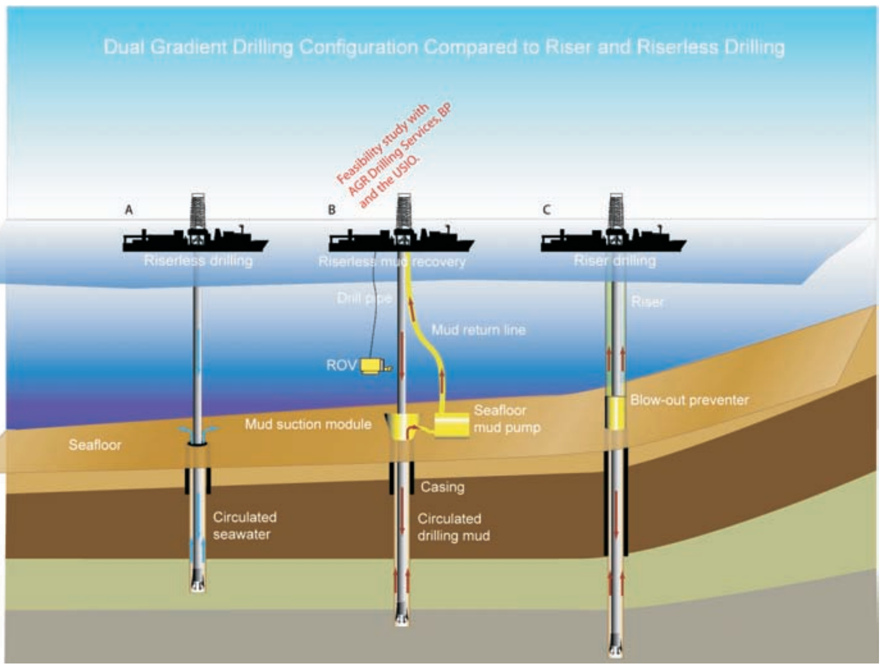

Figure 1. Dual gradient drilling (DGD) equipment may provide the technology needed to drill deep holes in deepwater. Riser drilling will still yield the deepest holes and riserless drilling will provide access to the deepest waters. Riserless [A] and riser [C] drilling configurations are depicted with a version of dual gradient drilling equipment provided by AGR Drilling services, named Riserless Mud Recovery (RMR) system [B].

Summation of Offshore Drilling Problem – Well Control and Costs

Whether a drill site is located in terrestrial or marine environments, several problems are common to rotary drilling operations. Drilling cuttings must be removed from the borehole, drilling fluid density must be managed to keep the borehole open without fracturing the formation, circulation must be maintained even when drilling fluid is lost to the formation, and pressure must be contained if over-pressured strata or gas are encountered (Weddle and Schubert, 2000). These problems are exacerbated for offshore wells due to hydrostatic pressure constraints, especially in the upper section of the borehole where the sedimentary overburden is reduced and/or increased pore pressures may be encountered (Fig. 2).

The result of this dynamic is a narrowing of the drilling "window" between the formation pore pressure and formation fracture pressure (Smith et al., 1999). As water depth increases, the "window" between the pore pressure and fracture pressure becomes even narrower as a result of the increasing influence of the weight of the fluid column.

Riserless drilling primarily uses seawater, rather than drilling mud, to manage the borehole because drilling mud cannot be recirculated. Seawater has a significantly lower density than drilling mud, thus the boreholes are more likely to collapse with increasing hole depth as the pore pressure exceeds the hydrostatic pressure exerted by the seawater. For deeper drilling, drilling mud with regulated density must be continuously circulated in order to keep the borehole from collapsing and to remove cuttings from the borehole. The widely accepted standard equipment to establish continuous circulation is a marine drilling riser, which provides a conduit for returning the mud and cuttings to the drill rig. Current riser depth capabilities, however, only extend to just over 3047 m and are extremely expensive. Scientific ocean drilling and the energy industry have ultra-deepwater targets of interest beyond the reach of current risers. Research is underway to design risers of even greater depth potential using a combination of metallic and composite materials. However, the stresses due to vibration of these long riser strings and the well control problems associated with hydrostatic pressure of the mud pose significant operational problems. The use of alternate techniques, such as riserless mud recovery and dual gradient drilling, could therefore provide an attractive option for both IODP and industry to drill deep holes in deep water settings where current capabilities are either insufficient or not economic.

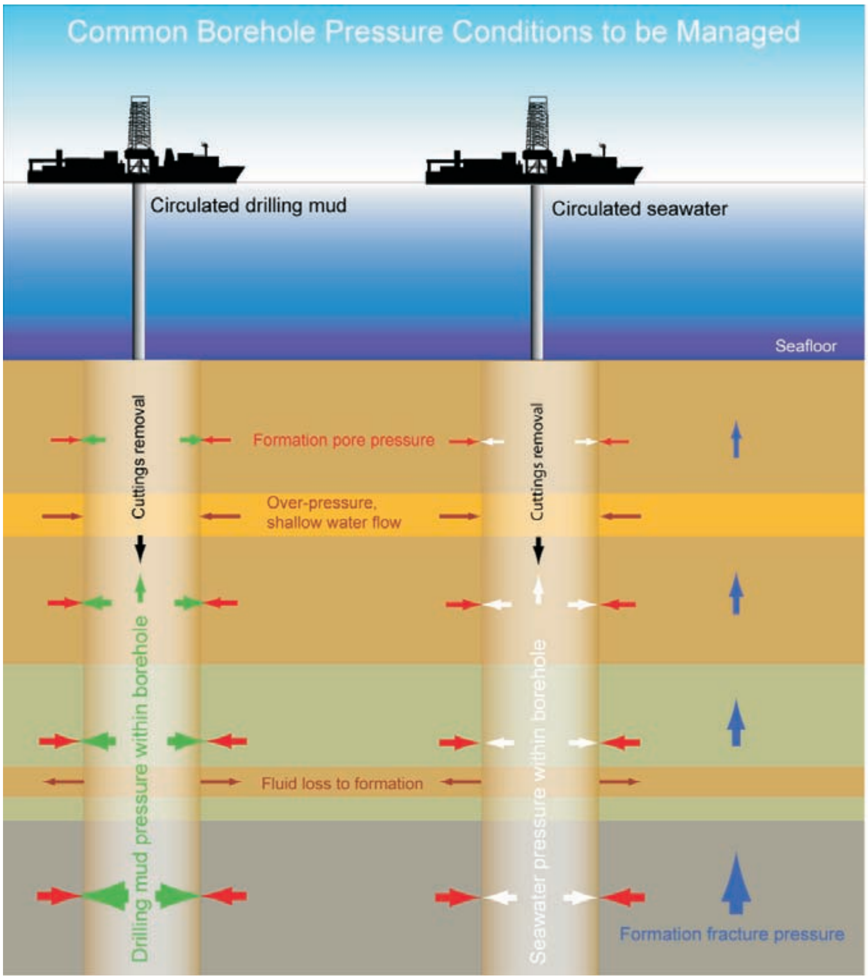

Figure 2. The pressure conditions within an offshore borehole are complex and must be precisely managed to achieve the target depth. Carefully selected drilling fluids provide the pressure needed to resist the formation pore pressure thereby keeping the borehole open without applying too much pressure and fracturing the formation. This optimal pressure zone between formation pore pressure and formation fracture pressure is known as the drilling "window". When drilling with seawater, the formation pore pressure overcomes the borehole fluid pressure leading to borehole collapse.

Dual Gradient Drilling Application for IODP

RMR provides a dual gradient drilling setup of the well, while capturing the drilling fluid and returning it to the drillship (Fig. 3). The term "dual gradient" implies two hydrostatic gradients: 1) the seawater gradient that begins at the sea surface, and 2) the drilling mud gradient that begins at the seafloor. Conventional drilling has only one pressure gradient for both seawater and mud that originates at the sea surface (Schubert, et al., 1999). Because dual gradient drilling has much less hydrostatic "head" associated with the drilling mud in the borehole, drilling fluids can be properly weighted, allowing drilling to be more easily contained within the "window" between the formation pore pressure (Fig. 3, red line) and the formation fracture pressure (blue line), thereby avoiding wellbore instability.

Riser drilling and dual gradient drilling provide different options for controlling borehole conditions while drilling. The primary difference is the point where the hydrostatic head of the drilling mud begins accumulating. Another way of visualizing dual gradient drilling is to imagine the drilling equipment positioned on the seafloor. In this scenario, the weight of the fluid column from the sea surface down to the seafloor is eliminated, thereby providing a larger drilling "window" between the formation pore pressure and formation fracture pressures, resulting in increased well bore pressure management.

In addition to well control, the RMR system also helps reduce the costs associated with deepwater drilling. First, the system eliminates the "pump and dump" drilling strategy, where mud that is sometimes utilized for well control in riserless drilling is directly discharged to the seafloor. Collecting and reusing drilling mud significantly reduces the amount of mud required to install an offshore well. Second, as the number of casing strings can be reduced, the upfront costs for this material can be significantly reduced. Thus, the RMR system offers a complementary solution to the capabilities of the *Chikyu* and the standard riserless capabilities of the *JOIDES Resolution*. *Chikyu* provides much deeper borehole penetration with blow-out prevention capabilities, but it has a limited water depth range. The current *JOIDES Resolution* provides hyper-deepwater capabilities but with limited borehole penetration. A drilling platform successfully equipped with RMR and dual gradient capabilities would fill in this technology gap in a cost-effective manner, allowing pursuit of deep drilling targets in water depths up to 3657 m.

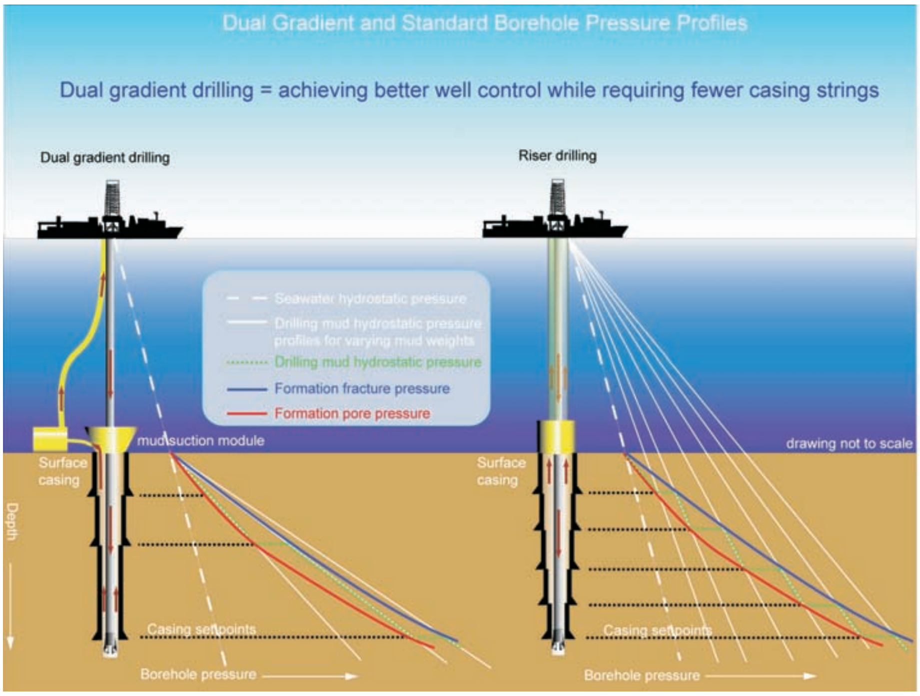

Figure 3. The dual gradient drilling approach establishes the drilling mud hydrostatic gradient at the seafloor which allows for the use of heavier drilling muds with an advantageous pressure increase with depth. The use of optimized drilling mud provides better well control and fewer casing points by keeping the drilling fluid within the drilling "window" for more depths within the borehole.

AGR Drilling Services has been providing RMR dual gradient drilling equipment to the energy industry for a number of years. The system has been successfully utilized in gas fields in Sakhalin (Brown et al., 2007) and the Caspian Sea. The equipment is mobilized and installed on the drill rig in modular sea-freight containers. Returning the drilling mud back to the drill rig for conditioning and recirculation requires seafloor mud suction equipment (Figs. 4 and 5), seafloor mud pumps, and a mud return line extending from the seafloor equipment back to the drill rig. In shallower water depths below 1524 m, this line can be a flexible, large-diameter hose. Beyond 1524 m, the mud return line will be fashioned from steel pipe, such as a drill pipe. The mud return line is deployed down to the seafloor and then secured as the pipe exits the rig's moon pool. A remotely operated vehicle (ROV) is utilized to provide visual inspection of the seafloor equipment setup. Following the equipment setup, the drill string is run to the seafloor, and the hole is spudded. The ROV system is deployed continuously to monitor the mud recovery system during drilling.

