IODP INVEST: BEYOND 2013

AUSTRALASIAN WHITE PAPER

Coordinated by the Science Committee of ANZIC (Australian and New Zealand IODP Consortium)

Chair: Assoc. Prof. Stephen J. Gallagher

In order for international collaborative ocean drilling to continue as a major research effort post-2013, it is necessary for the scientific community to demonstrate the societal relevance and impact of their work on a global scale. Increasingly, national earth science funding around the globe is focusing on research that directly influences society, most notably in the areas of climate change and hazard mitigation. Australia and New Zealand are unique among the members of IODP in that they are the only countries in the Southern Hemisphere. They direct scientific access to, and have direct national interest in, a vast region that extends from the Equator to Antarctica. This region incorporates the climatologically vital Southern Ocean and the active tectonic margins of the Southwest Pacific and Indian Oceans, major global sources of tsunami activity. Furthermore, the Australian and New Zealand earth science community includes world leaders in their fields who possess unique knowledge and expertise critical to any global scientific investigation. Bearing this in mind, we believe that our two countries can make a major contribution to the INVEST planning process and the ocean drilling research effort moving forward.

Contents

EXECUTIVE SUMMARY

This white paper represents the outcome of consultations with the marine geoscience community in Australia and New Zealand. An e-mail questionnaire was sent to 244 geoscientists on March 6, 2009, soliciting suggestions for planning IODP beyond 2013. Subsequently, an INVEST workshop was held at the Consortium for Ocean Geoscience of Australian Universities Conference (COGS) in Perth on July 6, 2009 (30 participants). To produce this white paper, the Science Committee of ANZIC (Australian and New Zealand IODP Consortium) edited and added to the contributions from the wider community. For each thematic section, we have not only provided broad overviews, but also some specific regional examples in the appendices.

PURPOSE

The purpose of this contribution is to facilitate the communication of ideas and suggestions by the marine geoscience community in Australia and New Zealand to contribute to INVEST, September 2009. The unique contributions and expertise of ANZIC scientists to both Southern Hemisphere and global research will be critical to the success of IODP beyond 2013. Accordingly, we present this white paper as a significant addition to the Japanese, ECORD and US CHART white paper contributions toward planning IODP beyond 2013.

The main results of the discussion are summarised below using the Conference Themes (CT) of INVEST 2009.

CT1: Co-evolution of Life and Planet

Six key priorities were identified for further IODP research: investigating the role of seafloor and sub-seafloor microbes in biogeochemical cycling; estimating the limits of diversity and symbiosis of microbial life in extreme environments; bioprospecting the seafloor floor and sub-seafloor for novel microbes or biomolecules; new methodologies for deep marine biosphere exploration; exploring the relationship between Antarctica, geomicrobiology and climate change; and Indo-Pacific reef initiation, expansion and relationship to seeps.

CT2: Earth's Interior, Crust and Surface Interactions

Seven priorities were identified that need further IODP investigation: passive margin formation; understanding long-lived subduction east of Australia; origin of reflecting interfaces within the oceanic crust; subduction initiation; subduction and geochemical evolution of the crust; igneous petrology and tectonics of rifted continental margins, and continuance of 'Mission Moho'.

CT3: Climate Change - Records of the Past, Lessons for the Future

Eight priorities were identified for further drilling: charting ocean and climate change in shelf to continental margin settings; evolution of boundary currents and zonal symmetries in Southern Hemispheric circulation; Australasian records of early Eocene hyperthermals; East

Antarctic climatic and biological evolution during the transition to a fully glaciated state; West Antarctic ice sheet stability; paleoclimate proxy-model comparisons, ocean anoxic events, and sea level change.

CT4: Earth System Dynamics, Reservoirs and Fluxes

Two priorities are identified as emerging fields: the role of fluids in convergent margin deformation, and active and extinct hydrothermal systems.

CT5: Earth-Human-Earth Interactions

Two priorities were identified: investigating passive margin geohazards, and ultra-high resolution records of ocean variability

CT6: Science Implementation

Four issues related to science implementation were identified: bridging the continental/oceanic divide through improved coordination between IODP and ICDP; increasing cooperation between IODP and industry; increasing opportunities to link IODP to geoscience education at all levels, and a proposal to achieve technological advances in drilling unconsolidated carbonates and high energy shallow reefs to obtain inaccessible (by present technology) high-resolution coral/carbonate climate archives.

CT1: CO-EVOLUTION OF LIFE AND PLANET

CT1.0 Overview

Microbial diversity and activity in the sub-seafloor were previously considered (nearly) non-existent due to pressure, temperature, and organic carbon limitations. However, ODP and IODP Deep Biosphere studies have revealed that this challenging environment may actually host the largest portion of Earth's metabolically active biomass. Exploring the deep sub-seafloor biosphere thus remains a continuing international science priority. For example, the Ridge 2000 Program of the U.S. National Science Foundation proposes to study multiple aspects of this environment in a cross-disciplinary approach "From Mantle to Microbes"; and the European Science Foundation advocates further exploration of the sub-seafloor biosphere, as described in its 2007 white paper "Investigating Life in Extreme Environments". The nature of these investigations requires cross-disciplinary resources and returns fundamental information about the potential impacts of seafloor microorganisms on seawater chemistry through geological time; the environmental distribution, limits and origins of life on Earth; and novel applications of seafloor microbes and/or cell-derived biomolecules. IODP Deep Biosphere science is essential for expanding our knowledge of microbial impacts on the geosphere and hydrosphere, and for making important discoveries at this intriguing biogeochemical frontier.

