7

A sampler of scientific results

These articles give an idea of the variety of drilling expeditions in our region in the period 2010 to 2013. They outline early results from these scientifically very diverse expeditions and were written in 2015 and 2016.
Sediments, rocks and chemical fossils in the Canterbury Basin, New Zealand: IODP Expedition 317

Simon C. George, Macquarie University, Sophia Aharonovich, Macquarie University, Greg H. Brown, GNS Science, and Julius S. Lipp, University of Bremen

Introduction

Figure 7.1. Drilled and proposed Expedition 317 sites, together with seismic grids, exploration wells Clipper and Resolution, and Ocean Drilling Program Site 1119

Source: Modified from Expedition 317 Scientists (2011)

IODP Expedition 317 drilled the Canterbury Basin east of the South Island of New Zealand and was devoted to understanding the relative importance of global sea level (eustasy) versus local tectonic and sedimentary processes in controlling continental margin sedimentary cycles (Expedition 317 Scientists, 2011). Sediments were recovered from four sites (Figure 7.1),
including three on the continental shelf (landward to basinward, Sites U1353, U1354, U1351), and one on the continental slope (Site U1352). The drilled sediments range in age from Late Eocene to Holocene, and provide a stratigraphic record of depositional cycles across a shallow marine transect most directly affected by relative sea-level change. Sedimentation is thought to have been controlled by the timing of uplift of the adjacent Southern Alps, as well as the influence of strong ocean currents, including the Antarctic Circumpolar Current and the Deep Western Boundary Current. The sedimentary record is being used to estimate the timing and amplitude of global sea-level change, and to document the sedimentary processes that operate during sequence formation. Sites U1353 and U1354 provided significant, double-cored, high-recovery sections through the Holocene and late Quaternary for high-resolution study of recent glacial cycles in a continental shelf setting (Expedition 317 Scientists, 2011).

The transformation of sediment into rock

At Site U1352, a continuously cored 1,927 m thick Holocene to Late Eocene section uniquely documents downhole changes in induration, from un lithified sediments to rock, using a wide range of petrological, petrophysical and geochemical data sets (Figure 7.2). Porosity decreases from around 50 per cent at the surface to about 10 per cent at the base of the hole, with a corresponding increase in density from around 2 to 2.5 g cm$^3$ (Marsaglia et al., 2017). There are progressive changes in the minerals with depth, including an increase in carbonate and a decrease in quartz and clay content. Grain compaction is first seen in rock thin sections at 347 m below sea floor (mbsf). Pressure solution begins at 380 m and is common below 1,440 m, with stylolite development below 1,600 m, and sediment injection features below 1,680 m. Pore water geochemistry (Figure 7.2) and petrographic observations document two active zones of cementation, one shallow (down to ~50 m), driven by methane oxidation by sulphate, transitioning to another burial-related cementation zone starting at ~300 m, resulting from carbonate dissolution and re-precipitation. Carbonate cementation becomes more common with depth. These results quantify downhole diagenetic changes and verify depth estimates for these processes inferred from outcrop and other well-based studies.
Figure 7.2. Downhole variation of methane from headspace analysis, and interstitial water, alkalinity and geochemical parameters relative to lithostratigraphy in Holes U1352A (red symbols), U1352B (black symbols) and U1352C (blue symbols).

Lithostratigraphic units I to II and their subdivisions are indicated. Parameters are methane (ppmv), yield of interstitial water (IW) per cm of squeezed whole-round cores; alkalinity (mM); sulphate (mM); magnesium (mM); calcium (mM); strontium (mM); potassium (mM); iron (μM); lithium (μM); ammonium (mM); and phosphate (μM). IAPSO seawater values are shown with the black-filled triangle and marked with ‘SW’.

Source: From Marsaglia et al. (2017)
Chemical fossils to define source input and palaeoceanography

Coastal ecosystems such as the Canterbury Basin are characterised by high biological productivity due to a significant amount of organic matter (OM) arriving from oceanic or terrigenous inputs. Local tectonic activity in New Zealand, such as the uplift of the Southern Alps and volcanic eruptions, created a significant input of eroded sediment and terrigenous OM into the marine environment. Marine productivity, on the other hand, was influenced by palaeoceanographic changes such as global sea-level variations, changes in currents and water temperature variation. The OM from the continental margin area contains information about both types of organic input. Hydrocarbons including chemical fossils (biomarkers) preserved in cored sediments from IODP Expedition 317 have been used to define the source of the OM and to determine sea surface palaeo-temperature reconstructions of the area. Rock-Eval pyrolysis (Expedition 317 Scientists, 2011) results combined with the distribution of aromatic hydrocarbons and biomarkers show good preservation of the OM (Figure 7.3). Calculated vitrinite reflectance based on the latter (Peters et al., 2005) varies from the early oil window in the Oligocene to immature for the Late Miocene and younger sediments.

