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Scientific Drilling

Reports on Deep Earth Sampling and Monitoring

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Editorial Preface

Dear Reader:

Earth in Motion is one of the four main topics of the new science plan for scientific ocean drilling 2013–2023 (see p. 55). Shortly before the plan's completion, a mega-earthquake and related tsunami hit eastern Japan on 11 March 2011. The effects were devastating to infrastructure and the Japanese people, and the event calls for increased efforts to understand the mechanisms and potential locations and magnitudes of such geohazards. Sampling seismogenic faults and installing observatories in boreholes in their vicinity is therefore a long-term and high priority for scientific ocean drilling. IODP is also preparing a rapid effort (see p. 61) to get a glimpse of the ephemeral properties at the east Japan earthquake fault zone as close as possible to conditions during rupture.

Other research topics of high societal importance include how climate and environment have changed over time and under conditions that vastly differ from those of the present time. These issues offer two unique research perspectives on climate history with the high latitude expedition to investigate Antarctic glaciation (p. 15) and the expedition to study environmental change through coring already fossilized coral from the Great Barrier Reef (p. 32). IODP research provides access to sampling of marine sediments that record ocean and climate change reaching back 100 million years or more, and it allows present-day climate change to be seen in a geologically significant context. Scientists are realizing that the high rate of anthropogenic forcing of some fundamental climate regulating factors, such as the amount of carbon and other greenhouse gases in the atmosphere, could push the 'climate clock' millions to tens of millions of years back to times of radically different climate. The new IODP science plan therefore seeks to provide long-term records of the past that will augment predictive modeling of the climate for future generations. It also targets to improvements in the public's understanding of Earth's dynamic climate and ocean system by reaching out to both the public and new generations of scientists about vital research findings made possible only by scientific ocean drilling.

The discovery during past scientific drilling of living microbes deep below the seafloor, and in environments that fundamentally differ from those of surface life fueled by photosynthesis, is still in an exploratory stage of trying to understand the distribution, genomics, metabolic processes, and, if possible, greater implications for possible life in the universe. All of these critical scientific questions will be examined on the basis of the fundamental planetary dynamics that form the integrated framework for understanding our planet. One highly ambitious goal in this regard is to finally penetrate the entire ocean crust and reach into Earth's mantle. To achieve this once elusive goal, IODP has started to assess its technological feasibility (p.46).

The new IODP 2013–2023 will continue to partner with other research programs, not the least being the International Scientific Continental Program. In this volume ICDP reports on geohazards including anthropogenic earthquakes (see p. 53) and natural arsenic water contamination (see p. 49) that will be addressed by future continental drilling projects, proving that both scientific drilling programs are solidly connected to the problems facing global society, now and in the future.

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Front cover: Enjoying the sun while it lasts during the IODP Expedition 318. (Photo: John Beck, IODP-TAMU)
Left inset: Labels placed on core pieces to identify samples from the IODP Expedition 324. (Photo: John Beck, IODP-TAMU)

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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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IODP Expedition 317: Exploring the Record of Sea-Level Change Off New Zealand

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Abstract

Expedition 317 investigated the record of global sea-level change (eustasy) within continental margin sedimentary sequences and how eustasy interacts with local forcing to produce preserved sedimentary architectures. The Canterbury Basin, on the eastern margin of the South Island of New Zealand, was selected to study these complex interactions because of high rates of Neogene sediment supply from the uplifting Southern Alps. This sediment input results in a high-frequency (~0.1–0.5 My periods) record of depositional cyclicity that is modulated by the presence of strong ocean currents. The expedition recovered sediments as old as Eocene but focused on the sequence stratigraphy of the late Miocene to Recent, when global sea-level change was dominated by glacioeustasy. A transect of three sites was drilled on the continental shelf (Sites U1353, U1354, and U1351), plus one on the continental slope (Site U1352). The transect samples the shallow-water environment most directly affected by relative sea-level change. Lithologic boundaries, provisionally correlative with seismic sequence boundaries, have been identified in cores from each site. Continental slope Site U1352 provides a record of ocean circulation and fronts during the last ~35 My. The early Oligocene (~30 Ma) Marshall Paraconformity was the deepest target of Expedition 317 and is hypothesized to represent intensified current erosion or non-deposition associated with the initiation of thermohaline circulation in the region. Expedition 317 involved operational challenges for *JOIDES Resolution*, including shallow-water, continental-shelf drilling and deep penetrations. Despite these challenges, Expedition 317 set a number of records for scientific ocean drilling penetration and water-depth.

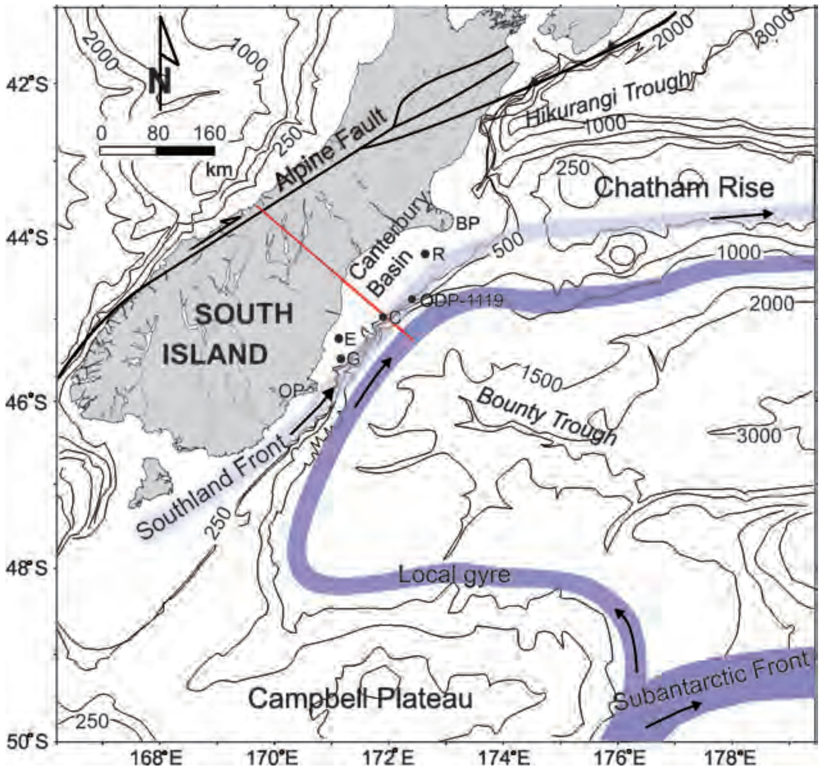

Figure 1. The Canterbury Basin underlies the present-day onshore Canterbury Plains and offshore continental shelf. It is bounded by the Miocene volcanic centers of the Banks Peninsula (BP) to the northeast and the Otago Peninsula (OP) to the southwest, and faces the Bounty Trough to the southeast. The Alpine Fault is the boundary between the Australasian and Pacific plates. Locations of the modern Southland Front and Subantarctic Front, together with local gyre within the Bounty Trough, are shown (Chiswell, 1996; Shipboard Scientific Party, 1999; Morris et al., 2001). Also shown are exploration wells in the offshore basin (Resolution, R; Clipper, C; Endeavour, E; and Galleon, G) as well as ODP Site 1119. The red line marks the approximate location of the schematic cross-section in Fig. 3. Bathymetric contours are in meters.

Introduction and Goals

In order to evaluate predictions of future changes in global sea level and shoreline location, it is vital to constrain the range of past variability. Throughout the "Icehouse" period of the last ~30–40 million years, the changing volume of continental ice has been the principal driver of high-amplitude and high-frequency (~1 My and less) global sea-level change (eustasy). The last ~1 million years have been dominated by ~100,000-year glacial/interglacial cycles, and the sea-level rise since the last glacial maximum provides particularly valuable constraints on potential future rates of rise. However, earlier periods—notably the early Pliocene (~5.3–3.0 Ma) when CO_2 levels were similar to today's, but temperatures were ~3°C warmer and sea level ~25 m higher—provide glimpses of the possible future state of the Earth system. In addition, the geological record shows that climate and sea level do not always respond linearly to forcing and that abrupt events can disrupt gradual trends. If we are to develop reliable predictions of future climate and sea levels, we must look to the geologic record to ensure that the models on which we base forecasts can also reproduce the past.

Continental margin sediments retain long records of global sea-level change. This stratigraphic record comprises stacked sedimentary units (sequences) separated by unconformities. Sequence stratigraphy highlights the cyclic nature of the continental margin record (Mitchum et al., 1977; Vail et al., 1991) and has led to the theory of eustatic control of sequences and the resultant eustatic cycle chart (Haq et al., 1987). However, basin subsidence, changes in the rate of sediment supply, and other local processes can superimpose their signatures on this record. Therefore, the application of sequence stratigraphy to sea-level studies has been contentious, largely because of uncertainty surrounding the complex interaction of global and local processes (Carter, 1985; Karner, 1986; Carter et al., 1991; Christie-Blick, 1991; Miall and Miall, 2001). Understanding how these processes interact to form preserved stratigraphy is a fundamental problem in sedimentary geology. Its solution will yield both a record of eustatic change and a greatly enhanced ability to read the record, covering many tens of millions of years of Earth history, beneath the world's continental shelves.

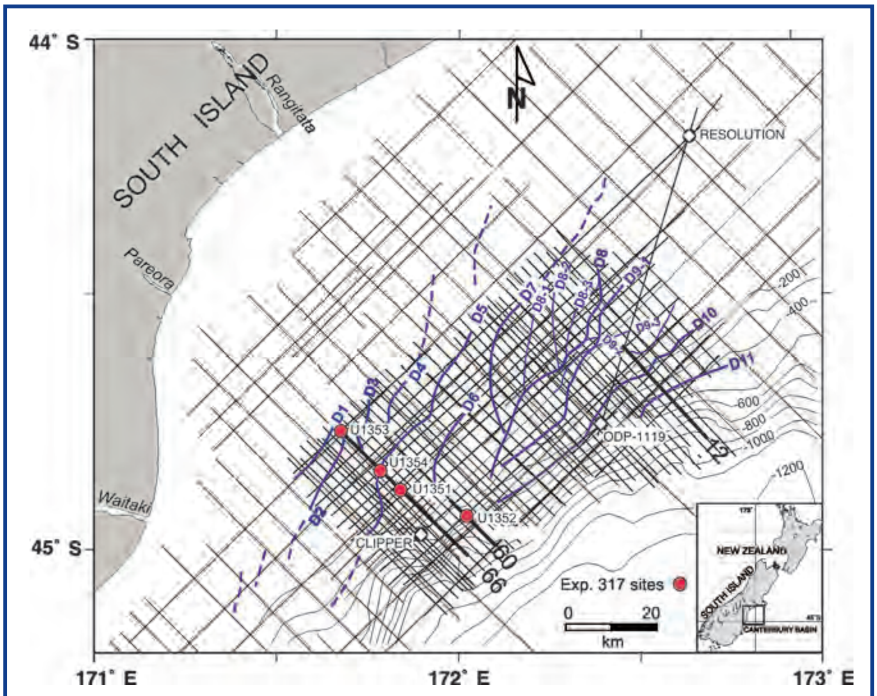

Figure 2. Expedition 317 sites (red), together with EW00-01 high-resolution (frequencies up to 300 Hz) seismic survey grid (dense grid of black straight lines), low-resolution CB-82 commercial seismic profiles (gray straight lines), exploration wells Clipper and Resolution, and ODP Site 1119. The EW00-01 survey was designed to provide improved vertical resolution (~5 m in the upper 1 s) to enhance definition of high-frequency sedimentary sequences. Also shown is the distribution of seismically resolvable sediment drifts (D1 to D11; blue curved lines mark crests of the drift mounds). Dashed blue lines represent drifts identified on CB-82 profiles. Locations of dip profiles shown in Figs. 4, 5, 6 (profiles 12, 66, and 60, respectively) are shown as thicker black lines. Bathymetric contours are in meters.

Scientific ocean drilling of globally coordinated borehole transects across continental margins provides the best way to distinguish local effects and extract the sea-level signal. Such drilling targets the geological environment directly affected by sea-level change as the shoreline migrates back and forth across the continental shelf. Coring the resulting sequence stratigraphic record provides information on ages, depositional environment, and past water depths during sea-level cycles from coastal plain to continental slope settings. Since boreholes provide information at only a few locations, integration with seismic imaging is crucial. Such integration performs three vital functions: 1) placing drilling results within a two- and three-dimensional context, 2) constraining the influence on sequence architecture of along-margin changes in sediment input and basin morphology, and 3) providing paleogeomorphological constraints on sedimentary processes and paleoenvironments.

Expedition 317 applied this approach in the offshore Canterbury Basin, on the eastern margin of the South Island of New Zealand (Figs. 1–3), where high rates of Neogene sediment supply preserved a high-frequency (0.1–0.5 My periods) seismically resolvable record of depositional cyclicity (Fulthorpe et al., 2011). The transect strategy was first applied and has been most thoroughly tested on the New Jersey Mid-Atlantic Transect (MAT) by ODP Legs 150, 150X, 174A, and 174AX. Most recently, IODP Expedition 313 used a mission-specific platform to drill on the New Jersey continental shelf (Mountain et al., 2010). Prior to Expedition 317, only ODP Leg 174A (Austin et al., 1998) had employed the *JOIDES Resolution* to drill shelf sites for sequence stratigraphic and sea-level objectives. Expedition 317, therefore, provided a rare opportunity to investigate the facies, paleoenvironments, and depositional processes associated with the sequence stratigraphic model on a prograding continental margin where large-scale depositional geometries and sequence architectures are well constrained by seismic data. Canterbury Basin complements MAT because the Middle Miocene to Recent Canterbury sequences are mainly younger than those calibrated so far on the New Jersey margin (Fig. 4). Furthermore, in line with the global approach to sea-level change advocated by previous planning groups, the Canterbury Basin allows expanded study of complex processes of sequence formation because of the following two reasons.

1) The stratigraphy records the development of the Antarctic Circumpolar Current and related southern oceanographic fronts (Fig. 1). Currents have strongly

influenced deposition, modifying sequence architecture and locally leading to the deposition of large sediment drifts, which aggraded to near shelf depths, within the prograding Neogene section.

2) Rifting is younger (Cretaceous) than the New Jersey margin (Jurassic), and from the earliest Miocene copious terrigenous sediment was supplied from a rapidly uplifting, nearby mountain range (the Southern Alps). Regional tectonic and geological histories have been intensively studied, allowing evaluation of the influence of sediment supply on sequence formation and of the tectonic evolution of the Alpine Fault plate boundary.

The principal scientific objective of Expedition 317 was to date clinoformal seismic sequence boundaries and sample associated facies to provide information (e.g., paleo-water depths, porosities) necessary for estimation of eustatic amplitudes using backstripping. A proper test of sequence stratigraphy necessitates drilling in shallow water (~100 m or less) on continental shelves. A related objective was to understand the interplay of along-strike and downslope sedimentary processes on this strongly current-influenced margin. Accordingly, our deepest drilling target was the Marshall Paraconformity, a regional unconformity thought to represent the mid-Oligocene initiation of ocean circulation on this margin. The final objective was to expand our knowledge of the erosion history of the Southern Alps using provenance studies and offshore sediment accumulation rates.

The Canterbury Basin is part of the Eastern New Zealand Oceanic Sedimentary System (ENZOSS; Carter et al., 1996). The distal (up to 4460 m water depth) component of ENZOSS was targeted by ODP Leg 181, which focused on drift development in the Southwest Pacific Gateway, principally under the influence of the evolving Antarctic Circumpolar Current and the Deep Western Boundary Current (Shipboard Scientific Party, 1999). Expedition 317 complements Leg 181 drilling by focusing on the landward part of ENZOSS.

Geological Setting

The eastern margin of the South Island of New Zealand is part of a continental fragment, the New Zealand Plateau, that rifted from Antarctica beginning at ~80 Ma (Anomaly 33). The Canterbury Basin lies at the landward edge of the rifted continental fragment and underlies the present-day onshore Canterbury Plains and offshore continental shelf (Fig. 1; Field and Browne, 1989). The plate tectonic history of the New Zealand Plateau is recorded in the stratigraphy of the South Island. The post-rift, Cretaceous to Recent sedimentary history of the Canterbury Basin comprises a first-order (80 My), tectonically-controlled, transgressive-regressive cycle (Fig. 3; Carter and Norris, 1976; Field and Browne, 1989).

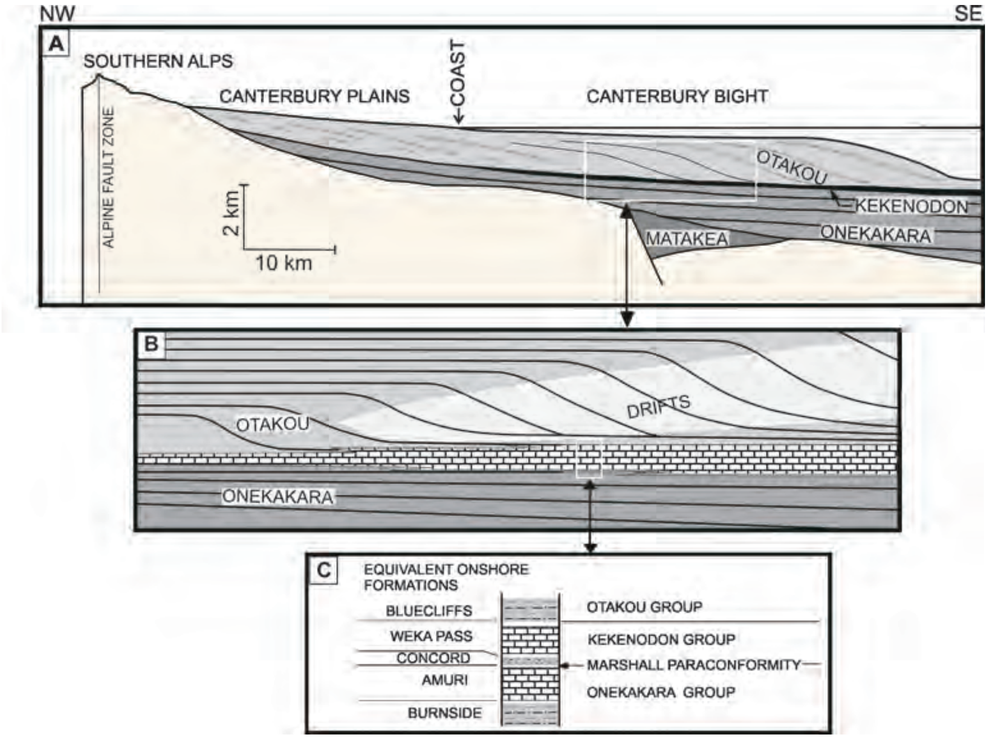

Figure 3. Schematic stratigraphy of the Canterbury Basin at three different scales. [A] Large-scale, post-rift stratigraphy (see profile location in Fig. 1). Onekakara, Kekenodon, and Otakou groups were deposited during regional transgressive, highstand, and regressive phases, respectively. [B] Seismic-scale stratigraphy. Sediment drifts occur within the Otakou Group. [C] Outcrop-scale stratigraphy across the Marshall Paraconformity. Modified from Fulthorpe et al. (1996).

The post-rift transgressive phase terminated during the late Eocene, when flooding of the land mass was at a maximum (Fleming, 1962). Reduced terrigenous influx resulted in deposition of regionally widespread pelagic limestone (Amuri Limestone), which ranges in age up to early Oligocene (~33 Ma). The sequence is then interrupted by the Marshall Paraconformity (Fig. 3; Carter and Landis, 1972). The paraconformity is recognized at drill sites throughout the region east of the Tasmanian gateway and is hypothesized to represent the initiation of thermohaline circulation upon opening of the seaway between Antarctica and Australia (~33.7 Ma; Carter et al., 2004). New Zealand lay directly in the path of the developing current system. Regression commenced in the late Oligocene or early Miocene in response to an increase in sediment supply provided by the initiation of Alpine Fault movement (Carter and Norris, 1976; Kamp, 1987). The Alpine Fault formed as a dextral transpressive zone with 500-km lateral displacement since the earliest Miocene (~23 Ma; Wellman, 1971; Kamp, 1987; King, 2000). The sediment influx following fault initiation is distinct from the later pulse related to uplift that culminated in the present-day Southern Alps. Uplift of the Southern Alps accelerated at ~8–5 Ma (Tippett and Kamp, 1993a; Batt et al., 2000) or ~10–8 Ma (Carter and Norris, 1976; Norris et al., 1978; Adams, 1979; Tippett and Kamp, 1993b), indicating an increased component of convergence along the fault and leading to further increase in the rate of sediment supply to the offshore Canterbury Basin (Lu et al., 2005).

This sediment influx was deposited as prograding clinoforms (Otakou Group; Fig. 3). However, currents continued to influence deposition. At present, the core of the northward-flowing Southland Current, inboard of the Southland Front (part of the Subtropical Front; STF) is over the ~300-m isobath (Chiswell, 1996). In deeper water, to at least 900 m, a local gyre of the Antarctic Circumpolar Current circulates clockwise within the head of Bounty Trough parallel to the Southland Current (Fig. 1; Morris et al., 2001). Large sediment drifts within the prograding section (Fig. 5) show that similar currents, probably strengthened during glacial periods, existed throughout much of the Neogene (Fulthorpe and Carter, 1991; Lu et al., 2003; Carter et al., 2004).

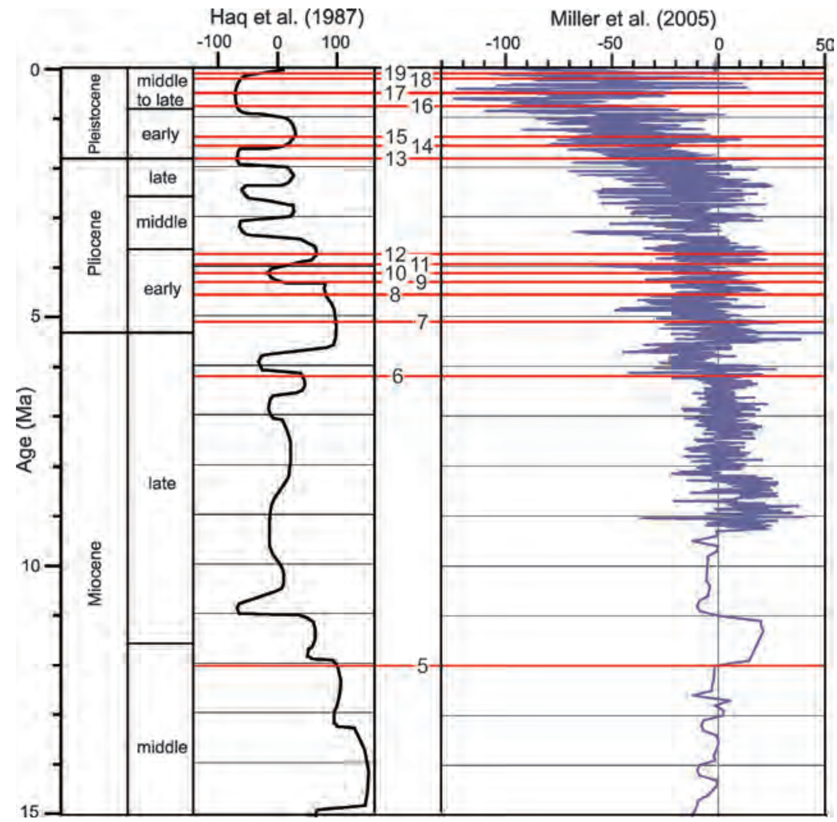

Figure 4. Global sea-level curves of Haq et al. (1987) and Miller et al. (2005) from the middle Miocene to Recent. Unconformities U5 to U19 are labeled and shown as red lines (shipboard ages are approximate). Note that much of the upper part of the Pliocene section is missing at Expedition 317 sites and a 5-My hiatus occurs in the upper Miocene, accounting for the large time gaps between some unconformities. Prior to 9 Ma, the Miller et al. (2005) curve is derived from backstripping of New Jersey MAT sites. However, the record since 9 Ma is a benthic foraminiferal $\delta^{18}O$ record, calibrated to represent eustasy, because the MAT record there is incomplete.

Drilling and Coring

Expedition 317 cored upper Miocene to Recent sedimentary sequences in a transect of three sites on the continental shelf (landward to basinward: Sites U1353, U1354, and U1351) and one on the continental slope (Site U1352; Fulthorpe et al., 2011). A transect of sites is required because of the need to drill each of the multiple target sequences in at least two locations: 1) landward of clinoform breaks or rollovers, presumed to represent paleo-shelf edges, where paleo-depth indicators are most reliable; and 2) drilling on the slope where increased abundance of pelagic microfossils provides the best age control.

Favorable weather conditions on arrival allowed us to follow the planned drilling strategy by drilling first at shelf Site U1351 at the deep-water end (121 m) of the shelf transect (Figs. 2, 6). This provided experience in shelf sediment drilling before moving to sites in even shallower water. The ship then moved ~15 km to slope site U1352, designed to provide age control for sequences drilled at site U1351 (Figs. 2, 7). An additional target at Site U1352 was penetration and recovery of the Marshall Paraconformity. On completion of slope drilling, the ship moved back to the shelf to drill the two additional shelf sites U1353 and U1354 (Fig. 6) to provide spatial control of facies within sequences and to recover the lowermost unconformities landward of their rollovers.

Because of the requirements to drill in shallow water and to achieve deep penetrations, a number of scientific ocean drilling records were set.

- Deepest hole drilled in a single expedition (Hole U1352C; 1927 m), also the second deepest hole in DSDP/ODP/IODP history
- Deepest hole drilled by *JOIDES Resolution* on the continental shelf (Hole 1351B; 1030 m) and also the second deepest (Hole 1353B; 614 m)

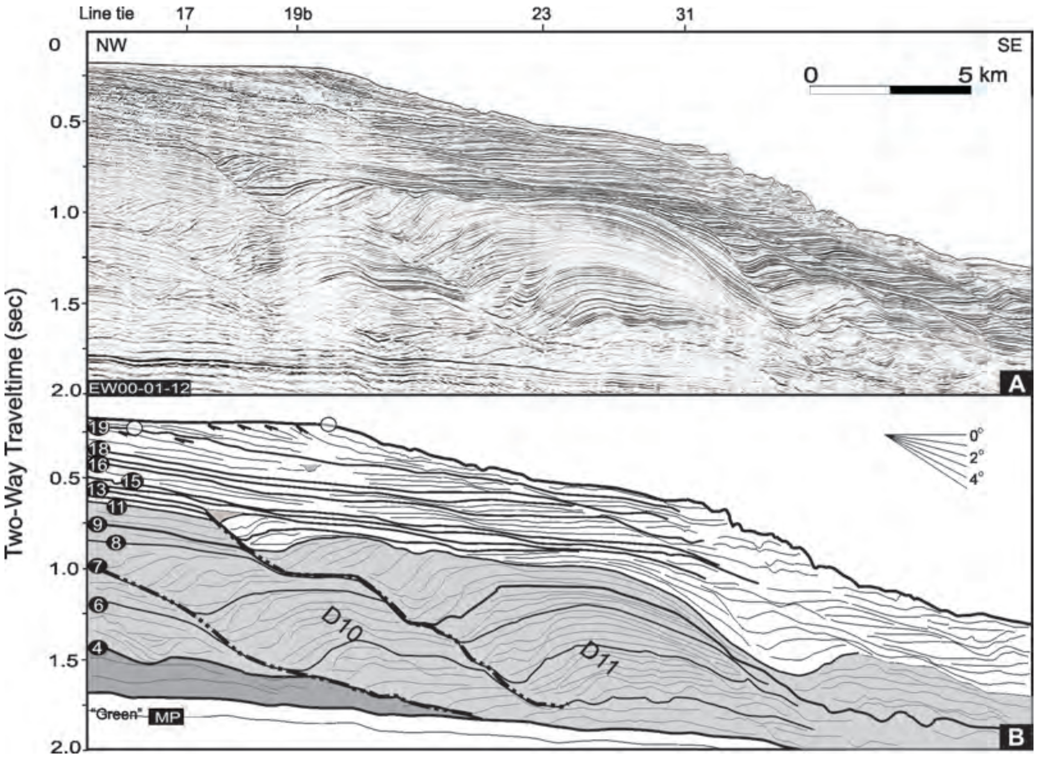

Figure 5. [A] Uninterpreted dip profile EW00-01-12 across the slope in the northern part of the survey grid showing mounded sediment drifts with adjacent (landward) moats (see Fig. 2 for location). [B] Interpretation showing sequence boundaries and selected locations of reflection truncation (arrows). Drifts D10 and D11 are the last of the succession of large elongate drifts of the Canterbury Basin (Fig. 2). Drifts migrate northwestward (landward) on dip profiles. Erosional unconformities at the landward edges of drift moats are diachronous, and they are intersected by multiple sequence boundaries. The underlying Marshall Paraconformity (MP) is also shown.

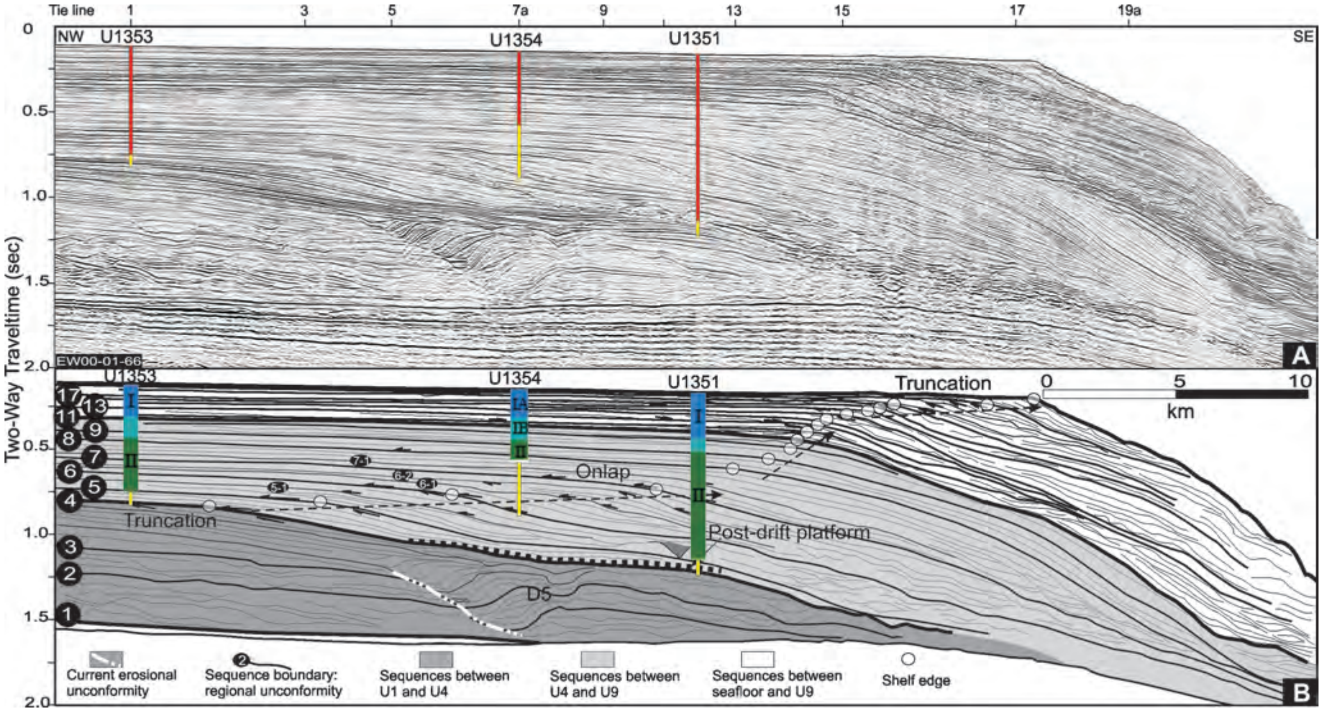

Figure 6. [A] Uninterpreted MCS dip profile EW00-01-66 from the southern part of the survey grid showing locations of sites U1351, U1353, and U1354. Actual penetrations shown in red, proposed penetrations in yellow (see Fig. 2 for location). [B] Interpretation showing sequence boundaries and selected locations of onlap, truncation, and downlap (arrows). Lithostratigraphic units defined at shelf Sites U1353, U1354, and U1351 are also shown. Clinoform rollovers, or breaks, representing paleoshelf edges, are marked by circles. Paleoshelf edges from U4 to U8 prograde steadily. The amount of progradation decreases from U8 to U12, increasing again from U13 to U19. U4–U10 are onlapped and truncate underlying reflections; internal reflection geometries from U4 to U10 are mainly sigmoidal. In contrast, U11–U19 are downlapped on paleoshelves, but also truncate underlying reflections, and internal reflection geometries from U11 to seafloor are oblique. Site U1351 sampled paleoslopes of U6–U7 and sampled U8–U19 landward of their paleoshelf edges. Sites U1353 and U1354 sampled sequence boundaries from U5 to U18 landward of their paleoshelf edges in more proximal settings. Sediment drift development in this area had largely ceased by U4; only drift D5 is present. Prograding clinoforms dominate later sequences.

- Shallowest water depth for a site drilled by *JOIDES Resolution* for scientific purposes (Site U1353, 84.7 m water depth)

- Deepest sample taken by scientific ocean drilling for microbiological studies (1925 m at Site U1352)

Sequence Stratigraphy and Sea-Level Change

Seismic sequence boundaries provide the large-scale understanding of subsurface architecture necessary for placing drilling results within a broader two- and three-dimensional context. The seismic stratigraphy of the Canterbury Basin was developed using high-resolution (~5-m vertical resolution for two-way traveltimes <1 second) multichannel seismic (MCS) profile collected by R/V *Maurice Ewing* in 2000 (EW00-01 profiles; Figs. 2, 5, 6, 7). These were augmented by commercial MCS data collected in 1982 (Fig. 2; CB-82 profiles).

Nineteen regional seismic sequence boundaries (U1–U19) are identified in the middle Miocene to Recent shelf-slope sediment prism (Fig. 4; Lu and Fulthorpe, 2004). Expedition 317 provides ground truth for sequences above U5. Two larger seismic units are defined, based on seismic architecture and facies, within the cored interval (Fig. 6).

1. U5–U10 feature rounded shelf-slope rollovers. Internal reflection geometries are predominantly sigmoid, and paleoshelves are smooth and defined by onlap and truncation.

2. U11-U19 are downlapped on paleoshelves. They truncate underlying reflections near paleoshelf edges, which tend to be angular. Internal reflection geometries are oblique and U- and V-shaped channels that incise paleoshelves indicate exposure during sea-level lowstands.

The influence of sea-level change is illustrated at several scales. At the largest scale, the boundaries between Lithostratigraphic Units I and II at shelf sites separate overlying heterolithic facies of Unit I from more uniform facies below in Unit II (Figs. 6, 7). Unit I contains a wide variety of facies and many green marl or calcareous beds with sharp (or bioturbated) bases. On the shelf, the more homogeneous Unit II is dominated by mud or muddy sand, with lower percentages of carbonate components and less frequent greenish calcareous beds, whereas on the slope this unit is represented by homogeneous sandy marlstone.