To investigate the feasibility of utilizing the RMR system on the *JOIDES Resolution* to 3657 m, a small team was formed by IODP-MI with members from the IODP United States Implementing Organization (USIO), AGR Drilling Services, and British Petroleum (BP). This team submitted afeasibility and planning proposal to DeepStar, an industry technology development consortium consisting of eight energy companies focused on advancing the technologies to meet deepwater and ultra-deepwater business needs. DeepStar provides a forum to execute deepwater technology development projects and leverage the financial and technical resources of the deepwater industry (www.deepstar.org).

The study, planned for completion by the end of 2008, will investigate the system requirements for several different well configurations and water depths ranging from 1523 m to 3657 m, depths of interest to both the energy industry and the scientific community. This study includes determining the feasibility studies of modifying the deepwater AGR

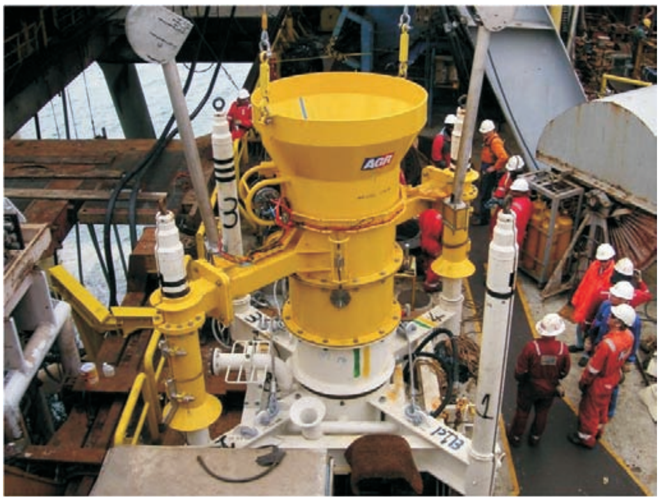

Figure 4. The AGR riserless mud recovery subsea equipment consists of a mud suction module (see above) and seafloor mud pumps. The mud is collected in the mud suction module and returned to the drillship via the seafloor mud pumps (image: courtesy of John Thorogood).

Figure 5. The AGR riserless mud recovery system deployed on an oil and gas exploration vessel.

system to operate in up to 3657 m of water and a feasibility study to determine the suitability of the *JOIDES Resolution* to deploy the AGR RMR system. Should the feasibility study show that the RMR system can be deployed from the *JOIDES Resolution*, IODP-MI will work with the USIO, AGR, and BP to secure funds for a Gulf of Mexico deployment within two years to test the system capabilities in actual field operations.

Conclusions and Applications

If RMR and dual gradient drilling prove feasible for use on the *JOIDES Resolution*, IODP will be in a much improved position to address drilling problems (Larsen and Kushiro, 1997) that consistently plagued the successful completion of highly ranked programs such as achieving deep crustal and even upper mantle objectives. And, it could open new areas of study in drilling deeper targets in over-pressured regions by providing a continuous supply of weighted mud needed to suppress shallow water flows (Myers et al., 2007). The modified AGR Drilling Services system could be leased as needed and deployed from the *JOIDES Resolution*, *Chikyu*, or another suitable platform as required to meet the scientific objectives of a given project.

Acknowledgements

The concepts and ideas presented in this article represent the amalgamation of previous work and informal discussions with many engineers from industry and scientific drilling circles. I wish to acknowledge all who have helped developed this concept on any level, in particular, Pierre Beynet and Warren Winters at BP, Tom Janecek of IODP-MI and Tom Williams helped turn these thoughts into an engineering initiative. Special thanks to Chris Haver and Jim Chitwood of the DeepStar consortium for hearing our proposal and seeing the value in symbiotic industry and scientific engineering efforts.

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Magnetic Susceptibility as a Tool for Investigating Igneous Rocks—Experience from IODP Expedition 304

by Roger C. Searle

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Introduction

Continuous measurements of magnetic susceptibility have been commonly used on Ocean Drilling Program (ODP) and Integrated Ocean Drilling Program (IODP) expeditions to study minor lithological variations (for example, those related to climatic cycles) in sedimentary rocks, but they have been less frequently used on igneous rocks, although important post-cruise studies have utilized them (e.g., Ildefonse and Pezard, 2001). Here I report its use (and that of the closely related electrical conductivity) on IODP Expedition 304 to examine igneous crustal rocks. Expedition 304/305 targeted the Atlantis Massif, an oceanic core complex on the Mid-Atlantic Ridge, and recovered a suite of igneous rocks comprising mainly gabbros, troctolites, and some diabases (Blackman et al., 2006; Ildefonse et al., 2006, 2007; IODP Expeditions 304 and 305 Scientists, 2005). Shipboard measurements (on *D/V JOIDES Resolution*) of physical properties were made to characterize lithological units and alteration products, to correlate cored material with down-hole logging data, and to interpret broader-scale geophysical data.

Shipboard Measurements

Magnetic susceptibility, k, is a dimensionless measure of the degree to which material can be magnetized in an external magnetic field:

$$k = M/H$$

where M is the magnetization induced in the material by an external field of strength H. Magnetic susceptibility is sensitive to variations in the type and concentration of magnetic grains in rocks and is thus an indicator of compositional variations.

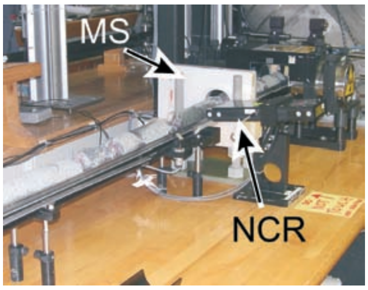

Figure 1. View of part of the multi-sensor track on *JOIDES Resolution* during Expedition 304, showing the MS and NCR sensors.

After recovery, cores were allowed to come to approximately room temperature (22°–25°C), then magnetic susceptibility (MS) and non-contacting electrical resistivity (NCR) were measured following standard IODP procedures on whole core in split liner in the multi-sensor track (Blum, 1997, Fig. 1).

MS was measured inductively at 2-cm intervals down core, using a model MS2C Bartington susceptibility meter, which has an 8-cm loop and operates at 0.565 kHz with a field intensity of 80 A/m (Bartington Instruments, 1995). The instrument is constructed so that for a core of diameter 65 mm, the recorded value is the absolute volume susceptibility. The diameter of the Expedition 304 cores was always smaller (~5.5–6.0 cm), so I report results in Instrument Units (IU), which under the conditions given above approximate to dimensionless Système International (SI) units × 10^{-5}. Because measured susceptibility depends on sample volume, measurements on pieces shorter than ~8 cm will be underestimated; such samples were flagged in my interpretations. A further complication is that the Bartington MS2C sensor currently has a maximum range of 10^4 IU; all readings greater than this lose the most significant digit, so that the signal appears to fall discontinuously to a low value, or "wrap around". As a result, intervals where k values appear to approach 10^4 IU and then fall rapidly should be examined and used with care. However, there is a potential solution to this as described below.

NCR was measured every 2 cm down core using a non-contacting inductive instrument, purpose-built for the MST by Geotek Limited (http://www.geotek.co.uk/site/index.php). Instrument output (in volts) is approximately inversely proportional to resistivity; the precise relationship was determined at the start of Expedition 304 by measuring brine samples of known salinity, though data in the IODP database are in uncalibrated voltages. The instrument is rated to

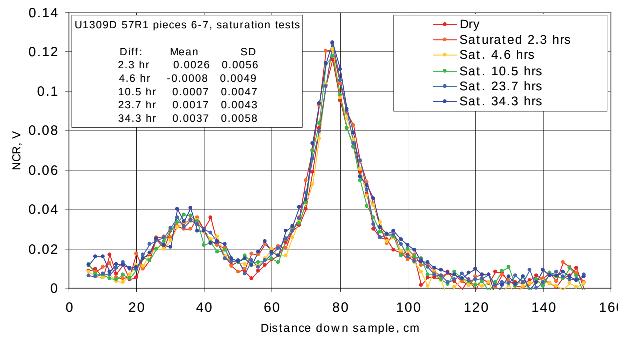

Figure 2. Results of repeated measurements of NCR on U1309D 57R-1 pieces 6 and 7, following drying and then saturation with seawater for periods from 2.3 h to 34.3 h.

measure resistivity in the range 0.1 to 10 ohm-meters. I obtained apparently useful measurements to >100 ohm-m, but these high values are poorly calibrated. It is often more useful and intuitive to consider the reciprocal of resistivity, which is conductivity, measured in siemen per meter (S m^{-1}), and values are presented as such here. Geotek estimates the spatial resolution of the NCR as approximately 2 cm down core (http://www.geotek.co.uk/site/scripts/module.php?webSubSectionID=31). My calibration showed, however, that the sensor has to be between 4 cm and 8 cm from the end of the sample before the full resistivity was measured. Thus, resistivity measured on pieces shorter than ~10 cm will be overestimated, and, as with MS, these were flagged.

The Origin of Conductivity and Susceptibility in Igneous Rocks

Electrical conductivity in rocks occurs by one of two mechanisms: ionic conductivity (in which the drift of ions through conducting pore-water carries the current) and electronic conductivity (in which electrons travel through conducting solid minerals). Most Expedition 304 rocks have low porosity (<3%), but the connectivity of pore spaces is critical in determining ionic conductivity. Normally, resistivity was measured on the MST about 2 h after the core came on board (the delay being the time required for core curation), and in this time the core can lose a significant proportion of its pore water. I ran a test on two long pieces (U1309D-57R-1 Pieces 6 and 7) from Hole 1309D Unit 137 (olivine-bearing gabbro), which was very conductive. After storage on board for several days allowed them to dry out, the working and archive halves were put together and held in place by elastic bands, and then were measured dry and after saturation in seawater for periods from 2.3 h to 34.3 h. Little variation was seen, suggesting that ionic conductivity was not the dominant mechanism (Fig. 2). Similar results were obtained from several other sections with varying lithology.

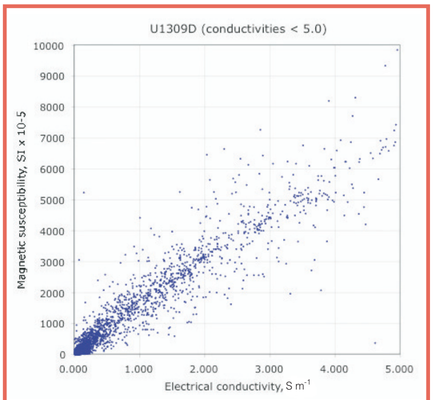

Figure 3. Plot of susceptibility versus conductivity for all values of conductivity <5 S m^{-1} from Hole U1309D measured on Expedition 304.

Early in Expedition 304 electrical conductivity and magnetic susceptibility seemed to be closely correlated, independent of lithology (Fig. 3). This strongly suggests that the same minerals are responsible for both the conductivity and susceptibility. A check of common minerals that exhibit high conductivity and high susceptibility produced the results shown in Table 1. Pyrrhotite, ilmenite, and magnetite all have high mean susceptibility and potentially high conductivity, and are relatively common in igneous rocks. Pyrrhotite was rare in the rocks recovered during Expedition 304, and I suspect that magnetite is the dominant mineral, as either a primary component or one produced during serpentinization.

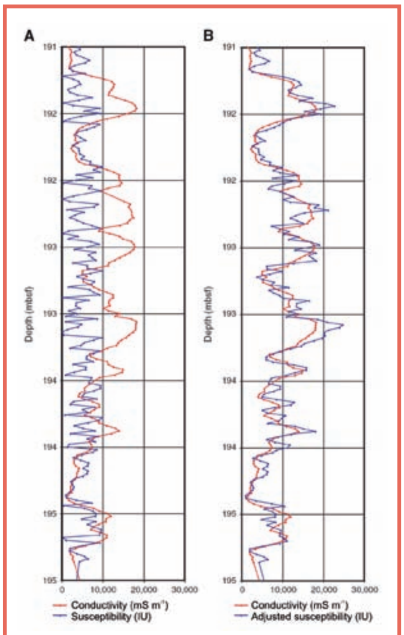

Figure 4. Plots of conductivity (red) and susceptibility (blue) against depth for sections U1309D 35R-1 to 36R-1 (unit 88, oxide gabbros). [A], logged values; [B] susceptibility augmented by integral amounts (1 or 2) of 10,000 IU to compensate for limited range of the installed susceptibility sensor. Note the good correlation with conductivity following this correction.

The strong correlation of conductivity and susceptibility offers a way of checking and perhaps correcting the wrap-around of strong susceptibility signals. Figure 4a shows measured susceptibility plotted alongside conductivity for sections U1309D 35R-1 to 36R-1 (unit 88, oxide gabbros). Some parts, particularly between 194 and 195 mbsf, correlate very well, while others do not. However, by adding 10,000 IU, or occasionally 20,000 IU, to the logged value, a much improved correlation is seen (Fig. 4b). While this manual correction can be applied in some places, it is tedious, and the number of wrap-around can be ambiguous; clearly, there is need for a susceptibility meter with extended range. Results here suggest it should be increased to at least 30,000 IU and probably to 50,000 IU.