The Canterbury Basin sediments contain high amounts of marine OM during the Oligocene and Early Miocene epochs (Figure 7.3), as shown by n-alkane profiles with little odd-over-even carbon number predominance, as measured by the low carbon preference index (Bray and Evans, 1961) and the low amount of aquatic plants (Paq = Proxy ratio that distinguishes between terrestrial plants and aquatic plants using mid-chain length n-alkanes; Ficken et al., 2000). The Middle Miocene to Pliocene section is characterised by an upward increase in terrigenous OM input, with carbon preference index values increasing to much greater than one, likely due to greater input from terrigenous vascular plants as the Southern Alps were uplifted (Figure 7.3). Similar trends in OM input can also be recognised based on the total organic carbon (TOC) and total nitrogen (TN) data collected aboard (Expedition 317 Scientists, 2011). Relatively low TOCdiff/TN ratios of up to 12 in the Early Miocene indicate predominant input of marine OM. Increasing TOCdiff/TN values above 20 through the Middle and Late Miocene suggest a mix of marine and terrigenous OM input, with greater influence of land-derived vegetation (Meyers, 1997).
The distribution of archaeal membrane lipids such as glycerol dialkyl glycerol tetraethers is being used to reconstruct palaeo sea-surface temperatures (SST), using the tetraether index of 86 carbon atoms (TEX86) (e.g. Schouten et al., 2002; Kim et al., 2010; Schouten et al., 2013). In addition, it has been suggested that the branched glycerol dialkyl glycerol tetraethers are derived predominantly from a terrestrial environment (e.g. Hopmans et al., 2004; Schouten et al., 2013). Varying input of terrigenous sediment into a marine environment can be calculated by the branched and isoprenoid tetraether index, and this generally shows a decrease of terrigenous input with increasing distance from deltas and river fans (e.g. Weijers et al., 2006; Kim et al., 2012). The Canterbury Basin sediments have been used to reconstruct palaeo SST. Initial data collected by Dr Julius Lipp were presented during the post-cruise workshop in 2011 in New Zealand and show decreasing temperatures from the Oligocene to the Holocene. In 2015, new collaboration between Sophia Aharonovich and Dr Lipp led to the sampling resolution being increased by adding an additional data set from Oligocene and Miocene
samples on the continental slope site U1352 (Figure 7.4). The results show a convincing trend of decreasing palaeo SST from around 30°C during the Late Palaeocene period to around 15°C during the Late Miocene. The development of the Antarctic Circumpolar Current and general changes in the seaways during the latter part of the Cenozoic may play a significant role in controlling the observed SST change in the eastern part of New Zealand (Lawver and Gahagan, 2003; Barker and Thomas, 2004).

Figure 7.4. Reconstructed sea-surface temperatures (SST) using the TEX86 index from the continental slope site (U1352)
The calculated branched and isoprenoid tetraether index (Weijers et al., 2006) shows variations in terrestrial input into the marine sediments.
Source: After Kim et al. (2010); and authors’ unpublished data

Conclusions
Our work and that of the other members of the scientific team shows that sedimentation was controlled by the timing of uplift of the adjacent Southern Alps, as well as the influence of strong ocean currents, including the Antarctic Circumpolar Current and the Deep Western Boundary Current. The sedimentary record also allows us to estimate the timing and amplitude of global sea-level change.
References


Wilkes Land climatic and oceanographic changes: IODP Expedition 318

Rob McKay, Victoria University of Wellington, and Kevin Welsh, University of Queensland

The East Antarctic Ice Sheet is the world’s largest ice sheet, and would be the equivalent to 60 m of sea-level rise if it were all to melt. The history and evolution of the ice sheet is likely to have dominated the Earth’s climate during the geological past, affecting global sea levels, planetary albedo, oceanic overturning and surface currents, the productivity of the Southern Ocean and, by extension, atmospheric CO$_2$ content. Despite this, there are remarkably few records that are capable of reconstructing its evolution and dynamics throughout its geological history.

Expedition 318 to Wilkes Land in East Antarctica in 2010 was the first visit by the Integrated Ocean Drilling Program (or its predecessor program) to the Antarctic for a decade. The primary aim was to understand the evolution and dynamics of this ice sheet since its inferred inception at the Eocene–Oligocene boundary. This region of Antarctica is of interest because (unlike other sectors of the East Antarctic Ice Sheet that are grounded above sea level) the ice sheet here sits on the Earth’s surface up to 2,000 m below sea level (mbsl), making it potentially sensitive to marine instability processes – in particular, glacial melting resulting from moderate changes in ocean temperature and warm waters upwelling next to the ice sheet. To capture these phenomena, a transect of drill cores was collected from shallow continental shelf drill sites to deep-water continental rise/abyssal plains to investigate oceanographic linkages to changes in continental climate and ice sheets in East Antarctica.

The principal goals of the expeditions were to:

- establish the timing and nature of the first arrival of ice at the Wilkes Land margin, inferred to have occurred during the earliest Oligocene (~34 million years ago (Ma))
- reconstruct variations in the volume of the East Antarctic Ice Sheet and oceanographic/biological changes during past climatic warm events and transitional climate states
- obtain an ultra high-resolution (i.e. annual) Holocene sediment record of climate and oceanographic variability.
A total of ~2,000 m of high-quality middle Eocene–Holocene sediments were recovered from water depths of between ~400 and 4,000 mbsl, and together the cores represent ~55 million years of Antarctic history. These cores provide an unprecedented history of the transition from an ice-free ‘greenhouse Antarctica’ and the cooling and onset of continental-scale glaciation of the East Antarctic Ice Sheet (Escutia et al., 2011).