The location of the unit boundary is difficult to identify precisely because the transition between units is gradational and also because of low recovery near some unit boundaries. However, the Unit I to Unit II boundary generally conforms to the interval around the predicted depths of seismic sequence boundaries U10 to U12 (late Pliocene), in a zone where high-amplitude seismic reflections related to clinoforms with angular shelf-slope rollovers transition downward to clinoforms with rounded rollovers (Fig. 6). The lithological contrast between Units I and II and the contrasting characteristics of sequence boundaries and seismic facies above and below ~U10 are inferred to occur because paleoshelves of U10 and underlying sequence boundaries were not subaerially exposed at lowstand, whereas those above U10, were exposed, probably because of increasing eustatic amplitudes during the Pleistocene.

At a finer scale, correlation of specific lithological features with seismic sequence boundaries is also possible. Erosion surfaces with associated overlying sediment facies were

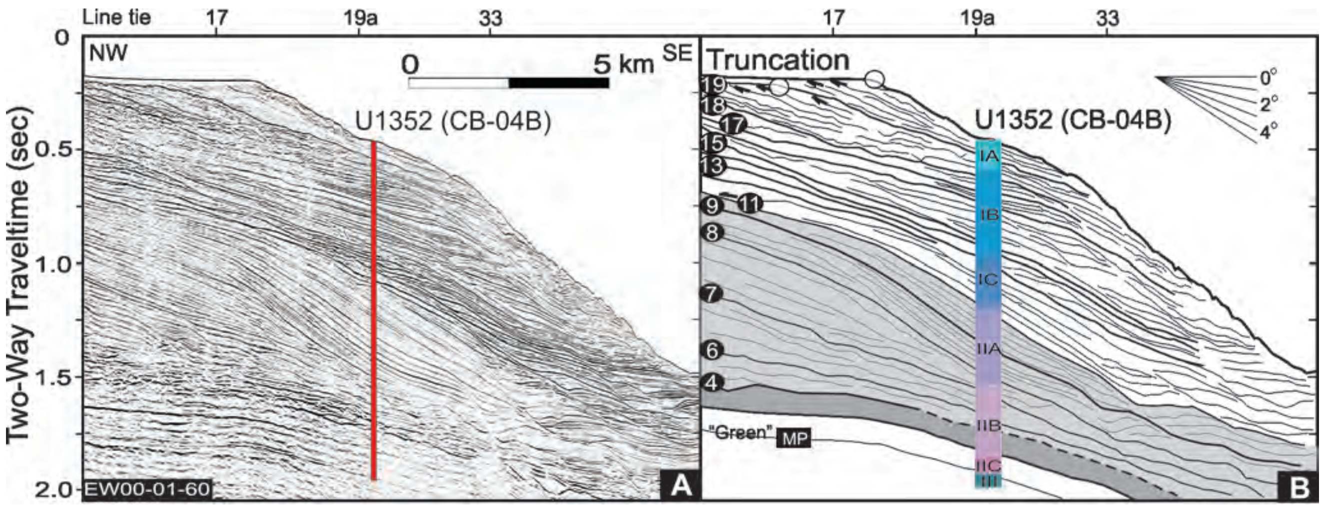

Figure 7. [A] Uninterpreted dip profile EW00-01-60 across the slope in the southern part of the survey grid showing location of Site U1352 (see Fig. 2 for location). [B] Interpretation showing sequence boundaries and selected locations of reflection truncation (arrows). Lithostratigraphic units are also shown. Site U1352 sampled slope facies of sequences, particularly important for age control, as well as the underlying Marshall Paraconformity (MP).

identified near the predicted depths of seismic sequence boundaries at all sites (Fig. 8). Identification is based on changes in lithologic composition, presence of transported sediments, and the nature of the contacts. When basal erosion surfaces were not recovered, surfaces may be inferred from the presence of sand—or the assumption of washed-out sands—and correlation to wireline logs. These lithologic surfaces and associated sediments are believed to be correlative between sites across the transect.

Candidate sequence boundaries are best identified in Lithostratigraphic Unit I at each site, where recovery was highest and where lithologic contrasts are most pronounced. Unit I erosion surfaces have been correlated with seismic sequence boundaries U19–U11 and, at Site U1351, are overlain by a series of lithofacies associations comprising upward-fining shelly sandy mud topped by coarsening-upward sandy mud (Figs. 8, 9). Together, the package is provisionally interpreted as a transgressive, wave-eroded ravinement surface overlain by a lag deposit corresponding to a transgressive systems tract. Subsequent highstand mud units are topped by the regressive, coarsening-upward sediments (Type 2 facies assemblage; Fig. 9). The facies assemblage includes decimeter- to centimeter-thick clay beds similar to those attributed to rapid deposition by flood events on modern shelves near sediment-rich fluvial systems. Truncated versions of this facies association, lacking the regressive highstand phase, occur in the upper 30 m at Site U1352, suggesting more frequent erosive episodes (Type 1 facies assemblage; Fig. 9). There are more such truncated facies associations than there are seismic sequence boundaries, and it is therefore possible that some of the truncated facies associations may represent higher-order cycles or autocyclicity. The facies associations, both complete and truncated, are similar to those known from the Wanganui Basin (Abbott and Carter, 1999; Saul et al., 1999; Abbott et al., 2005; Naish et al., 2005).

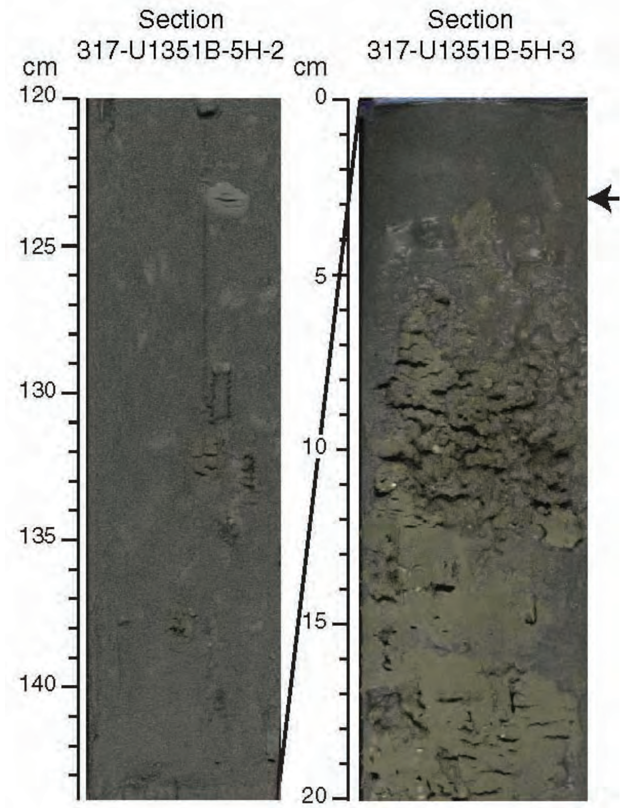

Figure 8. Core photographs of a lithologic surface and associated sediments in Unit I at outermost shelf Site U1351. Gray sand overlies greenish mud at a burrowed contact (arrow). This contact correlates with the predicted depth of seismic sequence boundary U18 (from Fulthorpe et al., 2011).

Erosion surfaces have not been identified in Unit II, which is more homogeneous and where recovery beneath the shelf was poorest. However, indurated intervals of *in situ* carbonate cementation may correlate with seismic sequence boundaries. Sediment recovered from Unit II was predominantly muddy, suggesting deposition on a shelf below fair-weather wave base. The lack of abundant shell debris suggests that the setting was more distal than during deposition of Unit I.

Fitting seismically resolvable sequences within the hierarchy of known global forcing has long been problematic. The relationship between high-frequency Milankovitch cycles and longer, seismic-scale sequences remains an unresolved area of research. Saul et al. (1999) showed that, for the Wanganui Basin, classic fourth- and fifth-order cyclothems are grouped together into third-order cycles that were controlled by basin-wide tectonic rhythms. Alternatively, Miller et al. (2005) have pointed out that some third-order cyclicity may be manifestations of longer wavelength Milankovitch periodicities of 1.2 My and 2.4 My, or of interference between these cycles.

The high accumulation rates of the Canterbury Basin provide the opportunity to link seismic sequences to specific Milankovitch frequencies, as revealed by oxygen isotopic records (Fig. 4). This will allow us to evaluate how predominant forcing frequencies change through time and to constrain the depositional parameters required to generate and preserve seismically resolvable sequences. The seismic sequences span the range between Milankovitch-scale cyclicity and longer period, third-order, seismically resolvable cycles. The two upper, seismically delimited sequences beneath the shelf (corresponding to the sequences overlying seismic sequence boundaries U18 and U19) almost certainly represent 100-k.y. cycles corresponding to marine isotope stages (MIS) 1–5 and 6–7, respectively, based on magnetic susceptibility and natural gamma ray time series. Correlations with older MIS stages are also likely as ages are refined. In contrast, Miocene to early Pliocene sequences represent longer cycles and may correlate with the 400-k.y. eccentricity cycle.

Influence of Ocean Currents on Deposition

Northeastward flowing currents (Southland Current, inboard of the Subtropical Front, and a gyre of the

Subantarctic Front) sweep the margin today to water depths of ~900 m (Chiswell, 1996; Morris et al., 2001; Fig. 2). The buried sediment drifts in the Canterbury Bight, as well as outcrop evidence of current-related deposition, suggest that similar currents have been active for the last 30 My (Fig. 5). However, the influence of currents on deposition at seismic scale varies markedly along strike, with large drifts developing in the northeast near ODP Site 1119 (Leg 181), while coeval sequences to the southwest at the Expedition 317 transect are clinoformal (compare Figs. 5 and 6). The role of along-strike processes in sequence stratigraphy has been unclear; sediment transport in the sequence stratigraphic model is viewed as essentially two-dimensional. Expedition 317 results provide insight into the interaction of along-strike and downslope processes within a sequence stratigraphic framework in a location where a current is known to have been present, but whose seismic stratigraphic signature varies greatly both spatially and temporally.

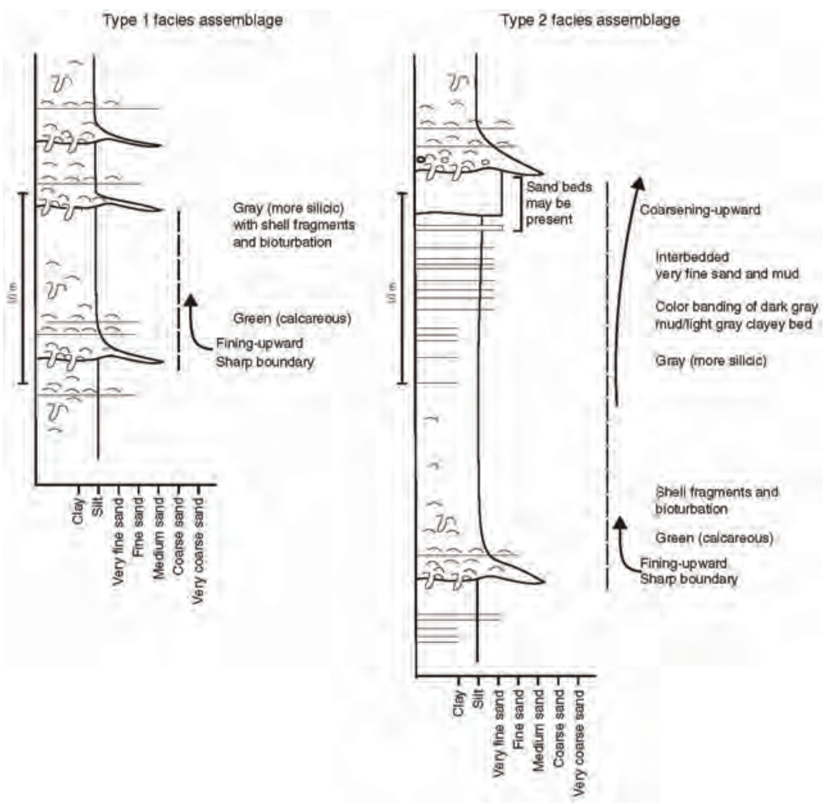

Figure 9. Schematic model of the repetitive facies assemblages that characterize lithologic Unit I. The Type 2 facies assemblage is composed of greenish-gray shelly bioturbated mud with a sharp lower contact (ravinement surface), followed by a transition uphole into dark gray micaceous very fine sandy mud with color banding and alternations of sand and mud showing upward coarsening. The Type 1 facies assemblage is the basal part of the Type 2 assemblage (from Fulthorpe et al., 2011).

Beginning at the seafloor, ODP Site 1119 sediments are interpreted as products of current reworking, corresponding to the clear seismic signatures of sediment drift development. In contrast, Site U1352 features a complex interplay of along-strike and downslope depositional processes. For example, the uppermost interval (Subunit IA; 0–98 m, Pleistocene to Holocene) is interpreted as a series of lowstand shelf-edge deltas fed by sediment gravity flows represented by sharp-based gray very fine to fine sands, whose mineralogy indicates direct offshore and downslope transport from sources in the Torlesse Terrane, located onshore adjacent to the drilling area. This interpretation is supported by the presence of reworked nannofossils consisting of mixed, poorly-preserved Eocene-Oligocene assemblages derived from onshore. However, the rest of Site U1352 (Subunit IB and below) and the slope interval of Site U1351 include sediment from the Otago Schist to the south, indicating increasing downhole importance of along-strike transport. Nevertheless, downslope transport is also interpreted in Subunit IB. Interbedded, sharp-based greenish sands that occur within dark gray hemipelagic mud are interpreted as mass flows; abundant shells in one sand suggest transport from a shallow marine environment. Therefore, Subunit IB is a transitional interval of increasing (downhole) contourite deposition culminating in Subunit IC, which contains a well-sorted, very fine-grained sand fraction consistent with considerable transport distance. Subunit IC also contains reworked nannofossils. However, in contrast to those in Subunit IA, these reworked assemblages are well-preserved and contain cold-water taxa from a monospecific age consistent with an along-strike source. This interpretation is more consistent with that of the coeval interval at Site 1119. Hemipelagic sediments of Units IIA and IIB at Site U1352 may have been deposited as sediment drifts; subtle seismic geometries suggest the influence of along-strike processes (e.g., paleoslopes on Figs. 6 and 7). Diagnostic sedimentary structures are rare, partly because of extensive bioturbation, but intermittent wavy laminations occur in Unit IIB. Alternations of light-colored marlstone with darker mud-stone may reflect switching between hemipelagic carbonate deposition and increased terrigenous influx corresponding to alternating along-strike and downslope sedimentary processes, respectively. Expedition 317 drilling therefore provides insights into the development of ocean circulation in this region, as well as the interaction of along-strike and downslope processes with implications for both sequence stratigraphy and models of clinoform development.

Marshall Paraconformity

The Marshall Paraconformity is a regional unconformity terminating the post-rift transgressive phase and capping the widespread Amuri Limestone formation. The paraconformity has been dated at its onshore type section using strontium isotopes as representing a minimum hiatus of

32.4–29 Ma (Fulthorpe et al., 1996). There, it is overlain by mid-late Oligocene cross-bedded glauconitic sand (Concord Formation) and calcarenite limestone (Weka Pass Formation). The paraconformity was the deepest target of Expedition 317 drilling and is hypothesized to represent intensified current erosion or non-deposition associated with the initiation of thermohaline circulation upon opening of the seaway between Antarctica and Australia (~33.7 Ma), prior to opening of the Drake passage (Carter, 1985; Fulthorpe et al., 1996; Carter et al., 2004).

The Marshall Paraconformity was represented by a lithologic change at 1853 m in Hole 1352B (Fig. 10). The paraconformity marks the boundary between overlying lower Miocene glauconitic limestone and underlying lower Oligocene recrystallized pelagic nannofossil limestone containing trace fossils and stylolites, equivalent to the onshore Amuri Limestone. Recovery was low across the paraconformity, which was represented by a decimeter-scale rubble zone in recovered core. No equivalent to the Concord Formation glauconitic sand was recovered, although logs from nearby Clipper-1 exploration well (Fig. 2) suggest that a boundary sand layer is present. One possibility is that sediment loading caused the Concord-Formation-equivalent greensand to be injected into the overlying sandy marlstones and limestones to produce distinctive glauconitic sand layers (Fig. 10). The hiatus at the paraconformity is estimated to be 11–12 My at Site U1352, conforming with previous observations that the hiatus is longer offshore than at the type section, perhaps owing to greater current-induced erosion at such deeper-water locations (Shipboard Scientific Party, 1999; Carter et al., 2004). Hole 1352B terminated in upper Eocene (35.2–36.6 Ma) limestone.

The Future: a Global Array of Sea-Level Transects

The study of global sea-level change requires a global approach. Worldwide correlation is essential to establish the degree to which sequence boundaries are synchronous and to confirm that eustatic amplitude estimates from individual margins are globally consistent. The Canterbury Basin is therefore one element in a worldwide array of scientific ocean drilling transects, some of which have been drilled while others remain in the proposal stage. New Jersey MAT drilling on the coastal plain, shelf, and slope has already yielded a record of global sea-level timing and amplitudes since the Late Cretaceous (Fig. 4; Miller et al., 2005; Kominz et al., 2008). Such records are derived using one- and two-dimensional backstripping, requiring as inputs sequence-boundary ages, paleobathymetry from benthic microfossils, porosity profiles (for decompaction calculations), and tectonic history. Drilling for long-term sea-level objectives has also been carried out in the Bahamas and on the Marion Plateau (ODP Legs 166 and 194, respectively).

Expedition 317 was designed using the strategy developed for MAT. We are following a parallel approach in refining Expedition 317 results with the ultimate goal of producing a late Miocene-Recent eustatic record for correlation both with MAT results and with the oxygen isotopic record of global climatic variation. Additional transects are required to cover both Greenhouse and Icehouse records. This approach will necessitate integration of onshore and offshore drilling and use of Mission Specific Platforms in

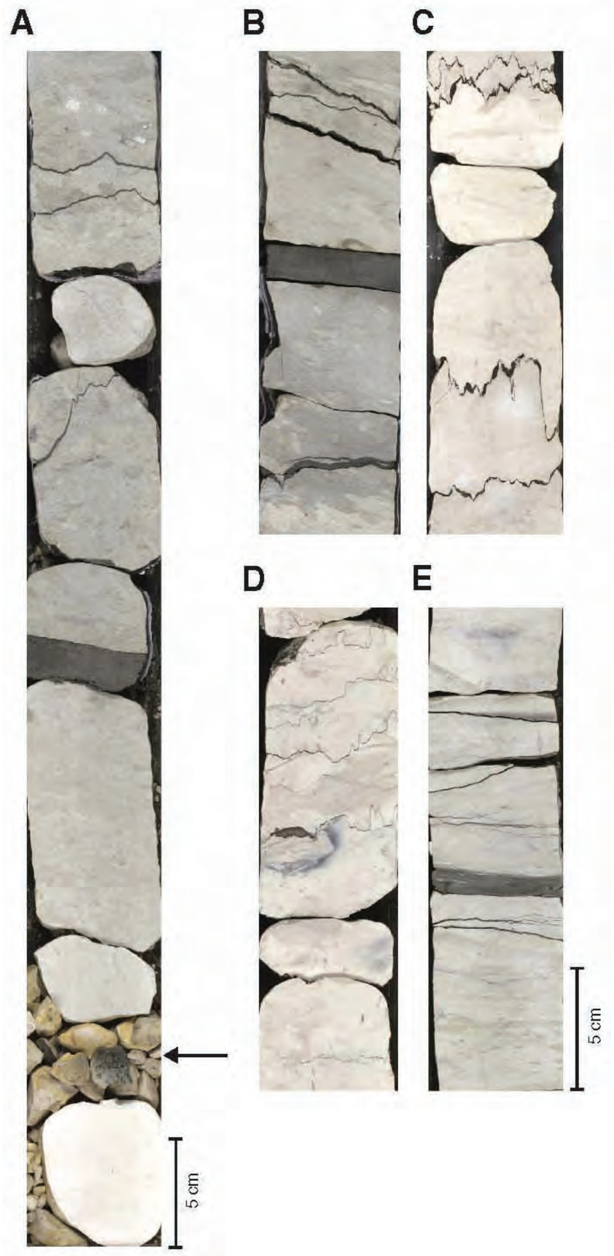

Figure 10. [A] Marshall Paraconformity (arrow) at contact between Units II and III at Site U1352. Only two limestone pieces and some rubble were recovered. However, unconsolidated glauconitic sand may have been present originally, but it was injected into the overlying glauconitic marlstone and limestone to produce the observed layers (see also B), some of which cross cut primary stratigraphy and/or display branching. [B] Glauconitic limestone above the paraconformity. [C] and [D] Stylolitic white limestone (Amuri Limestone equivalent) below the paraconformity. [E] Muddy limestone with layers of marlstone and purple banding below the paraconformity. B–E are at the same vertical scale (from Fulthorpe et al., 2011).

shallow-water settings, as has been done off New Jersey, Tahiti, and the Great Barrier Reef (IODP Expeditions 313, 310, and 325, respectively). Additional drilling of carbonate clinoforms is also required to evaluate how the response of such systems to sea-level change differs from that of siliciclastic systems. Finally, drilling on active margins should be explored to take advantage of very high rates of sediment supply that create expanded sections and allow study of eustatic cycles at orbital forcing frequencies, as well as illuminating the interplay of eustatic and tectonic forcing.

Acknowledgements

We thank the crew of the D/V *JOIDES Resolution* and all drilling operations personnel, who overcame the considerable difficulties associated with drilling deep boreholes in shallow water to ensure the success of Expedition 317. Many thanks are also due to the U.S. Implementing Organization technicians who are such a vital part of the drilling program. The authors also thank three anonymous reviewers for their helpful and insightful input.

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IODP Expedition 318: From Greenhouse to Icehouse at the Wilkes Land Antarctic Margin

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Abstract

Integrated Ocean Drilling Program (IODP) Expedition 318, Wilkes Land Glacial History, drilled a transect of sites across the Wilkes Land margin of Antarctica to provide a long-term record of the sedimentary archives of Cenozoic Antarctic glaciation and its intimate relationships with global climatic and oceanographic change. The Wilkes Land drilling program was undertaken to constrain the age, nature, and paleoenvironment of the previously only seismically inferred glacial sequences. The expedition (January–March 2010) recovered ~2000 meters of high-quality middle Eocene–Holocene sediments from water depths between 400 m and 4000 m at four sites on the Wilkes Land rise (U1355, U1356, U1359, and U1361) and three sites on the Wilkes Land shelf (U1357, U1358, and U1360).

These records span ~53 million years of Antarctic history, and the various seismic units (WL-S4–WL-S9) have been successfully dated. The cores reveal the history of the Wilkes Land Antarctic margin from an ice-free "greenhouse" Antarctica, to the first cooling, to the onset and erosional consequences of the first glaciation and the subsequent dynamics of the waxing and waning ice sheets, all the way to thick, unprecedented "tree ring style" records with seasonal resolution of the last deglaciation that began ~10,000 y ago. The cores also reveal details of the tectonic history of the Australo-Antarctic Gulf from 53 Ma, portraying the onset of the second phase of rifting between Australia and Antarctica, to ever-subsiding margins and deepening, to the present continental and ever-widening ocean/continent configuration.

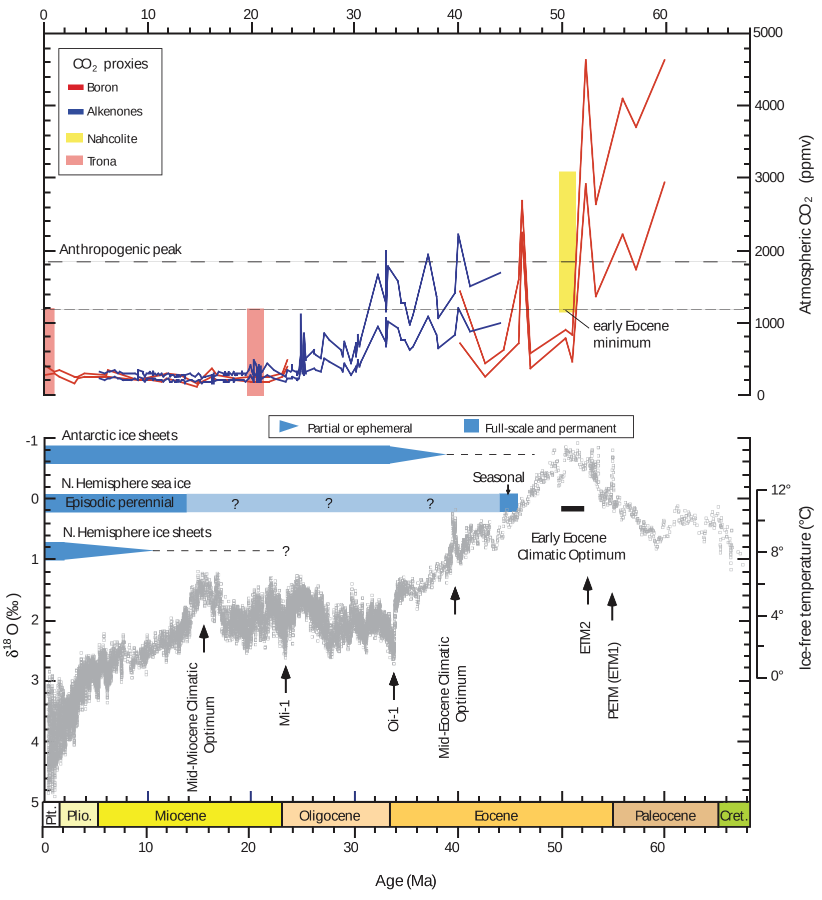


Figure 1. Updated Cenozoic pCO2 and stacked deep-sea benthic foraminifer oxygen isotope curve for 0 Ma to 65 Ma. NB: Updated from Zachos et al. (2008) and converted to the "Gradstein timescale" (Gradstein et al., 2004). Mi-1 = Miocene isotope Event 1, Oi-1 = Oligocene isotope Event 1, ETM2 = Eocene Thermal Maximum 2, PETM = Paleocene/Eocene Thermal Maximum, ETM1 = Eocene Thermal Maximum 1.

Introduction

Polar ice is an important component of the modern climate system, affecting among other things global sea level, ocean circulation and heat transport, marine productivity, air-sea gas exchange, and planetary albedo. The modern ice caps are, geologically speaking, a relatively young phenomenon. Since mid-Permian times (~270 Ma), parts of Antarctica became reglaciated only ~34 m.y. ago, whereas full-scale, permanent Northern Hemisphere continental ice began only ~3 m.y. ago (Zachos et al., 2008; Fig. 1). The record of Antarctic glaciation, from the time of first ice-sheet inception through the significant periods of climate change during the Cenozoic, is not only of scientific interest but also is of great importance for society. State-of-the-art climate models (DeConto and Pollard, 2003a, 2003b; Huber et al., 2004; DeConto et al., 2007; Pollard and DeConto, 2009) combined with paleoclimatic proxy data (Pagani et al., 2005) suggest that the main triggering mechanism for inception and development of the

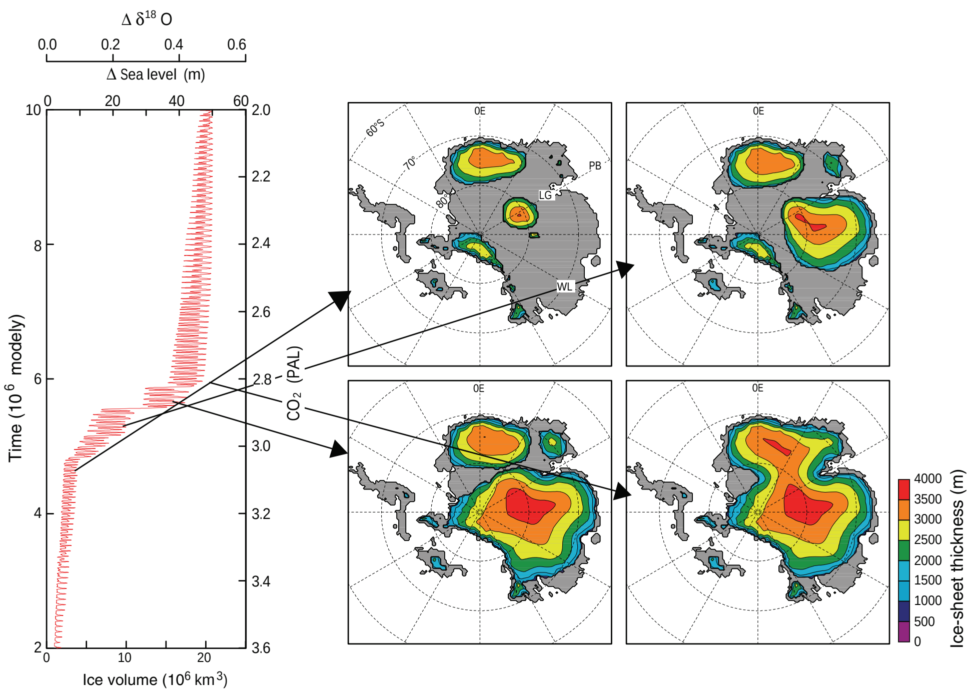


Figure 2. Simulated initiation of East Antarctic glaciation in the earliest Oligocene using a coupled general circulation model (GCM) ice-sheet model (from DeConto and Pollard, 2003a). These results are principally forced by gradual lowering of atmospheric levels of CO2 in the simulated atmosphere. Note that the glaciation takes place in a "two-step" fashion reminiscent of the two-step δ^{18}O increase recorded in benthic foraminiferal carbonates across the Eocene–Oligocene transition (Coxall et al., 2005). The first step results in glaciation in the Antarctic continental interior, discharging mainly through the Lambert Graben (LG) to Prydz Bay (PB). The second step results in the initial connection and subsequent rapid expansion of the ice sheet, reaching sea level in the Wilkes Land (WL) at a later stage. PAL = Preindustrial Atmospheric Level.

Antarctic ice sheet was the decreasing levels of CO_2 (and other greenhouse gases) concentrations in the atmosphere (DeConto and Pollard, 2003a, 2003b; Figs 1, 2). The opening of critical Southern Ocean gateways played only a secondary role (Kennett, 1977; DeConto and Pollard, 2003a; Huber et al., 2004). With current rising atmospheric greenhouse gases resulting in rapidly increasing global temperatures (Intergovernmental Panel on Climate Change [IPCC], 2007; www.ipcc.ch/), studies of polar climates are prominent on the research agenda. Understanding Antarctic ice-sheet dynamics and stability is of special relevance because, based on IPCC (2007) forecasts, atmospheric CO_2 doubling and a 1.8°C–4.2°C temperature rise is expected by the end of this century. The lower values of these estimates have not been experienced on our planet since 10–15 Ma, and the higher estimates have not been experienced since before the ice sheets in Antarctica formed.

Since their inception, the Antarctic ice sheets appear to have been very dynamic, waxing and waning in response to global climate change over intermediate and even short (orbital) timescales (Wise et al., 1991; Zachos et al., 1997; Pollard and DeConto, 2009). However, not much is known about the nature, cause, timing, and rate of processes involved. Of the two main ice sheets, the West Antarctic Ice Sheet (WAIS) is mainly marine based and is considered less stable (Florindo and Siegert, 2009). The East Antarctic Ice Sheet (EAIS), which overlies continental terrains that are largely above sea level, is considered stable and is believed to respond only slowly to changes in climate (Florindo and

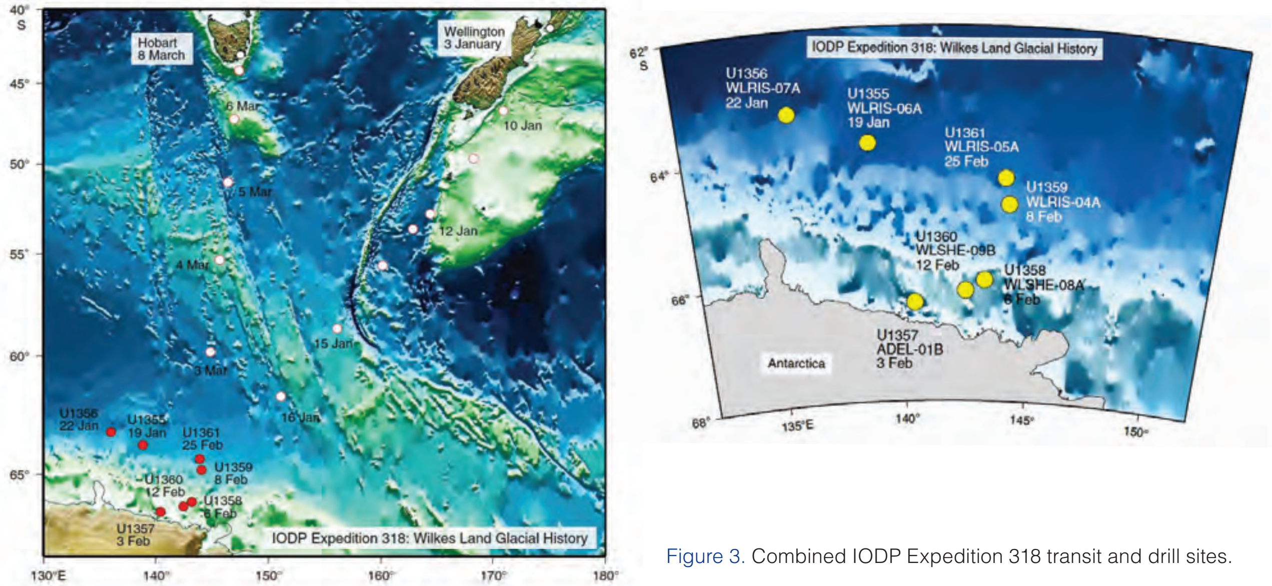
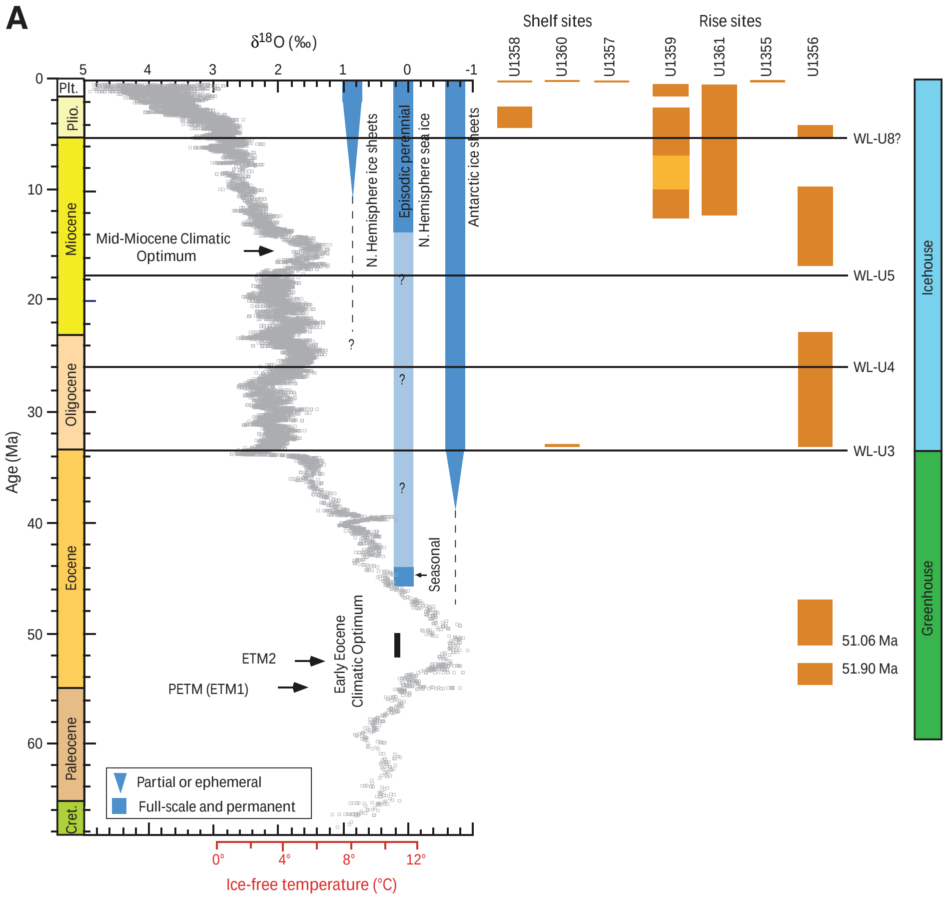


Figure 3. Combined IODP Expedition 318 transit and drill sites.