Applications

During Expedition 304, MS sometimes showed variations that are not immediately apparent in on-board lithological

Table 1. Common minerals with high electrical conductivity or magnetic susceptibility (Telford et al., 1990)

Mineral	Susceptibility mean, IU	Susceptibility range, IU	Conductivity mean, Sm^{-1}	Conductivity range, Sm^{-1}
Pyrrhotite	1.5	0.006–1.6	104	$20.0–1.5\times10^{5}$
Ilmenite	1.9	0.3–3.8		$20.0\times10^{-2}–1.0\times10^{3}$
Magnetite	6.3	$5.0\times10^{-6}–5.7\times10^{3}$		$1.8\times10^{-4}–2.0\times10^{5}$
Pyrite	0.0015		3.3	

descriptions. For example, Figure 5 shows the susceptibility logged for U1309B Unit 62, which appears to be a fairly uniform oxide diabase (Blackman, 2006), but it exhibits variations from essentially zero to over 5,000 IU (approximately 0.05 SI) over distances of ~1m. This observation spawned the hypothesis that the variations might be related to flow phenomena and perhaps grain size variations at the edges of the unit. On-board examination of photomicrographs suggested that the intervals with low susceptibility might be places where magnetite had been extensively altered to lower susceptibility ilmenite (R. Frost, pers. comm., 2004, 2007), and led to a program of post-cruise research, which has shown that the susceptibility actually correlates quite well with observed proportion of oxides in thin section.

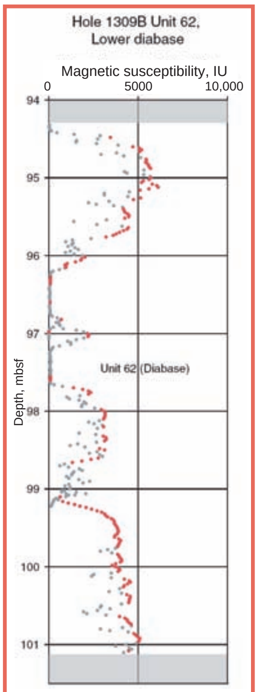

Figure 5. Susceptibility versus depth for Hole U1309B Unit 62, logged as a uniform oxide diabase. Red: MS measurements made >8 cm from the ends of pieces, which are considered reliable. Gray: points measured <8 cm from the ends of pieces, which are probably underestimates of true susceptibility.

Following this early success in using MS to identify potential lithological variations, we instituted the practice of routinely including MS in the visual core description sheets (so-called "barrel plots") produced on board (Fig. 6). These have already proved valuable for re-surveying the Expedition 304/305 cores post-cruise (B. John, pers. comm., 2007), and for investigations of the formation mechanism of serpentine from olivine-rich troctolites (R. Frost, pers. comm., 2007).

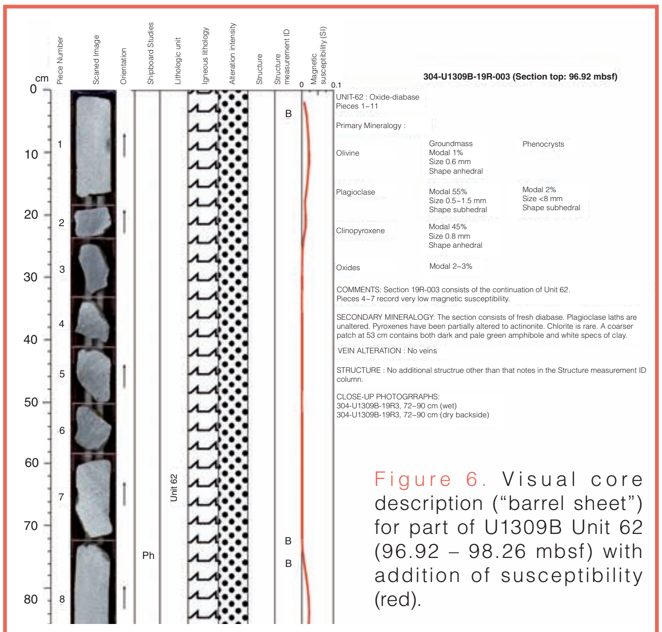

Figure 6. Visual core description ("barrel sheet") for part of U1309B Unit 62 (96.92 – 98.26 mbsf) with addition of susceptibility (red).

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I am indebted to the help of the Expedition 304/305 shipboard scientists, ship's crews, and coring staff. Special thanks go to Physical Properties Marine Laboratory Specialist for Expedition 304, Heather Paul, who expertly guided this neophyte through the complexities of the on-board Physical Properties Laboratory. My participation in Expedition 304 was funded by the Natural Environment Research Council's thematic programme UKIODP.

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Marine Impacts and Environmental Consequences – Drilling of the Mjølnir Structure, the Barents Sea

by Henning Dypvik, Philippe Claeys, Alex Deutsch, Frank T. Kyte, Takafumi Matsui, and Morten Smelror

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Introduction

In September 2007, thirty-three scientists attended an international workshop in Longyearbyen (Svalbard, Norway) to discuss impacts of extraterrestrial bodies into marine environment and to prepare for the drilling of the 142-Ma-old Mjølnir impact structure in the Barents Sea (Fig. 1; Gudlaugsson, 1993; Dypvik et al., 1996, Tsikalas et al., 1998). A field trip visited the ejecta layer in the Janusfjellet Mountain in Isfjorden, just outside Longyearbyen (Fig. 2).

The workshop focused on two topics: 1) mechanisms of marine impact cratering including ejecta formation and distribution, geothermal reactions, and the formation of tsunami, and 2) environmental effects of marine impacts. Both topics are highly relevant to the Mjølnir event and the geological evolution of the Arctic, as well as to the biological changes at the Jurassic-Cretaceous boundary. Against this background were a) concrete drilling targets formulated, b) plans outlined for compiling data from existing geological and geophysical surveys as the basis for Integrated Ocean Drilling Program (IODP) and International Continental Scientific Drilling Program (ICDP) drilling proposals, and c) a steering group and science teams established for compiling old and new material as a foundation for the development of drilling proposal.

Scientific Background

Asteroid and comet impacts are now recognized as an important and regular geological process releasing vast amounts of energy and resulting in near instantaneous increase in temperature and pressure, structural deformation, and redistribution of target materials. It is presently accepted that impacts, especially those in a marine environment, have very important influences on the development of the Earth. However, detailed knowledge of the geological and physical aspects of the impact process itself, as well as its environmental and biological consequences, is still limited. This is mainly due to the fact that a large majority of the ~170 currently known impact craters on the Earth and their ejecta deposits are rather poorly preserved. Only twenty-five of these craters represent marine impacts, and very few of those have remained submerged with a potential for preservation of the original structure (Dypvik and Jansa, 2003). No completely retained marine crater has been investigated in detail yet, while in the last years ICDP land coring projects in the Chicxulub, Bosumtwi, and Chesapeake Bay impact structures were of great scientific gain.

One of the best preserved known impact craters on Earth is the Mjølnir impact structure. It was discovered by seismic data during petroleum exploration in the Barents Sea but never sampled by coring. An extensive geophysical database has been collected over the Barents Sea, and more than sixty petroleum exploration wells have been drilled, particularly along basin margins and on structural highs. In addition, many shallow drill holes on sub-cropping sedimentary sequences have been drilled in the more central and remote areas of the Barents Sea. See also the Norwegian Petroleum Directorate (NPD; http://www.npd.no).

The Mjølnir Structure is 40 km in diameter and is located at the Bjarmeland Platform in the central Barents Sea (Fig. 1), beneath 350 m of water. Its elevated central high (Fig. 3) is

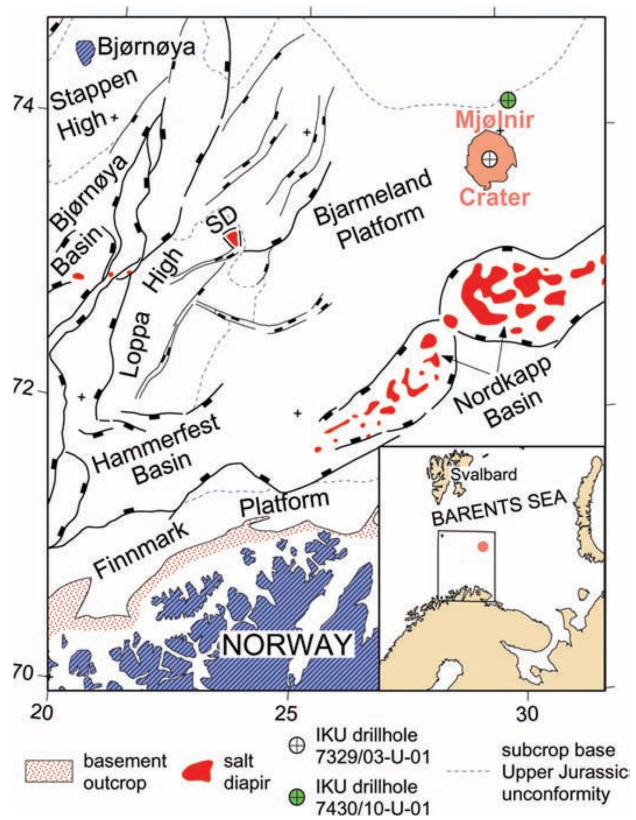

Figure 1. A tectonic map of the Bjarmeland Platform area in the Barents Sea, with a regional inset showing the Mjølnir and Svalbard position. The Mjølnir impact crater location and key shallow drillholes are shown in the main map.

covered by ~50 m of younger sediments. Geophysical, geological, and mineralogical data unequivocally substantiate the origin of the structure by an impact event into a sedimentary platform with 300–500 m paleo-water depth (e.g., Dypvik et al., 1996; Smelror et al., 2001; Sandbakken et al., 2005). The impact has been dated at about 142 Ma (Dypvik et al., 1996), very close to the Jurassic-Cretaceous boundary. At this time, the platform comprised upper Paleozoic strata, mainly carbonates and evaporates, overlain by 4–5 km of thick Mesozoic siliciclastic marine sediments (Dallmann, 1999).

The Workshop Program

The workshop included the following topics:

(1) Review the science behind marine impacts and the Mjølnir project. The state of knowledge, and ongoing geological and geophysical investigations in the Arctic realm, the Barents Sea, and Mjølnir were outlined by specialists of Arctic geology and members of the Mjølnir research group.
(2) Review of petroleum exploration drilling in the Barents Sea was presented by one representative from the NPD and representatives from Norsk Hydro and Statoil (now StatoilHydro). Drilling experts from ICDP, Drilling, Observation and Sampling of the Earths Continental Crust (DOSECC) and IODP presented different drilling options.
(3) Scientific goals and drilling strategies for the Mjølnir. A plenary session was followed by discussions in two break-out groups, whose recommendations are summarized below.
(4) An excursion was organized to the site of possible Mjølnir ejecta at the mountain Janusfjellet in Isfjorden (Fig. 2).

The Workshop Outcome

Deep wells in the Mjølnir impact structure would be of great interest to the international scientific community, in order to study the shock propagation, collapse, and re-sedimentation of the >6-km-thick sedimentary succession. Coring through this succession will make structural analysis and detailed understanding of crater generation and deformation possible and help constrain numerical modeling. However, the costs for deep coring in the harsh environments of the Barents Sea makes it

Figure 2. The sun over Isfjorden and the ejecta locality at Janusfjellet.

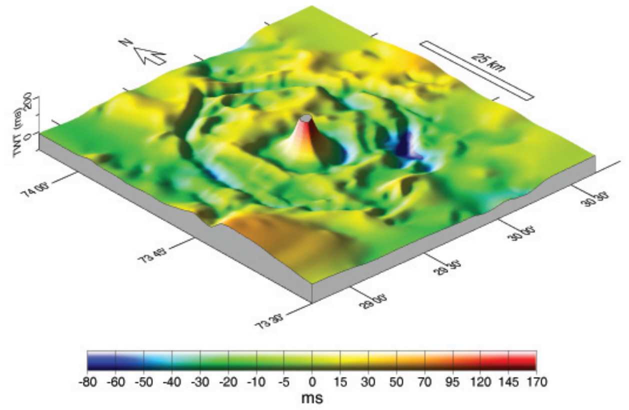

Figure 3. The seismic model of Mjølnir structure.

unrealistic to raise funding for such operations in the foreseeable future.