Fossilised pollen enabled a reconstruction of ‘Greenhouse Antarctic climates’ during the early Eocene (between 55 and 48 Ma). These data indicate that coastal regions of Wilkes Land were characterised by a lowland, warm rainforest dominated by tree ferns, palms and trees belonging to the Bombacaceae family whose modern relatives are found on Madagascar (Pross et al., 2012). Superimposed on this coastal pollen assemblage was an upland, mountain forest region with beech trees and conifers, revealing a more temperate climate in the East Antarctic interior and highlands. The pollen indicates that temperatures on the Antarctic coast were on average around 16°C, with summers reaching 21°C. Importantly, winters were warmer than 10°C despite Antarctica being in nearly the same position it currently is, with 24-hour darkness during winter months. Organic molecules preserved from Eocene soil bacteria confirm that the temperature was at least as warm as the pollen indicates.
Following this early Eocene warmth, a period of mid-Eocene cooling was also reconstructed from the analyses on fossil algae (dinoflagellate cysts) and organic biomarker proxies. These show cooling surface waters and Antarctic air temperatures coeval with the development of oceanic circulation through the Tasmanian Gateway. It is hypothesised that the onset of the westbound Antarctic Counter Current terminated the early Eocene hothouse, and continued cooling ultimately gave rise to the development of continental-scale glaciations on Antarctica (Bijl et al., 2013).

A continuous sedimentary record of the exact transition from the Eocene ‘greenhouse’ to the Oligocene ‘icehouse’ still remains elusive, as it is represented by a major hiatus in the IODP Expedition 318 cores – a common theme in previous Antarctic drill cores. However, earliest Oligocene (~34 Ma) glacially influenced sediments recovered from the continental shelf Site U1360 indicate that by this time a continental-scale East Antarctic Ice Sheet had extended to near the continental shelf edge (Escutia et al., 2011). This was accompanied by large relative sea-level variations, which probably exceed eustatic sea-level fall, causing local deepening (Stocchi et al., 2013). Fossil marine dinoflagellate cyst records indicate that the glacial onset and sea ice were associated with a fundamental regime shift in zooplankton–phytoplankton interactions and community structure in the Southern Ocean by the earliest Oligocene (Houben et al., 2013).

One of the longest running debates in Antarctic geosciences concerns the relative stability of the marine sectors of the East Antarctic Ice Sheet since its inception. Of particular importance is the Pliocene epoch, when global temperatures were 2–3°C higher than today and atmospheric CO₂ was ~400 ppm (parts per million), thus providing an insight into ice sheet response to climates similar to those predicted for the next century as a consequence of anthropogenic climate change. Marine mud deposited offshore of East Antarctica during the Pliocene revealed a geochemical fingerprint that enabled the science team to trace where it came from on the continent (Cook et al., 2013). They discovered that the mud originated from rocks that are currently hidden under the ice sheet, and would only be eroded by an ice sheet that had retreated inland. The scale of this retreat, combined with the loss of the smaller West Antarctic and Greenland Ice Sheets may have resulted in sea level rises of ~20 m above present-day levels. A study by Patterson et al. (2014) identified pulses of iceberg discharge from the East Antarctic associated with these major ice
sheet retreat events between 4 and 2 million years ago. They showed there was a major shift in the timing and intensity of iceberg discharge between 3.5 and 2.5 million years ago. Between 3.5 and 2.5 million years ago, naturally declining CO\textsubscript{2} levels (to 280 ppm) resulted in climate cooling and expansion of Southern Ocean sea ice. This sea ice cover prevented wind-driven warm water currents from penetrating far enough south to melt the ice sheets, and thus iceberg discharge decreased significantly at this time, indicating that the East Antarctic Ice Sheet was in general less likely to collapse when it was protected by its fringing sea ice belt.

Work continues on many other studies from cores collected during this cruise. Of particular interest are the first results to be published from Site U1357, a ~180 m long sediment core with annual-scale laminae present through the entire Holocene. This is a unique sediment core situated in one of the three main regions of Antarctic Bottom Water formation that has an ice-core or tree-ring style record. This core has the potential to fundamentally alter our understanding of natural variability of physical, chemical and biological processes in the high polar latitudes.

Figure 7.6. Icebergs are spawned from the Antarctic continent in the background
Source: Rob Dunbar, Stanford University
Figure 7.7. A school video broadcast from the ship with scientists talking about a core
Source: Rob Dunbar, Stanford University

Figure 7.8. Rob McKay analysing an Adelie Drift core collected offshore of East Antarctica
This core contains near annual layers of diatoms (marine algae) and is the most expanded Holocene sediment sequence ever recovered from the world's oceans.
Source: Rob Dunbar, Stanford University
References


Great Barrier Reef Environmental Changes: IODP Expedition 325
Jody M. Webster, Geocoastal Research Group, School of Geosciences, University of Sydney

Introduction
IODP Expedition 325, ‘Great Barrier Reef Environmental Changes’, which investigated the fossil shelf-edge reefs of the Great Barrier Reef (GBR), was the fourth IODP expedition to use a mission-specific platform, and was conducted by the ECORD Science Operator (ESO) for the European Consortium for Ocean Research Drilling (ECORD). The scientific objectives were to establish the course of sea-level change, define sea-surface temperature (SST) variations and analyse the impact of these environmental changes on reef growth and geometry over the period of 20–10 ka (thousands of years ago). Expedition 325 complemented and extended the findings of the 2005 Expedition 310, ‘Tahiti Sea Level’, which recovered postglacial coral reef cores from the flanks of Tahiti from 41.6–117.5 m below sea level (mbsl) and spanned ~16 to ~8 ka.