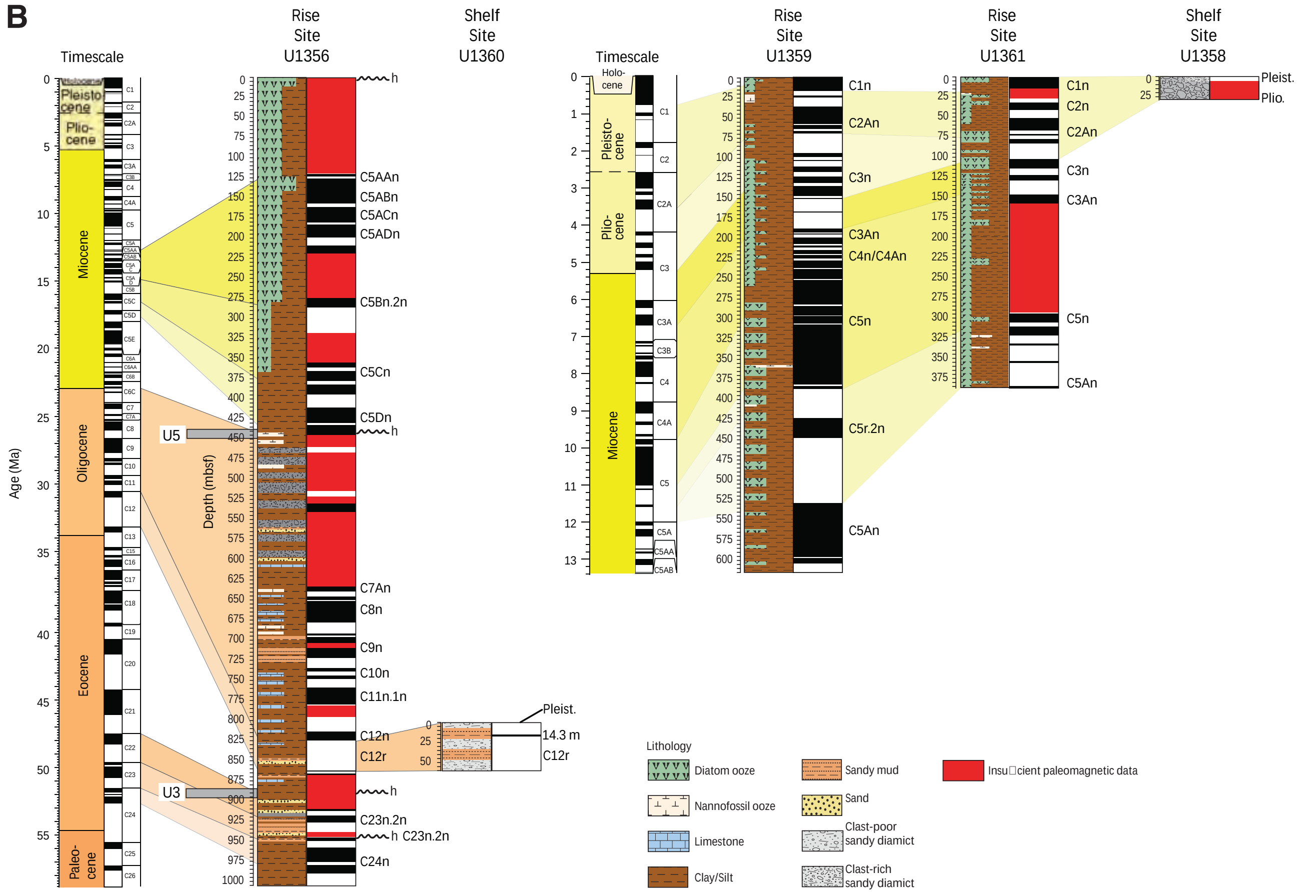


Figure 4. [A] Stacked deep-sea benthic foraminifer oxygen isotope curve for 0–65 Ma (updated from Zachos et al., 2008) converted into "Gradstein timescale" (Gradstein et al., 2004) and combined with chronostratigraphy of the sites drilled during Expedition 318. ETM2 = Eocene Thermal Maximum 2, PETM = Paleocene/Eocene Thermal Maximum, ETM1 = Eocene Thermal Maximum 1.

[B] Chronostratigraphic framework for sites drilled during Expedition 318. Timescales are those of Gradstein et al. (2004). [11x17 landscape]

Siegert, 2009). However, reports of beach gravel deposited 20 m above sea level in Bermuda and the Bahamas from 420 ka to 360 ka indicate the collapse of not only the WAIS (6 m of sea-level equivalent, SLE) and Greenland ice sheet (6 m of SLE), but possibly also 8 m of SLE from East Antarctic ice sources (Hearty et al., 1999). Therefore, during episodes of global warmth, with likely elevated atmospheric CO_2 conditions, the EAIS may contribute just as much or more to rising global sea level as the Greenland ice sheet. In the face of rising CO_2 levels (Pachauri, R.K., and Reisinger, A., 2007), a better understanding of the EAIS dynamics is therefore urgently needed from both an academic as well as a societal point of view.

A key region for analysis of the long- and short-term behavior of the EAIS is the eastern sector of the Wilkes Land margin, located at the seaward termination of the largest East Antarctic subglacial basin, the Wilkes subglacial basin. The base of the portion of the EAIS draining through the Wilkes subglacial basin is largely below sea level, suggesting that this portion of the EAIS can potentially be less stable than other areas of the EAIS (Escutia et al., 2005). Numerical models of ice-sheet behavior (Huybrechts, 1993; DeConto and Pollard, 2003a, 2003b; DeConto et al., 2007; Pollard and DeConto, 2009) provide a basic understanding of the climatic sensitivity of particular Antarctic regions for early ice-sheet formation, connection and expansion, and eventual development of the entire ice sheet. For example, in these models glaciation is shown to have begun in the East Antarctic interior, discharging mainly through the Lambert Graben to Prydz Bay. These models imply that the EAIS did not reach the Wilkes Land margin until a later stage. These models can only be validated through drilling and obtaining direct evidence from the sedimentary record.

Scientific Objectives

The overall objectives of Expedition 318 were to date the identified seismic units and to obtain long-term records of Antarctic glaciation to better understand its relationships with global paleoclimate and paleoceanographic changes. Of particular interest is testing the sensitivity of the EAIS to episodes of global warming and detailed analysis of critical periods in Earth's climate history, such as the Eocene–Oligocene and Oligocene–Miocene glaciations, late Miocene, Pliocene, and the last deglaciation. During these times, the Antarctic cryosphere evolved in a step-wise fashion to ultimately assume its present-day configuration, characterized by a relatively stable EAIS. Conceivably even more important than the history of the Antarctic glaciations are past lessons of deglaciations and periods of exceptional warmth. We therefore planned to core several sequences from the Pleistocene and Pliocene that formed during interglacial intervals of exceptional warmth, periods that may provide valuable information about Antarctica's response to warming predicted in the centuries ahead. Furthermore, seismic reflection and shallow coring data indicate that the Wilkes Land margin also includes sites with ultrahigh accumulation rates of sediments that document the Holocene deglaciation and subsequent climate and sedimentological variability extending over the past 10,000 y. In general, our strategy was to core and analyze sedimentary records along the inshore-offshore transect to constrain the age, nature, and environments of deposition, until now only inferred from seismic surveys of the Wilkes Land continental shelf, rise, and abyssal plain (Escutia et al., 1997; De Santis et al., 2003; Escutia et al., 2005).

The Expedition

IODP Expedition 318 (January–March 2010; Wellington, New Zealand, to Hobart, Australia), occupied seven sites (Fig. 3) across the Wilkes Land Margin at water depths between ~400 mbsl and 4000 mbsl. Together, we retrieved ~2000 meters of high-quality upper Eocene–Quaternary sedimentary cores (Fig. 4a, b). Sites U1355, U1356, U1359, and U1361 are on the Wilkes Land rise, and Sites U1358, U1360, and U1357 are on the Wilkes Land shelf. The cores span ~53 m.y. of Antarctic history, revealing the history of the Wilkes Land Antarctic margin from an ice-free "greenhouse Antarctica," to the first cooling, to the onset and erosional consequences of the first glaciation and the subsequent dynamics of the waxing and waning ice sheets (Fig. 4). Furthermore, we also were able to capture the record of the last deglaciation in terms of thick, unprecedented "tree ring style" records with annual to seasonal resolution taken in the Adélie depression (U1357) (Fig. 5).

Initial studies now also reveal details of the tectonic history of the Australo-Antarctic Gulf (at 53 Ma), the onset of the second phase of rifting between Australia and Antarctica (Colwell et al., 2006; Close et al., 2009), ever-subsiding margins and deepening, to the present ocean/continent configuration. Tectonic and climatic change turned the initially shallow, broad subtropical Antarctic Wilkes Land offshore shelf into a deeply subsided basin with a narrow ice-infested margin (Fig. 6).

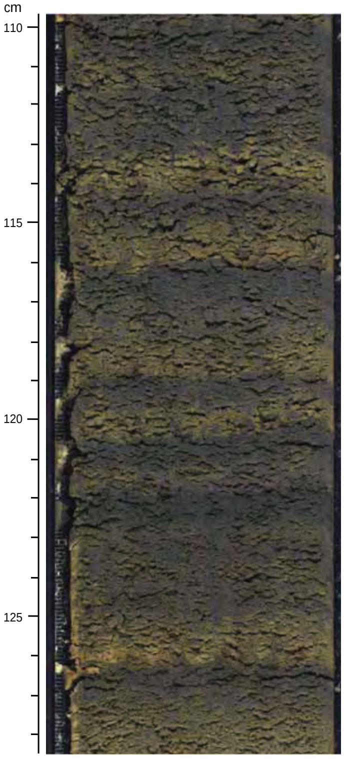


Figure 5. Example of a core section from Holocene diatomaceous ooze, Site U1357. Note the distinct seasonal laminations.

“Pre-Glacial” Regional Unconformity WL-U3 and the Timing, Nature, and Consequences of the First Major Phase of EAIS Growth

Prior to the expedition, the prominent unconformity WL-U3 had been interpreted to separate pre-glacial (Eocene) strata from (Oligocene) glacial-influenced deposits (Escutia et al., 1997, 2005). Drilling and dating of WL-U3 at continental rise Site U1356 and shelf Site U1360 (Fig. 3) confirmed that this surface represents major erosion related to the onset of glaciation at ~34 Ma (early Oligocene), with immediately overlying deposits dated as 33.6 Ma (Fig. 7). Below unconformity WL-U3 at Site U1356, we recovered a record that is late early to early middle Eocene in age and that includes peak greenhouse conditions and likely some of the early Eocene hyperthermals (Fig. 8). We infer subtropical shallow-water depositional environments for this section based on dinocysts, pollen and spores, and the chemical index of alteration, among other indicators. A hiatus spanning ~2 m.y. separates the lower Eocene from the middle Eocene record at Site U1356 according to dinocyst and magnetostratigraphic evidence. This hiatus may be related to tectonic activity related to the commencement of rapid seafloor spreading in the Australia-Antarctic Basin (AAB), reported to initiate around the same time (~50 Ma; Colwell et al., 2006). Also, combined Site U1356 and ODP Leg 189 dinocyst distribution patterns suggest earliest through-flow of South Pacific Antarctic waters through the Tasmanian Gateway to be coeval with this tectonic phase. Sedimentological and microfossil information from this interval from Hole U1356A also suggest some deepening during the early middle Eocene.

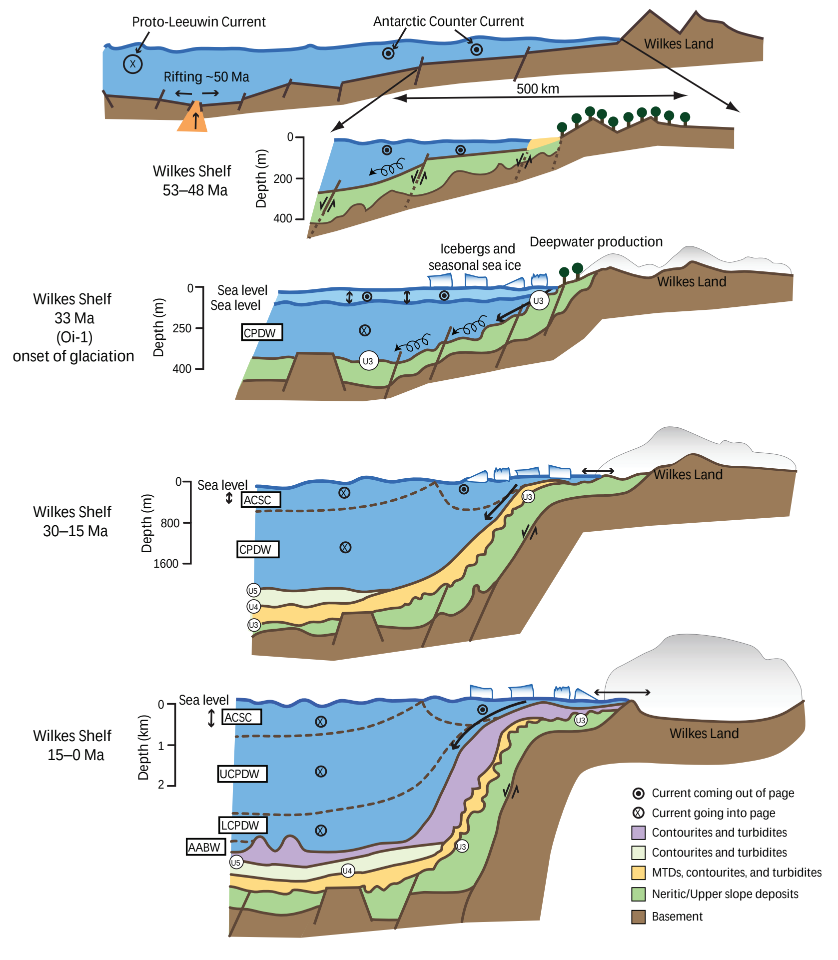


Figure 6. Conceptual illustration of tectonic, geological, sedimentological, and climatic evolution of the Wilkes Land margin since the middle early Eocene (~54 Ma). U3, U4, and U5 refer to seismic unconformities WL-U3, WL-U4, and WL-U5, respectively. Oi-1 = Oligocene isotope Event 1, CPDW = Circumpolar Deep Water, ACSC = Antarctic Circumpolar Surface Water, UCPDW = Upper Circumpolar Deep Water, LCPDW = Lower Circumpolar Deep Water, AABW = Antarctic Bottom Water. MTD = mass transport debris flows.

At Site U1356, the upper middle Eocene to the basal Oligocene is conspicuously missing in a ~19-m.y. hiatus at ~890 bsf (~47.9–33.6 Ma) marking unconformity WL-U3 based on dinocyst and paleomagnetic evidence. Despite ongoing tectonic reorganizations, it appears likely that the erosive nature of unconformity WL-U3 is notably related to the early stages of EAIS formation. The impact of ice-sheet growth, including crustal and sea-level response, and major erosion by the ice sheets, is proposed as the principal mechanism that formed unconformity WL-U3. This is supported by the abrupt increase in benthic foraminiferal δ^{18}O values and coeval sea-level change globally recorded in complete marine successions (Oligocene isotope event Oi-1; Miller et al., 1985; Coxall et al., 2005). Progressive subsidence—the large accommodation space created by erosion in the margin (300–600 m of missing strata; Eittreim et al., 1995)—and partial eustatic recovery allowed sediments of early Oligocene age to accumulate above unconformity WL-U3.

Microfossils, sedimentology, and geochemistry of the Oligocene sediments from Site U1356, at present occupying a distal setting (i.e., lowermost rise-abyssal plain) and immediately above unconformity WL-U3, unequivocally reflect icehouse environments with evidence of iceberg activity (dropstones) and at least seasonal sea-ice cover. The sediments, dominated by hemipelagic sedimentation with bottom current and gravity flow influence, as well as biota, indicate deeper water settings relative to the underlying middle Eocene environments. These findings imply significant crustal stretching, subsidence of the margin, and deepening of the Tasman Rise and the Adélie Rift Block (ARB) between 47.9 Ma and 33.6 Ma (Fig. 6).

Record of EAIS Variability

Drilling at continental rise Site U1356 also recovered a thick section of Oligocene to upper Miocene sediments (Figs. 4, 8) indicative of a relatively deep-water, sea-ice-influenced setting. Oligocene to upper Miocene sediments are indicative of episodically reduced oxygen conditions either at the seafloor or within the upper sediments prior to ~17 Ma. From the late early Miocene (~17 Ma) onward, progressive deepening and possible intensification of deep-water flow and circulation led to a transition from a poorly oxygenated low-silica system (present from the early to early middle Eocene to late early Miocene) to a well-ventilated silica-enriched system akin to the modern Southern Ocean. This change coincides with one of the major regional unconformities in the Wilkes Land margin, unconformity WL-U5, which represents a ~3 m.y. latest Oligocene–early Miocene hiatus (Figs. 4, 8). This unconformity marks a change in the dominant sedimentary processes at this site, which are dominated by mass transport processes below the unconformity and by hemipelagic, turbidity flow, and bottom-current deposition above.

A complete record with good recovery of late Miocene to Pleistocene deposits was achieved at continental rise Sites U1359 and U1361 (Figs. 4, 9), drilled on levee deposits bounding turbidity channels. We successfully dated the seismic units between unconformities WL-U6 and WL-U8, and the sedimentological, wireline logging, and magnetic susceptibility data exhibit relatively high amplitude variations, indicating strong potential for this record to reveal EAIS dynamics down to orbital timescales (100 k.y. and 40 k.y. cyclicity) (Fig. 10). This cyclicity likely documents the successive advances and retreats of the ice-sheet and sea-ice cover, as well as the varying intensity of cold saline density flows related to bottom water production at the Wilkes Land margin (e.g., high-salinity shelf water flowing from the shelf into the deep ocean to form Antarctic Bottom Water [AABW]). In general, typical Southern Ocean open cold-water taxa, with variable abundances of sea-ice-associated diatoms were recovered, indicating a high-nutrient, high-productivity sea-ice-influenced setting throughout the Neogene. Combined sedimentological and microfossil information indicates the ever-increasing influence of typical Antarctic Counter Current surface waters and intensifying AABW flow. Furthermore, the preservation of calcareous microfossils in several intervals indicates times when bottom waters were favorable to the preservation of calcium carbonate. These observations point to a very dynamic ice-sheet/sea-ice regime during the late Miocene through the Pleistocene. Detailed postcruise studies in sediments from the late Neogene will provide a history of glacial-interglacial climate and paleoceanographic variability, including a history of AABW production that can be linked to sea-ice variations in this margin.

Ultrahigh Resolution Holocene Record of Climate Variability

Coring at Site U1357 yielded a 186-m section of continuously laminated diatom ooze as well as a portion of the underlying Last Glacial Maximum diamict. Based on much shorter piston cores recovered from adjacent basins and banks, the onset of marine sedimentation during the deglacial interval began between 10,400 y and 11,000 y ago. The site was triple cored, providing overlapping sequences that will aid in the construction of a composite stratigraphy spanning at least the last 10,000 y. The Site U1357 sediments are unusual for Antarctic shelf deposits because of their high accumulation rate (2 cm y^{-1}), lack of bioturbation, and excellent preservation of organic matter as well as calcareous, opaline, phosphatic, and organic fossils. The sediments are profoundly anoxic, with levels of H_2S as high as 42,000 ppm at 20 mbsf. Larger burrowing organisms are completely

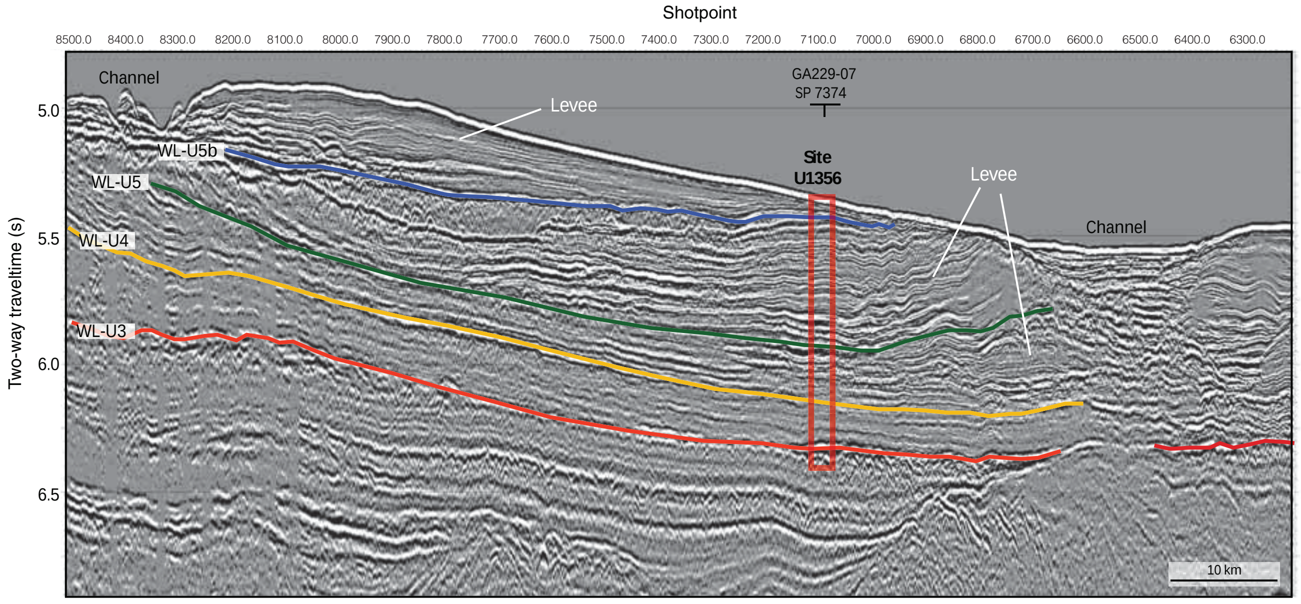


Figure 7. Multichannel seismic reflection profile across Site U1356 showing regional unconformities WL-U3, WL-U4, and WL-U5. Red rectangle = approximate penetration achieved at Site U1356.

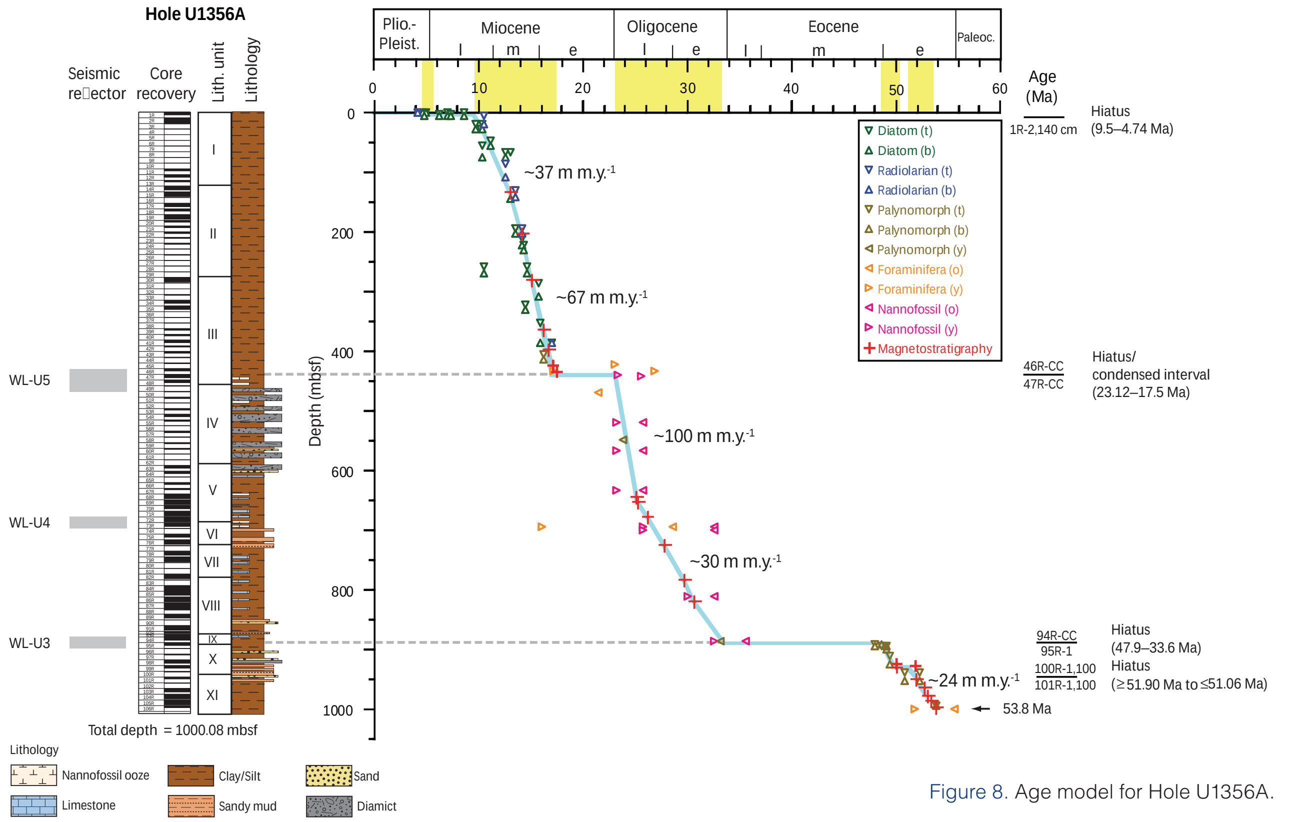


Figure 8. Age model for Hole U1356A.

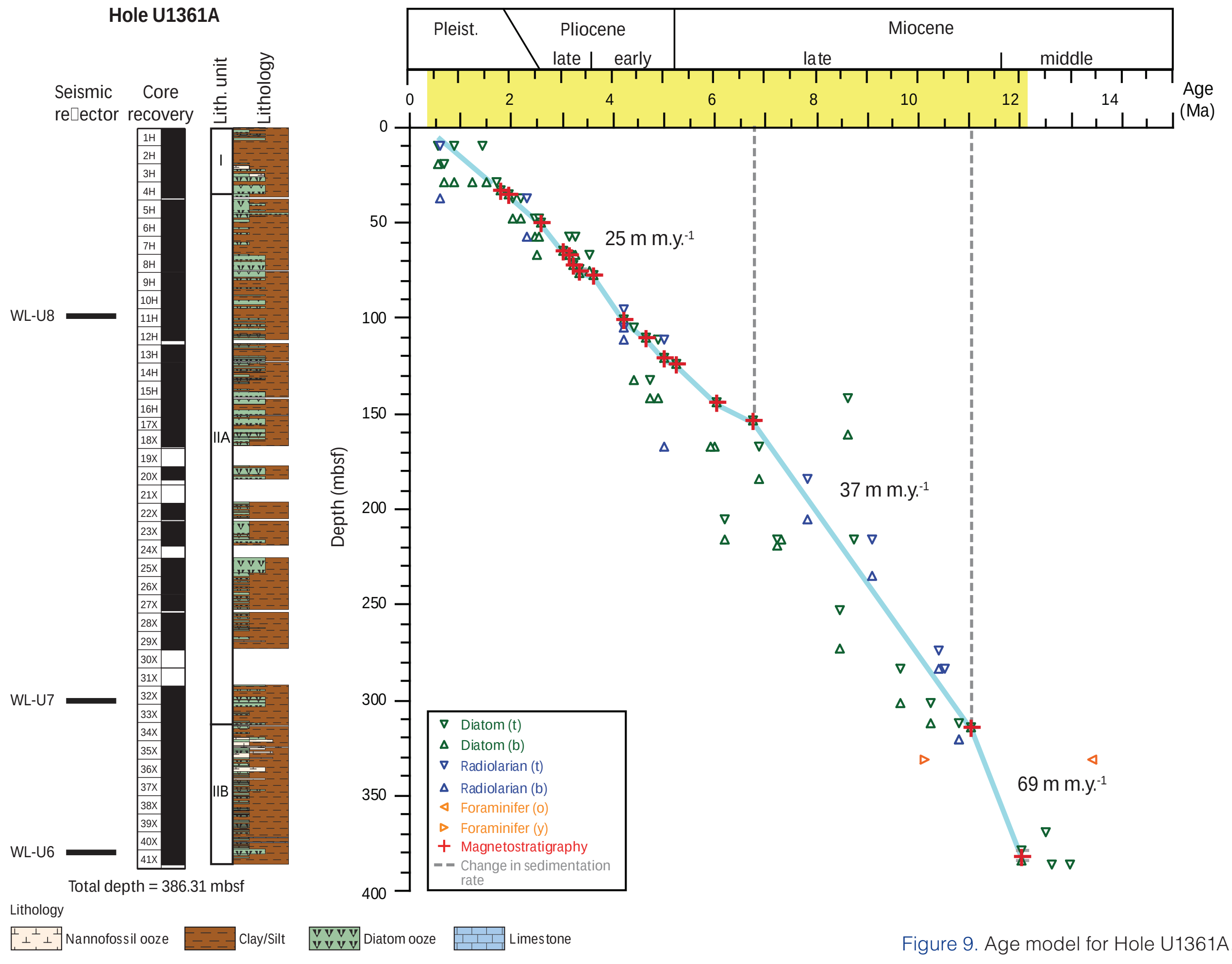


Figure 9. Age model for Hole U1361A.

excluded from this ecosystem, yet the regular occurrence of benthic foraminifers suggests that some oxygen is present at the sediment-water interface. These sediments provide an excellent sample set for geomicrobiology and sedimentary geochemistry studies. In fact, the upper 20 m of one of the three holes was intensively sampled for integrated pore water and microbiological studies.

A paramount achievement from a paleoclimatic standpoint was the retrieval of this continuously laminated deposit (Fig. 5). Spot checks of laminae from top to bottom of the split Hole U1357A sections suggest that paired light-dark laminae sets range in thickness from ~1 cm to 3 cm. Based on radiocarbon dating of a piston core taken earlier from this site (Costa et al., 2007), our own preliminary secular paleomagnetic findings, and the thickness of the deposit combined with the expected age at its base, it is very likely each laminae pair represents one year. If supported by our shore-based research, this will be the first varved sedimentary sequence extending through the Holocene recovered from the Southern Ocean. Analysis at the annual timescale will permit us to examine decadal to subdecadal variability in sea ice, temperature, and wind linked to the Southern Annual Mode (SAM), Pacific Decadal Variability, and possibly ENSO. We will also be able to address questions regarding rates of change during the Hypsithermal Holocene neoglacial events and the time immediately following the first lift-off and pull-back of ice at the end of the last glacial interval. In addition, we now have an excellent opportunity for ultrahigh resolution correlation to the nearby Law Dome Ice Core, one of the most important Holocene ice cores in Antarctica.

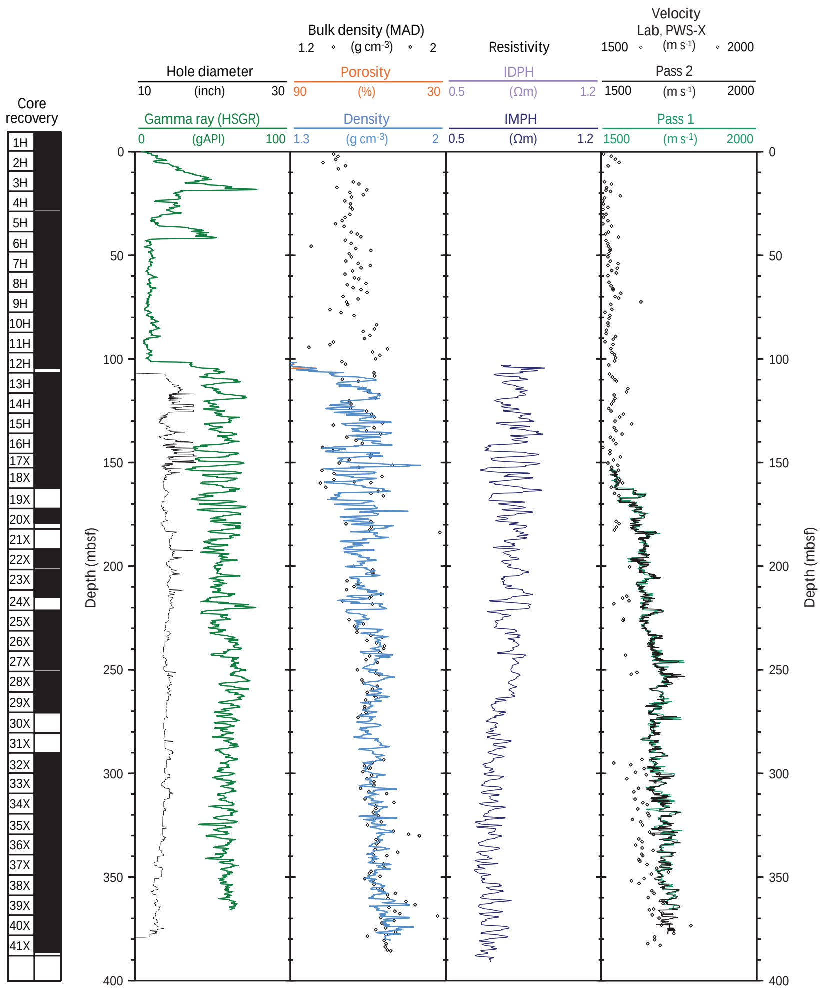


Figure 10. Downhole geophysical logs, Hole U1361A. HSGR = total spectral gamma ray, MAD = moisture and density, IDPH = deep induction phasor-processed resistivity, IMPH = medium induction phasor-processed resistivity, PWS-X = x-direction caliper.