One of the great scientific advantages with the Mjølnir impact crater is the clear correlation between the crater and its very well preserved ejecta found in shallow drillings in the Barents Sea and on land (Svalbard and possibly Siberia; Dypvik et al., 2004; 2006). During a large part of late Jurassic and early Cretaceous, the Barents Sea region formed an epicontinental sea dominated by anoxic sedimentation of black, organic-rich clays. The Mjølnir bolide impacted into these sediments, and the crater and portions of the ejecta localities were buried and have remained buried under sediments and water since its formation. Those ejecta localities are well-preserved and accessible by shallow drilling (e.g., Bugge et al., 2002). It is one of the few places on the Earth where such important relations can be studied in detail. This is clearly of great importance for understanding the crater and ejecta formation, including the study the environmental consequences of marine impacts (Dypvik et al., 2006; Smelror et al., 2002). We will use Mjølnir as a type locality to study ejecta generation and distribution and possible relationships between the impact and biotic evolution. Mjølnir ejecta may even serve as a Boreal-Tethyan stratigraphic marker and could be useful in correlation of these two distinct provinces near the poorly understood Jurassic-Cretaceous boundary (Smelror et al., 2001; 2002). Further research could greatly expand our initial knowledge on tsunami generation and formation, impact ignitions of hydrocarbons in the target area, fires and subsequent soot precipitation. Calculations show that organic matter equivalent to a year's oil production of one Norwegian Shelf giant field (about thirty million std. m^3 oil in place) was burned during the first twenty minutes of the Mjølnir event (Dypvik et al., 2008).

The development of the Mjølnir research program should be carried out in full cooperation with the NPD and in close contact with the oil industry active in the region (e.g., StatoilHydro, ENI), making use of their extensive geophysical database and deep wells. A two-step drilling project was recommended:

Step 1. Drilling of five to six, up to 300-m-deep core holes in 350–400 m water depth around the Mjølnir structure to map and understand ejecta formation and distribution, coupled with *in situ* disturbance of sediments due to seismic and shock waves, or erosion by displaced water near the crater. Analysis of the cored material will be accompanied by sophisticated simulation models (Shuvalov and Dypvik, 2004) of the formation and deposition of ejecta in a marine environment.

Step 2. Drilling of one or two deep holes within the central moat to understand the inner structure of a large crater. At this point, however, the cost of such a project possibly requiring riser drilling is difficult to assess.

Future Plans

An international steering group (the authors of this paper) was established and charged with producing a draft project proposed by the end of 2008. The steering group will also be responsible for compiling the final drilling proposals to IODP, ICDP, and the Norwegian Research Council (NFR) by spring 2009. For further information on the Mjølnir drilling project, please contact the authors or visit http://mjoelnir.icdp-online.org/.

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Drilling the North Anatolian Fault

by Georg Dresen, Marco Bohnhoff, Mustafa Aktar, and Haluk Eyidogan

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An international workshop entitled "GONAF: A deep Geophysical Observatory at the North Anatolian Fault", was held 23–27 April 2007 in Istanbul, Turkey. The aim of this workshop was to refine plans for a deep drilling project at the North Anatolian Fault Zone (NAFZ) in northwestern Turkey. The current drilling target is located in the Marmara Sea offshore the megacity of Istanbul in the direct vicinity of the main branch of the North Anatolian Fault on the Prince Islands (Figs. 1 and 2).

The NAFZ represents a 1600-km-long plate boundary that slips at an average rate of 20–30 mm·yr^{-1} (McClusky et al., 2000). It has developed in the framework of the northward moving Arabian plate and the Hellenic subduction zone where the African lithosphere is subducting below the Aegean. Comparison of long-term slip rates with Holocene and GPS-derived slip rates indicate an increasing westward movement of the Anatolian plate with respect to stable Eurasia. During the twentieth century, the NAFZ has ruptured over 900 km of its length. A series of large earthquakes starting in 1939 near Erzincan in Eastern Anatolia propagated westward towards the Istanbul-Marmara region in northwestern Turkey that today represents a seismic gap along a ≥100-km-long segment below the Sea of Marmara. This segment did not rupture since 1766 and, if locked, may have accumulated a slip deficit of 4–5 m. It is believed being capable of generating two M≥7.4 earthquakes within the next decades (Hubert-Ferrari et al., 2000); however, it could even rupture in a large single event (Le Pichon et al., 1999).

The most recent devastating earthquakes in the region occurred in 1999 near Izmit and Düzce with magnitudes >7.

Figure 1. Google Earth view of the Marmara Sea / Istanbul region. Red lines indicate major segments of the North Anatolian Fault Zone (NAFZ). Stars indicate major events that occurred in the last 2000 years.

Their western termination of rupture is located offshore below the eastern Sea of Marmara possibly extending to just south of the Princes Islands (Özalaybey et al., 2002) within ~20 km of Istanbul.

Current seismic activity in the eastern Marmara Sea indicates a complex fault network at the transition between the western end of the Izmit earthquake rupture and the assumed seismic gap south of Istanbul. The majority of focal mechanism solutions indicate dominant strike-slip motion with minor normal faulting activity (Örgülü and Aktar, 2001; Karabulut et al., 2002). However, existing seismic observations lack the spatial and temporal resolution required to accurately distinguish between locked and creeping segments of the NAFZ. This is due to the threshold (magnitude >2) of the existing seismic networks. The knowledge of the stress state at the NAFZ is rudimentary at best. Stress orientation (World Stress Map) with respect to the fault zone is mainly based on a small number of focal mechanisms of larger seismic events (Heidbach et al., 2004) and aftershocks (Bohnhoff et al., 2006). Maximum compressive stress is generally oriented at 35°–45° with respect to the fault trend and in agreement with predictions from Coulomb friction theory. In contrast to other major plate bounding faults, the NAFZ does not appear to be a weak fault. However, no data exist on stress magnitudes and on heat flow close to the NAFZ in the Marmara Sea region.

The GONAF initiative focuses on the installation of a borehole observatory in a deep borehole at the NAFZ. This will conduct long-term monitoring of seismic activity, stress, heat and fluid flow. The target area is located offshore Istanbul in the Marmara Sea close to the main branch of the NAFZ on the outermost island of Sivriada (Fig. 2). The projected observatory is located at the transition between the western end of the 1999 Izmit rupture and the 150-km-long seismic gap along the western NAFZ that may have accumulated a 4–5 m slip deficit within the past 250 years.

Figure 2. Proposed drilling location on the island of Sivriada that is located in direct vicinity to the main branch of the NAFZ.

Presentations at the workshop included an overview of existing fault drilling projects, a session on seismotectonics, seismology, and the geological setting of western part of the NAFZ and the Marmara Sea region, and deep borehole monitoring results and technology. The potential drill site on Sivriada island was visited during a one-day field trip. A summary of suggested pre-site and drilling-phase studies concluded the workshop. Key scientific and technical aspects of a deep drillhole and long-term geophysical observatory were discussed in order to prepare for a full drilling proposal to be submitted to the International Scientific Continental Drilling Program (ICDP).

Reports on fault mechanics and earthquake processes as well as technical and logistical challenges of a drilling presented included projects in California (San Andreas Fault Observatory at Depth; Hickman, et al., 2007), Taiwan (Taiwan Chelungpu-Fault Drilling Project; Ma and Tanaka, 2007), Japan (Nojima Fault; Ito et al., 2003), and Greece (Corinth Rift Laboratory; Cornet, 2007). All fault drilling projects produced new and ground-breaking results with regards to physics of faulting, slip distribution at hypocentral depth, source mechanisms, and the earthquake energy budget. Other presentations detailed the structure, kinematics, and seismotectonics of the western NAFZ emphasizing recent and partly unpublished field data. Unresolved fault structure and hypocenter locations in the Marmara Sea underscored the need for high-resolution long-term seismological observations and detailed wide-angle seismic profiling close to the planned drill site.

A final series of presentations focussed on state-of-the-art monitoring strategies for a borehole observatory including instrumentation and other technical aspects. In particular, detailed introductions presented new scientific results and technical achievements covering high-resolution earthquake monitoring, strain monitoring, velocity measurements, stress measurements, heat and fluid flow measurements, and borehole logging techniques.

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http://www.gonaf.de/

Scientific Drilling of the Terrestrial Cretaceous Songliao Basin

by Yongjian Huang, Chengshan Wang, and the Terrestrial Scientific Drilling of the Cretaceous Songliao Basin Science Team

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Investigations of critical climate changes during the Cretaceous have the potential to enhance our understanding of modern global warming because the extreme variances are the best-known and most recent example of a greenhouse Earth (Bice et al., 2006). Marine Cretaceous climate archives are relatively well explored by scientific ocean drilling programs such as the Integrated Ocean Drilling Program (IODP) and its predecessors. However, Cretaceous terrestrial climate records are at best fragmentary (Heimhofer et al., 2005). The long-lived Cretaceous Songliao Basin of NE China is an excellent candidate to fill this gap and provide important ocean-continent linkages in relation to environmental change (Fig. 1). This basin, located within one of the largest Cretaceous landmasses (Scotese, 1988), acted for about 100 million years as an intra-continental sediment trap; the present-day area of the basin is about 260,000 km^2. It provides an almost complete terrestrial sedimentary record from the Upper Jurassic to the Paleocene (Chen and Chang, 1994). Large-scale geological and geophysical investigations of lacustrine sediments and basin structures demonstrate that a rich archive of Cretaceous paleoclimate proxies exists. For example, the basin includes the Jehol Biota, a terrestrial response to the Cretaceous oceanic anoxic events (OAEs), and a potential K/T boundary (Qiang et al., 1998). An ongoing drilling program is supported by the Ministry of Science and Technology of China and by the Daqing Oilfield. It allowed for recovering of nearly complete cores from Upper Albian to the Uppermost Cretaceous in two boreholes (SK-I, SK II; commenced in 2006, Fig. 1). However, the older Cretaceous sedimentary record of Songliao Basin has not yet been cored. For that reason, a scientific drilling program has been proposed to the International Continental Scientific Drilling Program (ICDP) to sample the deeper sedimentary record of the Songliao Basin through a new drill hole (Figs. 1 and 2).

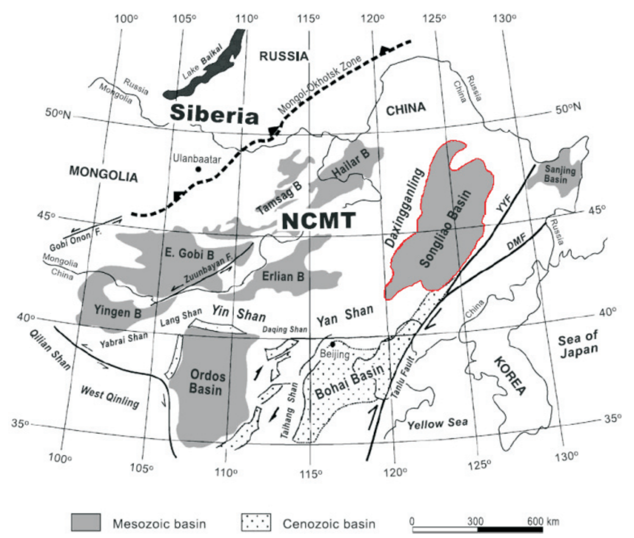

Figure 1. Location of the Songliao Basin in the tectonic framework of the North China–Mongolia Tract (NCMT). The NCMT is separated from the East Siberian Craton by the Mongolia-Okhotsk suture zone and is marked by the Yinshan-Yanshan Belt in the south and by the Daxing-Ganling Belt in the east. YYF=Yilan-Yitong fault; DMF= Dunhua-Mishan fault; HSZ = Honam Shear Zone; B= basin; F = fault.

In order to better constrain the scientific objectives, feasibility of deep drilling, and study of the core material, an ICDP workshop on "Deep Terrestrial Scientific Drilling Project of Cretaceous Songliao Basin" was held on 28–30 August 2007 in Daqing, China. The workshop was organized by the China University of Geosciences at Beijing and by the Daqing Oilfield and was jointly supported by the ICDP and sponsors from China: the Department of International Cooperation and Technology, Ministry of Land and Resources, China; Department of Basic Research, Ministry of Science and Technology, China (MOST); Department of Earth Science, National Natural Science Foundation of China (NSFC); and China Geological Survey.

About seventy participants (thirty-one from outside China) from eleven countries took part in the workshop. Three sessions were organized with more than fifty talks to meet the objectives of the workshop including "Evolution of Songliao Basin and East Asia, and Terrestrial Scientific Drilling Program", "Terrestrial Environment Change and Paleontological Response to Cretaceous Global Change" and "Cretaceous Paleoceanography".