This section will discuss our view of several priorities and challenges associated with IODP Deep Biosphere research. In terms of the evolution of paleo-ecosystems, integrating the geomicrobiology and stratigraphy in Antarctica is likely to yield evidence of climate change. Reef studies by the IODP currently focus on critical estimations of late Pleistocene sea-level variability. It is important to obtain a longer-term record of reef initiation and evolution in the Indo-Pacific. Understanding the threshold of reef initiation in the past will improve the understanding of the behavior of reefs into the future.

CT1.1 Role of seafloor and sub-seafloor microbes in the biogeochemical cycling of crustal elements and nutrients: implications for paleo- and modern ocean chemistry (contribution to WG1.2 and WG4.6)

Water-rock interactions in the seafloor essentially buffer the chemical composition of seawater. Micron-scale reactions mediated by seafloor-dwelling microbial communities exert planetary-scale impacts on the biogeochemical cycles of major elements (e.g. carbon, iron, sulfur, nitrogen, oxygen), trace metals (e.g. manganese, zinc, lead) and micro-nutrients (e.g. cobalt, selenium). Seafloor microbes catalyze oxidation-reduction reactions in marine sediments and basement rocks in the temperature range of 0-120°C. These reactions, in turn, determine the form and fate of many elements in pore fluids (i.e. whether they will be dissolved, volatilized, or precipitated). Thus, further development of our understanding of the dependence and impacts of microbial activity on biogeochemical cycles with depth, pore water chemistry, and sediment mineralogy/lithology/structure will yield new and significant insights into the role of the deep microbial biosphere in marine crustal and palaeo-ocean chemical evolution.

CT1.2 Estimating the limits, diversity and symbiosis of microbial life in extreme environments (contribution to WG1.3)

Exploring the deep seafloor microbial biosphere extends our knowledge of the limits of life, and reveals new modes of biological activity and survival under the most extreme environmental conditions. In such systems, where pressures and temperatures are too high for most life forms, "extremophiles" may exert significant influence over certain biogeochemical cycles. Basic research in this area of geomicrobiology yields direct and profound implications for the study of life's origins and distribution in our solar system. IODP provides the vehicle for such discoveries; analogous to planetary science exploration programs, the study of seafloor microbes indeed holds great value for the exciting field of astrobiology. Furthermore, IODP-supported discoveries of novel microbes and their derivative enzymes may yield new and exciting applications for fields such as biotechnology.

CT1.3 Bioprospecting the seafloor and sub-seafloor for novel microbes or biomolecules: industrial, medical, materials synthesis and biotechnology applications (contribution to WG5.5)

IODP Deep Biosphere research supports the potential exploration of seafloor minerals, energy and biotechnology resources, particularly within special formations such as gas hydrates, hydrothermal vents, and sub-seafloor coal beds. These resources could be recovered or harnessed more efficiently with an extensive and detailed knowledge of the biogeochemical processes essentially controlling their form and fate (e.g. the rate of metal-sulfide or methane formation/oxidization). Through IODP expeditions and collaborations, we may: recover and cultivate novel seafloor microbes for direct application to biomining or bioremediation efforts, discover new microbial enzymes for use in biotechnology, explore potential microbial responses to geologic carbon dioxide sequestration, or harness biogeochemical processes for natural resource recovery. Of special interest are microbes which can catalyse the dissolution or precipitation/immobilization of various elements (e.g. ferric iron reducers, sulphate reducers), and thereby mediate the extraction or recovery of desired elements. Deep sea/seafloor microorganisms may also prove useful for applications such as water or wastewater treatment and biofuel generation/refinement (e.g. methanogens, sulphate reducers and microbes involved in anaerobic methane oxidation). The opportunity for applied studies will enable more microbiologists and biotechnologists to be involved in Deep Biosphere research, since alternative funding sources are available for applied research as compared to fundamental (e.g. microbial ecology) studies. Moreover, the bioprospecting of novel enzymes calls for a cross-disciplinary approach involving microbiologists, biotechnologists, biogeochemists and aqueous geochemists. Finally, the possible applications of deep biosphere research may lead to mutually beneficial links with suitable industry partners.

CT1.4 New methodologies for deep marine biosphere exploration (contribution to WG6.1 and WG6.5)

IODP Deep Biosphere research allows opportunities to test and improve high-pressure and high-temperature sampling and incubation methods that can expand our knowledge of cultivable microorganisms, as compared with techniques using ambient pressure and temperature. Such microbes may also yield novel applications, as previously discussed. IODP should therefore continue to support and refine the implementation of microbiological sampling, processing, storage and archiving approaches and technologies. The microbiology laboratory aboard the drilling/research vessel *Chikyu* is an excellent example of next generation shipboard geomicrobiology/biogeochemistry research facilities, and future expeditions aboard this vessel will certainly test and improve this resource. Onshore IODP core and subsample repositories should also be considered with respect to potential investments in infrastructure and instrumentation for Deep Biosphere research. This area of investment is also appropriate for seeking greater partnership with industry colleagues who may have access to new technologies and/or technological support for IODP Deep Biosphere investigations.

We would like to note that we are also highly interested in the idea of establishing a CORK- (circulation obviation retrofit kit) based study at any one of several potential drilling sites. The opportunity to obtain regular information and samples over depth for pore fluid chemistry and planktonic microbial communities will give us an unprecedented look into the active deep biosphere.

CT1.5 Antarctica, geomicrobiology and climate change (contribution to WG1.5)

An integrated study of the geomicrobiology and lithostratigraphy of the sediments around Antarctica (especially in areas where glacial melt water streams enter the ocean) could reveal new information on the extent of long-term changes in the rate of sediment accumulation due to variation in melting of glaciers in response to climate change.