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and the IODP Expedition 318 Scientists

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IODP Expedition 324: Ocean Drilling at Shatsky Rise Gives Clues about Oceanic Plateau Formation

by **William W. Sager, Takashi Sano, Jörg Geldmacher, and the IODP Expedition 324 Scientists**

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Abstract

Integrated Ocean Drilling Program (IODP) Expedition 324 cored Shatsky Rise at five sites (U1346–U1350) to study processes of oceanic plateau formation and evolution. Site penetrations ranged from 191.8 m to 324.1 m with coring of 52.6 m to 172.7 m into igneous basement at four of the sites. Average recovery in basement was 38.7%–67.4%. Cored igneous sections consist mainly of variably evolved tholeiitic basalts emplaced as pillows or massive flows. Massive flows are thickest and make up the largest percentage of section on the largest and oldest volcano, late Jurassic age Tamu Massif; thus, it may have formed at high effusion rates. Such massive flows are characteristic of flood basalts, and similar flows were cored at Ontong Java Plateau. Indeed, the similarity of igneous sections at Site U1347 with that cored on Ontong Java Plateau implies similar volcanic styles for these two plateaus. On younger, smaller Shatsky Rise volcanoes, pillow flows are common and massive flows thinner and fewer, which might mean volcanism waned with time. Cored sediments from summit sites contain fossils and structures implying shallow water depths or emergence at the time of eruption and normal subsidence since. Summit sites also show pervasive alteration that could be due to high fluid fluxes. A thick section of volcaniclastics cored on Tamu Massif suggests that shallow, explosive submarine volcanism played a significant role in the geologic development of the plateau summit. Expedition 324 results imply that Shatsky Rise began with massive eruptions forming a huge volcano and that subsequent eruptions waned in intensity, forming volcanoes that are large, but which did not erupt with unusually high effusion rates. Similarities of cored sections on Tamu Massif with those of Ontong Java Plateau indicate that these oceanic plateaus formed in similar fashion.

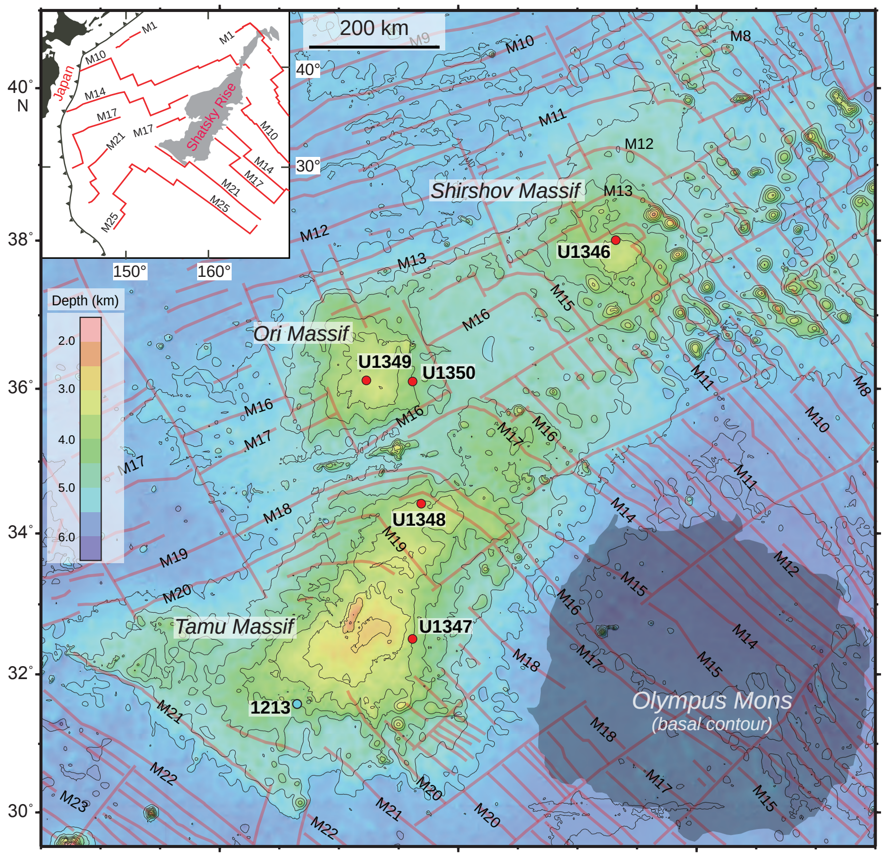

Figure 1. Shatsky Rise, surrounding magnetic lineations and fracture zones (heavy red lines; Nakanishi et al., 1999), Expedition 324 drill sites (red dots) and ODP Site 1213 (blue dot). Dark area at lower right shows the basal contour of Olympus Mons (Mars) at the same scale. Inset shows the location of Shatsky Rise relative to Japan.

Introduction

Large outpourings of basalt have occurred widely around the globe (Coffin and Eldholm, 1994). The greatest of these "large igneous provinces" (LIPs) produced continental flood basalts on land and oceanic plateaus under the sea (Duncan and Richards, 1991), the largest with volumes in millions of cubic kilometers. Plateau-building magmas must come from the mantle, but source depth and emplacement mechanisms are unclear. A widely held view is that plateaus form when the head of a nascent mantle plume—a huge thermal diapir from the lower mantle—rises to the surface, causing massive volcanic eruptions and sub-crustal intrusion (Duncan and Richards, 1991). An alternative explanation is that plateau eruptions come from decompression melting of unusually fusible upper mantle at plate edges (Foulger, 2007). This explanation is bolstered by the observation that many plateaus formed near ocean ridges, especially at triple junctions, a situation that is unlikely if the volcanism results from deep mantle convection independent of plate tectonics (Sager, 2005).

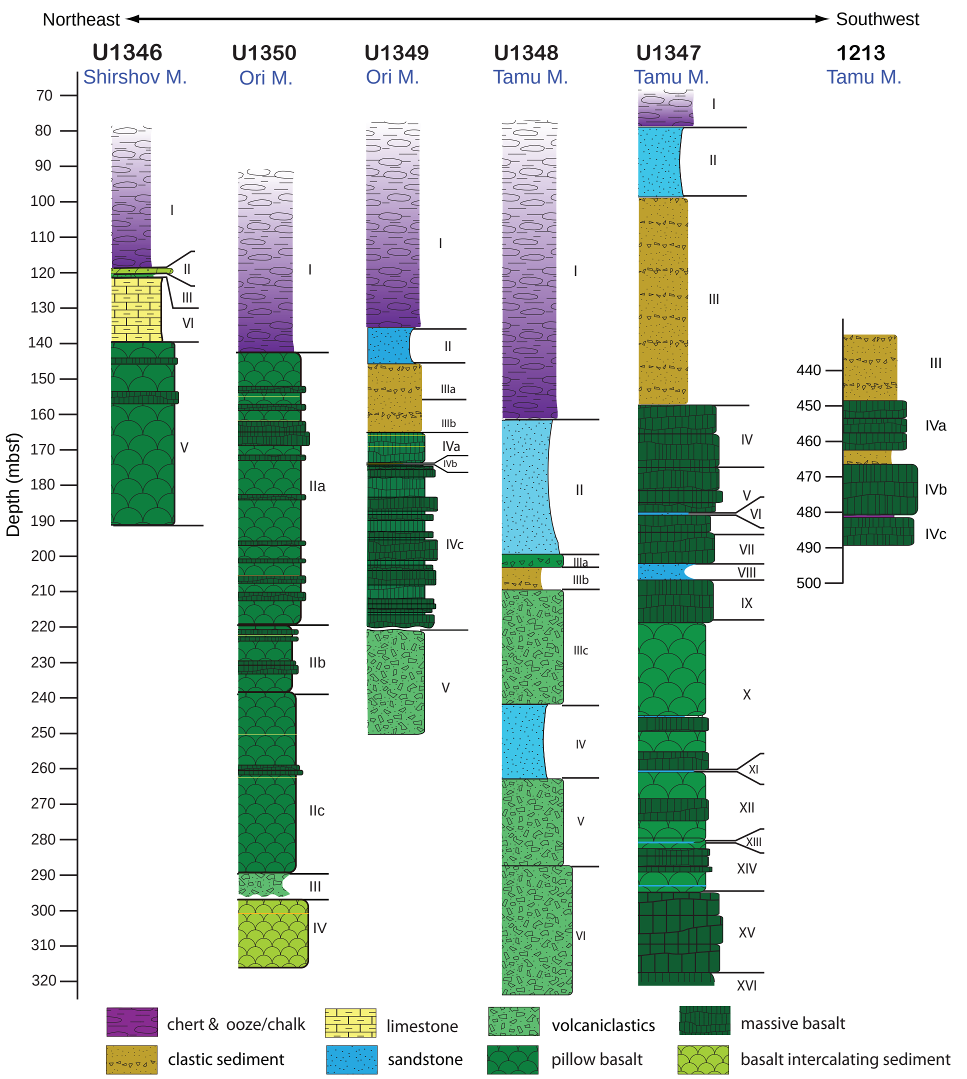

Figure 2. Lithology of Shatsky Rise drill sites, showing both basal sediment and igneous sections. Sites are arranged in transect order, from northeast (left) to southwest (right). Site 1213 from ODP Leg 198 (Shipboard Scientific Party, 2002) is shown at the same scale for completeness. Roman numerals indicate lithologic units, which are described in the Expedition Reports (Sager et al., 2010).

Aside from uncertainty about source mechanism, the processes of ocean plateau volcanism are poorly understood because few plateaus have been sampled extensively. Massive eruptions are deduced mainly from the size of plateau edifices coupled with inferred short eruption periods (Coffin and Eldholm, 1994). In addition, it is suggested that low oceanic plateau flank slopes imply high eruption rates and long flows similar to continental flood basalts (Keszthelyi and Self, 1998; Sager et al., 1999). Ocean Drilling Program (ODP) cruises have sampled the largest oceanic plateaus, Kerguelen (Leg 183; Coffin et al., 2002) and Ontong Java (Leg 192; Mahoney et al., 2001), and they have found that massive lava flows are common. A problem for these studies is that these plateaus formed mostly during the Cretaceous Quiet Period when there were no magnetic reversals to record the positions of mid-ocean ridges, so it is unclear how plate boundaries may have factored into their formation (Sager et al., 1999).

In contrast, Shatsky Rise (Fig. 1) is a large Pacific plateau (area ~4.8 x 10^5 km^2; Sager et al., 1999) with a clear tectonic setting. It erupted at a triple junction during the late Jurassic and Early Cretaceous and stretches over ~1700 km with three principal volcanic massifs: Tamu, Ori, and Shirshov (Fig. 1; Sager et al., 1999). Tamu Massif erupted at ~145 Ma (Mahoney et al., 2005). Other volcanic edifices must be younger than Tamu Massif because the lithosphere on which they repose is younger. Furthermore, isostatic compensation and interaction with spreading ridges imply that these edifices formed at the time the lithosphere was created, which means they are younger toward the northeast (Sager et al., 1999). Although some aspects of Shatsky Rise appear consistent with the plume head hypothesis, others are not. Emplacement apparently began with the construction of a huge volcanic edifice, Tamu Massif (~2.5 x 10^6 km^3), which possibly erupted in <1 Myr, coincident with an ~800-km jump of the triple junction (Nakanishi et al., 1999; Sager et al., 1999; Sager, 2005). Tamu Massif appears to be a large, central "supervolcano" with an area similar to that of Olympus Mons on Mars (Fig. 1), which is widely considered the largest volcano in the solar system. Subsequent volcanoes (Ori and Shirshov massifs) are significantly smaller (each ~25% the size of Tamu Massif), and together with a low volcanic ridge at the north end of the plateau, they may imply a transition from plume head to tail (Sager et al., 1999). Apropos of plate-edge genesis, Shatsky Rise displays a connection with triple junction tectonics that is repeated elsewhere in the Pacific (Sager, 2005). Moreover, basalts from ODP Site 1213 (ODP Leg 198), on Tamu Massif (Fig. 1), have isotopic characteristics similar to mid-ocean ridge basalt (MORB) (Mahoney et al., 2005).

Shatsky Rise was cored on IODP Expedition 324 because it has characteristics that can be attributed to both a mantle plume and ridge tectonics; thus, it is an excellent location to investigate the formation of oceanic plateaus. Here, we present a review of initial findings and insights from cores and logs collected during Expedition 324.

Drilling Overview

Expedition 324 drilled at five sites on Shatsky Rise (Fig. 1; Sager et al., 2010) to examine changes in volcanism along the presumed age trend. Site U1347 was cored to 317.5 m below the seafloor (mbsf), including 159.9 m of igneous basement consisting of submarine basalt flows (Fig. 2). This site and Site 1213, which penetrated 46.6 m of basalt on ODP Leg 198 (Shipboard Scientific Party, 2002), both sampled the upper flanks of Tamu Massif, the oldest edifice. Drilling at Site U1348, on the north flank of Tamu Massif, targeted a large basement high, recovering a ~120-m-thick section of highly altered volcaniclastic sediments. Farther north, sites U1349 and U1350 were situated to sample the summit and flank of Ori Massif. Drilling at Site U1349 penetrated to 250.4 mbsf and 85.3 m into igneous basement, recovering highly altered subaerial or shallow-water lava flows. At Site U1350, coring proceeded to 315.8 mbsf, with the last 172.7 m being in a section of slightly to moderately altered submarine lava flows. On the Shirshov Massif summit, Site U1346 penetrated to 191.8 mbsf, coring 52.6 m of moderately to highly altered basalt flows.

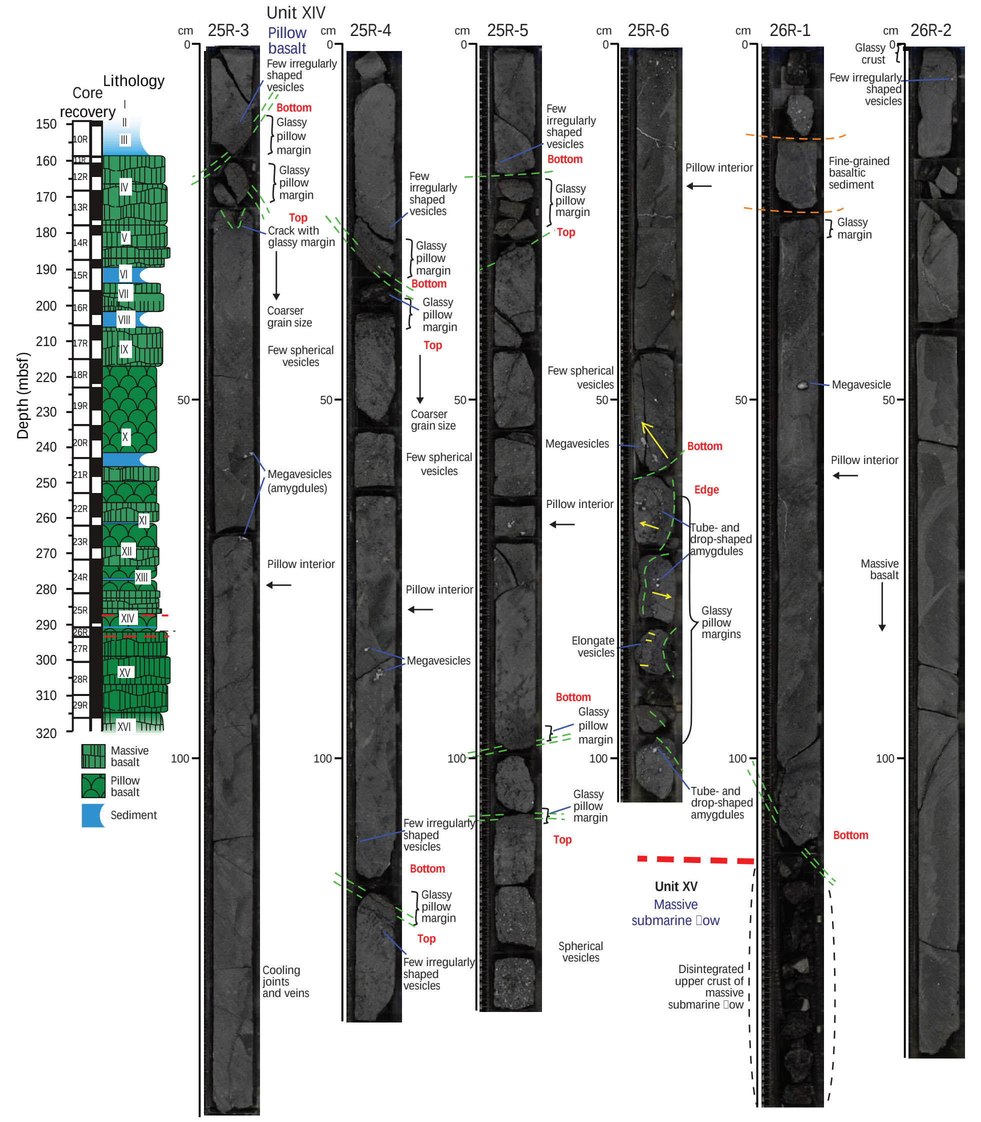

Figure 3. Core images showing pillow lavas and massive flows from Site U1347. The images are annotated with volcanological features and show a section spanning the transition between the lower pillow basalts (Unit XIV) and upper part of a massive basalt flow (Unit XV) from Sections 324-U1347A-25R-3 through 26R-2, Hole U1347A. Red dashed lines = lithologic unit boundaries, red text = top and bottom of pillow lobes, dashed green lines = glassy chilled margins. Dashed lines in lithologic column (left) show location of core sections portrayed.

Igneous Rocks

The signature structures of igneous rock sections cored on Shatsky Rise are pillow lavas 0.2–1.0 m in diameter and massive inflation flows up to 23 m thick (Figs. 2, 3). Both types of cooling units were distinguished in cores by the presence of chilled margins and internal vesicle patterns. Pillows are typical of submarine eruptions at low effusion rates and are often found on seamounts and mid-ocean ridge flanks (Ballard et al., 1979). Massive flows are characteristic of continental flood basalt provinces, and they indicate a high effusion rate (Jerram and Widdowson, 2005). They are formed by inflation of the massive interior as an elastic skin develops on the upper and lower chilled margins (Self et al., 1997). Similar massive flows were cored at ODP Sites 1185 and 1186 on the Ontong Java Plateau (Mahoney et al., 2001). In addition, we reinterpret three igneous units cored at Site 1213 on Tamu Massif, previously thought to be sills (Shipboard Scientific Party, 2002), as massive flows 8–15 m thick (Fig. 2; Koppers et al., 2010).

The pattern of igneous activity appears to change across Shatsky Rise. At Tamu Massif, massive flows dominate. The Site U1347 section consists of two pulses of massive flows separated by a ~75 m interval of mostly pillow flows. In total the igneous section contains ~33% pillows. This section is almost indistinguishable from that cored on Ontong Java Plateau at Site 1185. Approximately 220 km away at Site 1213, only massive flows were recovered. On the north side of Shatsky Rise at Shirshov Massif, the Site U1346 section is 90% pillows, with only two larger cooling units (1.9 m and 3.2 m thick) recognized. In between, at Ori Massif, the proportion of massive units appears intermediate. No pillows were recognized in the short Site U1349 section, but the thin massive flows there were emplaced near or above sea level, and none approaches the thickness of those on Tamu Massif. The Site U1350 section contains a mixture of flow types but consists of ~86% pillow units, and massive units are intermediate in thickness (≤6 m). It thus seems that volcanism at Tamu Massif was unusually effusive, with activity typical of the largest ocean plateaus and flood basalts, but the effusion rate apparently waned with time such that flow characteristics on Ori and Shirshov Massifs were similar to those of large seamounts, such as the Emperors (Tarduno et al., 2002).

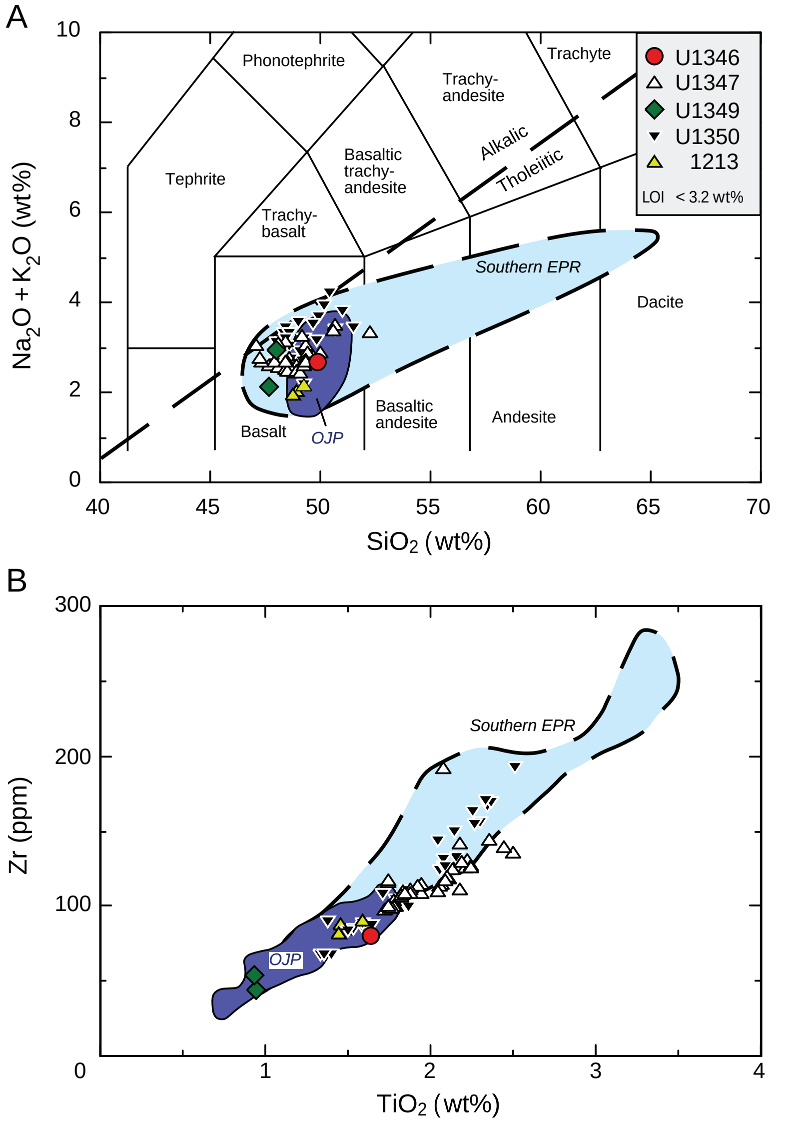

Figure 4. Chemical characteristics of Shatsky Rise basalt samples. [A] Total alkalis vs. silica for least-altered samples with rock classification of Le Maitre et al. (1989). Dashed line divides Hawaiian tholeiitic and alkalic lavas. All data are normalized to 100 wt% totals. [B] TiO_2 vs. Zr. Site 1213 data are from Mahoney et al. (2005). OJP = Ontong Java Plateau (data of Tejada et al., 1996, 2002; Fitton and Godard, 2004), EPR = East Pacific Rise (data of Sinton et al., 1991; Bach et al., 1994; Mahoney et al., 1994).

Cores from Site U1348 imply that explosive volcanism played an important role in building Shatsky Rise. The ~120-m-thick igneous section at that site consists almost entirely of compacted, highly altered volcanic glass fragments, ranging from principally submarine hyaloclastite to redeposited volcaniclastic turbidites (Fig. 2). This finding suggests that other basement highs and cones are composed of similar volcaniclastic materials.

The majority of igneous rocks from Sites U1346, U1347, U1348, and U1350 are plagioclase-clinopyroxene (micro) phyric basalts. The least-altered basalts (recognized by <3.2 wt% volatile loss on ignition, LOI) are from Sites U1346, U1347, and U1350, and are variably evolved tholeiites (Fig. 4). Similar to basalts from Site 1213 (Mahoney et al., 2005), their compositional ranges overlap those of MORB and Ontong Java Plateau basalts. Overall, they are slightly enriched in incompatible elements compared to normal MORB, showing some resemblance to enriched-type MORB. In contrast, lavas from Site U1349 are Cr-spinel-bearing, olivine-phyric basalts that appear to represent significantly less differentiated magmas than those recovered from other sites (Fig. 4).

Alteration of Shatsky Rise igneous rocks follows a pattern tied to basement elevation. The three sections from the rise flanks (Sites 1213, U1347, U1350) all exhibit low to moderate levels of alteration resulting from low-temperature interaction with seawater-derived fluids in anoxic to sub-oxic conditions. In contrast, the three sections cored at high points (Sites U1346, U1348, U1349) are highly altered, and in each case the alteration appears different. Site U1346 alteration is similar to that at the flank sites, but greater in degree. Although most samples are affected by low-temperature alteration, a few samples contain pyrite, which may be indicative of interaction with S-rich hydrothermal fluids. Site U1348 hyaloclastites are all highly altered, mostly converted to palagonite and cemented with calcite and/or zeolites. Basalts recovered at Site U1349 were affected by extensive water-rock interactions at varying temperatures and redox conditions with depth. Some samples from this site appear to record alteration under subaerial, oxidative conditions. The common aspect of all three sites, aside from being at bathymetric highs, is that the alteration implies significant fluid flow.

Sediments and Sea Level

In previous drilling, Shatsky Rise sediments were found to be dominantly pelagic carbonate sediments (ooze, chalk, limestone) with chert in the Mesozoic section. Expedition 324 drilling recovered a variety of sediment types from four of five sites (Figs. 2, 5) providing clues about depositional environments during and shortly after the formation of the volcanic basement, including the finding that some sites were near sea level during deposition. This is true for both sites on Tamu Massif. Radiolarian-bearing volcaniclastic siltstone and sandstones were cored in the 77 m above the top of basement at Site U1347. These sediments are marked by high content of zeolite and volcaniclastics; they display cross-bedding and intense bioturbation and contain a neritic (<200 m water depth) assemblage of benthic foraminifera. At Site U1348, calcareous sandstones with bioclasts (including material from reef-building fauna), volcanic fragments, and zeolitic clay were recovered. Both sections imply deposition in shallow water near a volcanic source. These findings are consistent with shallow water fossils that were recovered in a dredge haul at a similar depth ~140 km southwest of Site U1347 (Sager et al., 1999).

Site U1349 on the Ori Massif summit yielded volcanic sandstone, siltstone, claystone, and breccia in the ~30 m above igneous basement. At the bottom of this interval, a yellow-red clay layer of intensely-weathered basalt fragments, interpreted as a paleosol, indicates probable subaerial exposure under tropical conditions. The presence of montmorillonite and halloysite in this layer also support the interpretation of subaerial conditions. Only ~10 m deeper in the section, an oolitic limestone between lava flows implies a shallow marine environment. No significant non-pelagic sediment was recovered above basement at Site U1350 on the deep Ori Massif flank. Evidently, this site was bypassed by all but pelagic sediment.

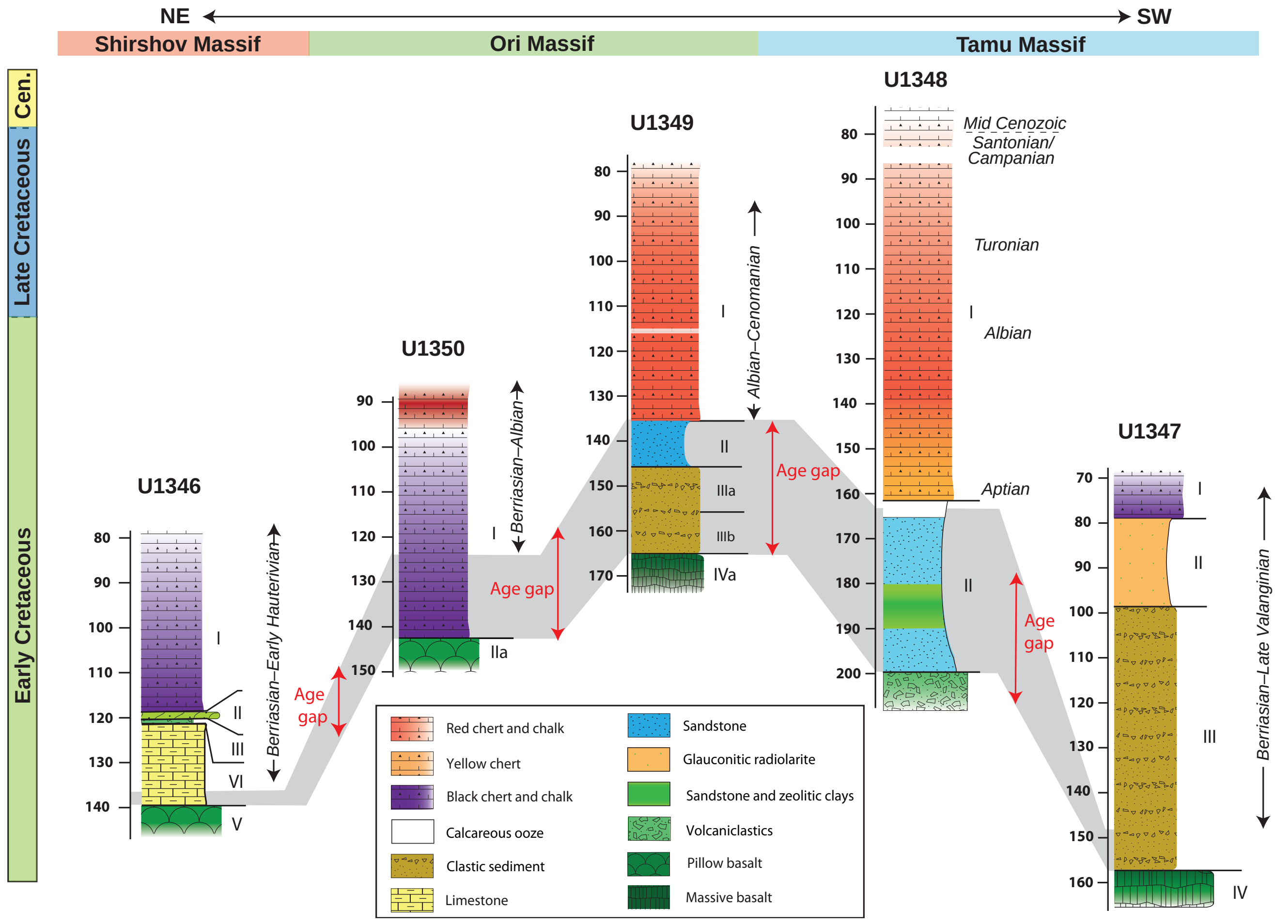

Figure 5. Overview of basal sediment lithology at Expedition 324 sites. Columns are arranged in geographical order from northeast (left) to southwest (right). Ages were deduced from biostratigraphy, as indicated to the right of each column. Vertical position is an indication of biostratigraphic age (left column). Gray band shows the gap between the oldest dated sediment and basement at each site.

At Site U1346 on Shirshov Massif the bottom ~17 m of the sediment column consists of clayey limestones and calcareous mudstone containing abundant shell fragments, a neritic (<500 m water depth) benthic foraminiferal assemblage, and small, probably wood fragments. These sediments are overlain by a short interval of fine-grained volcaniclastic turbidites and a debris flow of intermingled basalt and limestone showing soft-sediment deformation. Altogether, these observations are consistent with deposition in shallow water near forested, volcanic land and subsequent progressive deepening as the volcano subsided.

Sedimentary layers were found intercalated with basalt flows at Sites U1347, U1349, U1350 and at ODP Site 1213 (Shipboard Scientific Party, 2002). At Site U1347, three layers are ~4.5–5.0 m thick, but all other sedimentary interbeds at this and other sites are much thinner. In general, the interbeds consist of carbonate debris or volcaniclastic sandstone or siltstone, often containing fossil radiolarians. Although we have no reliable age progression data to define sedimentation rates of any interbeds, it appears that all were deposited over relatively short periods, implying that hiatuses between lava flows were of short duration, consistent with rapid emplacement of the igneous sections.

Implications

Although cores from Expedition 324 and prior drilling represent only a small sampling, they provide a clearer picture of Shatsky Rise's geology and give insights for other plateaus. Prior to Expedition 324, we knew that Shatsky Rise must be largely basaltic, but the style of volcanism was unknown. Virtually all sediments previously cored from Shatsky Rise were pelagic, so there was little information about other sedimentary environments or the role of explosive volcanism. Scant evidence existed that the summit of Tamu Massif was originally near sea level. Modestly-altered samples of igneous basement were available from only one site (1213); they exhibited isotopic characteristics similar to MORB (Mahoney et al., 2005), and were described as representing sills. Such characteristics seemed unusual, and their significance was unclear.

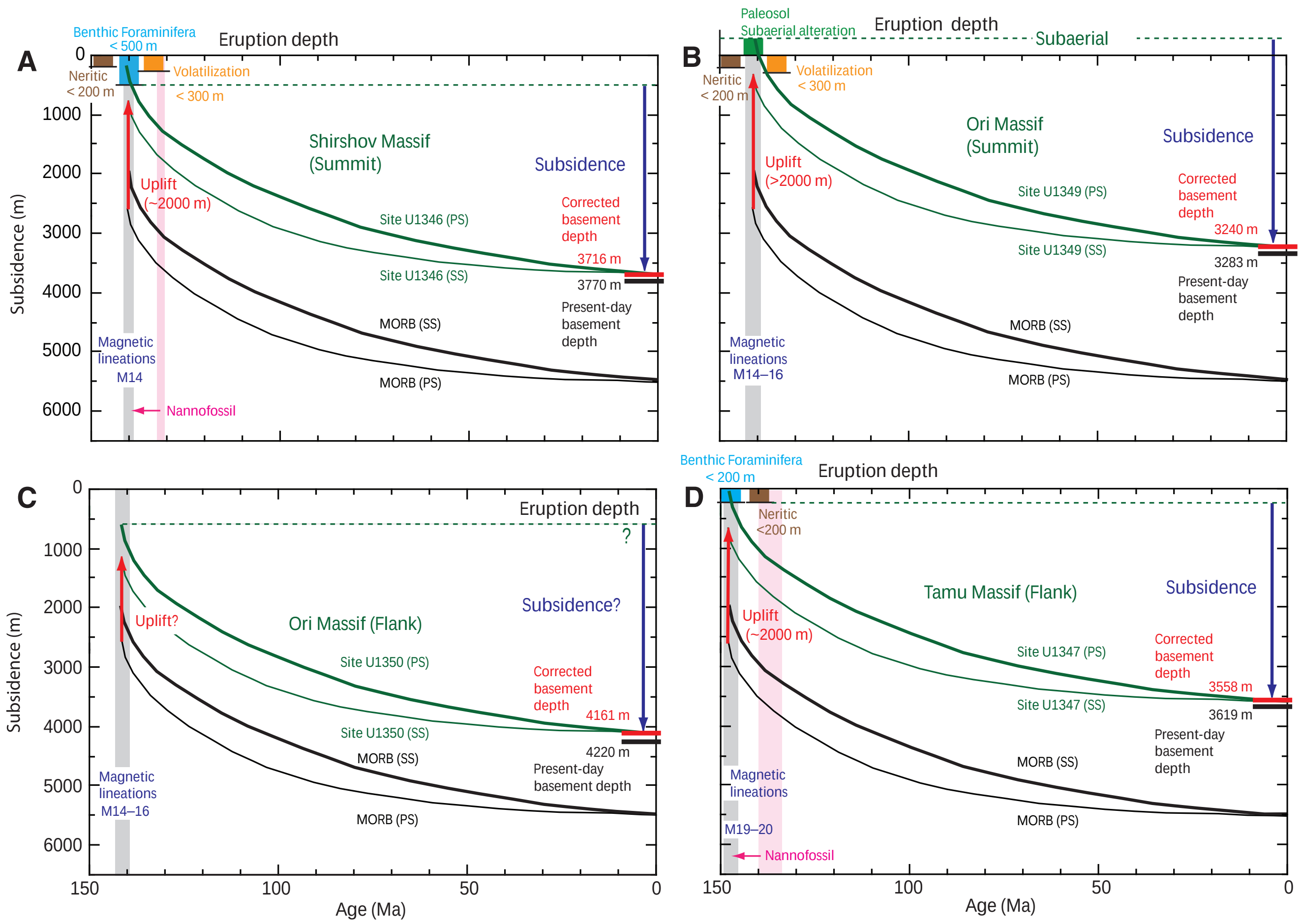

Figure 6. Subsidence curves calculated for Expedition 324 Sites. [A] Site U1346 (Shirshov Massif summit). [B] Site U1349 (Ori Massif summit). [C] Site U1350 (Ori Massif flank). [D] Site U1347 (Tamu Massif flank). Colored curves = extrapolated site depth at the time of eruptions, calculated by backtracking from the present depth (corrected for sediment loading; Crough, 1983) using thermal subsidence models. PS = Parsons and Sclater (1977) model, SS = Stein and Stein (1992) model. Paleodepth estimates from backtracking are compared with paleodepth indicators from Expedition 324 cores. Black curves = subsidence models for normal mid-ocean ridges, red arrow = difference between normal ridge and observed paleodepth, taken as the amount of uplift caused by volcano construction. Magnetic lineation ages are from Nakanishi et al. (1999) using the time scale of Gradstein et al. (2004).