During the workshop the following five key scientific goals for the project were defined:

- Improve understanding of the geodynamics of deep Earth, in particular the relation between the Cretaceous Super-Chron and Large Igneous Provinces;
- Quantify the biotic response to terrestrial environmental change and the deep biosphere (fossil DNA);
- Refine stratigraphic boundaries to improve the correlation between marine and terrestrial stratigraphy;
- Determine the terrestrial response to OAEs; and

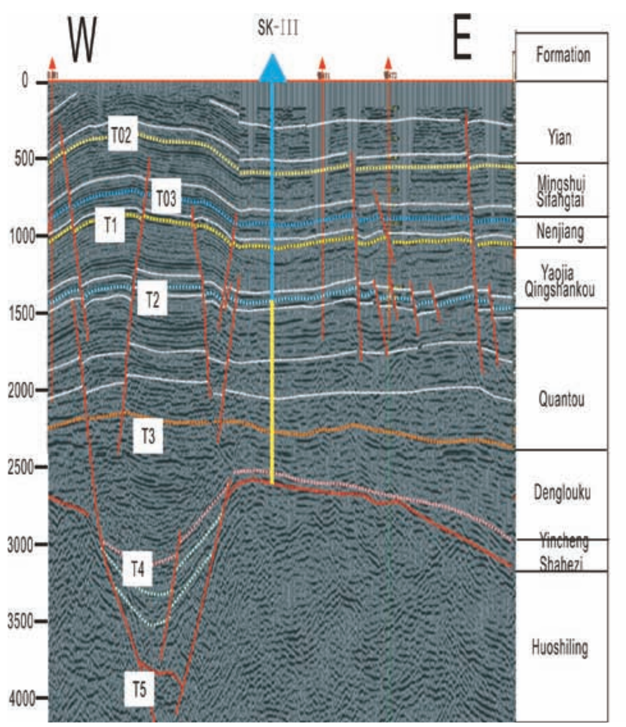

Figure 2. W-E Seismic profile showing the locale of the proposed Songke-III well with stratigraphic interpretation. The vertical blue line indicates the strata to be drilled in rotary mode. The yellow line indicates the planned wireline coring section down to the total depth of ~2700 m. This was done in order to avoid structural complications and to penetrate the most complete stratigraphic section.

- Investigate the formation of mass terrestrial hydrocarbon source rock.

In order to address these overarching research goals, workshop participants recommended that all boreholes (SK-I, SK-II, and the planned SK-III) should be incorporated into the planned ICDP project. The Upper Cretaceous core from SK-1 will especially serve to focus on the K/T boundary; SK-II cores will be analyzed to investigate mid-Cretaceous events; and samples from the proposed SK-III well will focus on the Lower Cretaceous including the J/K boundary, OAEs, and the evolution of the Jehol Biota. Preliminary results from existing boreholes and outcrop studies presented at the workshop showed great promise. During a field trip to the core curation facility of the Daqing Oilfield Company, the workshop participants were able to examine the cores of the SK-I and SK-II wells.

An important objective was to assess the feasibility of the deep drill hole (SK-III) in the Songliao Basin and its potential to recover strata older than Albian. Discussions of site selection concluded that the project should aim to core from the Albian Quantou to the Upper Jurassic Huoshiling Formations. Several site selection principles for drilling SK-III were defined as follows: to drill the most complete section, to find the least thickness of the overlying strata, and to preferentially drill fine-grained, clay-rich deposits. With these principles in mind, existing data were evaluated for identification of an optimum drilling location. The existing data base comprises, for example, over 250,000 km of seismic reflection profiles, some 3-D seismic reflection volumes, and about 50,000 wells (without coring). A preliminary site for SK-III has been selected in the center part of the basin (Fig. 2).

Finally, meeting participants agreed to form five strategic teams covering the objectives as outlined above. The goals of this science team are to compose a full drilling proposal and to submit it to ICDP and other potential funding agencies in early 2008.

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Related Web Link

http://songliao.icdp-online.org

CPCP: Colorado Plateau Coring Project – 100 Million Years of Early Mesozoic Climatic, Tectonic, and Biotic Evolution of an Epicontinental Basin Complex

by Paul E. Olsen, Dennis V. Kent, and John W. Geissman

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Introduction

Early Mesozoic epicontinental basins of western North America contain a spectacular record of the climatic and tectonic development of northwestern Pangea as well as what is arguably the world's richest and most-studied Triassic-Jurassic continental biota. The Colorado Plateau and its environs (Fig. 1) expose the textbook example of these layered sedimentary records (Fig. 2). Intensely studied since the mid-nineteenth century, the basins, their strata, and their fossils have stimulated hypotheses on the development of the Early Mesozoic world as reflected in the international literature. Despite this long history of research, the lack of numerical time calibration, the presence of major uncertainties in global correlations, and an absence of entire suites of environmental proxies still loom large and prevent integration of this immense environmental repository into a useful global picture. Practically insurmountable obstacles to outcrop sampling require a scientific drilling experiment to recover key sedimentary sections that will transform our understanding of the Early Mesozoic world.

To bring our insight into this critical time in Earth history to a new level, we developed the concept of the Colorado Plateau Coring Project (CPCP), an effort to recover continuous core spanning the early Mesozoic (Triassic-Jurassic) section of the Colorado Plateau and adjacent areas. The original basis for this was outlined at the 1999 International Continental Scientific Drilling Program (ICDP) and U.S. National Science Foundation (NSF) funded International Workshop for a Climatic, Biotic, and Tectonic, Pole-to-Pole Coring Transect of Triassic-Jurassic Pangea (http://www.ldeo.columbia.edu/~polsen/nbcp/pangeafinalreport.html, Olsen et al., 1999), section "Western Equatorial Pangea" (http://www.ldeo.columbia.edu/~polsen/nbcp/westpangea.html). Forty-five researchers from six countries attended the inaugural CPCP planning workshop held 13–16 November 2007, in St. George, Utah. The main goal was to develop a community consensus science plan for the CPCP (http://www.ldeo.columbia.edu/~polsen/cpcp/CPCP_home_page.html). The participants represented disciplines ranging from geochronology and physical stratigraphy through vertebrate paleontology and paleobotany. A plenary session with speakers highlighting the major science issues, precedents, and geoinformatics priorities was followed by thematic breakout groups. These included Stratigraphy, Geochronology and Magnetostratigraphy, Climate and Environments, Paleontology and Biotic Change, and Geoinformatics and Core-log Outcrop Integration. A half-day field trip was made to the St. George Dinosaur Discovery Site at Johnson Farm (http://www.sgcity.org/dinotrax/) and Warner Valley outcrops of Triassic-Jurassic strata (Fig. 3), and was followed by a plenary synthesis session. As developed by consensus at the workshop, the goal of the CPCP is to transform our understanding of the interplay between major biotic transitions, global climate change, plate position, and tectonics over 100 Ma of Earth histories (Fig. 2).

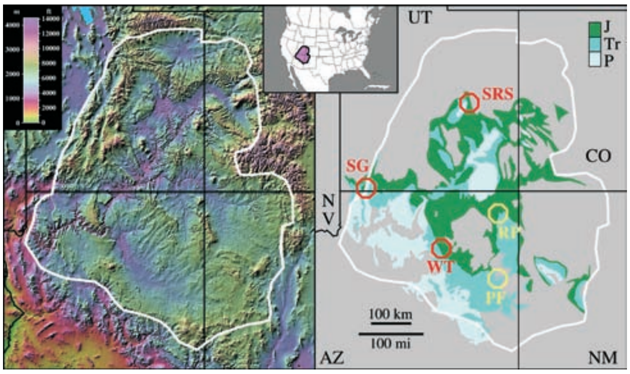

Figure 1. Map of the Colorado Plateau (white line) and adjacent areas: [Left] Shaded digital elevation map (courtesy of Andrew D. Birrell http://birrell.org/andrew/reliefMaps/ and http://birrell.org/andrew/copyright.html); [Right] Generalized geological map showing Permian and Triassic and Jurassic strata (modified from R. Blakely http://jan.ucc.nau.edu/~rcb7/Jurassic_erg_graphics.html). Core areas are: PF, Petrified Forest, Arizona; RP, Rock Point, Utah; SG, St. George, Utah; WT, Ward Terrace, Arizona; SRS, San Rafael Swell, Utah.

Overall Concept and Goals

Broad questions that could be profitably addressed in the Colorado Plateau venue include the following: what are the global or regional climate trends vs. plate position changes in "hot house" Pangea; how do largely fluvial systems respond to cyclical climate; what are the rates and magnitudes of the transition from the Paleozoic to essentially modern terrestrial ecosystems; and how does the stratigraphy reflect the interplay between growth in accommodation, uplift, and eustatic fluctuations? Based on these questions, the workshop identified eight goals attainable by coring of key Triassic/Jurassic sections:

1) Establishment of paleogeographic boundary conditions, particularly changes in paleolatitude.

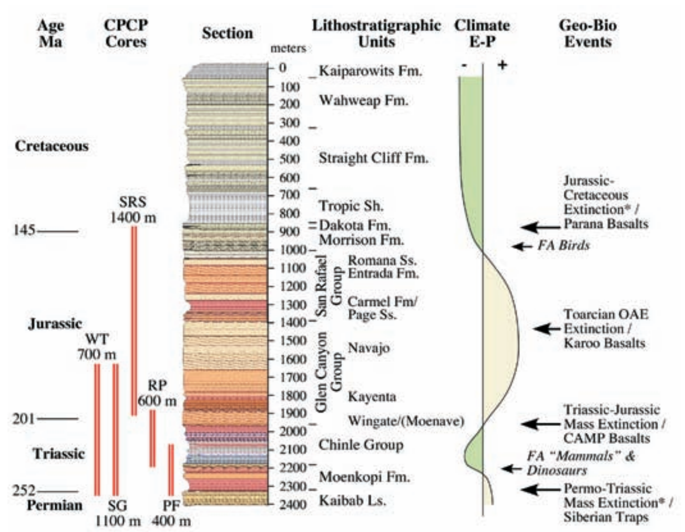

Figure 2. Details are given to the right.

Generalized Colorado Plateau section (Glen Canyon/Kaiparowits Plateau, based on http://jan.ucc.nau.edu/~rcb7/Glen_Can.jpg) with the cored sections recommended by the CPCP workshop participants, a generalized evaporation-precipitation (E-P) curve loosely based on climate sensitive facies, and some major geological and biological events (* actual boundary may or may not be present in rock section). See Fig. 1 for core area abbreviations. Note that the relative thicknesses of various stratigraphic units are generally different than what is shown in the color section and not the same between different coring areas.

The five major stratigraphic units shown here were deposited under dramatically changing climatic conditions that constitute the Triassic and Jurassic of the Colorado Plateau: the Early to Middle Triassic Moenkopi Formation (marginal marine and coastal sabka to semiarid fluvial and floodplain, minor eolian); the Late Triassic Chinle Group (humid to semiarid fluvial to lacustrine, some eolian near top); the latest (?) Triassic-Early Jurassic Glen Canyon Group (semiarid to arid, major eolian, fluvial, lacustrine); the Middle to Late Jurassic San Rafael Group (marine to coastal sabka, major eolian and fluvial arid to semiarid; from http://www.nps.gov/arch/); and the Late Jurassic Morrison Formation (semiarid to humid, fluvial and lacustrine). Determining the precise nature and origin of the large climatic transitions represented by these units is a major goal of the CPCP.

2) Development of the highest-resolution magnetic polarity stratigraphy for Early Triassic through Late Jurassic strata to facilitate detailed regional and global correlation.
3) Determination of how paleoclimates are expressed through time in the sedimentary record of western Pangea.
4) Identification of the precise stratigraphic position of major global biotic transitions (i.e., Permo-Triassic, Triassic-Jurassic, and Toarcian)
5) Refinement of lithostratigraphic and biostratigraphic correlations, considering regional unconformities and their possible relationship to eustacy and tectonics (c.f., Bachmann and Kozur, 2004).
6) Development of a chemostratigraphic ($\delta^{13}C$, cuticular CO_2 proxy, Nd, Sr, clays, etc.) reference sections.
7) Improvement of U-Pb zircon provenance stratigraphy and geochronology of ash beds.
8) Establishment of links among the temporal evolution of the Colorado Plateau sedimentary record, rifting of Pangea opening of the Atlantic Ocean, and emplacement of basalt provinces (Fig. 2).

Coring Plans

Given these overall goals, the workshop reached several conclusions that dictated the coring plan.

1) *Early Triassic through Late Jurassic Formations including the Morrison Formation should be cored* in order to cover the full range of climatic milieus represented by these rocks. Collectively, the group defined a three-tiered coring plan consisting of (1) three relatively thick (~1 km) synoptic intervals that together would yield an overlapping stratigraphic framework for the entire Jurassic and Triassic section, (2) two thinner (<500 m) cored sections that would tie to critical outcrop areas or to expanded critical intervals, and (3) a number of short sections to address more specific problems or provide regional coverage to the other five cores that are the nexus of the project.