Operational results
During Expedition 325, 34 holes were cored from 17 sites (M0030–M0058) at three locations (Hydrographer’s Passage, Noggin Pass and Ribbon Reef) in water depths between 42 and 157 mbsl from the research vessel Greatship Maya (Webster et al., 2011) (Figure 7.9). Locations are distributed along the margin to assess the impact of regional variations in oceanographic conditions, SST, sediment input, shelf-edge morphology (width and slope) and glacialhydro-isostatic behaviour on reef response. The drilling strategy focused on recovering fossil coral reef deposits from the Last Glacial Maximum (LGM) to 10 ka. This was achieved by drilling transects of holes through the most prominent fossil barrier reef structures between 40–50 mbsl and the series of well-developed reef terraces between 80–130 mbsl (Figure 7.9, bottom panel).
Two transects were drilled at Hydrographer’s Passage: a northern transect (HYD-01C), which includes Sites M0030–39, and a southern transect (HYD-02A) encompassing Sites M0041–48. In the Ribbon Reef region, only four sites (M0049–51) from the southern RIB-02A transect were
drilled. However, at Noggin Pass another transect (NOG-01B) consisting of M0052–58 – including a hole (M0058A) on the upper continental slope (Harper et al., 2015; Herrero-Bervera and Jovane, 2013) – was completed. Challenging drilling conditions (serious technical and weather difficulties, unconsolidated sediments, cavities, etc.) meant that average per cent recoveries (27.2 per cent: Yokoyama et al., 2011) were lower than Expedition 310 (57.5 per cent: Camoin et al., 2012; Yokoyama et al., 2011), according to standard IODP calculations. However, several strategies were employed over time to maximise core recovery and quality including shorter cores runs (1 m), drilling closely spaced (within 10 m) replicate holes to generate composite cores and, most importantly, the successful implementation of the HQ drilling string at the last Sites M0054–57 saw average recoveries increase to >40–50 per cent. Like Tahiti, efforts were made at several sites (M0042A, 55A, 56A, 57A) to drill deeper into the older Pleistocene deposits to understand the nature of the pre-LGM substrate and to provide new information about reef development, diagenetic environments and sea level prior to this period (i.e. Gischler et al., 2013).

Initial scientific results

At the time of writing this summary, the majority of Expedition 325 post-cruise analyses have been completed and their publication is still in progress. However, a synthesis (Camoin and Webster, 2014) of the initial results from the proceedings, published site survey data and the first papers already confirms that Expedition 325 represents an important new record of sea level, environmental changes and reef response over the last 30 ka.

Shelf-edge reef chronostratigraphy

Sixty-eight fossil coral samples were dated by U/Th and 14C-AMS from representative cores from the top, middle and bottom of the Expedition 325 sites. This was undertaken to provide a basic chronostratigraphy for the drowned GBR shelf edge reefs so as to better guide the sampling party and post-cruise analyses (see Webster et al., 2011 for details). These preliminary data suggest that the reefs are composed of two basic chronostratigraphic sequences (Figure 7.10): basal >MIS3 (~30 ka) deposits and the overlying MIS2 to last deglacial coral reef deposits (Camoin and Webster, 2014). Below the inner barrier at HYD-01C (Hole M0034A) and NOG-01B (Hole M0057A) and inner terrace at NOG-01B (Hole M0057A), the
>MIS3 deposits are clearly reefal, and diagenetic evidence (e.g. dissolution, brownish staining) suggests they have been subaerially exposed (Gischler et al., 2013) prior to reflooding, reef initiation and growth during the last deglacial. In contrast, the >MIS3 deposits below the deeper terraces (90–110 mbsl) (e.g. Holes M0031–39A, 43A, 55A, 53A, 54A, 54B) are composed of dark grainstones and packstones characterised by shells, coral, coralline algae, Halimeda and abundant larger benthic foraminifera representing lower shelf/slope settings (Webster et al., 2011). The contact between the two sequences represents a major unconformity surface and has also been recognised in the downhole and sample petrophysical data (Webster et al., 2011; Yokoyama et al., 2011), and mapped regionally as well-defined seismic reflectors (Hinestrosa et al., 2014).

Composition of the MIS2 to deglacial reef sequence

The MIS2 to deglacial coral reef deposits (~30–10 ka) are composed mainly of coral reef frameworks and detrital sedimentary facies (Figure 7.10). Three boundstone facies are defined based on their varying proportions of corals, coralline algae and microbial sediments. In these framework facies, coral growth forms include massive, robust branching, branching, tabular, encrusting and foliaceous, and they are commonly encrusted by thick centimetre-scale layers of coralline algae, encrusting foraminifera and associated vermetid gastropods (Webster et al., 2011). While they are not as ubiquitous as in Expedition 310 (Searl et al., 2011), some intervals within the deeper terraces, particularly at NOG-01B (Holes M0053A, 54A, 54B), are dominated by abundant microbialite crusts exhibiting complex laminated and thrombolitic morphologies. The coralgal to microbialite dominated boundstones are also associated with abundant consolidated and unconsolidated sediments that are composed of mollusks, benthic foraminifera, red algae and bryozoans that occur locally as internal sediments or as thick (1–19 m) intervals underlying the boundstone facies (e.g. Holes M0031–33A) (Figure 7.10). The most common facies succession includes unconsolidated sediments at the base of the cores overlying the >MIS3 lower shelf/slope sequence. These sediments then grade upward into 20–30 m thick framework-dominated intervals composed of coralgal-microbialite to coralgal boundstone deposits forming the MIS2 to deglacial reef sequence (Figure 7.10).
Figure 7.10. IODP Expedition 325 transect HYD-01C showing basic facies patterns and age structure defining the two main sedimentary sequences (after Webster et al., 2011)

The numbers in boxes to the right of the stratigraphic columns represent preliminary core catcher U/Th (red) and C14-AMS ages.