Expedition 324 provided samples of igneous basement at four new sites, and broadly MORB-like characteristics appear general. Massive flows are found at several locations, and the thickest and greatest percentage of total section are found on Tamu Massif, which is characterized by massive flows similar to those found in continental flood basalt provinces (Jerram and Widdowson, 2005) and Ontong Java Plateau (Mahoney et al., 2001). Because of its large size, shape, and style of volcanism, Tamu Massif appears to be a "supervolcano". It suggests that other oceanic plateaus may have formed from similarly colossal volcanoes. In contrast, massive flows are thinner and less abundant at Ori and Shirshov massifs, whose size and eruption style were probably similar to those of the present island of Hawaii—that is , big but not deserving of superlatives.

Expedition 324 cores suggest that the summits of Shatsky Rise volcanoes were near sea level or perhaps emergent. The large interior of the Tamu Massif summit may have been emergent, perhaps with significant elevation because the basal sediments of Site U1347 were deposited in shallow water, but the top of the volcano is ~800 m shallower. Site U1349, with evidence of both shallow water and emergence, suggests that the summit of Ori Massif was at the water's edge. Site U1346, located at the edge of a summit platform on Shirshov Massif, also indicates shallow-water sedimentation and implies that volcanic cones in the interior may have been emergent. It is likely that the plateau formed one or more islands through the late Jurassic and Early Cretaceous, but their size and duration are unclear. Backtracked subsidence curves for the sites (Fig. 6) show that the present depth of the top of igneous basement is consistent with that predicted by normal lithospheric subsidence. If there was dynamic uplift during plateau formation, for example, owing to the arrival of a plume head (Coffin and Eldholm, 1994), there is no evidence of it now.

Site U1348 provided a surprise with a thick pile of highly altered hyaloclastite. Prior to Expedition 324, no significant accumulation of such sediment had been recovered from Shatsky Rise. The finding of this material should not be a surprise, given that it is common on seamounts (Smith and Batiza, 1989). The large basement ridge at Site U1348, thought to be the top of a fault block, consists wholly or in part of the products of explosive submarine volcanism. With this discovery, it seems likely that many of the basement highs imaged on seismic sections (Sager et al., 1999) have a similar origin.

The extent of alteration of igneous basement was also a surprise. We thought it was possible to obtain relatively unaltered samples by drilling through the weathered carapace, but heavy alteration occurred throughout the three higher-elevation igneous sections (U1346, U1348, U1349). This finding implies that fluid circulation at the summits of the volcanic edifices was pervasive. Whether this is a result of proximity to sea level, to heat concentration, or of the volcanic structure is unclear. In contrast, flank flows appear to have been armored by subsequent flows, restricting fluid flow and consequent alteration.

Results now available from Expedition 324 are mainly physical descriptions of the processes of volcanism, sedimentation, and evolution of the Shatsky Rise plateau. Resolution of what caused Shatsky Rise formation is not yet feasible but should be closer after careful studies of the recovered samples, especially those involving high-precision age determination and isotopic and geochemical characterization of the igneous basement. Whatever mechanism is called upon to generate this plateau, it must explain the fact that initial eruptions built an enormous volcanic edifice with massive lava flows and rose to sea level during edifice building and subsided normally thereafter. Expedition 324 results also indicate that different parts of oceanic plateaus can have different styles of eruption, with some having characteristics similar to that of normal seamount volcanism elsewhere.

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IODP Expedition 325: Great Barrier Reefs Reveals Past Sea-Level, Climate and Environmental Changes Since the Last Ice Age

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Abstract

The timing and courses of deglaciations are key components in understanding the global climate system. Cyclic changes in global climate have occurred, with growth and decay of high latitude ice sheets, for the last two million years. It is believed that these fluctuations are mainly controlled by periodic changes to incoming solar radiation due to the changes in Earth's orbit around the sun. However, not all climate variations can be explained by this process, and there is the growing awareness of the important role of internal climate feedback mechanisms. Understanding the nature of these feedbacks with regard to the timing of abrupt global sea-level and climate changes is of prime importance. The tropical ocean is one of the major components of the feedback system, and hence reconstructions of temporal variations in sea-surface conditions will greatly improve our understanding of the climate system. The Integrated Ocean Drilling Program (IODP) Expedition 325 drilled 34 holes across 17 sites in the Great Barrier Reef, Australia to recover fossil coral reef deposits. The main aim of the expedition was to understand the environmental changes that occurred during the last ice age and subsequent deglaciation, and more specifically (1) establish the course of sea-level change, (2) reconstruct the oceanographic conditions, and (3) determine the response of the reef to these changes. We recovered coral reef deposits from water depths down to 126 m that ranged in age from 9,000 years to older than 30,000 years ago. Given that the interval of the dated materials covers several paleoclimatologically important events, including the Last Glacial Maximum, we expect that ongoing scientific analyses will fulfill the objectives of the expedition.

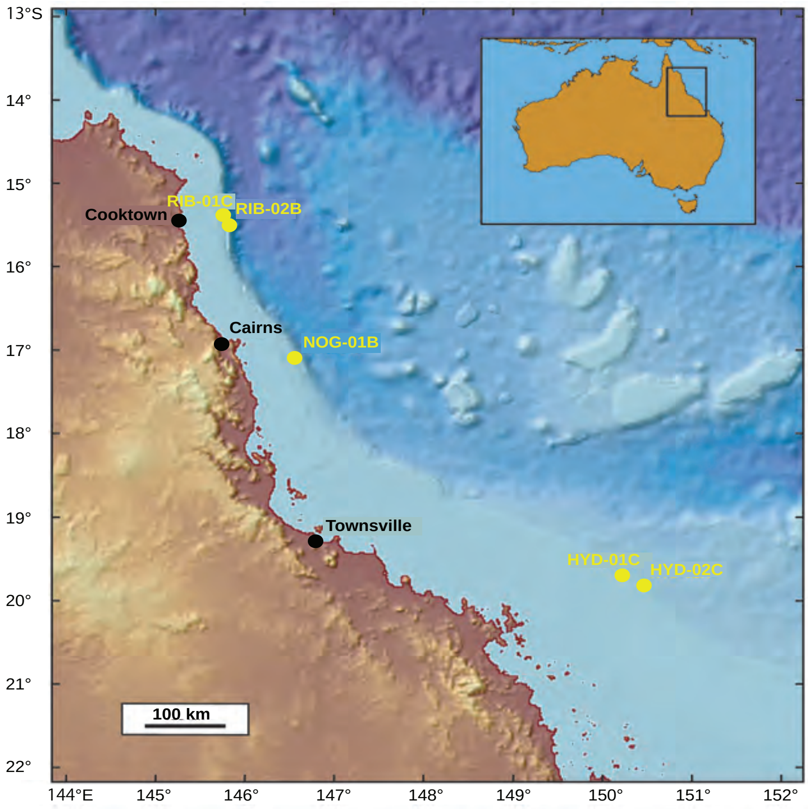

Figure 1. Map showing the locations of drilling sites.

Introduction and Goals

The most prominent feature of the current geological era (Quaternary) is the reoccurrence of glacial and interglacial periods. Waxing and waning of the ice sheets across the North American continent as well as northern Eurasia have been recorded. The Antarctic ice sheet, currently the largest ice sheet on Earth, was larger during the glacial times, with an estimated 10–30 m sea-level equivalent stored in global ice volume during the last glacial maximum at about 20 ka (CLIMAP, 1981; Denton and Hughes, 1981; Nakada and Lambeck, 1987; Yokoyama et al., 2001a, 2001b; Ivins and James, 2005). These ice sheets have been a key component in the global climate system due to their locations and size, as well as their ability to release freshwater into the high latitude ocean during melting. Global climate is regulated by ocean circulation, namely thermohaline circulation (THC), which starts in the high latitude oceans where dense and cold deepwater is formed due to the rapid cooling of the saline and warm Gulf Stream. In turn, the input of freshwater from the melting of ice sheets can strongly influence the strength of thermohaline circulation and

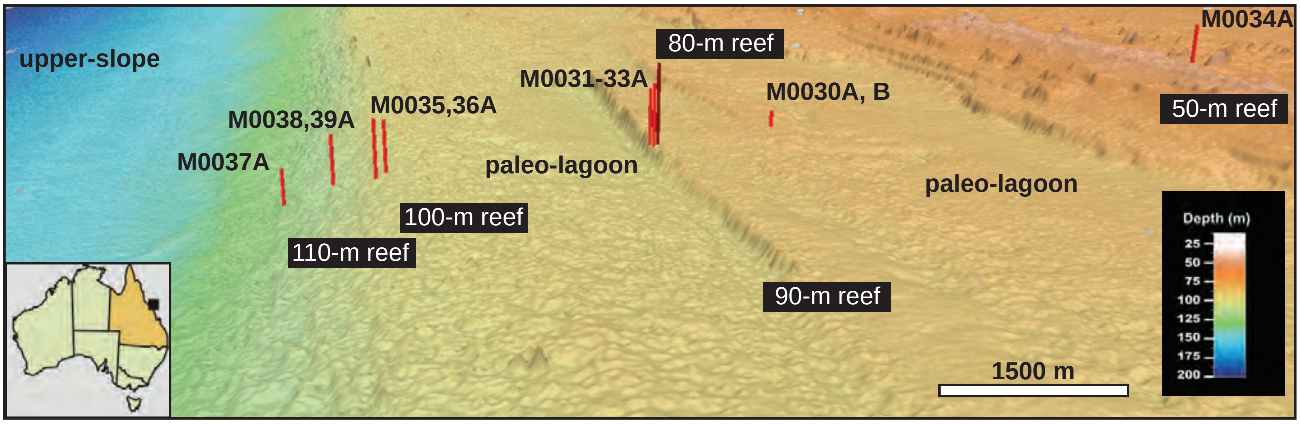

Figure 2. High-resolution multibeam image of Hydrographers Passage transect HYD-01C (multibeam data after Bridge et al., 2011; Abbey et al., submitted). The bathymetry data is gridded at 5 m, and the vertical red lines represent the positions and approximate penetration depths of sites M0030A–39A.

thus drive global climate perturbations (Broecker, 1994; Alley, 1998).

Sophisticated, fully coupled Atmosphere and Ocean General Circulation Models (AOGCM) now predict significant increases in sea surface temperature (SST) by year 2100 due to the release of anthropogenic greenhouse gases and associated atmospheric temperature increase, while ocean acidification, due to higher atmospheric CO_2 concentrations and increased solubility in the oceans, may influence large areas of the ocean basins (Solomon et al., 2007). Ice-sheet instability due to increasing temperatures is also anticipated. However, significant uncertainties associated with these model projections remain, and improvement using paleo-data is crucial. Particularly important are the Last Glacial Maximum (LGM: ca. 20 ka; Mix et al., 2001) and subsequent deglaciation (starting from 19 ka; Yokoyama et al., 2000b; Clark et al., 2009), including Bølling-Allerød, Younger Dryas and Heinrich events (Yokoyama, 2011a, 2011b), as the changes observed from LGM to the present day represent the most recent major global climate reorganization under natural climate forcing (Yokoyama and Esat, 2011).

Corals offer the opportunity to reconstruct past environmental information including sea-level and paleoceanographic changes. Reef building corals live in shallow water, and as they secrete their calcium carbonate skeletons, they encapsulate important oceanographic information such as sea-surface temperatures (SST), sea-surface salinity (SSS), and upwelling intensities. Corals are also the only marine calcifying organisms with a closed uranium series system (Stirling and Andersen, 2009), allowing the precise timing of past environmental events to be established (Edwards et al., 1987; Stirling et al., 1995; Gallup et al., 2002). Coupled with precise radiocarbon dating, these U/Th measurements allow the calibration of radiocarbon chronological data to calendar years (Bard et al., 1990; Edwards et al., 1993; Yokoyama et al., 2000a; Reimer et al., 2004; Fairbanks et al., 2005; Esat and Yokoyama, 2008). Massive *Porites* coral grow 1–2 cm annually, and their growth bands allow high temporal resolution (monthly to seasonally) to be made on environment reconstructions (Gagan et al., 1998; Cole et al., 2000; Tudhope et al., 2001; Abram et al., 2008; Felis et al., 2009). Geochemical analyses (stable isotopes, trace elements) of these growth bands allow us to reconstruct seasonal to multi-decadal ENSO signals that can contribute to understanding the natural variability of the climate system.

The Great Barrier Reef (GBR) is the world's largest reef, extending 2000 km laterally northwest-southeast (Davies et al., 1989). Timing of the reef building is proposed to have started around 0.4–0.5 million years ago (Alexander et al., 2001), which coincides with the Mid Pleistocene Climate transition (MPT) (Hays et al., 1976; Clark et al., 2006) or Marine isotope stage (MIS 11; Webster and Davies, 2003). MIS 11 is known as one of the "warmest" interglacials during the Quaternary, and a period when the 100-ka climate cyclicity between glacial to interglacial states was fully established along with higher sea-level amplitudes. Previous deep drilling investigations through the modern reef confirm that the evolution of the GBR has been strongly influenced by these environmental changes (Webster et al., 2008). Thus, investigating the shelf edge, where the GBR has tracked sea-level and climate change since the last ice age, will provide information about how the reef responded to environmental changes over millennial time scales.

The GBR is ideally situated for sea-level studies, as it is located on a passive margin and is far from former ice sheets (Fig. 1). Therefore, GBR sea-level records can be accurately translated to the ambient ice volume variations due to smaller solid earth deformations caused by glacio-hydro-isostatic adjustments (GIA; Nakada and Lambeck, 1987; Yokoyama et al., 2001a, 2001b; 2006; Lambeck et al., 2002; Milne et al., 2009; Yokoyama and Esat, 2011). After correcting the GIA effect, changes in sea level can be directly translated to ice volumes, meaning that the GBR provides the opportunity to remotely monitor the magnitude and timing of ice sheet fluctuations. Located in the southern margin of the Western Pacific Warm Pool (WPWP), the GBR is also well positioned to investigate the role of the tropical Pacific in the climate system. Fossil coral samples from the region can be used to constrain the temporal variations of size of the WPWP and mean temperature with regards to the global climate change.

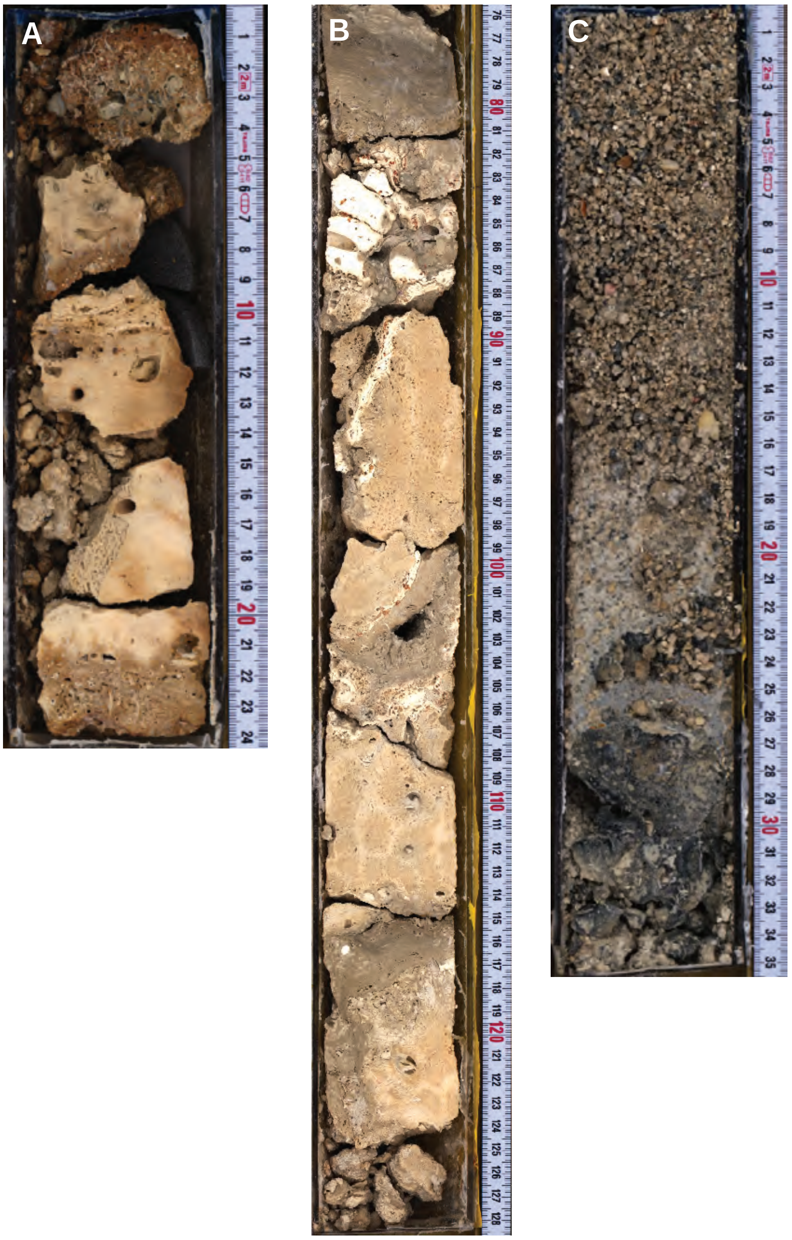

Figure 3. Representative litholostratigraphic succession from the fossil coral reef terraces (M0033A). The section was obtained from R1 (~90 mbsl) and contains coralgal boundstones typically found at the top of the reef structure [A]. Coralgal-microbialite boundstones were recovered from R5 (98 mbsl) from the same hole [B] and packstone together with unlithfied sediments sequence obtained from deeper part of the section (R21) at approximately 129 mbsl [C].

A diverse suite of fossil coral reef features were observed along the shelf edge of the GBR at 40–130 m depth during the site survey cruise (Fig. 1). The surface distribution and morphology of these reefs are described in detail elsewhere (Webster et al., 2008; Abbey and Webster, 2011; Abbey et al., submitted; Bridge et al., 2011; Webster et al., 2011). However, we present here a brief summary of the representative morphologic features defining transect HYD-01C on the Mackay shelf in Hydrographer's Passage and their drill sites (Fig. 2) to highlight their potential of recording reef growth back to at least the LGM. At this location a double-fronted barrier reef 200 m long and 100 m wide is observed, which is separated by a paleo-lagoon 2 km wide and as deep as 70 m. The barrier reefs occur at 55–51 m and were sampled by Hole M0034A. A steeply sloping 500-m-wide terrace with a sharp break in slope at 80 m defines the seaward expression of this feature. Following this, a complex 1-km-wide paleo-lagoon and reef terrace system is observed with prominent reefs at 80 m and 90 m that were sampled by M0030A, M0030B, and M0031-33A. Another 700-m-wide paleo-lagoon is observed grading into a complex system of reef pinnacles, terraces, and reefs down to the major break in slope at 100 m that defines the shelf edge. Here, M0035A and M0036A sampled the 100-m reef, and seaward of this M0037-39A intersected a series of smaller seaward reef pinnacles and terraces between 110 mbsl (meter below sea level) and 120 mbsl, before the seafloor grades into a gentle upper slope characterized by fore-reef slope sediments.

Following the success of the IODP 310 Tahiti drilling expedition (Camoin et al., 2007), detailed reconstructions have emerged of sea level (Deschamps et al., 2009; Thomas et al., 2009; Fujita et al., 2010), paleoclimate (Asami et al., 2009; DeLong et al., 2010; Inoue et al., 2010) and reef responses (Camoin et al., 2010; Abbey et al., submitted; Seard et al., 2011). However, due to the geometry of the flanks of Tahiti, IODP 310 did not recover a full range of the last deglaciation sequence older than ~16,000 years ago, in particular the LGM fossil reefs (Camoin et al., 2007). Therefore, details of reconstructions of sea level and paleoenvironments since the LGM are yet to be obtained.

The three main scientific objectives of Exp. 325 are as follows:

1) establish the course of sea-level rise during the last deglaciation (~20–10 ka) with a particular focus on the interval (>16 ka) not sampled by Exp. 310

Table 1. Operational summary of IODP 325

Hole	Latitude	Longitude	Water Depth (LAT from corrected EM 300 echo sounder data (m))	Water Depth (Drill string tagging seabed including predicted tidal variations (m))	Number of core runs	Interval cored (m)	Core recovered (m)	Core Recovery (%)	Penetration Depth SDF-A (m)	Hole recovery (%)	Time on Site (days)
M0030A	19.6819	150.2379	83.47	85.00	2	6.00	0.24	4.00	6.00	4.00	0.85
M0030B	19.6819	150.2379	83.47	85.00	3	9.00	0.55	6.11	9.00	6.11	0.40
M0031A	19.6790	150.2396	90.05	92.00	17	43.00	5.68	13.21	43.00	13.21	2.09
M0032A	19.6788	150.2397	91.58	93.00	20	36.70	5.99	16.32	36.70	16.32	1.15
M0033A	19.6789	150.2399	91.32	91.50	23	32.80	13.41	40.88	32.80	40.88	1.15
M0034A	19.6923	150.2303	51.00	55.00	16	23.10	6.71	29.05	23.10	29.05	3.19
M0035A	19.6726	150.2438	100.05	103.00	23	29.90	12.23	40.90	29.90	40.90	2.98
M0036A	19.6724	150.2440	103.21	103.00	22	34.00	8.91	26.21	34.00	26.21	1.77
M0037A	19.6707	150.2463	122.29	129.17	14	21.00	7.52	35.81	21.00	35.81	0.83
M0038A	19.6716	150.2449	107.04	108.58	1	1.50	0.18	12.00	1.50	12.00	0.53
M0039A	19.6716	150.2449	107.04	108.58	21	28.40	10.39	36.58	28.40	36.58	1.02
M0040A	19.7963	150.4814	126.07	132.67	12	21.50	11.73	54.56	21.50	54.56	0.61
M0041A	19.7963	150.4815	126.58	132.67	12	22.10	10.06	45.52	22.10	45.52	0.55
M0042A	19.8440	150.4480	50.78	56.32	29	46.40	10.94	23.58	46.40	23.58	2.19
M0043A	19.7989	150.4794	102.93	107.88	23	35.00	6.04	17.26	35.00	17.26	0.85
M0044A	19.7985	150.4796	105.25	104.31	9	11.00	1.67	15.18	11.00	15.18	0.72
M0045A	19.7984	150.4976	105.25	105.01	4	14.60	0.00	0.00	14.60	0.00	0.24
M0046A	19.7985	150.4796	117.49	120.41	11	20.40	2.52	12.35	20.40	12.35	0.45
M0047A	19.7998	150.4789	99.12	100.51	14	33.20	3.79	11.42	33.20	11.42	0.56
M0048A	19.8012	150.4777	97.47	102.31	4	7.10	0.69	9.72	7.10	9.72	0.28
M0049A	15.4724	145.8237	97.63	98.61	2	3.50	0.77	22.00	3.50	22.00	0.24
M0049B	15.4724	145.8237	97.63	100.00	13	15.60	2.79	17.88	15.60	17.88	0.52
M0050A	15.4723	145.8237	97.63	98.20	6	10.50	1.87	17.81	10.50	17.81	0.27
M0051A	15.4721	145.8230	78.13	80.90	2	2.50	0.15	6.00	2.50	6.00	0.35
M0052A	17.1011	146.5763	97.63	103.70	1	1.40	1.30	92.86	1.40	92.86	0.25
M0052B	17.1011	146.5763	97.63	103.70	4	6.90	0.46	6.67	6.90	6.67	0.30
M0052C	17.1011	146.5763	97.63	106.80	2	1.90	0.10	5.26	8.80	5.26	0.22
M0053A	17.1012	146.5763	97.87	104.60	33	37.30	12.18	32.65	37.30	32.65	1.59
M0054A	17.1007	146.5767	107.23	110.33	6	9.30	2.23	23.98	18.72	11.91	1.06
M0054B	17.1007	146.5767	107.23	110.33	12	27.84	8.25	29.63	33.20	24.85	2.26
M0055A	17.1019	146.5747	87.33	93.06	10	28.50	10.00	35.09	31.29	31.96	0.89
M0056A	17.1022	146.5741	81.22	85.56	16	40.20	12.73	31.67	41.29	30.83	1.05
M0057A	17.1050	146.5640	42.27	47.67	16	40.60	19.00	46.80	41.78	45.48	1.30
M0058A	17.0973	146.5893	167.14	172.41	15	41.40	33.94	81.98	41.40	91.98	1.06

2) reconstruct the nature and magnitude of seasonal to millennial scale climate variability (e.g., SST, SSS)

3) determine the biologic and geologic response of the GBR to abrupt sea-level and climate changes.

In this report we present a first summary of the operations, preliminary sedimentologic, chronologic, petrophysical, paleomagnetic, and geochemistry results and their implications and discuss the future plans for the post-cruise science.

Operations

The drilling platform chosen for Exp. 325 was the *Greatship Maya*, an IMO Class II dynamically positioned vessel with geotechnical coring capability. Operations were conducted between 12 February and 6 April 2010 (Table 1). Cyclone Ului, combined with several serious technical difficulties (Webster et al., 2011), meant that total percent recovery of the GBR cores was lower than IODP 310 Tahiti Sea Level (57.5% for Tahiti, whereas 27.2% for GBR; Camoin et al., 2007; Webster et al., 2011).

The vessel was equipped with a large moon pool and Bluestone TT150 derrick, capable of handling 9-m string lengths, with a Foremost Hydraulic top drive and relative motion-compensating heave (2.5-m stroke cylinders). Wireline operation of the core barrel was conducted through the top drive. Deployment of the wireline logging tools was conducted through the mud valve at the top of the top drive, from the rooster box, providing a heave compensated platform from which to zero in the tools.

Two types of QDTech coring tools were carried: an extended nose corer (EXN; equivalent to the extended core barrel [XCB]), and a standard rotary corer (ALN; equivalent to the rotary core barrel [RCB]), along with four bottom-hole

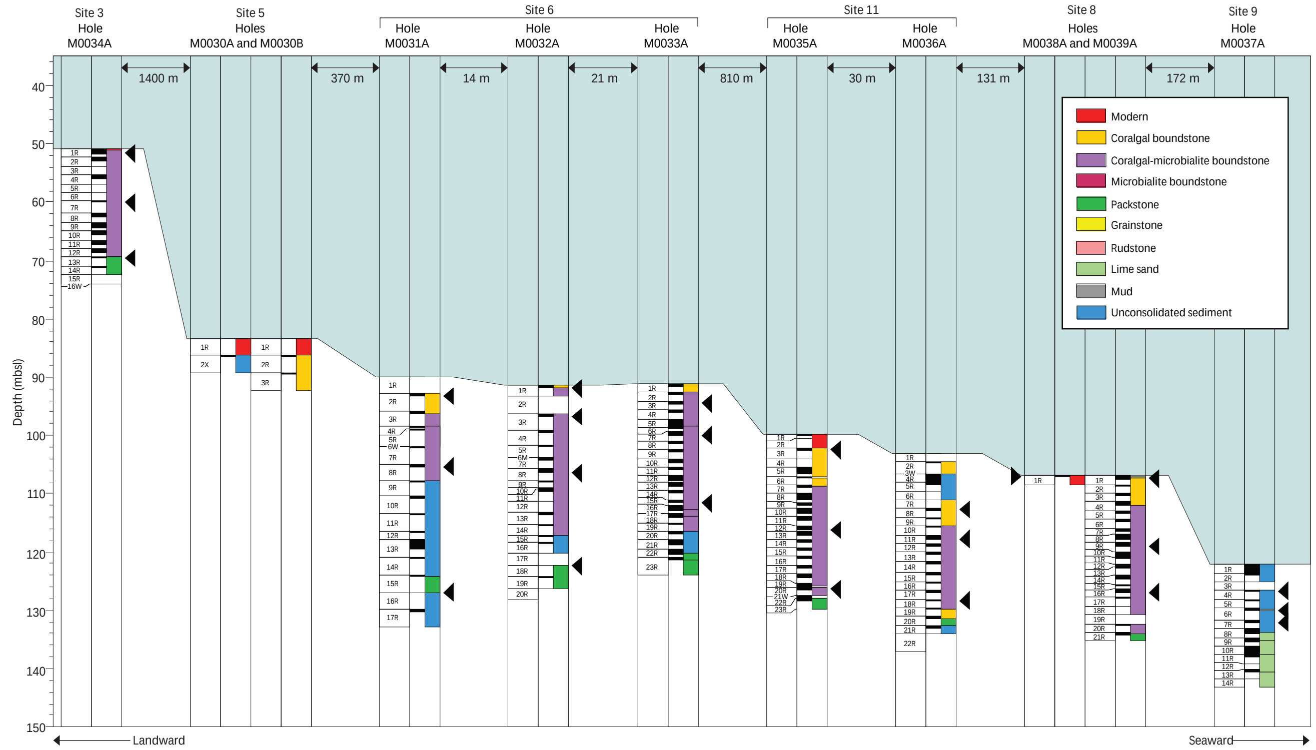

Figure 4. Lithostratigraphic summary of holes on the Transect HYD-02 (Sites from landward to seaward; M0034A, M0030A, M0030B, M0031A, M0032A, M0033A, M0035A, M0036A, M0038A, M0039A, and M0037A).

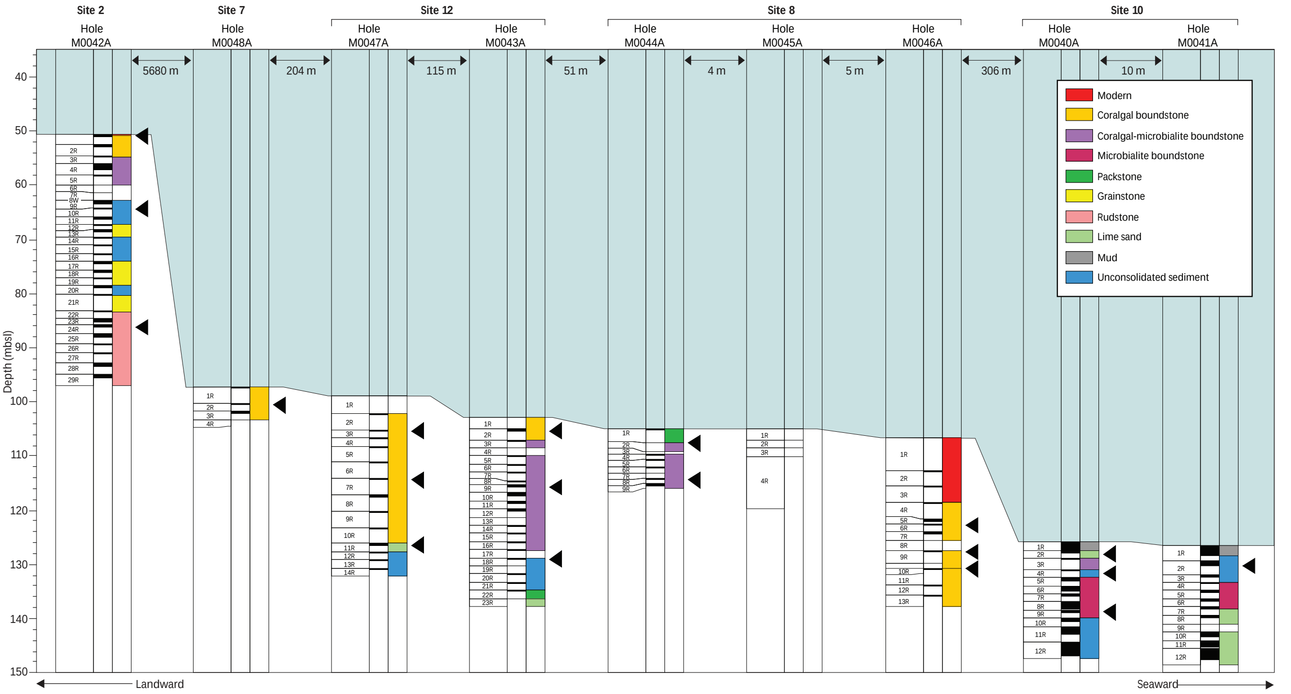

Figure 5. Lithostratigraphic summary of holes on the Transect HYD-01 (Sites from landward to seaward; M0042A, M0048A, M0047A, M0043A, M0044A, M0045A, M0046A, M0040A, and M0041A).

assemblies (BHAs), two each to fit the American Petroleum Institute (API) 4-inch-bore inner diameter string, and the Longyear HQ mining drill string.

At each site a pre-coring downpipe camera survey was conducted as part of the Environmental Management Plan agreed with the Great Barrier Reef Marine Park Authority (GBRMPA). Very strong bottom currents required the use of a seabed template to stabilize the drill string.

Offshore, the cores were carefully curated by ESO staff before ephemeral physical (multi-sensor core logger, MSCL), geochemical, and microbiological properties were measured and preliminary samples taken. Initial lithological and coral descriptions were conducted by visual inspection through the liner and using core catcher materials. No further sampling, core splitting, or analysis work was undertaken offshore.

All cores and data were transferred to the IODP Core Repository at Bremen, Germany (BCR) at the end of the offshore phase. Prior to the start of the Onshore Science Party (OSP), additional thermal conductivity measurements and computed tomography (CT) scans were undertaken on selected whole core sections. All the cores were assessed for the presence of massive corals, so as to instruct the core splitting procedure used. The complete Science Party plus ESO and BCR personnel and student helpers met at the BCR on 2–16 July to split, analyze, and sample the cores according to standard IODP procedures.