2) *Superposition is paramount.* Evaluation of the critical Early Mesozoic transitions is required of all Early Mesozoic units in clear superposition. The five major stratigraphic units identified as major coring targets reflect, from oldest to youngest: arid (Moenkopi); humid to semiarid (Chinle); very arid (Glen Canyon and San Rafael); and return to semiarid and humid (Morrison) (Figs. 2 and 4). These climate transitions have been explained in several ways—translation of the North American plate from equatorial to mid-latitudes through zonal climate belts (Dickinson, 2005; Kent and Muttoni, 2003; Kent and Tauxe, 2004); large scale changes in the climate system involving changes in the non-zonal components of the climate system, particularly the monsoon (Kutzbach and Gallimore, 1989; Parrish, 1995; Rowe et al., 2007); or fluctuations in greenhouse gases like CO_2 (e.g., McElwain et al., 1999; Kürschner, 2001). These fundamentally different hypotheses remain untested because the temporal evolution of major boundary conditions, most notably latitude, has not been resolved to a useful level of precision (Tauxe and Kent, 2004; Tan et al., 2007).

3) *Internal time calibration needed.* Correlation of the Plateau sequence is presently based on low-resolution non-marine biostratigraphic approaches, and it does not provide clear biogeographic patterns or determination of the rates of biotic change in these very fossiliferous sequences. None of the major intervals of biotic change (Permo-Triassic; Triassic-Jurassic; or Toarcian) are located with precision in this succession. A combination of polarity stratigraphy along with geochronologic dates from ash deposits and dispersed grains will allow global correlations, including: 1) Triassic and Early Jurassic reference sections (Szurlies, 2007); 2) the astronomically calibrated polarity time scale (Kent and Olsen, 1999, 2008; Olsen and Kent, 1999; Hounslow et al., 2004; Kemp and Coe, 2007); 3) the Germanic basin (Bachmann and Kozur, 2004); 4) fully marine Tethyan sections (Muttoni et al., 2005; Channell et al., 2003; Gallet et al., 2007); 5) non-marine Jurassic to Early Cretaceous sequences of China (Feursich et al., 2002; Yao et al., 2003; Xu, 2005);

and 6) possibly, the marine magnetic anomaly M-sequence (Channell et al., 1995; Sager et al., 1998).

4) *Minimize hiatuses.* Acquiring as much stratigraphic scope as possible through the more continuous units and testing any paleomagnetic reversal sequences across geography by designing stratigraphic overlap between cores will help overcome significant unconformities and possible smaller and cryptic hiatuses. The thickest sections, least likely to be affected by rampant hiatuses, are not confined to a single area in the Colorado Plateau because of lateral shifts in the basin's depocenters. Several cores will be necessary to get the most favorable sections of each of the units. However, the thick sections proposed for coring are far from comparable surface outcrops, and thus, subsidiary sections more proximal to sources of the surface data must be cored as well. The goal is to provide a long enough section with unambiguous ties to the outcrop and sufficient stratigraphic scope to correlate with the main, long cores.

5) *Thick eolianite successions should be avoided* while key limestone and eolianite tongues must be intersected for age control by lateral correlation to outcrop.

Using these five principles above, three areas identified for long (~1 km) cores are, from the uppermost stratigraphic interval downward (Figs. 1 and 2): 1) *Dry Mesa* (east side of San Rafael Swell, UT), ~1400 m from basal Cretaceous Cedar Mountain Formation to the Permian Kaibab Formation; 2) *St. George* (west of the Hurricane fault), ~1100 m from locally basal Navajo Formation to Permian Kaibab Formation; and 3) *Tuba City* (north of Ward Terrace): ~700 m from basal Navajo Formation to Kaibab Formation. Although the St. George and Tuba City sections appear to span the same overall section, they are actually critical complements. The Moenkopi and latest (?) Triassic-Early JurassicTriassic-Early Jurassic Moenave formations are well-developed, cyclical, and probably relatively complete in the St. George area, yet the Chinle Group is very thin and erosionally truncated. In the Tuba City area, the Chinle is very well-developed, but the Moenkopi is very thin and erosionally truncated. Also, the Moenave lacks the well-developed, cyclical lacustrine strata present around St. George.

The two medium depth sections (Fig. 2) are targeted for 1) the *Rock Point* area (north of Round Rock, Utah), ~600 m from basal Wingate Formation to Permian Kiabab Formation,

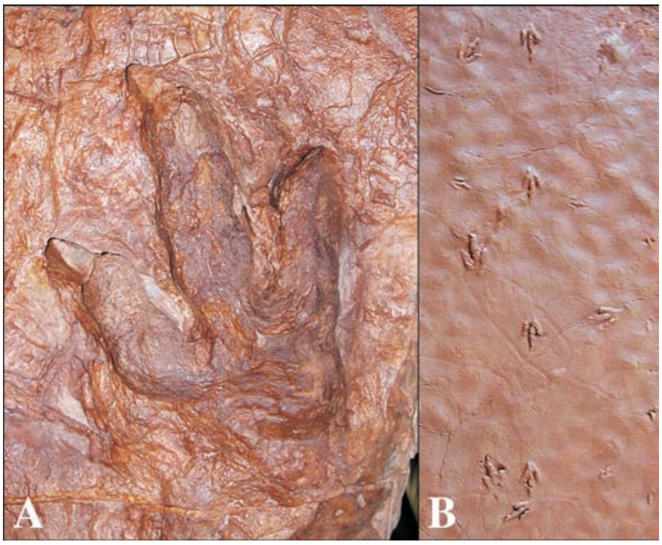

Figure 3. Examples of dinosaur tracks at the St. George Discovery Site at Johnson Farm in the lower Whitmore Point Member of the Moenave Formation: [A] Example of natural cast of *Eubrontes giganteus* (~35 cm long), plausibly made by a large theropod dinosaur similar to *Dilophosaurus* from the lower Kayenta Formation; [B] small theropod dinosaur footprints of the "Grallator" and "Anchisauripus" types (~10–15 cm long each). The importance of these fossil assemblages is that they document the terrestrial assemblages just after the Triassic-Jurassic extinction event that surprisingly is overwhelmingly dominated by carnivores.

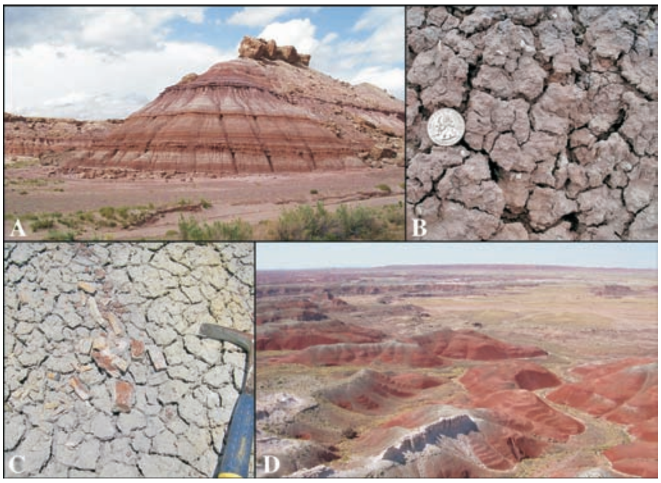

Figure 4. Details are given below.

Although the American Southwest, including the Colorado Plateau, is famous for spectacular exposures in striking badlands, the thickest sections of key time intervals are often projected from the subsurface. The most continuous sections in outcrop are often exposed as inaccessible vertical cliffs or are heavily weathered and geochemically altered, precluding research at the appropriate level of detail. Because of low bedding dips, the assembly of sections spanning large stratigraphic thicknesses requires long-distance traverses that often compromise the essential assumption of superposition because of facies changes. The problems are amply revealed by repeated attempts in the literature at compiling long, high-resolution sections that describe the succession in any specific area. Long, continuously cored intervals tied to outcrop in key areas are required for further substantial progress.

Opportunities and problems of working only with outcrops present themselves in examples of superb near-100% outcrops, especially of muddy facies (Fig. 4). Mudstones are often bentonitic and with a partial volcanic source, which means there are datable ashes; however, it also means that the outcrop surfaces present horrendous sampling problems where freshness and physical integrity are at a premium as for geochemistry or paleomagnetics. Two examples include the Late Jurassic Morrison Formation (Fig. 4A and 4B) and the Late Triassic Chinle Group (Fig. 4C and 4D).

Fig. 4A, Brushy Basin Member of the Morrison Formation west of Green River, Utah (from http://en.wikipedia.org/wiki/Morrison_Formation); Fig. 4B, typical "popcorn" surface of bentonitic mudstone of the Brushy Basin Member of the Morrison Formation west of Green River, Utah (same source as 4A); Fig. 4C, "popcorn" surface of the Chinle Group near Bluewater Creek, NM (Stop 1 of Lucas et al., 2007), with fragmentary weathered metoposaur amphibian dermal bones; and Fig. 4D, outcrops of bentonitic Painted Desert Member of the Petrified Forest Formation of the Chinle Group in Petrified Forest National Park with the U-Pb dated Black Forest Bed (Riggs et al., 2003) outcropping as the white bed in foreground.

and 2) the *Petrified Forest* area (within Petrified Forest National Park, AZ), ~400 m from Sonsela (mid-Chinle) to Permian. The Rock Point area is a critical target because it exposes the Triassic-Jurassic boundary section in the largely eolian Wingate Formation, based on both vertebrate paleontology and magnetostratigraphy, and it is a natural complement to the lacustrine-dominated Moenave Formation near St. George. The Petrified Forest area has produced the bulk of the Chinle fauna and flora, as well as dated ash beds, and it is a natural complement to the Chinle section in the Tuba City area. The workshop concluded that the geophysical logs of the core holes and cores will be critical in tying cores to outcrop (Szurlies et al., 2003).

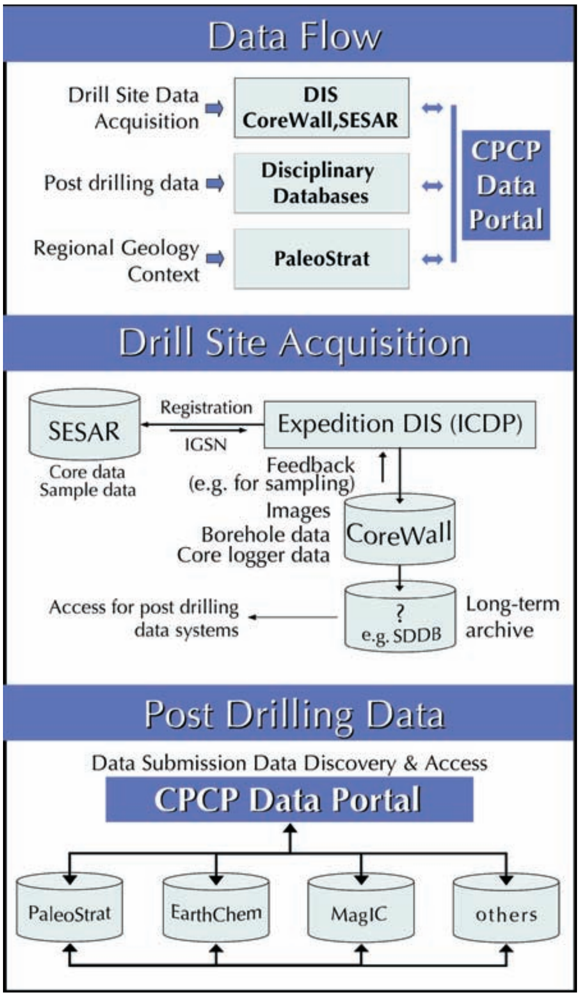

Figure 5. Details are given to the right.

Data management scenario for the CPCP showing the relationship between data gathering (i.e., from the cores and core holes) and the flow of information and samples derived from it to community access systems. Acronyms are: DIS, Drilling Information System; CoreWall, a real-time stratigraphic correlation, core description and data visualization system (http://www.evl.uic.edu/cavern/corewall/index.php); SESAR, System for Earth Sample Registration (http://www.geosamples.org/); PaleoStrat, a community digital information system for paleontology and sedimentary geology (https://www.paleostrat.com/); IGSN, International Geo Sample Number; SDDB, The Scientific Drilling Database is the repository for data from operations of ICDP (http://www.icdp-online.org/contenido/lakedb/front_content.php); EarthChem, system to facilitate the preservation, discovery, access, and visualization of geochemical datasets (http://www.earthchem.org/); MagIC, Magnetics Information Consortium (http://www.earthref.org/MAGIC/). A robust and effective data management/geoinformatics system, accessible through a CPCP Data Portal, will facilitate and support the science and provide the basis for education and outreach efforts. This will include coupling the Drilling Information System (DIS) of the ICDP with System for Earth Sample Registration (SESAR; www.geosamples.org), EarthChem (www.earthchem.org), CoreWall (www.evl.uic.edu/cavern/corewall), and PaleoStrat (www.paleostrat.org), a core-core hole-log integration system, and a novel digital framework of regional geology (Fig. 5).