Another area of interest is the Southern Ocean between Australia and Antarctica. We propose research on the response of microbiological communities on the highly variable productivity between the low-productivity area near Australia, the changing productivity across the oceanographic fronts, and the high productivity near Antarctica. This would be complementary to the proposed highly ranked South Pacific Gyre microbiological expedition (Proposal 662), but further south, with similar overall objectives, but generally not in such extreme low-productivity conditions (see **CT3.4 East Antarctic climatic and biological evolution during the transition to glaciated state**).

CT1.6 Indo-Pacific reef initiation: expansion and relationship to seeps (contribution to WG1.5)

The relationship between reef platforms and late Pleistocene sea level has been the focus of IODP drilling in Tahiti and the Great Barrier Reef. Proposals under consideration also include investigation of the Ryukyu reef front migration in the late Pleistocene. These projects do not focus on reef initiation and origin. Further deeper targeted drilling of Indian and Pacific Ocean reefs could investigate the relationship between the Mid Pleistocene Transition and the timing of Indo-Pacific reef initiation. The possible links between hydrocarbon seeps and late Pleistocene reefs in the eastern Indian Ocean could be investigated to establish if there is any microbial control on reef formation.

CT2: EARTH'S INTERIOR, CRUST AND SURFACE INTERACTIONS

CT2.0 Overview

Seven research topics were identified that need further IODP investigation: testing the various models of passive margin formation; understanding long-lived subduction east of Australia and timing of basin formation; origin of unexplained reflecting interfaces in the oceanic crust that formed during the Mesozoic; how and why subduction initiates; subduction and geochemical evolution of the crust; igneous petrology and tectonic processes in rifted continental margins; and finally the need to continue 'Mission Moho'.

CT2.1 Passive margin formation

It is unknown how passive margins truly form. Volcanic and non-volcanic passive margins surround Australia, but the process/es by which continental break-up transitions into seafloor spreading are poorly understood.

Different models have been proposed for the evolution of passive margins:

- symmetric, pure shear models (e.g. White 1989; Reston, 1990; 1993; 2007);
- asymmetric extension, simple shear models (e.g. Lister 1987, 1991);
- depth-dependent stretching (e.g. Kusznir 2005); and
- various combinations of the above models.

CT2.2 Understanding long-lived subduction east of Australia (contribution to WG2.5)

The Great Australian Bight is unique amongst Mesozoic/Cenozoic passive continental margins in terms of its formation over a mantle wedge, following the eastward motion of Australia over the eastern Gondwanaland subduction zone from 130 to 100Ma.

Melting of the mantle wedge or cold mantle is difficult, and in both cases gives rise to thinner crust. Preliminary evidence on mantle xenoliths sampled from the Japan arc suggests that the mantle wedge may have a high proportion of dunite, which would be difficult to melt further under standard upper mantle conditions.

Geoscience Australia, GNS Science (New Zealand), and IFREMER in France have undertaken extensive surveys of the region east of Australia for Law of the Sea purposes. Questions that can be addressed through ocean drilling include:

- the timing of basin formation related to subduction, and

- the effect of dynamic topography related to the long-lived subduction east of Australia by looking at the sedimentary sequences and how far they have subsided.

CT2.3 Origin of reflecting interfaces within oceanic crust (contribution to WG2.3)

A number of unexplained features exist within the oceanic crust, including strongly reflective oceanic basement layers, dipping reflectors crossing the entire oceanic crust, and apparent extended blocks in the lower crust northwest of Australia. These features occur over a wide area of crust which formed in the Late Jurassic to Early Cretaceous. It is unknown how these features formed, but their formation is mostly likely related to the thermal and mechanical evolution of oceanic crust as it ages and moves away from the spreading ridge.

Numerous recent numerical models have shown that there are peculiar P-T and compositional conditions at which plastic instabilities form in crustal rocks, even at ductile conditions, due to either thermo-mechanical feedback or other runaway mechanisms. The appearance of reflectors in the basement layer is likely due to the development of such faults. During their evolution, the crust and lithosphere cross a very wide range of P-T and 'volatiles content' conditions. The direct investigation of such reflectors would offer the possibility to directly test the theories of a faulting genesis for their development, and indirectly furnish fundamental information on the strength and properties of real rock materials at inaccessible P-T conditions in nature.

CT2.4 Subduction initiation (contribution to WG2.5)

How and why subduction zones initiate is poorly understood. It is unknown whether initiation of a new subduction zone is driven by plate motion or by some other mechanism (e.g. self-nucleation). Or if subduction zones are long-lived relatively stationary features that influence moving plates.

Although intense back-arc extension is known to be associated with early subduction, the forced subduction initiation model requires that a period of compression precedes the extensional phase. The ultimate driving mechanism in this case is related to forces that are distant from the incipient plate margin and overcome the initial plate bending and resistance from fault growth and subsequent fault slip. Subduction will initiate only after a critical amount of compression has occurred. The time of initiation should migrate with distance from the relative pole of rotation. Changes in plate motion should also pre-date initiation. Alternatively, in the self-nucleation model, the forces driving nucleation are entirely local, such as a localized source of buoyancy juxtaposed with lithospheric weakness at a fracture zone, and the earliest stage is extensional. Changes in plate motion should post-date subduction initiation.

In the forced subduction scenario, an initial phase of uplift on the over-riding plate is predicted to occur. This ridge then rapidly subsides during the onset of rapid back-arc opening. This type of forced uplift during nascent subduction is not predicted by spontaneous nucleation models and hence provides the basis for a test that can discriminate between the different models.

CT2.5 Subduction, crustal recycling, volcanoes and geochemical evolution of the crust (contribution to WG2.5)

The mechanisms and fluxes of major element recycling at subduction zones are still quite uncertain. For example, a recently published estimate of the rate of crustal recycling into the mantle at subduction zones is up to four times that of earlier estimates, and more than double the estimates of arc productivity rates. This is despite the global geochemical and freeboard arguments requiring a close match between these fluxes. Within the Tonga-Kermadec subduction system, there is a unique opportunity to study the long-term fluxes of major elements at the active plate boundary on lithosphere- or even mantle-scales, since most of the products of Tonga-Kermadec subduction are preserved.