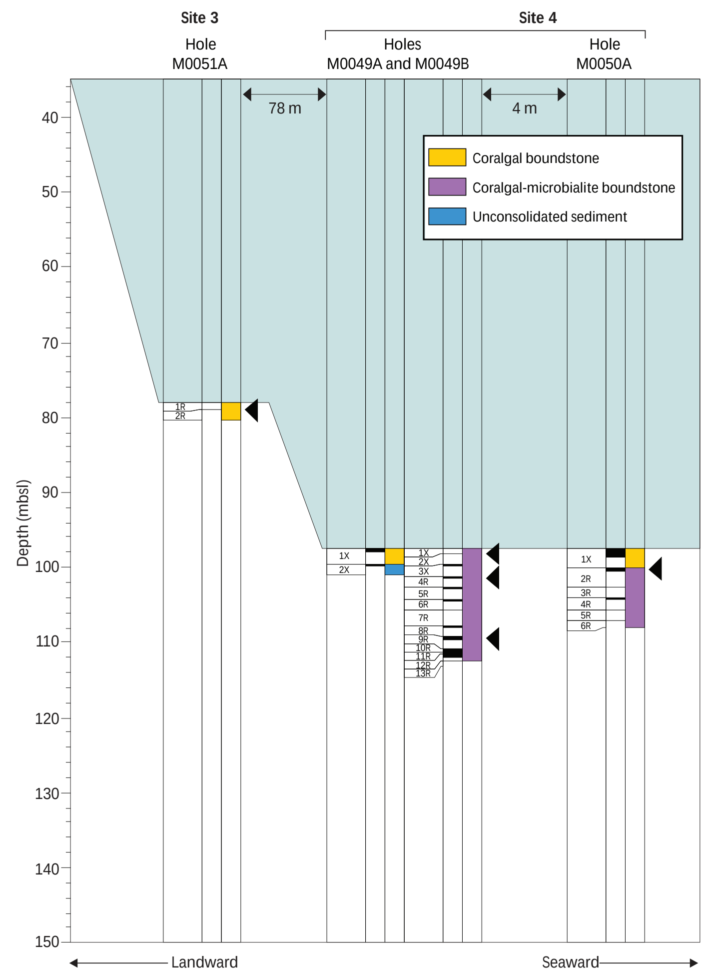

Figure 6. Lithostratigraphic summary of holes on the Transect RIB-02 (Sites from landward to seaward; M0051A, M0049A, M0049B, and M0050A).

Sedimentology

Sedimentological investigation of the cores was conducted during both the offshore and onshore phases of operations. Nine lithological types were recognized, and their main characteristics and distributions as distinct lithostratigraphic units are shown in Figs. 4–7 and summarized below.

Modern or sub-recent deposits consisting of lime sand to pebbles, locally in a muddy matrix, cover the boundstone lithologies at the top of a number of holes. Pebbles are made up of coralgal boundstone, coralline algae (some of them with reddish-pinkish color, indi-

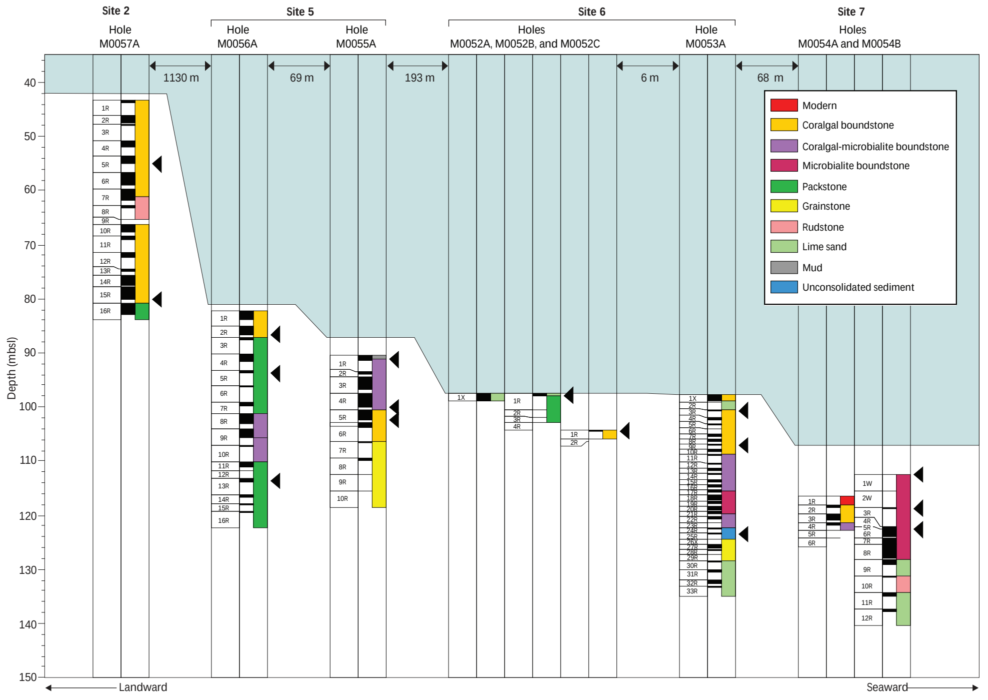

Figure 7. Lithostratigraphic summary of holes on the Transect NOG-01 (Sites from landward to seaward; M0057A, M0056A, M0055A, M0052A, M0052B, M0052C, M0053A, M0054A, and M0054B).

cating they were alive when recovered), serpulid worm tubes, mollusk shells and bryozoans. Some pebbles have brown staining. *Halimeda* have been identified, as well as larger benthic foraminifera (abundant and well-preserved or stained specimens of *Alveolinella, Amphistegina, Cycloclypeus,* Elphidiidae, *Heterostegina, Operculina,* and *Sphaerogypsina*).

Coralgal-microbialite and coralgal boundstones are the dominant lithologies in the recovered deposits (Fig. 3). The coralgal-microbialite boundstones, 10–30 m thick, are composed of corals partially coated by coralline algae and vermetids encrusted by microbialites, which volumetrically are the major component (Figs. 4–7). *Halimeda*, mollusks, benthic foraminifera, red algae, bryozoans, and echinoderms occur as pockets of internal sediment in the coralgal-microbialite frameworks. Coral assemblages are dominated by massive *Isopora,* branching *Acropora,* and *Seriatopora,* but massive *Porites* and *Faviidae* are locally abundant. *Hydrolithon onkodes* is the most abundant coralline alga, together with *Lithophyllum prototypum* and *Neogoniolithon fosliei*. *Amphistegina, Operculina, Heterostegina*, and *Alveolinella* are the most common larger benthic foraminifera. The relative proportions of coral, coralline algae, and microbialite vary within this lithology. The coralgal lithologies, ranging from 1 m to 24 m in thickness, only differ from the coralgal-microbialite boundstone in containing little or no microbialite.

Stratigraphically, the coralgal boundstones consistently overlie coralgal-microbialite units. However, in two holes (M0034A, M0055A) a thin unit of coralgal boundstone underlies a thicker coralgal-microbialite interval, and in five other holes (Holes M0046A, M0047A, M0048A, M0052A, M0057A) a coralgal framestone is the only recovered lithology bound by organisms (Figs. 5, 7).

Unconsolidated sediment <1–19 m thick underlies the coralgal-microbialite and coralgal boundstone units and is composed of bioclastic lime sand to pebbles containing mollusks, larger benthic foraminifera, *Halimeda,* fragments of corals and red algae, bryozoans, and echinoderms. In Hole M0036A, an unconsolidated unit 6 m in thickness is bracketed by coralgal boundstone, whereas in Hole M0037A—the most distal and deepest site (122 m) on the HYD-01A transect (Fig. 4)—only unconsolidated sediment was recovered. These unconsolidated sediments were likely to have been partly disturbed by coring operations.

Skeletal packstone to grainstone, up to 13 m thick, underlies the unconsolidated sediment or the coralgal/coralgal-microbialite boundstones in most holes. These lithologies are variably cemented and composed of fragments of shells, coral, coralline algae, *Halimeda*, and abundant larger benthic foraminifera. The top of the cemented lithologies is commonly bored by worms and sponges. Features indicating subaerial exposure, such as calcrete deposits, brownish staining, and rhizoliths, appear at the top of grainstones in the shallowest holes on transect NOG-01B. In Hole M0036A, a dark-colored boundstone, about 1.5 m thick, overlies the packstone. This blackened boundstone is made up of encrusting coral and thin coralline algae in its upper part, and a boundstone of coral, thin foliose coralline algae, and worm tubes in the lowest 10 cm. The dominant coral is massive *Goniopora*, with fragments of massive Faviidae and fine-branching *Seriatopora*.

Below the uppermost packstone-grainstone, a variety of lithologies were encountered. In the shallowest three holes on NOG-01B (Fig. 7) transect coralgal and coralgal-microbialite boundstones alternate with packstone-grainstone units, reaching up to 25 m in total thickness. All lithologies show dissolution surfaces, brownish stainings, and dissolution of aragonitic components. These features suggest several phases of emersion and weathering. In other holes, unconsolidated sediment underlies or alternates with cemented inter-vals of packstones and grainstones. In the deep holes of transects HYD-01C

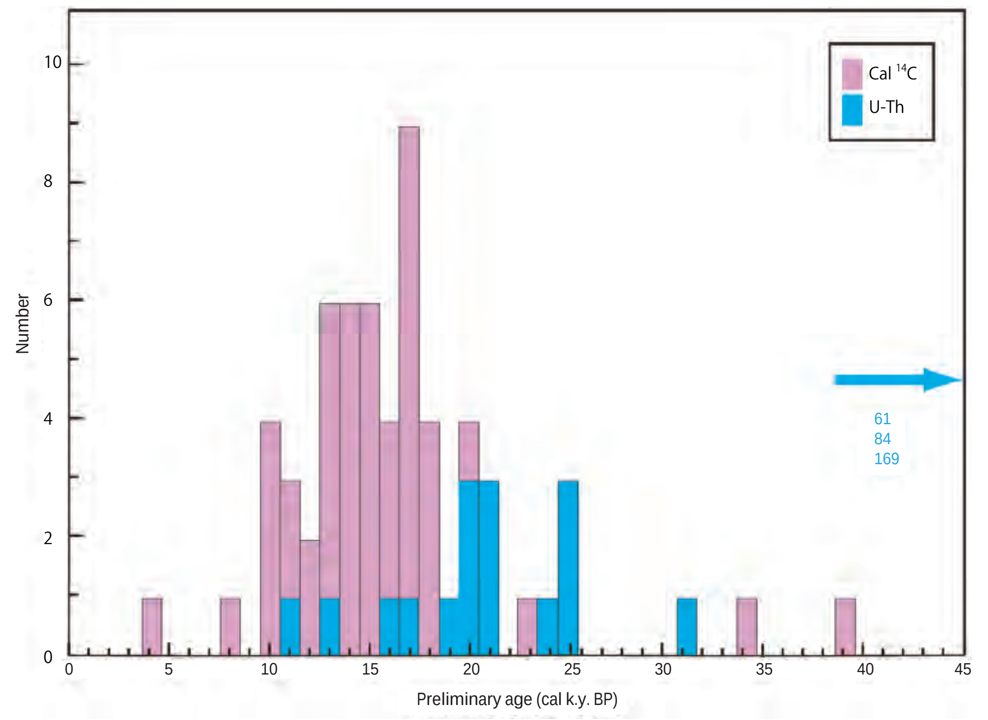

Figure 8. Age histograms of preliminary dating samples (1-ky rounded). All ages are in years before AD 1950. Numbers in blue listed below the arrow indicate 3 U/Th ages obtained for older samples.

(M0037A) and NOG-01B (M0053A and M0054A-B) lime sand rich in larger foraminifera and mollusks underlies the consolidated lithologies. Although there is clear evidence of downhole contamination in their upper part, these deposits appear to be undisturbed and are probably *in situ*, with minimal disturbance from downhole contamination. No consistent pattern has yet been extracted in the succession of these units.

Finally, the deepest hole of Exp. 325 was M0058A at a depth 167 m in the fore-reef slope; it recovered 41 meters of mainly unconsolidated green mud with two intercalated units of fine to medium sand and a few grainstone intervals. The three mud units in M0058A are characterized by a lack of bedding and scattered small fragments of mollusk shells and benthic foraminifera tests. The sand/grainstone units are up to 7 m thick and consist of fine to medium sand with fragments of well-cemented grainstone, mollusks, bryozoa, coralline algae, echinoids, larger foraminifera, and serpulids.

Chronology

Preliminary dating provided an important overview of the age of the material recovered during the offshore phase of Exp. 325. Subsamples of core catcher material (coral and mollusk) were taken during the offshore phase for U-Th or radiocarbon dating. The dated samples were free of visible diagenetic features of detrital contamination. Additional diagenetic screening of these samples using XRD and SEM is ongoing. To constrain the basic chronology of each hole, we collected samples from representative core sections from the top, middle, and bottom of the hole. A total of sixty-eight samples were sent to the University of Tokyo (Japan) and the University of Oxford (United Kingdom) for dating. Radiocarbon samples, after being graphitized at University of Tokyo, were transferred to the Australian National University for analysis by AMS (Accelerator Mass Spectrometry). To ensure that the chronological control on the lower portions of holes was not limited by the range of the radiocarbon chronometer (~50 cal k.y. BP [~50 thousand calendar years BP]), the deeper samples from each hole were selected for U-Th analysis, and the shallower samples were analyzed for radiocarbon (see Webster et al., 2011 for detailed information).

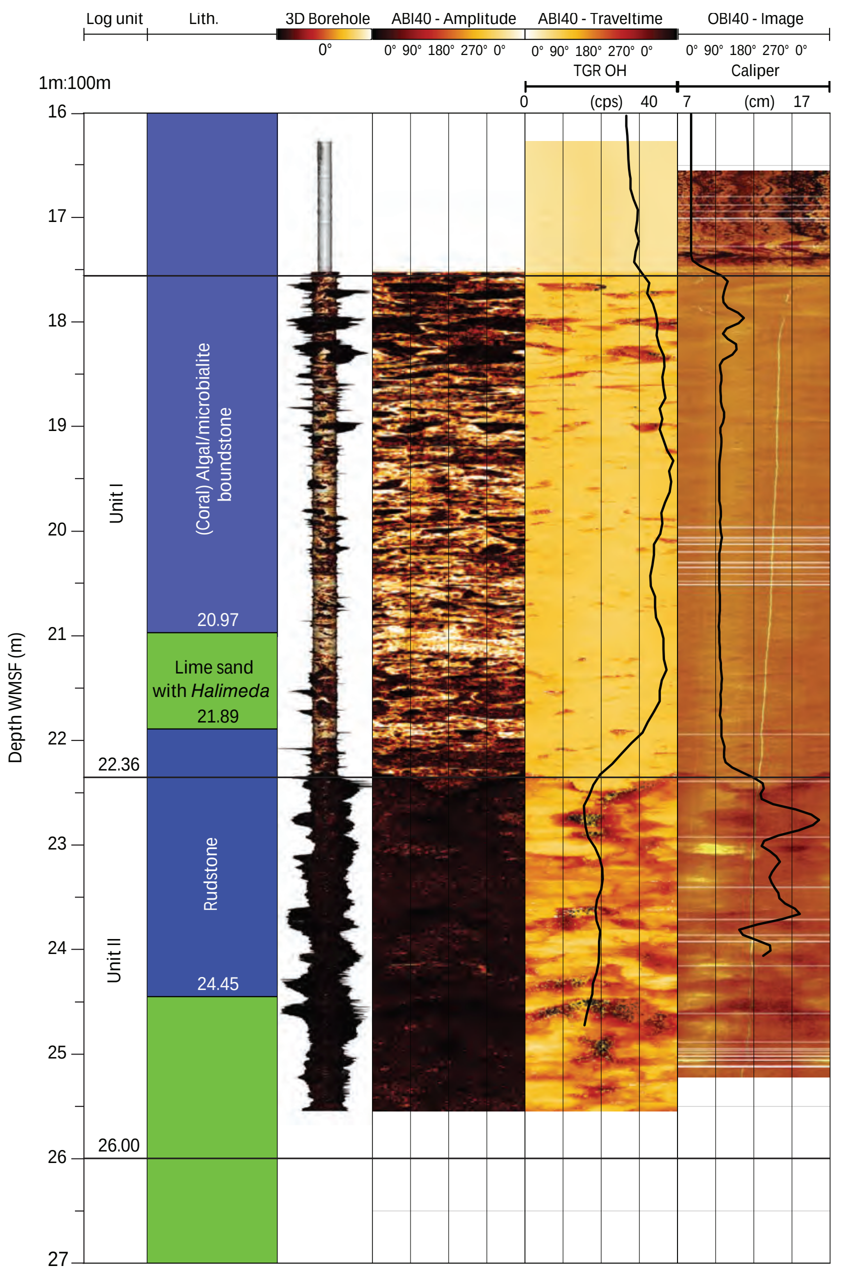

Figure 9. Examples of borehole logging data. The figure illustrates the detail obtained from the ABI40 tool and 3D virtual borehole, transect NOG-01B. (3D Borehole = 3D borehole visualization, ABI 40 traveltime image is overlain by total gamma ray (TGR), OH = open hole). Depth given as wireline log matched depth below sea floor (WMSF).

Except for Hole M0037A, all sample ages in all of the holes are in stratigraphic order. This provides confidence in the accuracy of the dates, and it ensures that the cores have sampled *in situ* reef framework, consistent with the sedimentologic observations. The majority of the deeper holes have U-Th dates near their bases that indicate the Last Glacial Maximum (LGM) was sampled, ranging between 20 cal k.y. BP and 25 cal k.y. BP (Fig. 8). Shallower samples from these cores (dated by radiocarbon) indicated dates as recent as 13–14 cal k.y. BP, which suggests that the early portion of the deglacial has also been captured by Exp. 325 drill cores. Holes drilled in shallower water have ages as young as 10 cal k.y. BP, indicating that early Holocene coral reef samples have been collected. This data opens up the possibility of comparison between these sites in the GBR with other localities that were drilled from onshore rigs. There appears to be a sharp decline in the number of samples postdating 10 cal k.y. BP (Fig. 8). This may reflect a reef drowning event at this time or may simply be an artifact of the relatively small dataset and/or a sampling bias.

U-Th ages prior to the LGM show promise for recovering high-quality material for dating of earlier periods in the Pleistocene. Holes M0032A, M0056A, and potentially M0033A have material from Marine Isotope Stages 4 and 3, whereas Hole M0042A may provide material from the transition between marine isotope Stages 7 and 6. Hole M0057A has U-Th isotope ratios that suggest that the age of the samples is older than the LGM and, although not yielding a closed system U-Th age due to its intermediate depth, this hole may enable insights into glacial-interglacial transitions older than the last interglacial.

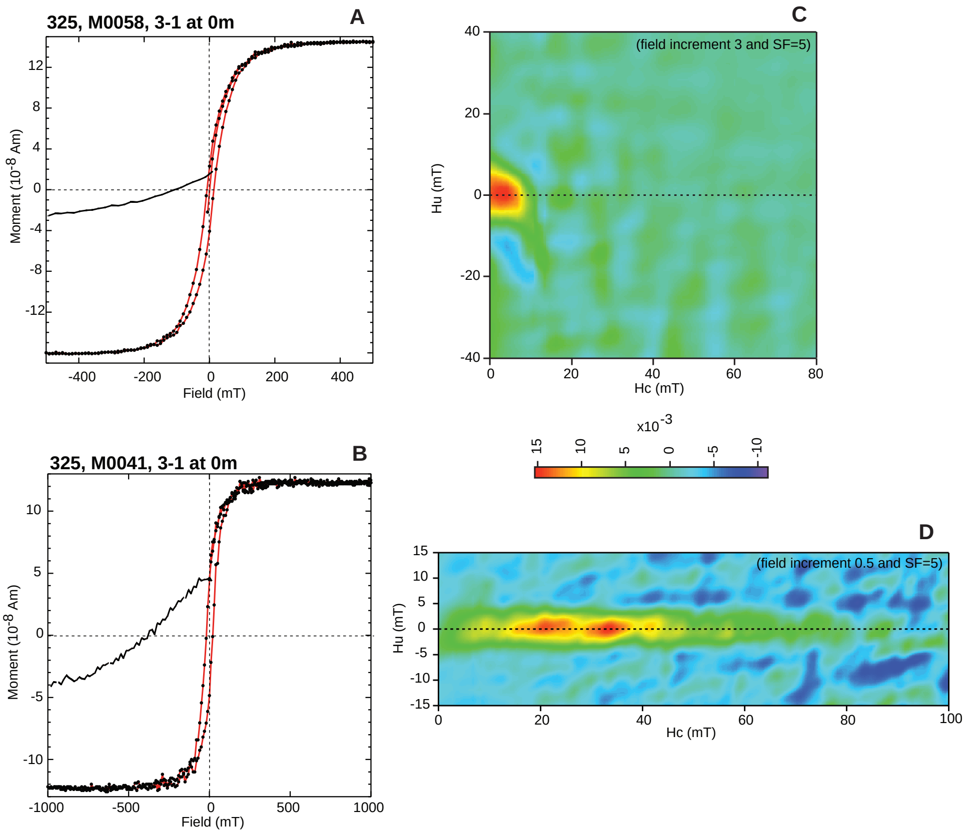

Figure 10. Hysteresis loops, back-field curve ([A], [B]) and first-order reversal curve (FORC) ([C], [D]) of samples from Hole M0058A and M0041A performed with software package FORCinel (Harrison and Feinberg, 2008). The sample from Hole M0058A (field increment 3 mT and SF=5) shows rock magnetic properties mainly of a low coercivity material terrigenous magnetite. The sample from M0041A shows the presence of non-interactive SD magnetite that may represent the presence of magnetosomes.

Petrophysics

A set of slimline borehole logging probes was chosen on the basis of the scientific objectives and geological setting of the expedition. The tool suite used during Exp. 325 comprised probes with the capability of yielding a variety of data including high resolution borehole images (optical [OBI40] and acoustic [ABI40] borehole televiewers; Fig. 9), borehole fluid characterization (IDRONAUT), borehole diameter (CAL3), and a variety of petrophysical measurements such as electrical conductivity (DIL45), acoustic velocity (SONIC), spectral natural gamma radiation (ASGR), and magnetic susceptibility (EM51). Downhole logging was performed in a total of four boreholes, with the majority of measurements being taken in open hole. The only exception to this was a preliminary spectral gamma log conducted through-pipe in each hole.

Downhole logging units were identified on the basis of combined data signatures. These logging divisions were found to be largely coincident with the lithostratigraphic units defined by core description (Fig. 9). A combination of whole core, split core, and discrete sampling petrophysical measurements were taken on the expedition cores. These measurements include density and porosity, resistivity, P-wave velocity, magnetic susceptibility, thermal conductivity, and color reflectance spectrophotometry. All cores recovered during the expedition were measured where appropriate and possible to do so. Multivariate analysis relating the physical properties data with different coralgal assemblage compositions (Lado-Insua et al., 2010) indicate that it is possible to infer important composition information from the petrophysical dataset. This has the potential for use as a proxy for the identification of sample types from the nondestructive, offshore physical properties measurements in future research. Future work planned by the Exp. 325 Science Party will move towards improving and furthering the integration of the different petrophysical and lithological datasets.

Paleomagnetics

A total of thirty cores were provided for paleomagnetic measurements. The AF demagnetization of the U-channels and of discrete samples from the fore-reef slope Hole M0058A suggests the presence of magnetic impurities and potential deformation during drilling operations. However, the magnetic susceptibility and artificial remnant magneti-

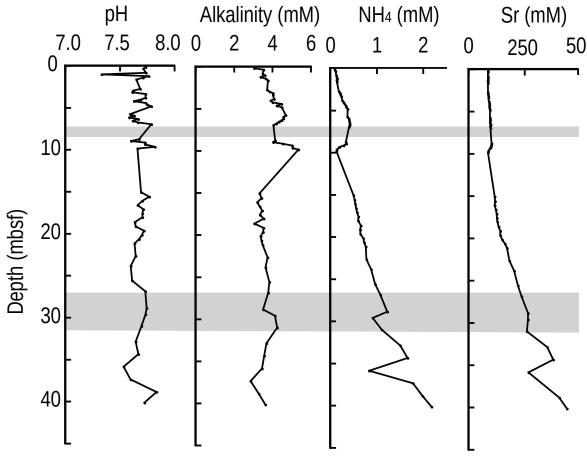

Figure 11. Porewater geochemistry data from Hole M0058A. Gray bars represent the two coarse sand/grainstone units

zations such as anhysteretic (ARM), isothermal (IRM), and indirect parameters (ARM/IRM, S-ratio, and HIRM) show clear separations, with two horizons of high concentrations of a low coercivity magnetic mineral (Webster et al., 2011). Rock magnetic properties confirm that the magnetic carrier is magnetite (Fig. 10a, 10c) with the two horizons characterized by a mixture of low and high-coercivity minerals. The magnetic horizons may correspond to two periods of higher terrigenous sediment input that likely correlate with the two sand/grainstone lithologic units observed in the core. While in the shelf edge fossil reef cores (e.g., M0041), a non-interactive single domain (SD) low coercivity mag-netic mineral (probably magnetite) was measured in discrete samples from fossil coral materials. We attribute that to the presence of magnetosomes of magnetotactic bacteria (Fig. 10b, 10d; Egli et al., 2010). Further studies of rock magnetic properties will provide more detailed information and help establish the nature of relationships between magnetic properties, coral formation, and climate change.

Geochemistry

A total of 115 interstitial water (IW) samples were acquired during Exp. 325, from transects of HYD-01C (16), HYD-02A (20), RIB-02A (2), and NOG-01B (77). (Numbers in parentheses indicate the number of samples obtained from each transect.) The majority of the IW samples was collected from the holes drilled into the carbonate reef complex of the GBR. The pH, alkalinity, and ammonium concentrations of IW collected from the holes drilled into the carbonate reef complex did not indicate any apparent depth-related or transect-specific variation, probably due to the scarcity of IW samples at each transect.

However, Hole M0058A (NOG-01B transect) consisted of fine to coarse sediments, unlike other holes, and therefore continuous IW sampling was possible. While there was no systematic vertical variation in the pH, alkalinity, and

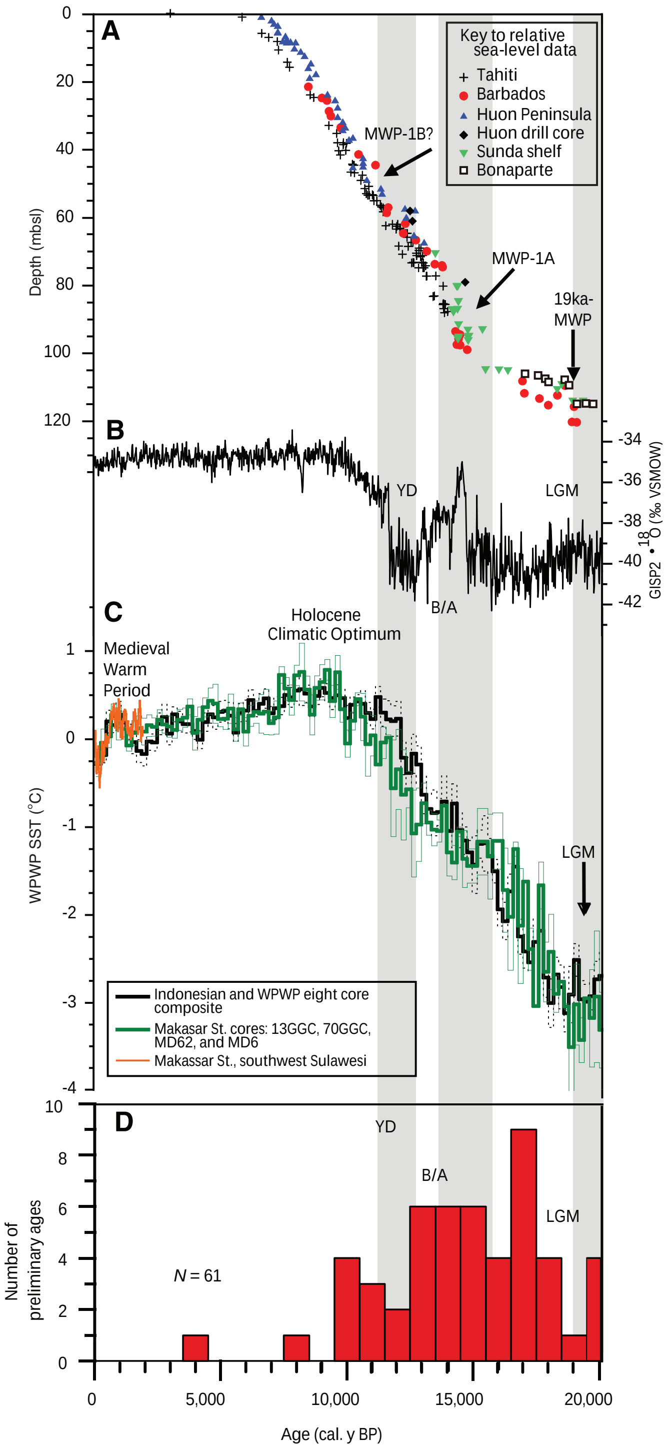

Figure 12. Comparisons of preliminary dating results and previously published sea-level and climatological data. [A] Previously published data on relative sea level from 20 cal k. y. BP through present. MWP= meltwater pulse. [B] GISP2 $\delta^{18}O$ proxy for temperature over Greenland. [C] Sea-surface temperature variation in the Western Pacific Warm Pool (WPWP) (Linsley et al., 2010). [D] Histogram showing preliminary dating results on core catcher samples. Age distribution clearly indicates that the recovered fossil coral reef cores cover key intervals of interest for sea-level changes and environmental reconstruction, including the last glacial maximum (LGM), Bölling-Alleröd (B/A), and Younger Dryas (YD). Sources of data: Tahiti = Bard et al., 1996, 2010; Huon Peninsula = Chappell and Polach, 1991; Edwards et al., 1993; Huon drill core = Cutler et al., 2003; Sunda shelf = Hanebuth et al., 2000; Barbados = Fairbanks, 1989; Bard et al., 1990; Bonaparte = Yokoyama et al., 2000b; 2001a; DeDeckker and Yokoyama, 2009. GISP2 = Stuiver and Grootes, 2000.

chloride, the ammonia and strontium concentrations increased with depth (Fig. 11). The notable characteristic of IW from Hole M0058A is that two large anomalies occur coincident with the two sand/grainstone lithologic units, in the profiles for total iron and manganese concentrations. The percentage quartz profile of the sediments displayed the opposite trend to that of percentage carbonate. These litho-logic units also contain low total organic carbon content, with an average value of 0.25%, compared to the rest of the core. Consistent with the paleomagnetic data, these findings suggest that the two sand/grainstone units may correspond to the increased input of terrestrial material during their deposition. Further investigations are needed to fully understand the cause of lithologic changes found at Hole M0058A.

Microbiology

The subsurface microbial ecology will be characterized using multiple molecular based techniques. Fine grain sediment cores collected from transect NOG-01B, Hole M0058A represent the bulk of microbiological sampling. Sediment was collected for cell enumeration and phylogenetic analysis during shipboard and onshore operations. Shipboard samples were taken at multiple depths downcore, immediately frozen at -80°C for the duration of the cruise and then shipped on dry ice to labs in the United States (Texas A&M University) and China (China University of Geosciences). Onshore, sediment was collected from locations adjacent to the samples collected during the offshore phase. These samples are designed to test shifts in microbial community activity and structure during 4ºC transit to, and storage in, Bremen, Germany against those samples collected immediately after coring that were frozen offshore. Samples remained at 4°C for approximately three months prior to shore-based sampling. Microbial communities in both shipboard and onshore sediment samples will be described for total structure and function using DNA- and RNA-based molecular targets, respectively. For cell enumeration, onshore sediment samples were preserved in 4% formaldehyde and stored at 4°C. By combining all microbial data, the total, potential, and active communities can be determined. The analysis will provide a unique advance in understanding subsurface microbial ecology, as well as a description of potential sediment composition and chemistry altering biological processes that may occur during standard IODP 4°C storage.

Concluding Remarks and Future Plans

During the course of IODP Expedition 325 offshore phase, thirty-four holes were drilled, obtaining 225 meters of core materials from water depths ranging from 42 mbsl to 167 mbsl (Fig. 12). The preliminary chronology of core catcher materials dated by both radiocarbon and U-series methods prior to the OSP provided a firm chronological framework for conducting further scientific analyses. Fulfillment of the Exp. 325 scientific objectives can be seen as follows:

1. Reconstruct the course of postglacial sea-level change in GBR from 20 ka to 10 ka. Coral-algal-microbialite lithologies of *in situ* and robust *Isopora* and *Acropora* assemblages are indicative of very shallow reef environments. They will contribute to the reconstruction of a robust sea-level curve from the LGM to 10 ka.

2. Establish sea-surface variations in the GBR from 20 ka to 10 ka. preliminary chronologic results clearly show that important coral reef deposits were recovered consisting of key paleoenvironmental intervals including LGM, Bölling-Alleröd, Younger Dryas, and Heinrich events. Massive coral colonies suitable for paleoclimate studies will help define SST variations and aid paleoceanographic reconstruction for the region.

3. Investigate the response of the GBR to environmental changes caused by sea-level and climate changes. Cores were recovered from various locations and water depths along the GBR. Their large geographical spread and shelf edge position will allow the results to be interpreted in both a broad temporal and spatial context, allowing a better understanding of the development of the GBR in response to environmental changes.

In addition to the main scientific outcomes summarized above, we expect three additional scientific outcomes will be achieved.

1. It is believed that sea-level and paleoclimate information can be extended back to the LGM and pre-LGM periods based on the preliminary age determinations. This will enable a reconstruction of the evolution of the GBR during these earlier periods.

2. High-resolution paleoenvironmental information obtained from a nearly continuous 41-m sediment core in the fore-reef slope of Noggin Pass (M0058A) will complement the sea-level and paleoenvironmental records obtained from reef cores recovered from shallower shelf sites.

3. The microbial community structure and function will also be assessed within the Hole M0058 sediments using direct count microscopy and RNA/DNA gene targets. Correlations will be made between offshore and onshore geochemical characterizations in order to better describe the subsurface biosphere ecology.

Future work will now focus on more detailed sedimentological, petrophysical, geochemical, and geophysical investigations in the various laboratories of the IODP Exp. 325 Science Party members. The results obtained from these studies will improve our understanding of sea-level and climate change as well as coral reef response since the LGM.

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Initial Feasibility Study to Drill and Core the Ocean Mantle

by Nicolas Pilisi and Bill Whitney

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Introduction

An initial feasibility study (Pilisi and Whitney, 2011) of drilling through the Mohorovičić discontinuity (Moho) into the oceanic mantle specifically focused on future requirements for planning, drilling and coring a hole 500 m into the oceanic mantle from three candidate locations in the Pacific Ocean (Cocos Plate, Baja California, and offshore Hawaii). The study points out some of the critical issues that need to be resolved before embarking upon such a challenging project. It was conducted on the basis of data provided by the Integrated Ocean Drilling Program–Management International (IODP-MI), the Center for Deep Earth Exploration (CDEX) operating the drilling vessel *Chikyu* within IODP, public domain information, and past experience that Blade Energy Partners (hereafter mentioned as "Blade"; http://www.blade-energy.com/) has had with frontier projects in the offshore deepwater oil and gas and geothermal industries.