Source: Webster et al. (2011); Camoin and Webster (2014)
Figure 7.11. Comparison of preliminary dating results from Expedition 325 with previously published sea level and palaeoclimate data

A. Previously published relative sea-level data from Tahiti, Barbados, Huon Peninsula, Bonaparte Gulf and the Sunday shelf. B. GISP2 δ18O proxy for temperature over Greenland. C. Sea-surface temperature variation in the Western Pacific Warm Pool (WPWP). D. Histogram showing the initial U/Th and C14-AMS dating results from the core catcher samples (Webster et al., 2011). The age distribution 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 warming (B/A), and Younger Dryas (YD). Note that more than 850 new dates have since been generated by the Expedition 325 dating teams.

Source: After Yokoyama et al., 2011 and see this reference for all original data sources.
In the Expedition 325 cores, coral assemblages are dominated by massive Isopora, robust branching Acropora and branching Seriatopora, but massive Porites and Faviidae, encrusting Porites, and Montipora with foliaceous Agariciids are locally abundant. Hydrolithon onkodes is the most abundant coralline algae, together with Lithophyllum prototypum and Neogoniolithon fosliei (Webster et al., 2011; Yokoyama et al., 2011). Comparison with their modern environments in the GBR suggests that these assemblages are characteristic of shallow reef crest to deeper reef slopes, and are consistent with the reconstructed Expedition 310 environments (Abbey et al., 2011; Camoin et al., 2012) and other studies of Indo-Pacific reef systems (Montaggioni, 2005).

Preliminary observations confirm that deepening upward coral-algal successions are common in the top 3–5 m of the cores. Combined with other sedimentological characteristics (i.e. intense bioerosion, manganese and iron staining) (Webster et al., 2011), this represents a classic reef drowning signature also observed at the top of the Expedition 310 deglacial reef (Abbey et al., 2011; Camoin et al., 2012), and the adjacent GBR dredge samples. For example, Abbey et al. (2013) conducted sedimentologic, palaeoenvironmental and chronologic studies of dredged coral, algae and bryozoan specimens from the tops of the GBR shelf edge reefs. Two distinct generations of fossil mesophotic coral community development are observed between 13–10 ka and 8 ka that have been influenced by widespread, massive flux of siliciclastic sediments associated with the flooding of the GBR shelf during deglacial sea-level rise.

**Potential for reconstructing reef growth, sea level and palaeoclimate change**

IODP Expedition 325 recovered fossil coral reef deposits from 46 to 145 mbsl, with a preliminary age range of between 9 ka to older than 30 ka. Figure 7.11D shows the distribution of the core catcher ages and their relationship to previously published sea level (Figure 7.11A) and palaeoclimate data (Figures 7.11B, 7.11C) since the LGM (see Yokoyama et al., 2011). This figure highlights the excellent chronologic coverage of the key palaeoenvironmental intervals (LGM, Bölling-Alleröd, Younger Dryas, and Medieval Warm Period (MWP) events) provided by Expedition 325 cores, particularly in the context of the +900 new U/Th and C14-AMS measurements on corals and algae that have now been obtained. Combined with firm palaeowater-depth estimates provided by
facies and coralgal analysis and glacial isostatic modelling, these ages will allow the reconstruction of a robust, new sea-level curve from 30 to 10 ka. Numerous massive coral colonies suitable for palaeoclimate studies were also recovered that will help define SST and sea surface salinity variations during this period in the southwest Pacific. For example, based on new stable isotope and Sr/Ca data from the Expedition 325 corals, Felis et al. (2014) reported that the SSTs in the GBR were significantly cooler than previously assumed, and that a larger than expected north–south temperature gradient existed 20–13 ka. Finally, once the precise stratigraphic, chronologic and sea-level framework has been established, 3D numerical reef modelling will allow the investigation of the response of the GBR to major environmental perturbations over the last 30 ka.

References


A (wandering?) tail of two plumes, Louisville and Hawaii: IODP Expedition 330

Benjamin Cohen, then University of Queensland, now University of Glasgow

Even a cursory look at a map of the planet reveals that the ocean floor is littered with underwater mountains – with over 100,000 such ‘seamounts’ above 1 km high at last estimate (Wessel et al., 2010). The most striking of these underwater mountains form long semi-linear chains extending thousands of kilometres across the ocean basins (Figure 7.12), with the volcanoes becoming progressively older in the direction of plate motion (McDougall, 1964). In the early days of plate tectonic theory, the idea developed that these volcanic chains represent the surface expressions of mantle plumes – tails of buoyant hot material rising from deep within the planet, causing volcanism where the hot rock reaches the surface (Wilson, 1963). If such plumes remain fixed within the mantle, then the volcanoes formed above them should act like a tape recorder, tracking the speed and direction of plate motions back through geologic time (Morgan, 1971; Sharp and Clague, 2006). The archetypical example of hotspot volcanoes recording a change in plate motion is the Hawaiian-Emperor chain, which has a prominent bend at approximately 50 Ma (Figure 7.12).