CT2.6 Igneous petrology and tectonics of rifted continental margins (contribution to WG6.2)

Focus is needed on the magmatic and tectonic processes within the relatively understudied regions of rifted continental margins. Research on rifted continental margins could make use of the new IODP riser drillship *Chikyu* to provide long-term sub-seafloor monitoring and in-situ measurements to study rifting mechanics and dynamics. In addition, mission-specific platforms could be used to study these margins in shallow coastal areas.

CT2.7 Continuance of 'Mission Moho' (contribution to WG2.3)

Research should continue towards the long-term goal of recovering a complete section of oceanic crust and uppermost mantle generated at a fast-spreading ridge, known as 'Mission Moho'. Recovery of a complete crustal section will help determine the structure, composition, mineralogy and in-situ physical properties of the oceanic crust, and the geological nature of the seismic Moho discontinuity.

CT3: CLIMATE CHANGE - RECORDS OF THE PAST, LESSONS FOR THE FUTURE

CT3.0 Overview

One priority identified is to pursue further continental margin studies in "risky" hydrocarbon-prone areas. With the introduction of riser technology, most regions that were previously beyond the *JOIDES Resolution*'s reach are now possible targets for the *Chikyu*. These targets are often enriched with site survey data from the hydrocarbon industries. These targets have two additional important features: (1) high sedimentation rates that aid high-resolution studies; and (2) an abundance of well-preserved biological material (organic matter, carbonate shells), which is now recognized as essential for robust paleoclimate proxy studies.

Other priorities recognized by the Australasian community have a distinctive Southern Hemisphere theme, such as investigating the evolution of boundary currents and ocean front development. Furthermore, researching the southwest Pacific high- to low-latitude record of the early Eocene hyperthermals and other extreme climate events in the early Paleogene, would be an important contribution to understanding greenhouse climates. This information would also add to the well-known Atlantic, Tethyan and central eastern Pacific records. Other priorities include: resolving the sectoral response of the Western Antarctic Ice Sheet and the marine margins of the East Antarctic Ice Sheet to climate perturbations over the last 65 million years; the biotic response to East Antarctic development; and ocean anoxia.

In order to integrate terrestrial, onshore and offshore records the research strategy in this theme should be to coordinate paleoclimate drilling projects in IODP, ICDP and ANDRILL and other drilling and outcrop-based paleoclimate studies and develop a PAGES-style pole-equator-pole (PEP) comparisons for pre-Quaternary time slices. For late Quaternary studies, integration of IODP goals with IMAGES, PAGES and ice-core drilling initiatives is recommended.

CT3.1 Charting ocean and climate change in shelf to continental margin settings (contribution to WG3.6)

Hydrocarbon prospective shelves and continental margins are sparsely targeted by the IODP. This is partly due to the limitations of the *JOIDES Resolution* platform. However, this limitation has been overcome through the introduction of the riser drilling vessel and other mission-specific platform options. Terrigenous-rich sediments of continental margins are being increasingly targeted for paleoclimate studies for two primary reasons. Firstly, high sedimentation rates provide the opportunity for high-resolution studies. Secondly, organic-rich thermally immature successions yield a range of organic biomarkers that can be used as proxies for sea temperature (e.g. TEX_{86}) and other climate parameters. Moreover, high clay contents appear to protect carbonate shells from diagenesis; therefore, the organic proxies can be combined with inorganic proxies derived from "glassy" foraminifera shells ($\delta^{18}O$, Mg/Ca) to yield robust paleoclimate data. Continental margin records also have the potential for land-ocean comparisons, especially through studies on sedimentation rates and spore/pollen assemblage variations, and for investigating the links between climate and sea level (e.g. New Jersey and Canterbury Basin legs). A downside, however, is that the records are also subject to the vagaries of shelf deposition, with changes in sea level and increased current flows often resulting in significant hiatuses.

Many ocean currents and fronts directly influence the climate of shelf regions (e.g. Leeuwin and Kuroshio Currents and Subtropical Convergence). There are many unknowns within this field:

- what controls the evolution of currents and fronts in these shallow oceanic settings;
- how they can be detected in the fossil record (using microfossil proxies, etc.);
- if the “paleo” current record can be related to modern oceanographic monitoring; or
- if the behaviour of these currents can be predicted based on their behaviour in the past.

In the past there is evidence from the deep-sea record, of changes in the positions of the ocean fronts. Shelves and shelf margins are prime regions to detect changes in temperature or nutrients. The many currents that travel along shelf margins are present in areas that have been explored extensively for hydrocarbons. However, the vast seismic and well (usually cuttings with sparse core) databases that exist for these regions have been considerably under-utilised, even though this data would be superb site survey data. There is a fantastic opportunity for IODP beyond 2013 to maximise the science in these hydrocarbon regions and perhaps even draw some cross-subsidization from the petroleum industry. Many of the paleoclimate archives in continental margin regions are also important components of petroleum systems: source, reservoir and seal rocks.

Further research on the transition between continental and oceanic crustal sequences will shed light on the role they play in the evolution of passive continental margins (see also **CT2.1 Passive margin formation**) and the development of petroleum systems in under-explored frontier basins.

Studying the dynamics of sediment transport and supply on continental margins will enhance our understanding of the vulnerability of these margins to sediment destabilisation during earthquakes, slumping and tsunami (see **CT5.1 Passive margin geohazards**).