Project Challenges

The challenges associated with drilling/coring a hole through the Moho and into the mantle have been understood for some time and have been comprehensively discussed in previous IODP and legacy program reports and documents. Blade's focus was therefore not to re-examine the issues, but rather to evaluate them in terms of current and trending technologies in oilfield and geothermal industries to determine how difficult it will be to resolve the issues. The obvious constraints for this project versus "normal" offshore drilling operations are the extreme water depths where operations need to be conducted, the extreme high temperatures present in very hard igneous rocks that push the limit of all the drilling, and coring tools that are routinely used in less demanding environments. The main challenges that need to be overcome include the following:

1. Riser drilling in ultra-deepwater environments with water depths around 4000 m (which will set a new world record)
2. Drilling and coring in very high temperature igneous rocks with bottom-hole temperatures that are estimated to be as high as 250°C
3. Drilling and coring a very deep hole having a total drilled/cored interval of up to 6700 m in the oceanic crust below the Pacific Ocean seafloor

Feasibility Study Results

The study (Pilisi and Whitney, 2011) included a detailed analysis of the drilling riser design requirements for the environmental conditions expected at the three candidate locations (Fig. 1). The analysis looked at the operational envelope of the current riser configuration on riser equipped drillship *Chikyu* (Fig. 2), as well as alternative designs for five other possible riser configuration options (current riser with lighter buoyancy modules, titanium riser, slim riser, hybrid riser, current riser with two additional riser tensioners). The analysis concluded that there are existing available technologies, equipment, and materials in the ultra-deepwater industry that should enable the *Chikyu* to conduct operations in the expected water depth range (3650–4300 m) at the candidate locations.

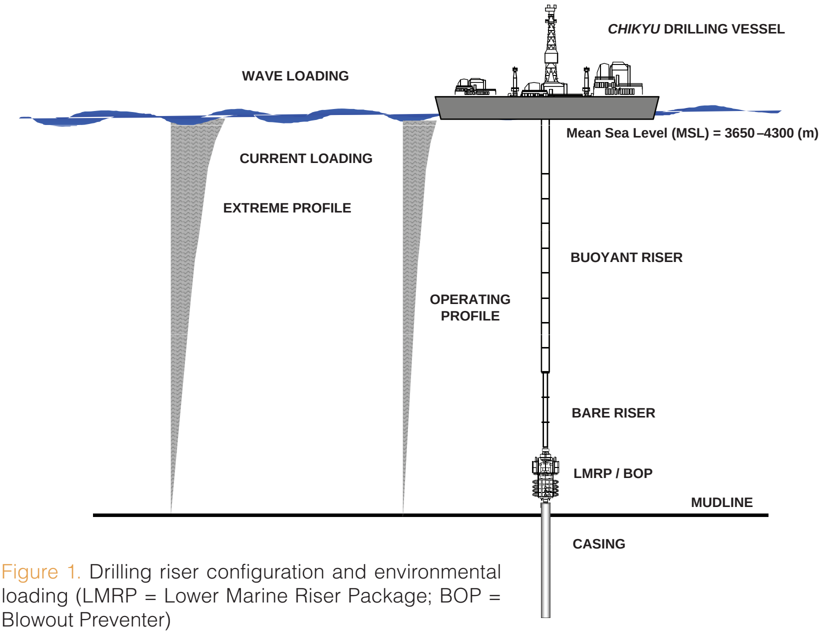

Figure 1. Drilling riser configuration and environmental loading (LMRP = Lower Marine Riser Package; BOP = Blowout Preventer)

The study also looked at different well design scenarios in order to further define the key operational and design issues that will need to be resolved prior to drilling into the mantle well. Most of the information about the downhole conditions is presently unknown. Therefore, assumptions had to be made about the fundamental downhole conditions that impact well design. For example, the assumed downhole temperature profiles for the candidate locations were based on previous models of formation burial depth and age provided by IODP-MI and from operations conducted at the Cocos location in the IODP Hole 1256D (Alt et al., 2007). In addition, a downhole pressure estimate was developed in order to develop a casing program. In most deepwater wells the presence of abnormal pressure is a fundamental criterion for determining casing points and the drilling mud density required to reach total depth. Since the Moho wellbore is expected to be entirely normally pressured (1.03 specific gravity [SG]), abnormal pressure is not an issue. Therefore, the selection of casing points and mud weights will be based on wellbore stability considerations. For example, if the mud weight is too low, the hole will essentially collapse due to a compressive shear failure in the rock. However, a trade-off must be made between the allowable mud weights and the number of casing strings that are used. There are only so many casing strings that can fit in a well; running multiple strings is time-consuming and costly, and it complicates the geometry of the well. It is certainly advantageous to minimize the number of casing strings used for the Moho well, if only to minimize the sizes of the rotary core barrel bits that would need to be developed.

This effort resulted in the development of a base case wellbore configuration that assumes that significant parts of the wellbore will need to be cased off in order to reach total depth (Fig. 3). With the wellbore thus defined, the expected downhole circulating temperature profiles could be modeled, and the issues around the design of a drill string could be examined. It was determined that the circulating temperatures exceed the temperature ratings of most downhole tools that are commercially available today. Increasing the downhole tools' temperature rating is a significant issue that will need to be addressed. On the other hand, it was determined that the Moho wells could be drilled today with a

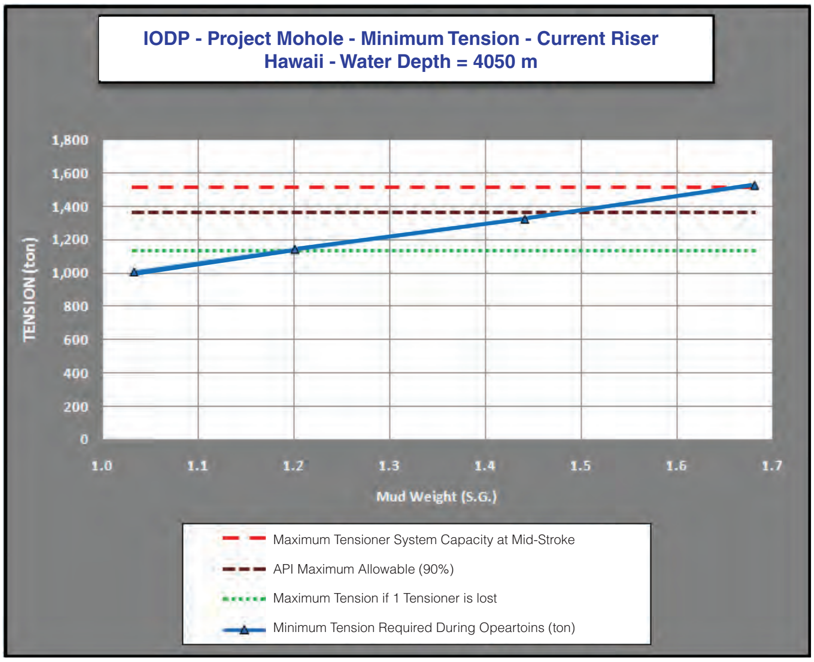

Figure 2. Riser tension requirements vs. mud weight for the current *Chikyu* drilling riser at the Hawaii location (*Chikyu* Spec. 2008.pdf).

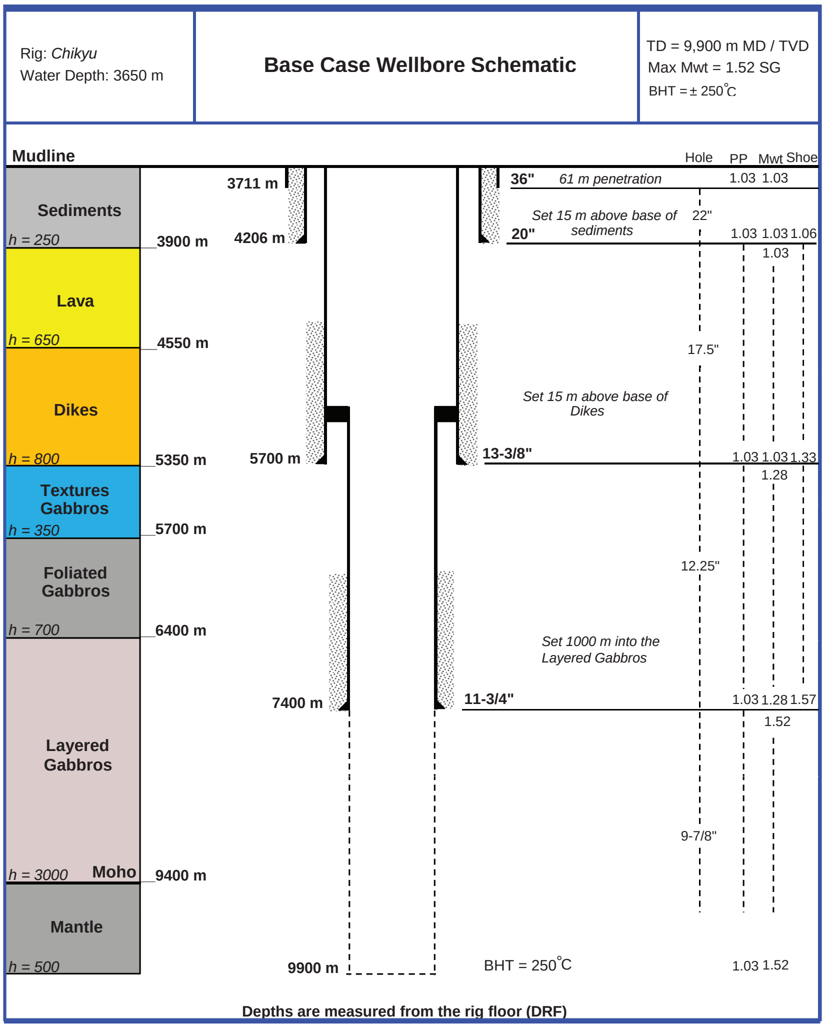

Figure 3. Base case wellbore configuration.

combination of readily available oilfield drill pipe and the *Chikyu*'s existing drill pipe. Therefore a non-standard, special high strength drill string is not needed.

Operational time estimates for four different scientific drilling cases were developed for each of the candidate locations (Table 1). Case 1 assumed that that the hole is continuously cored to total depth. Case 2 assumed long sections of continuous core are taken across the major lithologic and geophysical transition intervals of key sections. Case 3 assumed that only spot coring is done during the last 10 m of hole before each bit trip. And , Case 4 assumed that the hole is drilled to the Moho and that only the mantle is cored. Operations time curves were developed for each different case and location (Fig. 4). It was determined from this work that the time spent tripping for a new drill bit was as much as 40% of the overall operational time. The development of drill bits with enhanced operation hours will therefore have a tremendous impact on the time and cost it will take to drill/core the Moho well.

Table 1. Operational time estimates (based on current technologies).

Candidate Location	Water Depth (m)	Total Depth Below (m): Rig Floor	Total Depth Below (m): Sea Floor	Drill/ Core Time (days)	Total Project Time (days)
Cocos Location					
Case 1	3650	9900	6250	696	756
Case 2	3650	9900	6250	564	617
Case 3	3650	9900	6250	433	480
Case 4	3650	9900	6250	374	418
Baja Location					
Case 1	4300	10,400	6100	807	866
Case 2	4300	10,400	6100	642	693
Case 3	4300	10,400	6100	405	445
Case 4	4300	10,400	6100	386	425
Hawaii Location					
Case 1	4050	10,750	6700	876	934
Case 2	4050	10,750	6700	688	737
Case 3	4050	10,750	6700	448	485
Case 4	4050	10,750	6700	422	443

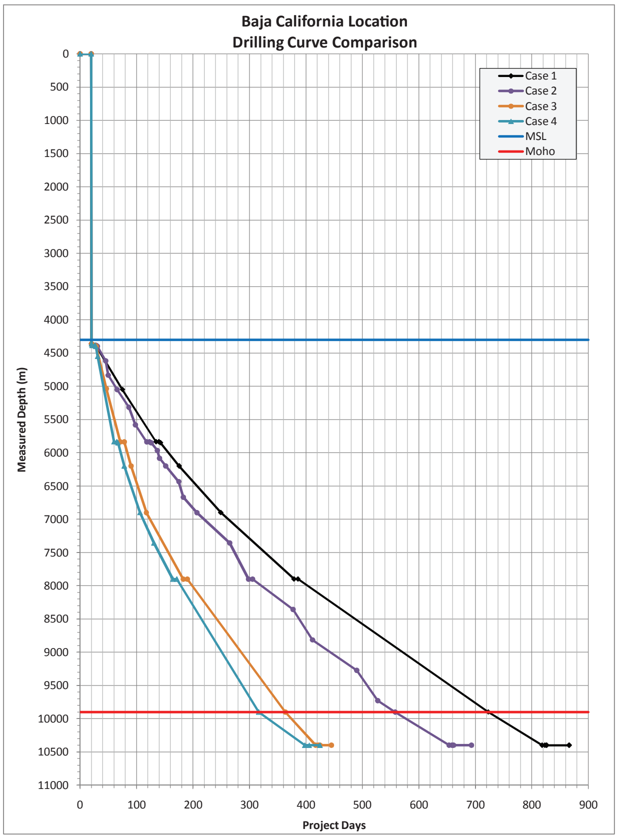

Figure 4. Depth vs. duration of operations. Example for Baja location comparing the four scientific drilling cases

Conclusions

The results of this study show that drilling/coring a scientific hole into the upper mantle is certainly feasible, and that existing solutions are currently available to many of the technological challenges based on work being done in the oilfield and geothermal industries. In addition, technologies and techniques are continuously advancing and can be expected to continue to close the gap between what is required for the "Moho Project" and what is currently possible.

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For full references, see the full report at http://www.iodp.org/weblinks/Featured-Publications-HOME-PAGE/IODP-Project-MoHole-Initial-Feasibility-Study-PDF-

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International Drilling to Recover Aquifer Sands (IDRAs) and Arsenic Contaminated Groundwater in Asia

by Alexander van Geen

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A group of forty-four scientists and students from fourteen countries met on 25–27 April 2011 in Hanoi, Vietnam to set the stage for a new continental drilling program focused on the groundwater arsenic (As) problem in Asia. Half of the participants were from low and lower-middle income countries directly facing the major health threat of elevated groundwater As. This issue affects over 100 million rural inhabitants across Bangladesh, Cambodia, China, India, Myanmar, Nepal, Pakistan, and Vietnam who rely on shallow (typically <100-m-deep) wells as their main source of drinking water (Ravenscroft et al., 2009). Groundwater from these areas can contain As at levels that have been shown to cause deadly cancers and cardiovascular disease and to inhibit the mental development of children (Smith, A.H. et al., 2000; Wasserman et al., 2004; Kapaj et al., 2006; Argos et al., 2010).

There is broad agreement within the international scientific community that reductive dissolution of iron (Fe) oxyhydroxides in river basins across Asia is a key factor leading to widespread occurrence of As in shallow groundwater (Kinniburgh and Smedley, 2001; Fendorf et al., 2010). The underlying reason is the strong affinity of As for Fe oxyhydroxides that results in As accumulation on the coatings of suspended particles. Upon burial, As is released to groundwater by microbially mediated dissolution of these Fe oxyhydroxides. There is a lack of necessary data, however, to discern the relative importance of other mechanisms, including the role of local vs. advected sources of reactive organic carbon that drive aquifers towards reduction. There is also a lack of critical information required to identify the cause of the extraordinary variability of groundwater As concentrations across a wide range of spatial scales (Fig. 1.) It is clear that this spatial variability is not directly controlled by the bulk As content of the sediment which, although not particularly elevated, is sufficient to increase groundwater As concentrations to over 1000 times the World Health Organization's guideline of 10 $\mu g\ L^{-1}$ for As in drinking water if released.

Recent work reviewed at the International Drilling to Recover Aquifer Sands (IDRAs) workshop highlighted the importance of understanding the interactions between geology, hydrology, geochemistry, and microbiology that must be understood to understand and predict the release of As that occurs mostly in aquifers <100 m deep (Fig. 1a). Because of the difficulty of distinguishing some of these processes, participants agreed to focus their efforts on the issue of greatest societal relevance, which is the vulnerability of those aquifers that are currently low in As (von Brömssen et al., 2007; Michael and Voss, 2008; Winkel et al., 2011). Tapping those aquifers, shallow or deep, that are low in As has had a much bigger impact in terms of lowering exposure than any other form of mitigation, including water treatment or rainwater harvesting, and it will likely continue to do so for the foreseeable future (Ahmed et al., 2006).

Workshop participants agreed that an effective approach to gaining a better understanding of the vulnerability of low-As aquifers is to study pronounced lateral and vertical concentration gradients and determine whether such transitions could shift in response to massive groundwater pumping in some regions. In this context, one key question is whether a low-As aquifer is more likely to become contaminated because of inflow from a high-As zone or because of *in situ* As release triggered by a change in groundwater composition induced by massive pumping for irrigation or municipal and industrial use (Fig. 2). This is a critical distinction. A number of plausible mechanisms have been proposed by which changes in the flow or composition of groundwater in response to pumping could either increase or decrease the As levels in groundwater (Klump et al., 2006; Neumann et al., 2010; McArthur et al., 2010), but none have been demonstrated across a broad range of settings.

Workshop participants agreed that a decade-long integrated research program is required in order to identify the mechanisms that are most relevant to predicting the fate of low-As aquifers. A guiding hypothesis for such a program was formulated at the workshop as follows:

"The distribution of As in reducing groundwater is anchored to the local geology across a range of spatial scales and therefore naturally evolves on 100–1000 year time scales. The scale of human perturbations of the natural groundwater flow that threaten aquifers that are currently low in As on 10-yr timescales can be predicted by considering a limited set of parameters."

Initial studies would be focused on a subset of previously studied sites from which background information is already available, as well as a on series of new transects that are scientifically relevant but also cross the borders between affected countries, some of which are politically sensitive (e.g., Pakistan-India, India-Bangladesh, and Cambodia-Vietnam). The objective of in-depth study of selected sites would be to identify which minimum set of geological, hydrological, geochemical, and microbial parameters must be considered to make reasonably accurate predictions of the vulnerability of low-As aquifers across the affected region in the absence of a full-scale study.

A key factor that has impeded progress in understanding the processes regulating groundwater As levels is that matched samples of uncompromised groundwater and aquifer sediment from precisely the same interval are typically not available for detailed analysis and incubation. Participants agreed that a transportable drilling facility with new technology for collecting and processing paired groundwater and sediment samples under sterile and anoxic conditions would be an important catalyst for a long-term collaborative interdisciplinary research program across the affected region. The new technology is based on isolating a coring tube until the desired depth has been reached, followed by sealing the end of the coring tube before retrieval by *in situ* freezing.

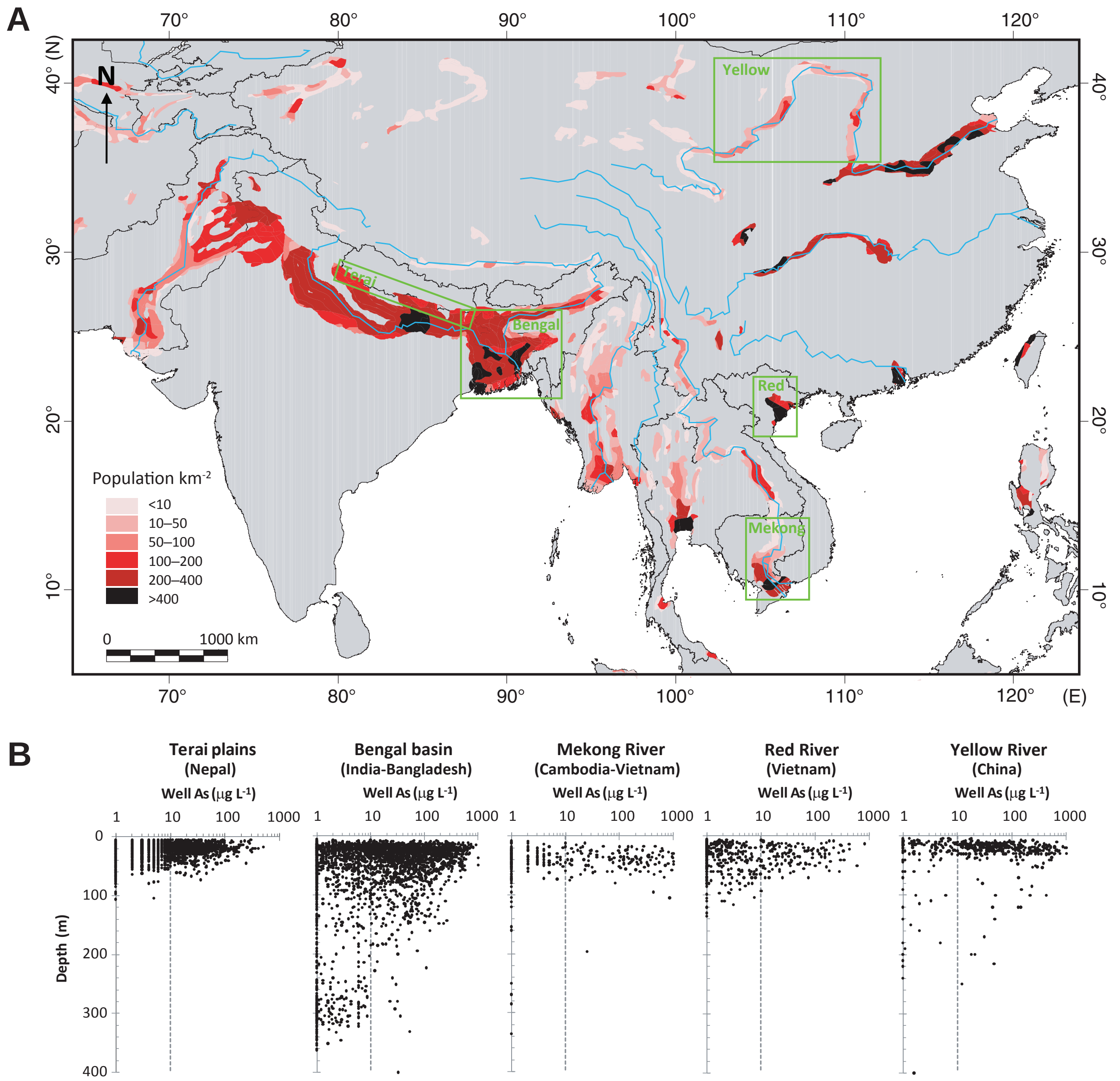

Figure 1. [A] Map of population density within regions where groundwater As concentrations are potentially elevated. [B] Geographic information system (GIS) files with population density from Ravenscroft (2007). Distribution of As in groundwater as a function of depth within five areas indicated by green rectangles in [A]. The vertical dashed line marks the WHO guideline of 10 μg L^{-1}. Sources include Kinniburg and Smedley (2001), Guo et al. (2003), Shrestha et al. (2004), Nickson et al. (2007), Buschmann et al. (2008), Guo et al. (2008), Deng et al. (2009), Gao et al. (2010), Han et al. (2010), and Winkel et al. (2011). These regions were outlined by considering a limited set of hydrogeological and climatic factors. Whereas groundwater contamination with As has been confirmed by actual measurements in many of the predicted regions, groundwater As concentrations have also been measured and found not to be elevated in some, including the lower reaches of the Yellow River in China and Chao Praya Delta in Thailand. In other areas such as the lower Mekong River, groundwater As levels may be elevated but the local population does not drink the water because it is affected by salt intrusion (Ravenscroft et al., 2009).

Such a drill rig, sampling tools, and a machine shop for repair and maintenance included with the mobile facility would fit in four 6-m shipping containers.

The proposed drilling facility would be complemented with a fifth containerized laboratory equipped to sterilize sampling tools, extrude aquifer samples anaerobically, analyze labile properties, and prepare samples for shipping to laboratories for further analyses. The facility would have the ability to test for sample contamination with drilling fluids using techniques developed under the Integrated Ocean Drilling Program (Smith, D.C. et al., 2000). The facility has been designed for sampling both groundwater and aquifer sediment from depths of up to 300 m, which will be important to determine the fate of the particularly deep low-As aquifers that are increasingly relied on in the Bengal Basin (Fig. 1).

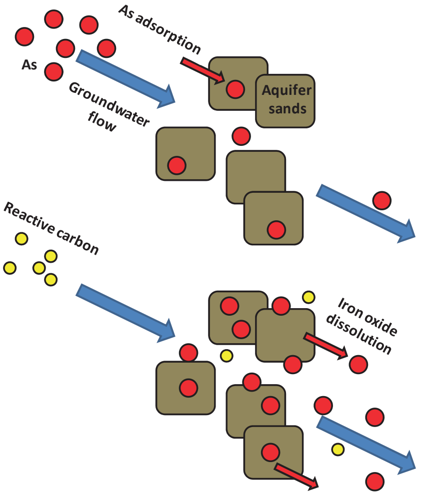

Figure 2. Conceptual representation of processes regulating the As content of groundwater. A distinction is drawn between a low-As aquifer that is contaminated by As released elsewhere (top) and locally (bottom). Groundwater flow could play a role by supplying As directly or indirectly by supplying reactive organic carbon that triggers reductive dissolution of iron oxides.

Over the next several months, workshop participants as well as interested scientists who could not join this particular meeting will prepare a full International Continental Scientific Drilling Program (ICDP) proposal for the January 2012 deadline. Key features were outlined at the Hanoi workshop, including identifying a viable management structure for prioritizing study sites, ensuring broad participation, standardizing methods, and securing supplemental funding. The group's likely strategy will be to focus during a first five-year phase on sites with sufficient geophysical and hydrological background information that are either unperturbed by groundwater pumping (e.g., portions of Vietnam or Cambodia) or so strongly perturbed by municipal pumping (e.g., around Kolkata, Dhaka, or Hanoi) that groundwater flow patterns are fairly predictable. Based on the new knowledge generated during the first phase, the group expects to be ready to study sites that are affected by more complex patterns of irrigation pumping in other regions in a second five-year phase. This multi-year and multi-country project is unique in scientific drilling, and it will require strong management, communication, and coordination. Participants agreed that annual workshops and support for scientists and students from countries affected by As to work in countries other than their own will be key to maintaining the momentum generated in Hanoi by providing a forum for planning and reviewing the latest findings.

IDRAs Workshop Participants

Australia: Bibhash Nath (University of Sydney); Bangladesh: Kazi Matin Ahmed (University of Dhaka), Ashraf Ali Seddique (Jessore Science & Technology University), Mohammad Tauhid-Ur-Rahman (Shahjalal University of Science & Technology), Anwar Zahid (Bangladesh Water Development Board); Canada: Roger Beckie (University of British Columbia), Mario Bianchin (Lorax Environmental); China: Huaming Guo (China University of Geosciences); France: Laurent Charlet (University of Grenoble); Germany: Sebastian Behrens, Andreas Kappler (Eberhard-Karls-University Tuebingen), Harald Neidhardt, Thomas Neumann (Karlsruhe Institute of Technology), Thomas Wiersberg (Scientific Drilling ICDP), India: Sudipta Chakraborty (Kanchrapara College), Debashis Chatterjee (University of Kalyani), Syed Hillal Farooq (St.Xavier's College), Manoj Kumar, Sonnenchien Kushagra, Al Ramanathan, Chander Kumar Singh (Jawaharlal Nehru University), Abhijit Mukherjee (Indian Institute of Technology (IIT)-Kharagpur); Japan: Harue Masuda (Osaka City University); Nepal: Jaya Kumar Gurung (Nepal Development Research Institute), Bishal Nath Upreti (Tribhuvan University); Pakistan: Abida Farooqi, Mehwish Ramzan (Fatima Jinnah Women University), Sweden: Prosun Bhattacharya (Royal Institute of Technology); Switzerland: Michael Berg, Rolf Kipfer, Lenny Winkel (Eawag); U.S.A.: Benjamin Bostick (Lamont-Doherty Earth Observatory), Karen Johannesson (Tulane University), Natalie Mladenov, Diana Nemergut (University of Colorado), Dennis Nielson (DOSECC), Peggy O'Day (University of California, Merced), David Smith, Athur Spivack (University of Rhode Island), Alexander van Geen (Lamont-Doherty Earth Observatory); Vietnam: Ngoc Son Nguyen (Vietnam National Assembly Committee), Thi Ha Nguyen (Centre of Water Resources Monitoring and Forecast), Pham Thi Kim Trang, Pham Hung Viet (Hanoi University of Science).

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Related Web Link

http://hanoi.icdp-online.org

Deep Scientific Drilling to Study Reservoir-Triggered Earthquakes in Koyna, Western India

by Harsh Gupta, Shailesh Nayak and the Koyna Workshop Committee

doi:10.2204/iodp.sd.12.07.2011

Introduction

During 21–25 March 2011, the International Workshop on Scientific Deep Drilling in the Koyna region in western India was held. It was organized by the National Geophysical Research Institute (NGRI), Hyderabad. The main objective of the workshop was to discuss a proposal for deep scientific drilling down to earthquake focal depths of ~7 km at Koyna, a classical site of Reservoir Triggered Seismicity (RTS) in an intra-plate setting, and to design a comprehensive experiment through discussions with national and international experts. Participants of the workshop included seismologists, geologists, and drilling experts, many of them associated with active fault zone drilling projects worldwide, such as the San Andreas Fault Observatory at Depth (SAFOD) in California, the Chelungpu Fault Drilling Project in Taiwan, the Nojima Fault Drilling in Japan, the Gulf of Corinth in Greece, and the Latur Fault of India. There were twenty-six international participants from Canada, France, Germany, Italy, Japan, New Zealand, Poland, Taiwan, and the U.S.A., and fifty Indian participants represented major earth science organizations, institutes, and universities within the country. The workshop was supported by the Ministry of Earth Sciences (MoES), Government of India, and the International Continental Scientific Drilling Program (ICDP).

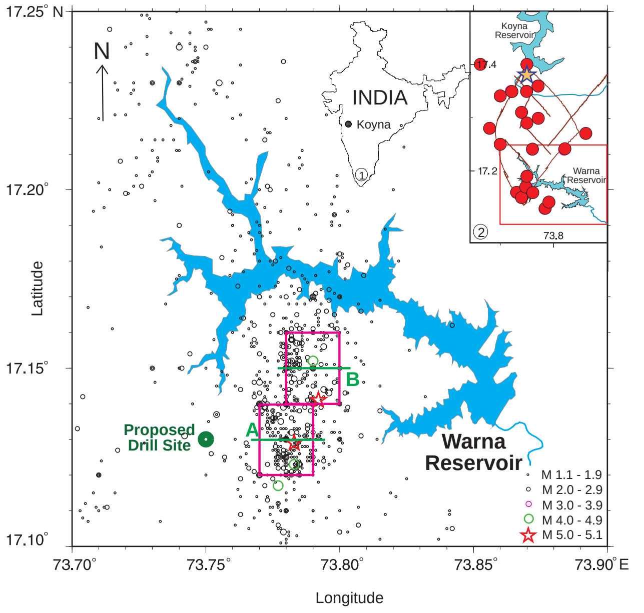

Figure 1. Seismicity in the Warna region south of Koyna, western India, during 2009–10 (red rectangle in inset 2). Inset 1: Map of India indicating the Koyna region; Inset 2: Earthquakes of magnitude 5 and above in the Koyna-Warna region since 1967.

The Koyna region near the west coast of India is globally the premier site of RTS, where induced earthquakes have been occurring in a restricted area of 20 x 30 km since the impoundment of Shivajisagar Lake in 1962. These include the largest triggered earthquake of M~6.3 on 10 December 1967 and twenty-one earthquakes of M>5 since 1962 (Fig. 1). The RTS was further enhanced by impoundment of the nearby located Warna reservoir in 1993. The seismic zone is quite isolated with no other source of activity within 50 km of the Koyna Dam. The continued seismicity in an isolated zone that can be easily monitored provides a unique opportunity to directly measure the physical and mechanical properties of rocks, pore fluid pressure, hydrology, temperature, and other parameters of an intra-plate active fault zone in the "near-field" of earthquakes before, during, and after their occurrence. The focal depths, especially in the Warna region to the south, are mostly within 7 km (Fig. 1), and they can be accessed by drilling with available expertise. This active seismic zone, therefore, forms an ideal site to set up a borehole observatory which will permit direct and continuous monitoring of an intra-plate seismic zone at depth, leading to a better understanding of the mechanics of faulting and the physics of reservoir triggered earthquakes, and it will contribute appreciably to earthquake hazard assessment and forecasting.

Structure of the Workshop

The initial part of the workshop had four thematic sessions including (i) Global Review of Reservoir Triggered Seismicity, Models and Hypotheses, (ii) Geology and Geophysics of the Koyna Region, (iii) Global Status of Drilling into Fault Zones, and (iv) Designing the Koyna Scientific Drilling Experiment. The presentations provided an up-to-date status of expertise on fault drilling projects worldwide and brought out the core issues with respect to deep drilling investigations in the Koyna region. The next phase of the workshop included a field trip to the Koyna region and breakout group discussions for detailed planning of the required investigations. The participants were divided into four breakout groups based on their expertise: (i) Seismology/Borehole Location(s)/RTS, (ii) Drilling/Coring/Geological Logging/Fault Zone Studies, (iii) Geophysical Logging/Petrophysical Properties/Long-term

Monitoring, and (iv) Temperature/Hydrogeology/Fluid and Gas Sampling. The breakout group discussions started at Hyderabad and continued through the field visit to Koyna and for another full day at Karad. The hallmark of the event was the gathering of experts from all major fault zone drilling programs worldwide, all working together to address the major challenges of undertaking the deep drilling investigations at Koyna.

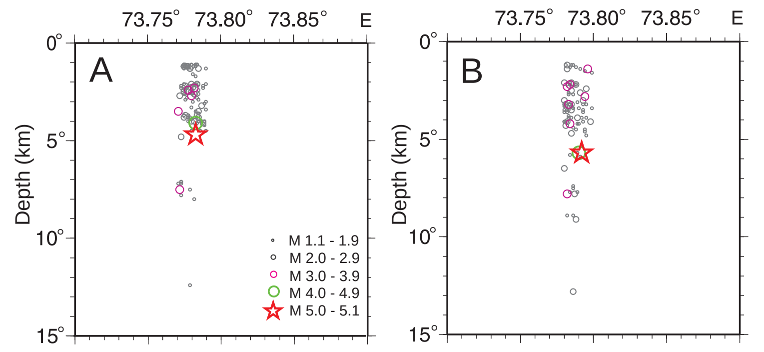

Figure 2. Depth sections of the two blocks shown in Fig. 1 in pink. Number of earthquakes during 2009–2010 in [A]: M1.1–1.9 (81 events), M2–2.9 (26 events), M3–3.9 (5 events), and one earthquake each of M4.3 and M5.0. In [B], M1.1–1.9 (54 events), M2–2.9 (24 events), M3–3.9 (7 events), and one earthquake each of M4.2 and M5.1.

Suggested Site for Deep Borehole

A borehole site for deep scientific drilling (green dot in Fig. 1, about 2 km west of block) was suggested on the basis of observed seismicity in the past two years (2009 and 2010), accessibility, and other logistic considerations. In Fig. 1, hypocenters are plotted of earthquakes of magnitude M1.1 and larger that occurred during 2009 and 2010 in block A. The seismic activity has been quite intense, as there were 81, 26, and 5 events of M1.1 to M1.9, M2.0 to M2.9, and M3.0 to M3.9, respectively. During 2009 and 2010 there was also one earthquake each of M4.3 and 5.0 in block A. A majority of these events are confined within a focal depth of 1–5 km in block A.

Outcome of the Workshop

All the participants at the workshop agreed that Koyna is an outstanding world-class geological site and a natural seismic laboratory to conduct a deep borehole experiment for earthquake studies. The MoES has declared its support to the program, and the ICDP has offered to make available its technical expertise in deep drilling and logging, training of manpower, and support towards drilling after receiving a successful drilling proposal. Experts from around the world have offered to bring in new tools and techniques for measurements and modeling.