Next Steps

The CPCP workshop endorsed aiming full drilling proposals to ICDP and U.S. National Science Foundation (NSF) Continental Dynamics. In preparation for this, there will be an international CPCP proposal planning workshop in Albuquerque, N.M., to be advertised in the near future.

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ICDP Workshop on Borehole Monitoring at the Nankai Subduction Zone: Building a Land-Ocean Borehole Network to Study the Seismogenic Zone

by Takeshi Sagiya

doi:10.2204/iodp.sd.6.13.2008

Examples of subduction processes are currently investigated around the Kii Peninsula, Honshu Island by Japanese as well as international projects. The most well-known is the NanTroSEIZE project conducted by the Integrated Ocean Drilling Program (IODP). Drilling (riserless) with the drillship *Chikyu* started southeast off the Kii Peninsula in October 2007. In addition, the Japanese government launched a new project called Dense Ocean floor Network System for Earthquakes and Tsunamis (DONET) to install an integrated ocean bottom cable system for continuously monitoring earthquakes and tsunamis between the Kii Peninsula and the NanTroSEIZE drilling site. On land on the Kii Peninsula, an array of shallow boreholes for monitoring changes in groundwater level and strain is being constructed by Japan's National Institute of Advanced Industrial Science and Technology (AIST, Fig. 1). As part of the latter project, the International Continental Scientific Drilling Program (ICDP) organized and funded a workshop to prepare for land-based intermediate depth drilling to install monitoring equipment complementing the AIST and NantroSEIZE projects.

The "ICDP Workshop on Borehole Monitoring at the Nankai Subduction Zone: Building a Land-Ocean Borehole Network to Study the Seismogenic Zone" was conducted on 20–23 August 2007 at Nagoya University. Thirty-five scientists from four countries participated. Eighteen presentations addressed the seismic activity along the Nankai Trough subduction zone, geologic background of the Kii Peninsula, present status of various ongoing projects (NanTroSEIZE, DONET, etc.), and state-of-the-art observatory technologies.

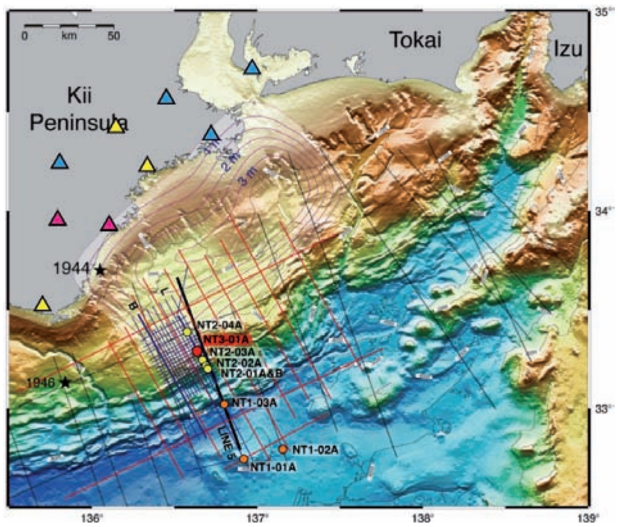

Figure 1. Location map of the Nankai Trough and boreholes in Kii Peninsula. Circles denote drilling sites in the NanTroSEIZE project. Triangles on land denote IST boreholes.

Other key topics included pore pressure measurements and technical aspects of the planned monitoring system and its installation. The discussion of the merits of pore pressure measurement led to the conclusion that such data must be one of the main parameters to be monitored in the Nankai Trough subduction complex. For strain measurements, two options were considered in detail. An integrated monitoring system of the Tono Research Institute of Earthquake Science in Mizunami, Japan, shows high sensitivity and good stability. Alternatively, optical fiber strain meters can be installed outside the borehole casing to allow using the boreholes for other purposes such as repeated downhole logs or permanent measurements inside casing. Another finding was that seismological monitoring and analysis should be included to study non-volcanic deep tremors.

A major part of the workshop was dedicated to preparation of a drilling proposal including discussion of prioritized scientific targets. Considering recent findings like non-volcanic deep low-frequency tremors (e.g. Obara, 2002), slow slip events (e.g. Ozawa et al., 2002), and ultra-slow earthquakes (e.g. Ito et al., 2007), participants agreed that the goal of drilling and monitoring is to resolve the complex behavior of the plate boundary megathrust at the deeper end of the locked zone.

A field trip was made to the Kii Peninsula to visit two geologic sites exhibiting Miocene igneous acidic rocks characterizing the southeastern part of the Kii Peninsula. The integrated borehole groundwater observatory constructed by AIST visited Kumano City (Fig. 2). The observatory was designed to detect precursory ground water level changes before a large megathrust earthquake (there were reports of ground water level change before the 1946 Nankai earthquake) and to investigate various

Figure 2. Field trip to the integrated borehole groundwater observatory of AIST.

plate boundary phenomena with precise observation with strainmeter, tiltmeter, and a seismograph. Finally, Kata village of Owase City, Japan was visited, where tsunami run-up heights were recorded and displayed on a telegraph pole (Fig. 3). The 1944 Tonankai and the 1854 Anse-Tokai earthquakes also shook this area. This display teaches us that the last earthquake in 1944 was a moderate one, and the region may have to prepare for a stronger one similar to the 1854 event.

The whole workshop was very successful in raising the understanding on various ongoing projects, introducing state-of-the-art monitoring techniques to potential project proponents as well as technical problems to be resolved. It also defined the goals and milestones towards a full drilling proposal planned for submission to ICDP by fall 2008.

Figure 3. Display of tsunami heights (in red on pole) in Kata village, Owase City.

Acknowledgements

The author would like to express sincere thanks to ICDP and the Japan Drilling Earth Science Consortium (J-DESC) for their financial support of the workshop.

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Upcoming Workshops

Marine Research Drilling in the Atlantic (Magellan WS Series)

10–12 September 2008, Montpellier, France

Participation on invitation only. Conveners: Marguerite Godard (Université Montpellier 2), Gretchen Früh-Green (ETH Zurich), and Christopher MacLeod (Cardiff University). **Contact: Dr. C. J. MacLeod**, e-mail: macleod@cardiff.ac.uk

Ultra-High Resolution Geological Records of Past Climate Change

29 Sept.–1 Oct. 2008, Potsdam, Germany

See details at: http://www.iodp.org/climate-ws-workshop/

Scientific Drilling of Sediment in Lake Ohrid (SCOPSCO)

13–17 October 2008, Ohrid, Republic of Macedonia

Scientific collaboration on past speciation conditions in Lake Ohrid (SCOPSCO), Republic of Macedonia, will be discussed to prepare drilling of sediments in the oldest lake in Europe. See details at: http://ohrid.icdp-online.org

Arctic Ocean History Workshop

3–5 November 2008, Bremerhaven, Germany
Application Deadline: 24 August 2008

To participate in this workshop, details are given at: www.oceanleadership.org/arctic. Partial travel support is available. Please contact **Bernard Coakley** (bernard.coakley@gi.alaska.edu) or **Ruediger Stein** (rstein@awi-bremerhaven.de) for further information.

Scientific Drilling for Human Origins

17–21 November 2008, Addis Ababa, Ethiopia

Following recent, successful lake drilling projects in Africa with implications for human origins, the time is right to consider new targets for drilling. A highly promising approach to this goal is to target lacustrine sedimentary sequences currently exposed on-land, in sedimentary basins of world-class importance to hominin evolutionary history. See details at: http://www.magadi.icdp-online.org

7th International Symposium for Subsurface Microbiology

Shizuoka, Japan, 16–21 November 2008, Regular Registration: 30 September 2008

The application of molecular approaches to the study of subsurface microbial ecology has been most encouraging in the past decade. As would naturally be expected, the deeper we delve, the more diverse the discoveries. For more detailed information, **contact: Prof. Kenji Kato** (Chair), **Sanami Nishida** (Secretary), e-mail: shizissm@ipc.shizuoka.ac.jp.

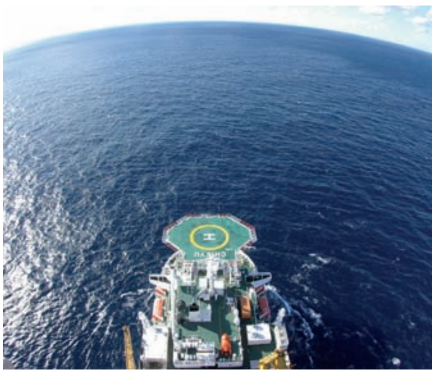
Distinguished Lecturer Program

Application Deadline 30 September 2008

ECORD is sponsoring an initiative for a lecture series to be given by leading scientists involved with the IODP. This program is designed to bring the exciting scientific discoveries of the IODP to the geosciences community. For more information, please contact: ESSAC Office (ECORD Science Support & Advisory Committee); e-mail: essac@cerege.fr, and apply via: http://www.doodle.ch/4nxs78whk6xmedh9.

IODP Conference on Future Scientific Ocean Drilling

The IODP is funded for the period 2003–2013, and is now starting to plan for its renewal beyond 2013. A community-wide, major conference on future directions of scientific ocean drilling is planned for 23–25 September 2009. The meeting location will be the University of Bremen, Germany. Based on this conference and other planning documents including past and future workshops, a science plan that defines new goals and effectively meets the challenges of future ocean drilling will be drafted during 2010. The conference will be open to all scientists with an interest in scientific ocean drilling. More information at http://www.iodp.org.



Chikyu and the boundless ocean view from IODP Exp. 316. Photo courtsey JAMSTEC/IODP.

Internships Available in Scientific Drilling

DOSECC Internships promote student involvement in projects where drilling has provided data and materials for study. Students can undertake research related to ongoing or past drilling efforts. The internships are open to undergraduate or graduate students, and primary and secondary school teachers worldwide. Internship funding will be available in the summer of 2009 and budgets of $2,000 to $5,000 are appropriate. See application details at: http://www.dosecc.org/html/internship.html. **Contact: David Zur**, e-mail: dzur@dosecc.org.

Distinguished Lecture Series

DOSECC's Distinguished Lecture Series makes available geoscientists to give talks or lectures on their areas of expertise. DOSECC covers travel costs for the lecturers, and the host institution is asked to provide food and lodging costs. Lecture themes include:

- Paleoclimate and Human Evolution;
- Global sea-level changes over the past 100 million years;
- Celestial Mechanics, Mass Extinctions, and Giant Volcanic Eruptions;
- 32 Million Years of Astronomical Forcing of Climate from Tropical, Triassic-Jurassic Pangea;
- New insights into African paleoclimate from the Lake Malawi Drilling Project;
- Sublacustrine Paleoseismology: Coring Earthquake Event Horizons in the Great Salt Lake; and
- Terrestrial Impact Cratering: The Earth's Record of Bombardment from Space.

Further details and speaker contact information is available at http://www.dosecc.org/html/distinguished_lectures.html. To apply, **contact: David Zur**, e-mail: dzur@dosecc.org.

ICDP Drilling Training

Geoscientists leading drilling missions need special management skills, but this know-how is often not part of their academc background. Industry helps by providing training, but scientists usually start learning on the job during a drilling project. The Operational Support Group of ICDP offers a comprehensive one-week training course covering key topics of scientific drilling to address this issue. The idea is not only to transfer specific knowledge and expertise but also to demonstrate the dependencies and linkages among different subjects involved, especially between engineering and science. Classes are taught by specialized instructors with practical industrial or academic experience in several basic modules. Content and training level can be customized (deadline for training proposals is 15 January each year), and costs for invited participants are paid by ICDP.

The 2007 ICDP Training was held in Germany at the drill site of the KTB from 5–9 November, attracting 33 scientists from 19 countries. A highlight of the training, in addition to the lectures at the fully equipped field lab and core repository, was an excursion to two drill sites, at a 4.5-km-deep geothermal well and a site where the newly developed scientific drilling facility InnovaRig was located.

ICDP training is usually held in conjunction with an active drilling project to bridge the gap between the classroom and practical applications in the field and to provide training on the job.

The next ICDP training is scheduled for 6–10 October 2008 in Germany. Further information: http://www.icdp-online.org

Contact: Thomas Wöhrl, ICDP, GFZ Potsdam, e-mail: woehrl@gfz-potsdam.de

MSPHDS Professional Development Program

Partnering with the MSPHDS (Minorities Striving and Pursuing Higher Degrees of Success in Earth System Science) Professional Development Program, the Consortium for Ocean Leadership supported four students to attend the IODP Science Steering and Evaluation Panel meeting in Busan, Korea. Mentored by panel members, the students gained an inside look at the proposal process for a large-scale science program and had the opportunity to meet and discuss science issues with international colleagues. One student commented, "The importance of writing succinct proposals with clear and concise objectives was a great lesson learned by observing the meeting." See details at http://oceanleadership.org/diversity/professionals

New Member of IODP:Australia

An agreement between the Australian Research Council and the Lead Agencies of IODP to make Australia an Associate Member of IODP effective 1 January 2008 was in the process of final signing by early July 2008. The Australian membership is intended to be amended by membership of New Zealand within a joint AUS-NZ consortium.