CT3.2 Evolution of boundary currents and zonal asymmetries in Southern Hemispheric circulation (contribution to WG3.4)

Southern Ocean climate variability on orbital and higher-frequency time scales is similar to that in the Northern Hemisphere. The Southern Ocean thermal response (SST change, sea-ice, movement of frontal indicators, IRD) and changes in carbonate chemistry lead northern hemisphere climate response at terminations, thus challenging the classic hypothesis of glacial-interglacial cycles being paced by changes in northern hemisphere insolation. Furthermore, the Southern Ocean response at past glacial terminations lags changes recorded in the surface ocean at intertropical latitudes, suggesting that the role of low-latitudes might be paramount (and so far strongly underestimated) in switching on the shift from a glacial to an interglacial state.

The southwest Pacific is in an ideal position to decipher the variable influences and timings of climate signals originating from both low vs. high (southern/Antarctic) latitudes, and to reconstruct paleoceanographic conditions, mechanisms, and variability through time in the Antarctic Circumpolar Current system, its fronts, and the main boundary currents. In order to resolve this timing of changes in circulation and Southern Hemisphere climate, a key priority is the recovery of sediment records of sufficient resolution (i.e. high accumulation rate) to detect abrupt climate events such as deglacial melt water pulses whose origin is still disputed, and whose resolution is key to understanding the relative roles of Northern and Southern Hemisphere ice sheets in sea-level change.

Much research on climate change mechanisms is now focused on the role of oceanic and atmospheric polar heat transport. This is in view of the fact that reduced poleward heat transport by ocean currents is considered as one of the variables responsible for the thermal isolation of Antarctica and the evolution of the ice sheet. Apart from this meridional component, we need to consider how variability in the Antarctic Circumpolar Current system is sometimes assumed to be zonal in character, but differences among sectors may have been significant. These differences may actually provide clues about paleocirculation and meridional heat transport (through zonal thermal anomalies). As an example of this, we still do not have reliable reconstructions of zonal heterogeneities in pCO_2 in the Southern Ocean that would allow us to discern the distribution of carbon dioxide source and sink regions and their evolution over time, and therefore provide reliable estimates of the contribution of the Southern Ocean to the atmospheric CO_2 content.

The southern westerly wind system, its importance for the global system, and its significance as an indicator of variability in pole to equator gradients in the oceans and atmosphere are all important climate indicators. A way to reconstruct past movements of fronts and zonal provinces can be to apply information on their current position as derived by modern biota and sediment-type distributions. Such an approach can shed light on how Southern Ocean circulation and frontal systems react to changes in the wind forcing and position of the atmospheric jet stream.

CT3.3 Australasian records of early Eocene hyperthermals (contribution to WG3.5)

The Paleocene-Eocene thermal maximum (PETM) and subsequent early Eocene "hyperthermals", which culminate with the early Eocene climatic optimum (EECO) have been heralded as the best (possibly only) geological examples for greenhouse-gas induced global warming. For the PETM, a massive burp of submarine methane hydrates was proposed as the cause of a 5-8°C warming in less than 10,000 years. However, studies now suggest that initial warming preceded the main methane release and the source of the methane remains contentious. Equally contentious is the regional pattern of warming associated with both the PETM and EECO episodes, with high-latitude regions warming to a far greater extent than can be simulated by the current generation of climate models.

Tropical temperatures have been reported for the PETM and/or EECO in southern mid- to high-latitudes east of Australia and New Zealand (paleolatitudes of 55-65°S). To investigate whether this scale of warming was a consequence of poleward ocean heat transport or some other process of polar amplification of ocean temperatures, both new high and new mid-to low latitude records of these early Eocene hyperthermals are required. Sites south of Australia or New Zealand will test if the thermal gradient increases at the Antarctic margin (e.g. Campbell Plateau pre-proposal, possibly Wilkes Land). Sites north and east of Australia and New Zealand (e.g. South Pacific Paleogene proposal) will test if pronounced warming during hyperthermals is localised, suggesting a role for ocean heat transport, or a general feature of the western and central South Pacific.

A complication to reconstructing sea temperature records during these hyperthermals is the now widely recognised diagenetic overprint on planktic foraminifera in deep sea sediment cores that results in oxygen isotope based sea temperature estimates being too cool by 5-10°C. Continental margin terrigenous records appear to yield the most reliable sea surface temperature records.

CT3.4 East Antarctic climatic and biological evolution during the transition to glaciated state (contribution to WG3.2 and 3.5)

An East Antarctic climate record of the critical interval during the transition to a glaciated state should be drilled to enable comparison with the recently drilled ANDRILL records in the Ross Sea, which was a re-entrant, and not an ocean-facing environment. Sections through the Cenozoic of the East Antarctic will allow documentation of changes, possibly recorded in botanical parameters, as Antarctica changed. Questions to answer include: whether East Antarctica had the same changes, with the same timing, as are now recorded in the Ross Sea/Antarctic Peninsula region; and if East Antarctica was re-colonised at the same times as the Peninsula/Ross Sea region and how the changes relate to other Southern Hemisphere continental areas.

CT3.5 West Antarctic ice sheet variability (contribution to WG3.2 and 3.5)

Sediment drilling in the Ross Sea and the Eastern Ross Sea provides the opportunity to address the variability in the West Antarctic Ice Sheet through the Cenozoic. A full assessment of East versus West Antarctic contributions to the global system is vital, as is the vulnerability or stability of the Antarctic end member of the global system. Models already show significant West Antarctic influence by the Oligocene/Miocene boundary and significant variability in early Neogene high CO_2 worlds. Drilling offers the opportunity to assess discrepancies between ice sheet models and far-field sea level records and to refine the climate sensitivities incorporated into greenhouse climate models, which is one of the largest gaps in the forth assessment report of the Intergovernmental Panel on Climate Change (IPCC AR4).