On the basis of intensive discussions among the participants and important suggestions received from experts from India and abroad, a few key areas were identified for detailed preliminary studies. Foremost among these is the need to understand the hydrology of the region and connectivity between the reservoirs and host country rock. We also need to constrain the fine structure of the seismic zone in the area including detailed mapping of the causative faults, both of which would be critical in locating the deep borehole observatory in the region. The following three-tiered action plan was agreed upon.

1. Revisiting old data and acquiring new data
    - Compile all available earthquake data for Koyna area and apply the most appropriate techniques to improve hypocenter locations.
    - Deploy a larger number of seismic stations, especially in the region close to the active Warna seismic zone.
    - Take up geophysical surveys like seismic reflection, magnetotelluric, deep electrical sounding, gravity and magnetics to constrain the fine structure of the seismic zone.
    - Acquire very high-resolution Light Detection And Ranging (LIDAR) data.

2. Studying hydraulic connectivity
    - Initially drill about four test boreholes around the seismic zone, each penetrating about 200 m into the pre-Trappean basement.
    - Perform suites of measurements on geochemical and geophysical parameters in and across these boreholes.
    - Model regional hydraulic connectivity.

3. Plan the main borehole based on 1 and 2.

The workshop provided an excellent opportunity for the global community of concerned scientists to discuss the ideas and data collected and results obtained from the Koyna site of RTS for over the last four decades. The suggestions and plan of action as summarized above is now being implemented.

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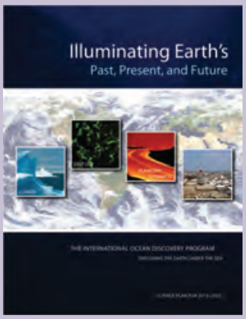
New Science Plan on Ocean Drilling Published



The science plan for the new ocean drilling program, the International Ocean Discovery Program 2013–2023, was published in June 2011. The title of the science plan is “Illuminating Earth’s Past, Present and Future”. The science plan (available on www.iodp.org) has been in preparation for more than two years with input from a broad scientific community representing Earth, ocean, climate and life sciences. Numerous workshops were held, and white papers invited from across the community. The planning process culminated with the INVEST Conference in September 2009 at the University of Bremen, an event that was attended by approximately 600 scientists from 21 countries.

Based on the extensive report from the INVEST meeting, a select group of researchers prepared a draft science plan that underwent extensive community review in 2010 before being completed in spring of 2011. It was presented to the international press on 16 June (http://iodp.streamco.tv/IODP_-_Livestream_16th_of_June_2011.html).

The science plan includes four major themes (see below) and within these, 14 specific challenges.

- Climate and Ocean Change: Reading the Past, Informing the Future
- Biosphere Frontiers: Deep Life and Environmental Forcing of Evolution
- Earth Connections: Deep Processes and Their Impact on Earth’s Surface Environment
- Earth in Motion: Processes and Hazards on Human Time Scales

The New Web-Based Journal *Frontiers in Extreme Microbiology* Invites Manuscripts

*Abstract deadline: *15 July 2011*
*Manuscript deadline: *15 September 2011*

The new web-based journal “*Frontiers in Extreme Microbiology*” will mark its launch with a special topic, deep subsurface microbiology, and invites abstracts and manuscripts.

Deep subsurface microbiology focuses on the molecular detection and quantification, cultivation, biogeographic examination, and distribution of bacteria, archaea and eukaryotes that permeate the subsurface biosphere of deep marine sediments and the basaltic ocean crust. The deep subsurface biosphere abounds with uncultured, only recently discovered and (at best) incompletely understood microbial populations. In spatial extent and volume, the subsurface biosphere is only rivaled by the deep sea water column. So far, no deep subsurface sediment has been found that is entirely devoid of microbial life; microbial cells and DNA remain detectable at sediment depths of more than 1 km; microbial life permeates deeply buried hydrocarbon reservoirs, and it is also found several kilometers down in continental crust aquifers. Severe energy limitation, either as electron acceptor or donor shortage, and scarcity of microbially degradable organic carbon sources are among the evolutionary pressures that have shaped the genomic and physiological repertoire of the deep subsurface biosphere. Its biogeochemical importance as a long-term organic carbon repository, inorganic electron and energy source, and subduction recycling engine is a major focus of current research at the interface of microbiology, geochemistry and biosphere/geosphere evolution. The *Frontiers in Extreme Microbiology* special topic will address some of the central research issues in deep subsurface microbiology and biogeochemistry: phylogenetic and physiological microbial diversity in the deep subsurface; microbial activity and survival strategies in severely energy-limited subsurface habitats; cell-specific microbial activity as reflected in process rates and gene expression patterns; biogeographic isolation and connectivity in deep subsurface microbial communities; and the ecological standing of subsurface biospheres in comparison to the surface biosphere. Is this region an independently flourishing biosphere, or merely a site of survivors that tolerate burial (along with organic carbon compounds), or a combimnation of both? Studying these issues on Earth’s deep subsurface biosphere has far-ranging implications, not the least being in the field of astrobiology and the search for subsurface life beyond Earth.

*Abstracts and manuscripts will be considered with some fliexibility (one or two months later than the posted deadliens).

Web Link: www.frontiersin.org/extrememicrobiology/specialtopics/deep_subsurface_microbiology.

Edited by Andreas Teske (UNC Chapel Hill), Axel Schippers (BGR), Peter Dunfield (Univ. of Calgary, Virginia Edgcomb (WHOI), and Jennifer Biddle (University of Delaware)

Call for IODP-Canada Graduate Student Research Awards

Application deadline: 18 November 2011

To enhance the experience of graduate students investigating marine geology questions related to the research themes of the Integrated Ocean Drilling Program, IODP-Canada offers merit-based awards of up to $3000 to students enrolled in either an MSc or PhD program or employed as a post-doc at a Canadian institution. The research awards are intended to support projects directed toward the objectives of upcoming or past DSDP/ODP/IODP expeditions, utilizing core material and/or shipboard data.

Please contact the IODP-Canada Coordinator (coordinator@mail.iodpcanada.ca) for more information.

The Netherlands Joins ICDP

Starting 2011, the Netherlands is a member country of ICDP. Dutch community, ICDP-NL, is an open platform that intends to bundle the expertise of (sometimes rather small) research groups and specialists and to support the ambitions of the Dutch scientists. The community consists of scientists of a broad variety of Earth science disciplines, ranging from archaeology to tectonics. It not only involves universities but also the Netherlands Organisation for Applied Scientific Research (TNO). The Board of ICDP-NL is chaired by Stefan Luthi (TU Delft) and advised by a representative of the drilling industry. The membership fee is financed by the Earth and Life Science division of the Netherlands Organization for Scientific Research (NWO).

A first symposium was held on 14 February 2011, during which also the agreement between NWO and ICDP was signed. ICDP-NL will cooperate closely with IODP-NL, for instance, by organizing joints meetings.

Dutch scientists already have a long track record in continental drilling. ICDP-NL will build on the expertise gained during these collaborative projects and is looking forward to now becoming fully involved in initiating and executing ICDP projects.

Contact details, the press release and the first newsletter can be found on the ICDP website under National Programs.

Australia and New Zealand in Scientific Drilling

ANZIC IODP activities are proceeding smoothly. The 2010 ANZIC Annual Report is now available on www.iodp.org.au. The report not only covers Australian and New Zealand activities in IODP in 2010, but looks at the future and makes the point that we are fully committed to IODP, now and in the future. Australia now has funding until the end of the present phase of IODP, and New Zealand is actively pursuing such funding. Planning is underway for an IODP session at the International Geological Congress in Brisbane in mid-2012 (www.34igc.org), and a large number of international participants are expected to attend.

In the first six months of 2011, four ANZIC scientists participated in IODP expeditions: two aboard the Louisville Seamount Trail expedition (330), one aboard the CRISP expedition (334) and one aboard the Superfast Spreading expedition (335).

A New Zealand Scientific Drilling Workshop was held in Dunedin in March 2011, and a white paper is currently under development to sketch the concept and importance of the DrillNZ initiative to various stakeholders. A New Zealand-led IODP workshop "Conceptual framework for ocean drilling to unlock the secrets of slow slip events" was held at Gisborne, New Zealand in August 2011. Since beginning of August 2011, NIWA (the Natonal Insitute of Water and Atmosphere) has joined the consortium of New Zealand Universities and Crown reseach Institutes contributing to ANZIC, and has committed funds towards the New Zealand IODP membership fee up to 2013–2014.

An Indian Ocean IODP workshop will be held in Goa, India over the period 16-18 October 2011. The organizers are India and ANZIC. The aim of the workshop is to further develop existing proposals and design new ones, in the hope that *JOIDES Resolution* will be in the Indian Ocean in 2014.

Australia and New Zealand are making important scientific contributions to IODP, and a number of major coring expeditions in our region have improved and will improve the understanding of global scientific questions. Although IODP is now working outside the region, these two countries remain keen supporters of global IODP science.

2nd Swiss ICDP Meeting (March 2011, Zürich)

About 40 scientists gathered in March 2011 in Zurich to exchange news about past, present and future ICDP projects with active Swiss involvement. Since Switzerland became an ICDP member through support from the Swiss National Scceince Foundation only three years ago, a series of projects with Swiss participation have been already drilled or are underway, and more are planned, reflecting an active contribution to the overall ICDP program. Scientists from Swiss institutions are acting as as PIs and Co-PIs in several drilling projects targeting lake sediment records, the subsurface biosphere, volcanic domains, sedimentary basins and groundwater contamination.

One of the main goals of the meeting was to address new themes to take further advantage from the Swiss ICDP membership. For example, several ideas were raised in the context of research on geothermal energy, where large commercial projects are currently underway, and it was suggested that a geothermal component could complement any continental drilling project. In the same context, CO_2 sequestration gained wide attention and might be further explored in the near future. New ideas will address drilling targets also within Switzerland. For example, a drilling initiative involving scientists from perialpine countries aims to explore the timing and extent of alpine glaciations and related erosion and sedimentation through drilling the sedimentary infill of overdeepened troughs all around the Alpine region. Kick-off meetings with international partners are planned to explore possibilities for an ICDP workshop proposal. In a similar fashion, the Alps themselves provide a series of drilling objectives that may serve as unique records of tectonic and petrologic processes. One example is the highly metamorphic Ivrea Zone (Southern Alps), where lower-crust rocks are outcropping at the surface and where a drill hole could reach upper mantle rocks (i.e., the Moho) in much shallower depth as in its original location.

Altogether, the Swiss scientific drilling community is very active, and the combined IODP and ICDP memberships will continue to provide the ideal platform to conduct and realize these fascinating drilling initiatives. Contact: flavio.anselmetti@eawag.ch.

D/V *Chikyu* Damaged by Tsunami, Repairs Planned

At 2:47 p.m. JST on 11 March, the Tohoku region in the northern Pacific coast of Japan suffered an M9 earthquake followed by a 7+ m tsunami strike and numerous aftershocks. At that time, D/V *Chikyu* was in port at Hachinohe preparing for IODP Exp. 337. The *Chikyu* immediately evacuated port; however, during the emergency evacuation the vessel suffered damage. All personnel and visitors aboard, including a visiting delegation of local elementary school students, were safely accounted for.

On 20 March, *Chikyu* arrived at the port of Muroran in southern Hokkaido where divers made a provisional assessment of the ship's damage. From 20 April until 18 June, the *Chikyu* was dry-docked for repair at the Yokohama Dockyard and Machinery, and returned to sea for testing on 18 June 2011.

One of DV/ *Chikyu*'s azimuth thrusters suffered damage as tsunami waves buffeted the vessel in the Hachinohe port, and its replacement is currently being manufactured. The new thruster is expected to be installed by the end of March 2012.

IODP-Canada Summer School Scholarships

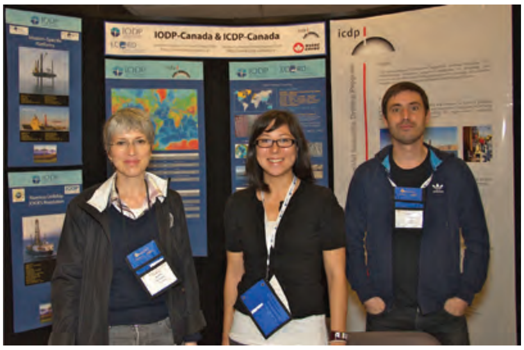
IODP-Canada is pleased to announce that five students received scholarships to attend one of the 2011 ECORD summer schools held in Bremen, Germany and Urbino, Italy.

Congratulations to Thi Hao Bui (PhD student, McGill University), Jon Furlong (MSc student, University of Victoria), Fritz Griffith (MSc student, University of Ottawa), Lucie Hubert-Théou (PhD student, McGill University), and Stefan Markovic (PhD student, University of Toronto).

IODP/ICDP-Canada Booth at GAC-MAC 2011

IODP-Canada and ICDP-Canada shared an exhibition booth at the joint annual meeting of the Geological Association of Canada and the Mineralogical Association of Canada, held at the University of Ottawa on 25–27 May 2011. Over 1050 Earth scientists (including 285 students) from Asia, Canada, Europe, and the U.S. attended the conference.

Anne de Vernal, Chair of IODP-Canada, and the Coordinators of IODP-Canada and ICDP-Canada staffed the booth and met with students, faculty and funding agency representatives. Many ECORD, IODP and ICDP outreach materials were distributed, and subscribers to the Canadian mailing list increased by over 10%. The new IODP-Canada Website (www.iodpcanada.ca) was launched just prior to the start of the conference.



ICDP Dead Sea Core Opening Party, Part I

Within the framework of the ICDP Dead Sea Deep Drilling Project (DSDDP) a first core opening party took place at the GFZ German Research Centre for Geosciences, Potsdam, in June 2011. A group of 18 involved scientists and student helpers from Israel, Japan, Switzerland, and the U.S., together with the German team around Prof. Dr. Achim Brauer, opened and described around 470 meters of a total of 720 meters of sediment cores that had been obtained during the drilling campaign at the Dead Sea deep basin from November 2010 to March 2011. Additional assistance was given by the ICDP Operational Support Group. Furthermore, modern non-destructive scanning techniques, such as micro-XRF analyses, magnetic susceptibility measurements and photographic line-scanning, have been applied at the sediments, encouraging the scientists to work in a two-shift system seven days a week in order to cope with the enormous amount of Dead Sea sediments from one 450-m deep borehole and several short cores. First estimations based on the succession of salt, laminated sequences and detrital sediment flux point out that the sediments comprise at least two climatic cycles, hence covering the last ~200 thousand years. All scientists are looking forward to meeting again at the GFZ laboratories in October this year to perform the same procedure with the remaining 250 meters from the second deep borehole and to get new insights into this fascinating archive of natural climate dynamics and seismic activity.

ANDRILL Coulman High Project – Site Survey Outcomes and Future Plans

Field surveys were conducted from November 2010 through January 2011 on the Ross Ice Shelf (RIS), northeast of McMurdo Station and Scott Base, in Antarctica, in preparation for the proposed ANDRILL Coulman High (CH) Project. The survey work is chronicled in a well-illustrated blog provided by Dr. Frank Rack, which is online at <http://www.andrill.org/science/ch/news>.

The CH Project surveys, which involved integrated planning and execution by a combined international team from New Zealand and the United States, achieved all primary and secondary objectives. A transverse route from Ross Island to CH across the RIS was established using a tracked-vehicle-mounted ground-penetrating radar system supplemented by airborne radar. Four GPS stations and a weather station were established to measure lateral and vertical motions of the RIS and to monitor environmental conditions. A series of combined U.S.-NZ field camps on the RIS were occupied, and the ANDRILL hot water drill (HWD) system was used to melt numerous holes through 260–275 m of ice. Oceanographic moorings comprised of inductive oceanographic instruments were deployed through the RIS at two sites, and were recovered to the ice surface after two months; one mooring was then redeployed to accomplish multi-year observations at CH. Video camera observations of the interior and basal surface of the ice shelf were made at several sites and these observations were integrated with conductivity-temperature-depth (CTD) measurements through the ice shelf to the seafloor at each site. The Submersible Capable of under-Ice Navigation and Imaging (SCINI) underwater remotely operated vehicle (ROV) was deployed through the ice to explore the underside of the ice shelf while conducting operational tests. SCINI discovered an unusual biological community living in the ice and recovered biological samples using an improvised suction pump (Rack et al., 2011); these samples and extensive imagery are being further investigated.

ANDRILL is a multinational scientific program to investigate Antarctica's glacial and tectonic history. Of specific interest is Antarctica's past and future role in global environmental change as revealed through stratigraphic drilling along the Antarctic margin and related numerical modeling of climate and ice sheet behavior. ANDRILL is developing the CH Project to investigate Early Miocene and Paleogene paleoenvironmental and tectonic history by drilling at two sites on the Ross Ice Shelf, approximately 150 km east of McMurdo Station, over the subsea geologic structure known as the Coulman High. Further information about the project is available at <http://www.andrill.org/science/ch>.

The ANDRILL Science Committee (ASC) has issued an international call for submission of statements of interest in the CH Project from international scientists. This survey is available online at <http://www.andrill.org/science/ch-survey>. The scientific team for the project will only be selected from nations that belong to the ANDRILL consortium. If you would like to know more about how your nation might join the ANDRILL consortium as a participating member, please contact Dr. Tim Naish, Chair of the ASC, at <tim.naish@vuw.ac.nz> or contact Dr. Frank Rack, Secretary of the ASC and Executive Director, ANDRILL Science Management Office, University of Nebraska-Lincoln, at <frack2@unl.edu>.

Reference

Rack, F., Levy, R., Falconer, T., Zook, R., Mahacek, P., Carroll, D., Williams, M., Stewart, C., Limeburner, R., and the ANDRILL Coulman High Site Survey Team, 2011. PS14.3: Interdisciplinary outcomes of the ANDRILL Coulman High Site surveys. [paper presented at 11th International Symposium on Antarctic Earth Sciences, Edinburge, Scotland, 10–15 July 2011]

Bighorn Basin Coring Project (BBCP)

The Bighorn Basin Coring Project (BBCP) initiated drilling operations in the Bighorn Basin of Wyoming (U.S.) on 13 July 2011 and completed drilling on 4 August 2011. The main goal of the project is to recover complete, unweathered core samples from Paleogene continental strata that record rapid global warming events known as hyperthermals (e.g., Paleocene-Eocene Thermal Maximum [PETM] and Elmo). By applying various geochemical, geophysical, and paleontological methods on these high-quality (HQ) cores, the project aims to better understand the causes of these climate events and their effects on continental systems. The project was highly successful in achieving all of its drilling goals with >95% core recovery in each hole. Three sites in the basin were targeted (Basin Substation, Polecat Bench, Gilmore Hill) with two holes drilled at each site to get overlapping cores. A total of 921 meters of HQ core was recovered in liners with all but one of the sites being drilled with municipal water only, thus reducing the potential for core contamination. In mid-August, the cores started their journey from Powell, Wyoming to the IODP Bremen Core Repository at the University of Bremen, Germany, where they will be split, described, and sampled by the BBCP Science Team in early 2012. BBCP web page: http://earth.unh.edu/clyde/BBCP.shtml

Facebook page with real time updates: http://www.facebook.com/pages/Bighorn-Basin-Coring -Project/120607821348013.

ISAES-11 Antarctic Shallow Scientific Drilling Workshop

Following the 11th International Symposium on Antarctic Earth

The PASADO Core Processing Strategy: A Flexible Protocol for Sediment Subsampling in Multidisciplinary Drilling Projects

Subsampling of sediment cores is the important first step of almost every study. Sampling procedures were developed within IODP/ODP/DSDP to ensure the reproducibility of core treatment as well as its documentation. In contrast, procedures for lacustrine sediment cores are as manifold as the corresponding scientific questions and communities. A sampling assembly and a flexible sampling protocol are described in the version adapted to the PASADO project. This protocol introduces a core splitter and a sampling assembly consisting of a divider and a D-scoop for fast and efficient subsampling. Detailed information can be found in our recently published paper (Ohlendorf et al., 2011).

The core splitter cuts plastic core liners without contamination of the sediment by liner material. The core sampling assembly is used to sample one core half completely in contiguous steps. The core half is split into slices of similar thickness by inserting thin disks through a comb-like divider, and the D-scoop is used to sample these sediment disks (Fig. 1). The utilization of the sediment is optimized because all sediment is sampled in one step. Subsamples with known volume can then be taken from the exact same stratigraphic level in the core. Quality flags are defined to document the condition of every (sub)sample and to allow a first classification of the sediment character.

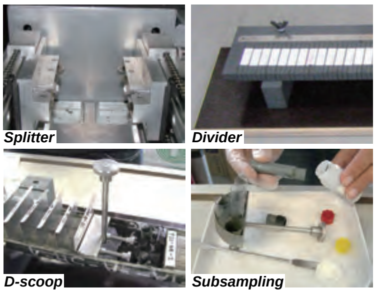


Figure 1. Photographs of core splitter and the sledges with the four blades, divider, and the D-scoop.

Reference

Ohlendorf, C., Gebhardt, C., Hahn, A., Kliem, P., Zolitschka, B., and the PASADO science team, 2011. The PASADO core processing strategy - A proposed new protocol for sediment core treatment in multidisciplinary lake drilling projects. *Sediment. Geol.*, 239:104–115, doi:10.1016/j.sedgeo.2011.06.007.

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and the PASADO science team

Related Web Link

http://www.icdp-online.org/front_content.php?idcatart=2794

Sciences (ISAES-11) in Edinburgh, Scotland, a one-day workshop on Antarctic Shallow Scientific Drilling was held in the John McIntyre Conference Centre of the University of Edinburgh (Scotland) on Sunday, 17 July 2011. The workshop, which attracted over thirty-six international attendees from six countries, was co-convened by Frank Rack (University of Nebraska-Lincoln) and Bruce Luyendyk (University of California, Santa Barbara). The presentations explored the use of numerical models and data-model integration strategies to answer important scientific questions, identified potential shallow drilling targets from specific sites around the Antarctic margin, including land-ocean transects, and reviewed the status of existing and emerging technology options that could be used to implement shallow (up to 200 mbsf) scientific drilling/coring of glacial and glacial-marine sediment and rocks in ice-covered seas (e.g., mission specific platforms, including options for either ship-mounted rigs or seafloor drills). Further information about the outcomes of the workshop will be available online in the near future at <http://www.shaldril.org>.

International Workshop on Scientific Drilling in the Indian Ocean

17–18 October 2011, Goa, India

The Indian Ocean has experienced an extremely complicated tectonic history. From the disintegration of Gondwanaland to the collision of the Indian plate with Asia and the subduction of the Indian plate in one of the most prominent subduction zones, the region has a diversity of key tectonic features. Much geo-scientific knowledge regarding the Indian Ocean was gained from the International Indian Ocean Expedition program (IIOE-1960–65). Since then, integrated geophysical and geological studies have considerably improved our understanding of geological evolution of this region. Results from previous studies in association with the ODP/DSDP boreholes in the Indian Ocean have further strengthened our knowledge.

Despite these remarkable efforts, several key questions related to the Indian Ocean with significant global relevance are still unanswered. Decades of geo-scientific work focused on this sector has produced compelling hypotheses on various fronts. Our present understanding vis-a-vis these propositions requires corroboration from direct measurements such as deep ocean cores. The need for scientific drilling in the Indian Ocean sector is highly evident by several active IODP drilling proposals at various stages (e.g. proposal nos. 549, 552, 595, 667, 701, 702, 704, 717, 724, 727, 760, 776, 778, 780 and 783).

IODP-India in association with ANZIC is organizing an international workshop to discuss various scientific proposals for drilling in the Indian Ocean sector as well as to encourage discussions of new proposals in this sector for the new phase of the IODP. The Indian Ocean IODP Workshop will be held in Goa on 17–18 October with about 100 participants from all over the world. The workshop is planned back to back with the seventh Asian Marine Geology Meeting, also taking place in Goa during the previous week.

Because there has been no scientific ocean drilling in the Indian Ocean for nearly a decade, this workshop is vital to developing strong new drilling proposals. Also, India itself has only joined IODP recently, and such a workshop will provide wide exposure to the Indian science community of IODP science and IODP capability. The following four themes have been arranged for the workshop and with planning subcommittees largely formed:

1. Cenozoic oceanography, climate change, gateways and reef development: broad questions related to the Indian Ocean, and narrow ones such as the Indonesian Throughflow, sea-level changes, and the origin of late Pleistocene reefs.
2. The history of the monsoons: tectonics, uplift, weathering and erosion, sediment deposition, climate and oceanography, and discussions/nurturing of proposals that have emerged since the 2008 Detailed Planning Group (DPG) workshop on monsoons.
3. Tectonics and volcanism: tectonism of the Indian Ocean, including plate tectonics, the evolution of the oceanic crust and mid-ocean ridge formation, the formation of large igneous provinces, continental rifting and related deposition, and subduction, arc volcanism and earthquakes.
4. The deep biosphere: studies of the “extremophiles” of the deep biosphere in sediments and basalts focusing on the nature of the oceanography and inputs of organic matter into the Indian Ocean.

More information on this workshop can be found at www.iodp.org/workshops/8/ or www.ncaor.gov.in/iodp/index.html.

Workshop conveners:

Dr. Dhananjai K. Pandey, Program Officer (IODP-India), e-mail: iodp.india@ncaor.org, and Professor Neville Exon: ANZIC Program Scientist, e-mail: neville.exon@anu.edu.au.

International Review of the ICDP with Outstanding Results

On behalf of the Assembly of Governors, (AOG) and at the request of the main funding partners of the program, the International Continental Scientific Drilling Program was evaluated in May 2011 by an international review committee of independent experts with key expertise in major programs in the geosciences and funding organizations.

The committee concluded that ICDP is a highly successful program, achieving with very modest investments world-class science of global impact. The program has been highly effective in community-building and is driving integration in modern Earth system science. It has demonstrated strong scientific leadership and effective allocation of its limited financial resources. The program holds great promise to further attract new member states, organizations and industrial partners.

One important outcome of the assessment is to start developing a new ICDP Science Plan. The AOG has therefore initiated the planning for an International Symposium on Continental Scientific Drilling in 2013.

Drilling into the Fault Zone of the Giant Tohoku Earthquake?

Following the 11 March Tohoku earthquake, IODP mobilized a Detailed Planning Group (DPG) to investigate the feasibility of drilling into the seismogenic fault. Box 1 on page 61 is an excerpt from the report produced by the DPG.

A DPG meeting in May led to a full proposal for drilling within an area of 6–7 km water depth near the trench where the fault can be reached within 1 km subseafloor. Later plans are to measure ephemeral properties related to the rupturing of the fault as a baseline; repeat observations are a key target. Properties include an expected friction induced temperature anomaly providing a proxy for fault strength (friction) during rupture. Drilling is required within about 18 months after rupture before a temperature anomaly has dissipated too much. This is a unique opportunity to sample a fault as close in time as possible to a major and large displacement earthquake event, but drilling and casing a hole in these water depths is a technological challenge. The study, if deemed feasible and implemented, will complement ongoing studies in the Nankai Trough, which targets a strong mega-fault expected to rupture within a few decades.

References for figures in Box 1 available in the full DPG Report, which is at http://www.iodp.org/weblinks/Featured-Publications-HOME-PAGE/Tohoku-Rapid-Response-Drilling-DPG-Report/.

Used by permission.

Box 1: The 2011 Off the Pacific Coast of Tohoku Earthquake (M_w9.0)

The March 11, 2011 Tohoku earthquake came as a disheartening surprise to the geophysical community. With a historical record of nearly 500 years including 13 M_w7 and 5 M_w8 earthquakes, this region was thought to be relatively well understood in terms of the locations and sizes of expected subduction zone earthquakes. An M_w9 event breaking through the entire region of many fault segments, with the associated huge tsunami, was not at all anticipated for this thoroughly studied area. This failure highlights the need for a more physically-based understanding of initiation and rupture.

The sequence started with an M_w7.2 foreshock, which occurred 2 days before and about 40 km NE of the mainshock hypocenter. In the hour after the mainshock, there were large M_w7.9 and M_w7.7 aftershocks. In addition to the countless aftershocks in the immediate region, the seismic activity of small earthquakes increased across most of Japan with several M_w5 and a few M_w6 earthquakes over the following month. Small earthquakes were also triggered at 13 volcanoes according to the Coordinating Committee for Prediction of Volcanic Eruption.

Apart from the foreshocks, there were no clear precursory signs or large pre-slip. The foreshocks themselves were only identified as precursory with hindsight. Current models of earthquake clustering suggest that the probability of having an M_w 9.1 earthquake following an M_w 7.2 earthquake within 2 days is <0.001% and thus a societally useful prediction could not be provided based on the foreshocks alone.

Modeling of seismic, crustal deformation, and tsunami data shows very large slip on the fault plane, with values up to 30–50 meters (e.g. Simons et al., 2011, Sato, et al., 2011, Ammon et al., 2011, Ohta et al., 2011, Lay et al., 2011). The area of maximum slip is on the shallow portions of the fault trenchward of the hypocenter. The large and shallow slip near the trenchward limit of the megathrust caused large deformation of the seafloor, which generated the devastating tsunami. Because of the dense network of observations in the region prior to the earthquake, the extremely large slip has been verified by direct observations of displacement on the seafloor through repeat bathymetry and GPS.

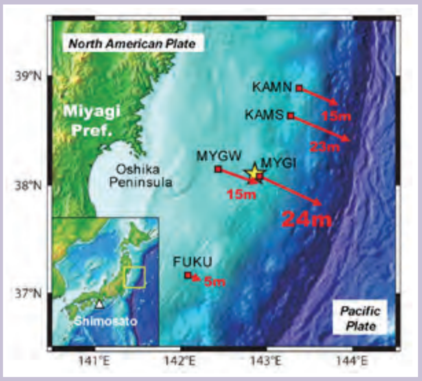

Figure 2. Horizontal coseismic displacements at seafloor benchmarks, associated with the Tohoku earthquake. Red squres are locations of GPS benchmarks and yellow star is the epicenter of the mainshock (Sato et al., 2011b)

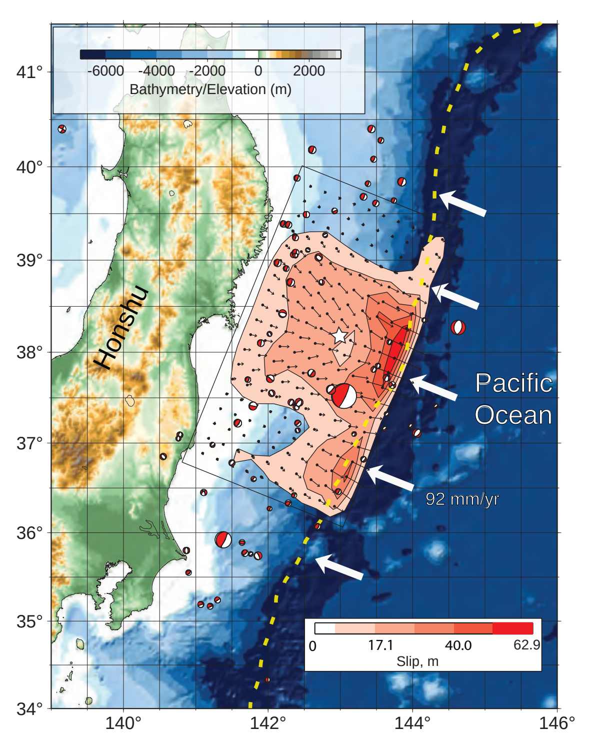

Figure 1. Teleseismic P-wave inversion for slip (Lay et al., 2011). Maximum slip ranges from 40–80 for a suite of inversion models with the majority of models placing large slip near the trench. Most models do not directly incorporate the ocean bottom observations in Figure 2 and 11 which require large slip towards the updip end of the rupture.

The earthquake produced severe strong ground motions with accelerations over 1 g and long durations of about 100 s. However, the large losses of lives and property were mainly due to the tsunami, and shaking damage was relatively limited, considering the size and intensity of the earthquake. Even the well-publicized problems at the Fukushima No. 1 nuclear power plant were caused by loss of power due to the tsunami inundation, and not by the shaking itself. The resilience of most structures throughout the region can be attributed to the high seismic standards of Japanese construction.

During the Tohoku earthquake, the regions of the fault that produced the dominant high-frequency energy are different from the areas of large slip. The large slip is on the shallow updip portion of the fault, while the high-frequency radiation originated from the deeper downdip portions of the fault (e.g. Ide et al., 2011, Wang and Mori, 2011, Koper et al., 2011). The difference in frequency of the radiated energy for different portions of the fault reflects variations in rupture dynamics. The deeper portion appears to be have undergone a more brittle rupture with a higher proportion of radiated energy, while the large shallow slip probably absorbed more energy through dissipated processes. The greater dissipation may be characteristic of tsunami earthquakes and can be studied by sampling this portion of the fault with a borehole.

Schedules

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

	ESO Operations	Platform	Dates	Port of Origin
	No expedition is currently scheduled.			
	USIO Operations *	**Platform**	**Dates**	**Port of Origin**
1	336 - Mid-Atlantic Ridge Microbiology	*JOIDES Resolution*	16 Sep.–17 Nov. 2011	Bridgetown, Barbados
2	339 - Mediterranean Outflow	*JOIDES Resolution*	17 Nov. 2011–17 Jan. 2012	Ponta Delgada, Azores
3	340T - Atlantis Massif Oceanic Core Complex	*JOIDES Resolution*	17 Jan.–6 Feb. 2012	Lisbon, Portugal
4	340 - Lesser Antilles Volcanism and Landslides	*JOIDES Resolution*	6 Feb.–18 Mar. 2012	St. John's, Antigua
5	341 - Southern Alaska Tectonics Climate and Sedimentation Experiment	*JOIDES Resolution*	2013 (dates TBD)	Victoria, B.C., Canada
6	342 - Newfoundland Paleogene and Cretaceous Sediment Drifts	*JOIDES Resolution*	18 Jun.–17 Aug. 2012	Curacao, Dutch Antilles
	CDEX Operations **	**Platform**	**Dates**	**Port of Origin**
7	337 - Deep Coalbed Biosphere off Shimokita	*Chikyu*	Cancelled***	Hachinohe, Japan
8	338 - NanTroSEIZE Plate Boundary Deep Riser - 2	*Chikyu*	Jun. 2012–Dec. 2012	Shingu, Japan

TBD=to be determined

* Sailing dates may change slightly. Staffing updates for all expeditions to be issued soon.

** CDEX schedule subject to OTF and SAS approval.

***Expedition is currently postponed indefinitely due to earthquake in northeastern Japan.

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

	ICDP Projects	Drilling Dates	Location
1	Colorado Plateau	Oct. 2011	Arizona, U.S.A.
2	Lake Ohrid	Jun. 2011–Jul. 2012	Macedonia, Albania
3	Campi Flegrei	Sep. 2011–Sep. 2012	Naples, Italy
4	Songliao Basin	Sep. 2011–Sep. 2012	Daqing, China
5	COREF	Jan. 2012–Jul. 2012	Ryukyu Islands, Japan
6	GONAF	Apr. 2012–Jul. 2012	Istanbul, Turkey