In the years following the development of plume theory, however, it was argued that plumes may not be fixed, but instead could be bent by changes in mantle convection currents, also known as the ‘mantle wind’ (Tarduno et al., 2009). Knowledge of the origin – and fixity – of hotspot volcanoes and underlying purported plumes is crucial, not only to understand the formation of thousands of seamounts scattered across the ocean basins, but also because the time–space distribution of hotspot volcanoes provides an important reference frame in reconstructing past motions of Earth’s plates back through geological history.
Deep-sea drilling has been instrumental to test the fixity of mantle plumes. The first investigation focused on the Hawaiian-Emperor chain (Tarduno et al., 2003), with four seamounts drilled during DSDP Leg 55 and ODP Leg 197 (Figure 7.12). A highlight of these expeditions was the palaeomagnetic measurements, which revealed that the Hawaiian-Emperor plume had moved by ~15 degrees of latitude prior to 50 Ma (Figure 7.13). Thus it appears that the Hawaiian plume has wandered in the past, although recent analysis (Whittaker et al., 2007) also calls for change in plate motion at 50 Ma.
Figure 7.13. Palaeomagnetic results from deep-sea drilling of two hotspot chains in the Pacific

Results from Hawaiian-Emperor chain indicate latitudinal motion of up to ~15 degrees, but there is minimal latitudinal hotspot motion for the Louisville chain. 
Source: Modified after Koppers et al. (2012) and Tarduno et al. (2003)

The Hawaiian-Emperor plume is but one example. Had other plumes also been influenced by mantle convection? To find out, on December 2010, the IODP ship JOIDES Resolution set out to drill the Louisville seamounts, in the southwest Pacific Ocean (Figure 7.12). Drilling of the older (northern) end of the Louisville chain enabled a direct temporal comparison between two plumes (i.e. between ~80 and 50 Ma; Figure 7.13), but on opposite ends of the Pacific Plate. The Louisville expedition (IODP 330) was highly successful, recovering over 800 m of remarkably fresh volcanic and sedimentary rocks, at an average recovery of 72.4 per cent – an ocean drilling record for hard-rock recovery. Palaeomagnetic measurements were also successful but, in contrast to Hawaii, results from Louisville are within analytical error of the modern-day hotspot location, indicating minimal latitudinal hotspot motion (Figure 7.13). Thus it appears that Louisville and Hawaii are moving independently, and are not influenced by the same convection systems in the mantle. The Louisville data also rule out true polar wander as the cause of the Hawaiian palaeomagnetic results.
In addition to this question of hotspot fixity, the scientists aboard were also carrying out a multidisciplinary range of research, including measuring the longevity and eruptive rates at the volcanoes, investigating the links between the Louisville chain and the Ontong Java Plateau (the world’s largest igneous province – covering an area comparable to the size of Greenland), the remarkable geochemical homogeneity of the Louisville lavas, the palaeoclimate record of sediments and fossils on top of the volcanoes, the amount of CO₂ sequestered by seawater alteration of the volcanic rocks, and the presence of microbiological activity many hundreds of metres below the sea floor (mbsf) (e.g. Figures 7.14A–D). As such, the rocks obtained from this expedition will provide a valuable scientific resource and enduring legacy, with various investigations set to continue years into the future.

Figure 7.14. A selection of other scientific highlights from IODP 330, including a variety of exceptionally fresh volcanic rocks

(A) fresh olivine and augite phryic lava (image 25 mm long) suitable for a variety of geochemical analyses; (B) fresh plagioclase (in this case 1 mm long with a distinctive JR ship-shaped outline), which is suitable for geochronology; and (C) fresh glass, which is ideal for chemical analyses, and for trapping volatile volcanic gases (image ~5 mm wide). The dark edges on the glass are numerous tubular features formed by microorganisms. (D) The expedition also recovered fossil-bearing sediments that provide a biological and climatic record for the southwest Pacific (image 5 mm long).

Source: Ben Cohen
The future of seamount exploration is very promising. Exciting targets remain – especially in the Atlantic and Indian Oceans – providing ideal sites for the International Ocean Discovery Program to continue the path set by the *Glomar Challenger* in the early years of scientific drilling.

**References**


The Japan Trench Rapid Drilling Project (JFAST) yields new insights into the mechanics and structure of subduction thrust faults: IODP Expeditions 343 and 343T

Virginia G. Toy, University of Otago, Dunedin

(Expedition 343 and 343T Scientists, c/- CDEX, JAMSTEC, 3173-25 Showa-machi, kanazawa-ku, Yokohama Kanagawa 236-0001, Japan)

The 2011 Mw9.0 Tohoku-oki earthquake ruptured the Japan Trench, with a very large coseismic slip occurring on the shallow part of the décollement. A significant consequence of this large slip was the generation of a devastating tsunami that impacted coastal Sendai. To better understand the controls on rupture propagation and slip, the plate boundary décollement and over-riding and subducting plate materials (Figure 7.15) near the trench were investigated by downhole logging and coring, and a temperature observatory was installed during IODP Expeditions 343 and 343T (the Japan Trench Fast Drilling Project (JFAST)) from April to July 2011. The onboard science party of 34 included experts from 11 countries.