CT3.6 Proxy-model comparisons (contribution to WG3.6)

Proxy-model comparisons are a key theme in the draft chapter outlines for the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC AR5) [chapter 5, climate archives]. The primary focus of these comparisons should be the generation of robust proxy records from tropical and polar regions (temperature, precipitation, salinity, productivity), following rigorous review of veracity of existing proxies (e.g. $\delta^{18}O$); refinements to new proxies (e.g. TEX_{86}); development of new proxies (esp. for CO_2 and other greenhouse gases). Expeditions and sites need to be selected to resolves proxy-model mismatches in sea temperature estimates; especially warm poles-cool tropics anomalies and mid-latitude sites to validate thermal gradients.

Expected new outcomes and capabilities from these studies include:

- refined existing and complementary new methodologies for estimating climate parameters from biological and geochemical proxies;
- reconciliation of proxy records and General Circulation Models, especially in relation to the polar amplification of sea temperature and extent of tropical warming;
- high-resolution records of greenhouse climate analogues, such as the Paleocene-Eocene Thermal Maximum, in all ocean basins and in a full range of oceanic regimes; and
- a robust CO2 reconstruction for the Cretaceous and Cenozoic, leading to constraints on temperature sensitivity to greenhouse gas levels.

CT3.7 Ocean anoxic events (contribution to WG3.1)

Understanding the relationship between greenhouse events and ocean anoxic events (OAEs) is important in the context of future climate change. Studies of the circumstances that led to Cretaceous and Cenozoic events allow direct comparisons with present deep ocean anoxia in rift settings.

CT3.8 Sea level change (contribution to WG3.3 and WG3.5)

Eustatic sea level curves have been used for many purposes, but require further refinement. They have been the focus of several previous and future drilling legs, such as the Great Barrier Reef Expedition 319, and the highly-ranked Proposal 667 on the North West Shelf. This subject should remain an important future focus for IODP beyond 2013.

CT4: EARTH SYSTEM DYNAMICS, RESERVOIRS AND FLUXES

CT4.0 Overview

Two emerging science priorities were identified which, in particular, contribute to the aims of WG4.4 (fluid flow, heat flow and hydrothermal systems), WG5.5 (sub-seafloor resources) and WG1.3 (limits and evolution of life on Earth and beyond): the role of fluids in convergent margin deformation, and advancing the understanding of active and extinct hydrothermal systems. These two interdisciplinary topics span the fields of tectonics, geochemistry, geomicrobiology and paleoceanography, as well as all three of the current IODP themes (Solid Earth Cycles and Geodynamics, the Deep Biosphere and the Subseafloor Ocean, and Environmental Change, Processes and Effects).

CT4.1 Role of fluids in convergent margin deformation (contribution to WG4.4, WG5.5, WG6.2 and WG6.3)

The role of fluids is critical in determining the mechanical strength and seismogenic behavior of major fault systems, including plate boundary faults. Hence a better understanding will lead to more accurate assessment and prediction of earthquake and tsunami hazards. Fluid migration also leads to the formation of natural resources such as petroleum, gas hydrates, and metal ores. Furthermore the fluxes of global fluids at subduction zones are very large and likely play a significant role in modulating both local and global environmental parameters.

Studies along the Hikurangi Margin, North Island, New Zealand show a clear relationship between the fluid expulsion and major seaward-vergent thrust faults, near the outer edge of impermeable rocks that form the core of the deforming accretionary wedge. Furthermore, these thrust fault appear as primary fluid conduits sourced from the décollement and near transitions from seismic to aseismic behavior. Whether fluid pressure drives slip behavior on the subduction interface is contentious and previous and ongoing IODP Expeditions have only highlighted the complexity of convergent margin hydrology.

Of key significance is the technology needed to sample these fluids, measure *in situ* properties and promote instrumentation for long term observatories. Riser drilling is going to be a key technology and hence the identification of key sites that are within the technical limits, especially those in sufficiently shallow water, is important. The Hikurangi margin offers an interesting mixture of good local infrastructure, a mature science basis, and water sufficiently shallow that riser drilling is possible right to the outer toe of the wedge (because of the nature of the incoming plate).

CT4.2 Active and extinct hydrothermal systems (contribution to WG1.3, WG4.4 and WG5.5)

Currently active (i.e. “black smoker” vents) and extinct seafloor hydrothermal systems are focused along various plate boundaries, notably including divergent boundaries marked by mid-ocean ridge systems of the Pacific and Atlantic Oceans, and convergent margins and back-arc basins of the south and western Pacific Ocean. Within the Australasian region, there are several excellent areas to study both active and extinct hydrothermal systems: the Kermadec Arc, Eastern Manus Basin, Lau Basin, and North Fiji Basin. Offshore New Zealand, the convergent Kermadec-Tonga intraoceanic arc is host to the most hydrothermally active suite of submarine volcanoes in the world. Shallow hydrothermally active back-arc basins (water depths ~ 1500 m) are defined by the Eastern Manus Basin off Papua New Guinea and the Valu Fa spreading Ridge of the Eastern Lau Spreading Centre in the Lau Basin off Fiji and Tonga. Hydrothermal systems are a portal to processes related to rifting and subduction, with discharged volatiles being an important flux of carbon and sulfur species gases into the oceans. These systems are important in terms of their role in: high- and low-temperature fluid alteration of the oceanic crust, seafloor oxidation and weathering processes, formation of economic mineral resources, regulating ocean chemistry, and forming unique environments for specialist and “extremophile” marine biota (i.e. vent fauna and microbes). All of these factors make seafloor hydrothermal systems an important emerging scientific field for cross-disciplinary international research collaborations.