New Members of ICDP: Sweden and Switzerland

The Swedish Deep Drilling Program (SDDP) was initiated in early 2007 to address fundamental issues of the dynamic Earth system including (Palaeo)proterozoic orogens or ore genesis. The SDDP working group is planning a drilling program to attract funding for four world-class deep boreholes over a ten-year period.

Recently, the strongly anticipated financial support for a Swedish ICDP membership has been granted by the Swedish Research Council, greatly supporting the efforts of SDDP. Please visit the SDDP website at http://www.sddp.se for information.

Contact: Henning Lorenz, e-mail: henning.lorenz@geo.uu.se

ICDP Switzerland was initiated during the Swiss ICDP meeting on 1 February 2008 by about fifty scientists. Several are involved in ongoing or planned paleoclimate drilling projects and are discussing projects in Quaternary deep Alpine valleys and the Ivrea Zone. The Swiss National Science Foundation recently assured the Swiss participation for the next five years. **Contact: Flavio Anselmetti**, e-mail: flavio.anselmetti@eawag.ch, and web link: http://www.swiss-drilling.ethz.ch.

Joint EUROFORUM 2008

For the first time, IODP and ICDP held a joint EUROFORUM meeting during the EGU General Assembly in Vienna on 17 April 2008. This afternoon meeting provided eleven talks in a platform to exchange latest research highlights of various drilling projects covering new NanTroSEIZE results, paleoclimate science on various marine and terrestrial archives, as well as deep subsurface life and the planned volcanic risk research at Campi Flegrei.

The EUROFORUM was followed by a Joint Town Hall Meeting for latest program development updates and discussions.

First Joint IODP-ICDP Town Hall Meeting held in Japan

J-DESC sponsored the first joint IODP-ICDP town hall meeting on 27 May, while Japan Geoscience Union Meeting 2008 was also being held in Japan. The town hall event got ~100 scientists and graduate students together to exchange program news and other informaton. This will be an annual event.

The Thrill to Drill in Japanese

The ICDP brochure "The Thrill to Drill" was produced jointly by ICDP and J-DESC Japan in 2006 in English, and now its Japanese version is available from J-DESC or can be downloaded from www.j-desc.org.

Deep Earth Academy's Sea90E Poster and Web Site

Deep Earth Academy's poster and Web site won a 2008 Distinguished Achievement Award from the Association of Educational Publishers in the category of curriculum for teaching science for grades for six to eight, and more information at http://www.aepweb.org/awards/curricwin.htm. It features a bathymetry map, scientist profiles, student Q&As, and science challenges. See poster at http://www.oceanleadership.org/learning/materials/posters/sea90poster.

Aurora Borealis: A European Project

The European Commission identified developing of the icebreaker *Aurora Borelis* for the highest scientific priority. A European Research Icebreaker Consortium (ERICON) of 15 institutions, funding agencies and companies from 10 European nations, including Russia, has been formed to develop management structures for this unique facility and to implement it into the European Research Area. The Alfred Wegener Institute for Polar and Marine Research coordinates the final engineering work for the development with funds from the German Federal Ministry for Science and Education. In December 2007, SCHIFFKO GmbH was awarded a design contract for the initial design concept (Fig.1), general arrangement planning, and full tender documentation. Currently the ice-tank and open water tests are being carried out. The new technical details include:

- 55 MW, twin hull icebreaker
- 201 m length, 49 m width
- 15 kn max. speed
- dynamic positioning, two moon pools
- riserless drilling, in max. 5000 m water for 1000 m core

Contact: Dr. Nicole Biebow, AWI, 27568 Bremerhaven, Germany, e-mail: nicole.biebow@awi.de, web link at : www.eri-aurora-borealis.eu.

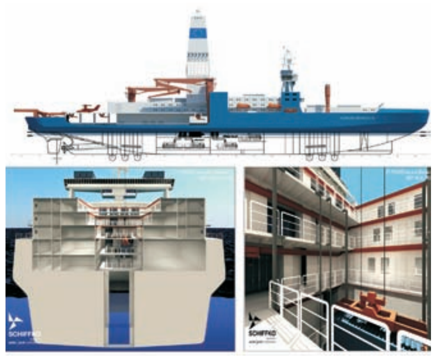


Figure 1. Side view of the *Aurora Borelis*, detailed cross sections.

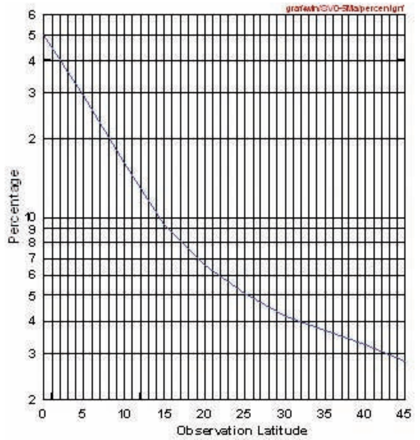
D/V Chikyu Undergoes Repairs

Damage to the azimuth thruster gears on the *D/V Chikyu* was discovered during a dry-dock survey in the late spring of 2008. Fabrication and reassembly of six new gears are expected to be completed by January 2009, after which NanTroSEIZE drilling operations will resume (see back cover for schedule).

Comment: Magnetization of the Oceanic Crust

C. Harrison

In the March 2007 issue of *Scientific Drilling* there is a report of the "Mission Moho" meeting. Mission Moho is being proposed to the Integrated Ocean Drilling Program to investigate the formation and evolution of oceanic lithosphere. Deep drilling has been one of the main objectives of the drilling program ever since the first phase (Deep Sea Drilling Project) started in 1968. Shortly afterwards, a committee was formed to look at scientific objectives of deeper penetration into the oceanic crust. Part of the rationale for deeper penetration was to understand how the oceanic crust is magnetized and how this magnetization contributes to the formation of sea floor spreading magnetic anomalies. More recently the COMPLEX Meeting (May 1999, Vancouver, Canada http://www.odplegacy.org/PDF/Admin/Long_Range/COMPLEX.pdf) had a section on "How do marine magnetic anomalies relate to crustal architecture, cooling, and alteration". It is pointed out that "To fully understand the depth distribution of magnetization requires drilling of an intact crustal section". The CONCORD report (July 1997: Tokyo, Japan, http://www.odplegacy.org/PDF/Admin/Long_Range/CONCORD.pdf) on Ocean Riser Drilling posed the question "What role do the lower crust and upper mantle play in the origin of marine magnetic anomalies?" The Initial Science Plan (http://www.odplegacy.org/PDF/Admin/Long_Range/IODP_ISP.pdf) for IODP "Initiative: 21st Century Mohole" states that "…the source of marine magnetic anomalies will be much better understood when a complete section of the lower oceanic crust is available for analysis". These suggestions seem to have been forgotten by the "Mission Moho" group. The only place that crustal magnetization is discussed is in one phrase: "better understand the origin of magnetic anomalies". No mention was made of the desirability of drilling at higher latitudes in order to unscramble the magnetic signal. The main site for drilling lies at 6.5°N (but was probably formed closer to the equator). I have recently compiled a data set of paleomagnetic observations over the past 5 Ma in which Virtual Geomagnetic Poles from all latitudes were used. From this data set it is possible to determine, as a function of observation latitude, how frequently a field direction with positive inclination occurs when the core field is reversed (see figure).



For a recording latitude of 6.5° fully 25% of the samples of positive inclination will have been produced by the secular variation during a time that the main field is of reversed polarity. Inclination is the only way of determining a sample's magnetic polarity in the absence of horizontal orientation, and an error rate of 25% renders the data relatively useless. It will be very difficult to unscramble the magnetization values gathered at such a place so as to be able to determine the external magnetic signature of the crustal rocks. Even at a recording latitude of 25° the probability is still 5% of confusing reversed with normal polarity. The IODP scientific advice structure should give serious consideration to choosing drilling sites at higher latitudes, preferably greater than 25°. Alternatively, they should ensure that a proven method of horizontal orientation of cores is available by the time "Mission Moho" starts.

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e-mail: charrison@rsmas.maiami.edu

Response to: Magnetization of the Oceanic Crust

B. Ildefonse, et al.

We fully share Dr Harrison's concerns about the difficulty in deciphering the magnetic signal at low latitudes, such as the location of ODP/IODP Site 1256D , and we thank him for bringing everyone's attention to the critical need for a method to provide azimuthal orientation. Although this topic was not discussed in the workshop report published in the March 2007 issue of *Scientific Drilling*, it was extensively discussed at the Mission Moho Workshop. We would like to take this opportunity to emphasize the following points, which were also articulated in the Mission Moho proposal that was submitted to IODP in April 2007 :

- Although Site 1256D is the site for current deep drilling in the upper crust, it will not necessarily be the deep crustal, MoHole site. The latter has yet to be chosen. Site selection for deep drilling in the fast-spread ocean crust faces a few major trade-offs, dominated by water depth vs temperature at Moho, and also magnetic geometry vs weather window. Sites under consideration near San Diego and near Valparaiso would satisfy Dr Harrison's concerns.

- Site 1256D, the "6.5 °N main site" mentioned by Dr Harrison is favored for the near future for reasons including gaining engineering experience in deep gabbro holes and for better predicting the thermal structure, which will be useful even if we eventually choose a site at a higher latitude.

- We cannot emphasize enough the importance, for the future of scientific drilling in the ocean crust, to be able to reorient cores in a geographic reference frame. A Hard Rock Core Orientation (HRCO) system would be the ideal solution, and further development and implementation requires community support.

- Measuring the downhole magnetic field with logging tools does meet some of the objectives that Dr Harrison suggests in choosing a site far from the equator. Remanent magnetic data from samples collected over nearly 40 years of drilling still do not provide an unambiguous solution to the dominant source for lineated magnetic anomalies. This is partly related to the prominent effect of drilling induced remanence, and every effort to reduce this effect should be encouraged. While much can be learned from the magnetization of drillcore samples, detailed magnetic logging is arguably the best way to establish the relative contributions of the various parts of the crust to the magnetic anomalies. A reliable gyro-oriented tool should be designed, developed, and regularly used in IODP to achieve this goal.

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Schedules

IODP – Expedition Schedule http://www.iodp.org/expeditions/

	ESO Operations *	Platform	Dates	Port of Origin
1	313 - New Jersey Shallow Shelf	MSP	May '09–Aug. '09	TBD
2	Great Barrier Reef	MSP	Sep. '09–Nov. '09	
	USIO Operations **	**Platform**	**Dates**	**Port of Origin**
3	317 - Canterbury Basin	*JOIDES Resolution*	12 Nov. '08–04 Jan. '09	Wellington, New Zealand
4	318 - Wilkes Land	*JOIDES Resolution*	04 Jan. '09–09 Mar. '09	Wellington, New Zealand
5	320 - Pacific Equatorial Age Transect (PEAT)	*JOIDES Resolution*	09 Mar. '09–09 May '09	Wellington, New Zealand
5	321 - PEAT/ Juan de Fuca Remedial Cementing	*JOIDES Resolution*	09 May '09–09 Jul. '09	Honolulu, Hawaii, U.S.A.
	CDEX Operations ***	**Platform**	**Dates**	**Port of Origin**
6	319 - NanTroSEIZE — Kumano Basin Riser	*Chikyu*	Mar '09 – mid Jun. '09	TBD
6	NanTroSEIZE — Sediment Inputs	*Chikyu*	Mid Jun. '09 – late Jul. '09	
6	NanTroSEIZE — Riserless Observatory Casing	*Chikyu*	Late Jul. '09 – Aug. '09	

MSP = Mission Specific Platform TBD = to be determined
* Dates subject to change pending final platform tenders.
** Dates of expeditions subject to change pending final delivery of vessel from shipyard.
*** CDEX schedule subject to final program approval.

ICDP – Project Schedule http://www.icdp-online.org/projects/

	ICDP Projects	Drilling Dates	Location
1	Iceland Deep Drilling Project	Jun. '08–'10	Krafla, Iceland
2	Lake El'gygytgyn Drilling Project	Apr. '08–May '10	Chukotka, Russia
3	PASADO (Lake Potrok Aike)	Sep. to Oct. '08	Patagonia, Argentina
4	New Jersey **	May to Jul. '09	Offshore New Jersey, U.S.A.
5	Lake Van	Summer 2009	Anatolia, Turkey

**IODP-ICDP joint project

All dates are approximate. Schedules are subject to approval.