Figure 7.15. Schematic diagram illustrating the structure of the accretionary prism at the Japan Trench sampled and monitored during the JFAST expeditions

Source: Professor Jim Mori, Kyoto University
JFAST set a number of records in scientific ocean drilling. Major project achievements include drilling the world’s deepest research borehole below sea level (6,889.5 m water depth + 850.5 m borehole = 7,740 m below sea level (mbsl); the previous record was 7,049.5 mbsl during DSDP Leg 60, Hole 461A in the Marianas Trench in 1978, where in a water depth of 7,034 m the project achieved 15.5 m penetration below the sea floor). The JFAST expeditions recovered the deepest oceanic research core (7,734 mbsl), sampled the Japan Trench plate boundary décollement (subduction thrust fault) between Miocene and Cretaceous sediments for the first time, and installed and recovered the first temperature observatory across an active plate boundary fault soon enough after it experienced earthquake-generating slip to measure the thermal perturbation resulting from frictional heating during the slip.

Analysis of samples and data arising from Expeditions 343 and 343T has already yielded new insights into subduction thrust fault mechanics. Significant research results published so far include the following:

- Borehole breakouts that were imaged downhole (Lin et al., 2013) indicate the hanging wall accretionary prism above the décollement changed to an extensional stress regime after the earthquake. This confirms seismological suggestions that the shallow parts of the fault accomplished near total stress release during the 2011 event. It is more generally found that faults release only a small proportion of the stress resolved at their earthquake foci (e.g. Baltay et al., 2011).

- Part of the plate boundary décollement was sampled in core (Chester et al., 2013; Figure 7.16). It is revealed to be a narrow (<5 m), localised sheared zone comprising scaly phaccoids that have striated lustrous surfaces and asymmetry consistent with the sense of shear on modern plate boundary. Lithologically, the décollement material was originally volcanigenic sediment, but it has been extensively authigenically altered. Mineralogical analyses using X-ray diffraction reveal it is particularly rich in the clay mineral smectite (78 per cent; for comparison Nankai trough plate boundary rocks have 31 per cent smectite).
Frictional experiments have been performed at low to high (1.3 m/s) velocities on décollement materials (Ujiie et al., 2013). These indicate the weak, foliated clay has a very low friction coefficient ($\mu_k = 0.19$ if fully drained or $\mu_k = 0.03$ if placed between impermeable forcing blocks so thermal pressurisation occurs during slip). Foliated and unfoliated gouges and injection structures generated in the experiments are distinctive microstructures that can be compared to natural faults to help us predict their behaviour.

The temperature observatory data (Fulton et al., 2013; Figure 7.17) contain a thermal anomaly of 0.31°C at the décollement. This indicates that a maximum temperature of 1250°C was attained during slip and 27 megajoules/square metre of energy was dissipated. Thus coseismic frictional strength was very low ($\mu_k = 0.08$), consistent with experimental data if some thermal pressurisation did occur. Careful modelling of how thermal perturbation can occur in rock suggests the anomaly at the depth of the décollement is not a result of flow of hot fluid up the fault, but such fluid flow does explain thermal perturbations around more steeply dipping faults shallower in the prism.
To date, New Zealand–based researchers and their collaborators have contributed to understanding of the plate boundary décollement by:

1. Making measurements of particle size and shape developed in two contrasting lithologies by drilling-induced fragmentation (Toy et al., 2013a). These data will be related to drilling parameters in an attempt to quantify energy input for comparison with the results of natural fragmentation processes.

2. Study of development of fabrics throughout the prism, in collaboration with Dr Ake Fagereng then at the University of Cape Town, South Africa, and now at Cardiff University in Wales (Toy et al., 2013b). We are trying to address how the fabrics within the scaly clay of the décollement form: are they just a highly evolved version of the lithologically defined lozenges observed in the hanging wall accretionary prism, or do they specifically form in materials with the particularly clay-rich composition of the décollement? What is the relative timing of alteration of the incoming sediments to clay and development of the fabrics? We are combining thin
section observations of hanging wall and foot wall material with
tomographic images obtained via shipboard (core scale), micro- and
even synchrotron-scale tomography that reveal the three-dimensional
geometry of the structures. Exciting recent thin section observations
of the plate boundary décollement materials clearly illustrate that
the microscale clay fabric is aligned around many lozenge margins;
thus its structure is likely very important in imposing weakness that
facilitates shear localisation and large coseismic slip.

In summary, the very smectite-rich shallow décollement materials are
demonstrated experimentally, and by the very small temperature anomaly
generated during slip, to be extremely frictionally weak (µ~0.05–1.0)
due to a combination of unique mineralogy and fabric. They could also
have experienced thermal pressurisation resulting in additional coseismic
weakening. This allowed an energetic rupture that had initiated deeper on
the subduction thrust to accomplish a very large slip in the surface during
a near total stress-drop earthquake. The described composition, fabric and
mechanical properties will inform interpretation of the potential of other
subduction thrusts to accommodate very large slips, provided we can also
sample them – a good target for future IODP expeditions.

References

doi.org/10.1029/2011GL046698

Chester, F., Mori, J., Eguchi, N., Toczko, S., and the Expedition 343 and 343T
Scientists, 2012. Integrated Ocean Drilling Program Expedition 343/343T
Preliminary Report, Japan Trench Fast Drilling Project (JFAST). Proceedings
of the IODP.