The systematic survey of hydrothermal emissions over the past 10 years along intraoceanic arcs, with a focus being the Kermadec-Tonga and Mariana arcs, has highlighted the frequency of venting and the range in chemical composition of fluids being discharged into the oceans. Within the Kermadec arc, 80% of the volcanoes are hydrothermally active, ranging from high-temperature (300°C), metal-rich discharge, to low-temperature (< 120°C), very acidic (pH = 1), metal-poor but gas-rich discharge. Thus the flux of various gases and metals into the oceans is variable, as is the depth of discharge (typically from near surface to 1500 m below sea level). Increasingly, it is becoming apparent that discharge of magmatic volatiles from these volcanoes is an important and common feature of these hydrothermal systems. However, it is unclear how these volatiles are being transported to the seafloor and indeed, the role they might play in supplying vital nutrients to the sub-seafloor biosphere.

The oxidation and weathering of both active and extinct seafloor hydrothermal systems are important processes in the alteration of the oceanic crust, formation of seafloor mineral resources and regulating ocean chemistry. There is currently little information regarding the on-going alteration and weathering processes within an extinct seafloor hydrothermal mound, once venting has ceased or migrated to a different area. It is also unknown how these systems evolve and degrade following the final pulse of hydrothermal fluid. IODP research could involve drilling into an active hydrothermal system; and for comparison, into the periphery/extinct portions of the system, to investigate the evolution of secondary mineral alteration within hydrothermal fluid pathways vertically and laterally throughout the system.

The tectonically and hydrothermally active North Fiji Basin, northwest of Fiji is of interest to a large community of scientists, including: hydrothermal researchers, plate tectonic modelers, geodynamicists and petrologists. The North Fiji Basin is a back-arc basin formed by a rapid roll-back of the subduction hinge. The area is quite unique and new investigations could provide new clues for our understanding of subduction processes and models. New ideas about subduction zone positions and developments over the last 200-300 million years have emerged in recent years. IODP drilling could provide an important milestone in proving several new plate tectonic hypotheses.

Seafloor hydrothermal systems in tectonic environments such as back-arcs and along intraoceanic arcs have been shown to be rich in economic mineral resources, where elements such as Cu, Zn, Pb, Ba and Ag are highly concentrated. Moreover, deposits discovered thus far are all notably enriched in Au. Some of these sites are planned to be commercially exploited/explored in the Australasian region (e.g. Manus Basin, north of Australia and the Rumble II West and Brothers volcanoes, NE of New Zealand). Further research on active seafloor systems is needed to investigate the critical factors leading to ore formation in the submarine environment, and in particular, the role of magmatic volatiles in the transport of metals), as these tectonic settings may prove to be host to vital economic resources.

Hydrothermal systems also influence worldwide ocean chemistry. Isotope ratios obtained from marine sediments are traditionally used as important proxies for past ocean temperatures and thus paleo-ocean circulation and paleo-ocean chemistry. Research into marine sediments associated with extinct seafloor hydrothermal systems could place crucial constraints on such paleo-oceanographic proxies

Commercial exploitation of mineral resources associated with seafloor hydrothermal systems has the potential to impact active hydrothermal vent ecosystems within the local vicinity. There are currently few studies available on the re-colonisation of vent biota and microbes following the final pulse of hydrothermal fluid prior to vent extinction. If mining of these areas is to proceed, it will be valuable to document the occurrence and absence of “extremophile” biota and microbes in both active and extinct hydrothermal systems from the same area (see also **CT1.2 Estimating the limits, diversity and symbiosis of microbial life in extreme environments**).

CT5: EARTH-HUMAN-EARTH INTERACTIONS

CT5.0 Overview

Several of the topics to be covered by working groups under this theme have been discussed elsewhere, especially those relating to climate change (WG5.4, 5.7 and 5.9 – see **CT3: Climate Change – Records of the Past, Lessons for the Future**) and sub-seafloor resources (see **CT1: Co-evolution of Life and Planet** and **CT4: Earth System Dynamics, Reservoirs and Fluxes**). Two additional priorities were identified: passive margin geohazards and ultra-fine resolution records of climate change. Most hazard research concentrates on active margin settings, but the potential danger of passive margin failure has been long recognized yet understudied. In addition, obtaining ultrahigh resolution paleoclimate records is critical if we are to reconstruct pre-instrumental records of climate and ocean change which are comparable to the instrumental records that form the basis of many of the climate projections utilised by the United Nations Intergovernmental Panel on Climate Change (IPCC).

CT5.1 Passive margin geohazards (contribution to WG5.2)

Much of the focus on hazard investigation has been on active margins, but passive margins are also prone to strong earthquake activity and massive slumping. The potential danger of passive margin failure has been long recognized yet understudied. Off Norway, the Storegga slide led to a large tsunami and is currently the subject of an IODP proposal. Similar processes have led to massive submarine slides on the Australian eastern margin, and tsunami risks in the southwest Pacific.

CT5.2 Decadal-resolution records of past ocean variability (contribution to WG5.9)

The world's oceans exert a major influence on global climate through heat transfer and ocean-atmosphere interactions (e.g. Atlantic Multidecadal Oscillation, ENSO and the Indian Ocean Dipole). Due to the brevity of the instrumental records for the ocean there is a very real need to recover records of ocean variability for the recent past. The Holocene provides the baseline for understanding present-day climate variability, and immediately pre-Holocene glacial-interglacial records are extremely valuable test cases for climate model validation. Records from these periods that can resolve decadal/near decadal (or better) ocean climate variability are of particular interest; as they could provide insights into climate variability at time scales important to society. Targeted IODP drilling of ancient coral reefs and corals, and high-accumulation oceanic sediments able to yield decadal or better records, could enhance our understanding of the role of the ocean in modulating decadal-scale climate variability, and would make a significant contribution to understanding the long-term evolution of the global climate system.