Chester, F.M., Rowe, C., Ujiie, K., Kirkpatrick, J., Regalla, C., Remitti, F.,
Moore, J.C., Toy, V.G., Wolfson-Schwhe, M., Bose, S., Kameda, J., Mori,
J.J., Brodsky, E.E., Eguchi, N., Toczko, S., and the Expedition 343 and 343T
Scientists, 2013. Structure and composition of the plate-boundary slip-zone

Fulton, P.M., Brodsky, E.E., Kano, Y., Mori, J., Chester, F., Ishikawa, T., Harris,
R.N., Lin, W., Eguchi, N., Toczko, S., and the Expedition 343/343T
and KR13-08 Scientists, 2013. Low coseismic friction on the Tohoku-oki


A study of the Asian Monsoon in the Japan Sea: IODP Expedition 346
Stephen Gallagher, University of Melbourne

Expedition 346 drilled seven sites in the Sea of Japan/East Sea and two closely spaced sites in the East China Sea in August and September 2013 (Figure 7.18). In total, this expedition recovered 6,135.3 m of core – a record amount to be recovered by any single expedition during IODP. The drilling yielded an unparalleled archive of atmosphere–ocean linkages relating to the East Asian monsoonal system. Sediment in the Sea of Japan/East Sea was last investigated by scientific ocean drilling during ODP Legs 127 and 128, nearly 25 years ago. Expedition 346 was the first scientific drilling expedition to focus exclusively on the climate system in this area. With the East Asian Monsoon directly affecting the water supply of one-third of the global population, the outcomes of this expedition will have a direct bearing on society’s understanding of this hugely important and complex atmosphere–ocean climate system.

Objectives addressed by drilling the Sea of Japan/East Sea and East China Sea

1. Determining the timing of onset of variability of the East Asian Summer Monsoon and East Asian Winter Monsoon and their relationship with the variability of jet stream circulation.

Dark and light layers of the deep-sea sediment in the Sea of Japan/East Sea represent changes in the intensity of East Asian Winter Monsoon rainfall in South China. Today, this monsoon produces rain that covers thousands of kilometres of southeast Asia, and is a major source of heat to drive planetary atmospheric circulation. Any study that improves the geohistorical knowledge of this system will improve our understanding of global climate and its possible variability with future climate change. It is possible to trace centimetre- to metre-scale (and often millimetre-scale) dark and light layers across hundreds of kilometres, suggesting that the Sea of Japan/East Sea responded as a single system to climatic and/or oceanographic change. These dark and light layers started at ~2.6 million years ago (Ma) and became more frequent and distinct from ~1.2 Ma to the present. This suggests the variability and intensity of this important monsoonal system increased at this time.
The presence of ice-rafted debris and the occurrence of deep-water ventilation are also related to the intensity of the East Asian Winter Monsoon. Colour reflectance ($L^*$) of the sediment reflects bottom-water ventilation. Expedition 346 showed that deposition of ice-rafted debris (possibly related to cold outbreaks from Siberia) started at ~3.2 Ma at Site U1422 and ~2.7 Ma at Sites U1423 and U1424, whereas $L^*$ increased significantly from ~2 to ~1.5 Ma at all deeper-water sites. These findings provide glimpses of changes in sedimentation that are related to the evolution of East Asian Winter Monsoon behaviour and the geohistory of related cold outbreaks emanating from Siberia and northern hemisphere ice sheet evolution. Finally, deep-sea sediment recovered from the Sea of Japan/East Sea sites yield wind-blown dust, and can be used to document changes in the Asian westerly jet stream.

The East Asian Summer Monsoon is a major climate system related to the Indian monsoon that initiates near the Philippines and extends as far north as the Yangtze River Basin and Japan. It is a major source of precipitation in the region and is related to the amount of snow cover in the Tibetan Plateau.

Sites U1428 and U1429 in the northern East China Sea yielded a continuous sequence of strata covering the last ~0.4 million years, which provides evidence of strong variability in sea–surface temperature and salinity, reflecting Yangtze River discharge and the history of the East Asian Summer Monsoon. This evidence is presently being compared with terrestrial loess and stalagmite climate records, allowing the link between climatic hydrology on the Asian continent (traced through reconstruction of Yangtze River discharge) and atmospheric processes to be established.

2. Reconstructing changes in surface and deep-water circulation and surface productivity in the Sea of Japan/East Sea over the last 5 million years.

Palaeoceanographic studies of the history of ventilation of enclosed or partially enclosed seas like the Sea of Japan are important as they not only tell us about potential variability with future climate change, they also form an important analogue for studying similar fossilised marine systems that are often associated with the source and generation of hydrocarbons and/or mineral deposits. Sedimentary colour reflectance ($L^*$) reflects deep-water ventilation. Continuous deep-sea sedimentary records up to 4 Ma were cored at Site U1422, ~5 Ma at Sites U1423, U1424, and U1426, and ~12 Ma at Sites U1425 and U1430 (Figure 7.18). The darker
layers are not well burrowed, suggesting oxygen-poor conditions, whereas the lighter layers are more burrowed, suggesting more oxygen-rich conditions. Some of the dark layers are brownish and rich in microfossils such as diatoms, nannofossils, radiolarians and foraminifers, suggesting high marine surface biological productivity. Orbital-scale dark–light colour cycles appeared at ~2.6 Ma, and millennial-scale dark–light cycles appeared at ~1.2 Ma. Orbital-scale dark–light colour cycles also appeared from ~12 to ~8 Ma at Sites U1425 and U1430.

Figure 7.18. Bathymetric map of Expedition 346 sites (red circles) in the Sea of Japan/East Sea and the East China Sea
Sites previously drilled by the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) (white circles) are also shown. Also illustrated are surface current systems within and surrounding the Sea of Japan.