CT6: SCIENCE IMPLEMENTATION

CT6.0 Overview

Four issues were identified by ANZIC for science implementation. The success of the New Jersey Margin drilling legs should be followed by a closer integration between IODP and ICDP beyond 2013. Further efforts should be made to leverage support for IODP from the petroleum, minerals and bioprospecting industries; both through co-funding expeditions of scientific and commercial interest and through making data available to assist in the development of proposals. IODP initiatives in geoscience education are strongly supported and recognized as a way of extending the benefits of the program to a broader cohort of students and educators. Technological advances in the drilling of unconsolidated carbonates in high-energy shallow reefs are necessary if we are to obtain high-resolution records of decadal scale climate change similar to speleothem records.

CT6.1 Bridging the continental/oceanic divide IODP/ICDP (contribution to WG6.7)

With the success of the drilling on the New Jersey continental margin it is important to replicate this in other regions. Continental margin studies are essential if we are to understand shelf development and progradation under various scenarios of sea level change and sediment supply (see also **CT3.1 Climate and ocean change in shelf to continental margin settings**). These studies are critical for understanding the geo-historical relationship between ocean and climate dynamics, and for investigating lowstand, highstand and transitional deposits. In particular, the correlation between marine and terrestrial sediment deposition, will yield important records of paired glacial climate and sea-level tie points (see **CT3.8 Sea level change**).

CT6.2 Bridging the gap between IODP and the petroleum, minerals and bioprospecting industries

IODP's efforts to improve linkages with industry are welcomed. As the economic costs of scientific drilling continue to rise, it is crucial to build bridges with industry for several reasons: from the subcontracting of drilling vessels to co-funding expeditions of mutual interest. Good relations with industry may also facilitate access to data that will save on costs for site surveys and allow for more rapid progress of proposals from concept to drilling. Initiatives to improve linkages with the petroleum, minerals and bioprospecting industries also have the potential to make the benefits of scientific drilling more tangible to politicians and national funding agencies.

The IODP has submitted a proposal to industry with the objective that an Ocean Drilling Consortium (ODC) of petroleum companies should be formed to support a separate industry-focused ocean drilling program using the *JOIDES Resolution* drill ship. The petroleum industry has provided significant amounts of important baseline data (seismic/wireline logs, etc.) for well-site appraisal prior to some selected IODP drilling legs. Petroleum and several marine mineral exploration companies hold significant amounts of information that could be useful for future expeditions. Hopefully an ODC or a new subcommittee within IODP would be able to assist and advise applicants how to maximise the synergy with industry as a way forward for future IODP projects.

Further, if industry is interested in cross-subsidising drilling or exploration, this committee could provide "high level" interaction to facilitate this funding collaboration.

CT6.3 IODP and geoscience education

IODP has made great advances in developing outreach and geoscience education initiatives around drilling expeditions. The initiatives need to be maintained and enhanced because they work to extend the benefits of IODP membership to a much broader cohort of students and educators, as compared with the small number of scientists actually participating in expeditions. This is especially the case for associate members with few shipboard positions per year. Opportunities for student participation in expeditions, shore-based real-time ancillary projects, and post-cruse student projects should be investigated. Summer schools and field programs linked to IODP should continue to be supported.

CT6.4 Emerging need for advances in submerged coral drilling

Corals and coral reef deposits have unique attributes which make them exceptional archives of environmental change and past sea-level during the late Quaternary (also see **CT5.2 Decadal-resolution records of past ocean variability**). The ability of corals to yield high-resolution multi-decadal long records of tropical climate change is well established. Precise ^{230}Th ages for fossil coral records, which generally have errors of less than 1%, greatly increase their inherent value. These records, together with well-dated ice cores and the emerging generation of precisely dated speleothem records, will be crucial for understanding global climate change on time-scales immediately relevant to society.

The scientific need to recover drill-core from submerged coral reefs and carbonate platforms is compelling, yet the technical challenges posed by such diverse (and unpredictable) geological settings are still daunting. Mission-specific platforms have been designed to maintain position, compensate for heave, and keep pressure on the drill bit in shallow water (0-200 m) above coral reefs and carbonate platforms. However, the technical reality is that it is still exceedingly difficult to recover unconsolidated carbonate materials, in addition to cores from the corals themselves. And, ideally, the drill-holes should cater to *in situ* analysis of fluid flow in coral reefs to understand the processes of diagenesis.

Given these technical hurdles, the spatial and temporal coverage of late Quaternary climate and sea-level studies remains limited, and compelling questions about the role of the tropics in global climate change remain unanswered. The challenge is to develop economical instrumentation with the unparalleled flexibility required to drill and recover material from complex marine carbonate systems. IODP would provide the essential coordinated international program required to ensure that the highest priority scientific objectives are pursued.

APPENDIX CT0: ANZIC IODP SCIENCE COMMITTEE MEMBERS

Expertise and affiliation

Stephen Gallagher (Chair)	Stratigraphy, foraminifera, paleoceanography University of Melbourne	sjgall@unimelb.edu.au
Neville Exon (Program Scientist, Australian IODP Office)	Marine geology and geophysics Australian National University, Canberra	neville.exon@anu.edu.au
Lindsay Collins	Sedimentology, petroleum geology Curtin University of Technology, Perth	L.Collins@curtin.edu.au
Chris Fergusson	Sedimentology, tectonics University of Wollongong	cferguss@uow.edu.au
Michael Gagan	Isotope palaeoclimatology Australian National University, Canberra	michael.gagan@anu.edu.au
Mary Gee	Archean mantle processes, basalt magmatism, glacioisostatic effects University of Western Australia, Perth	mgee@segs.uwa.edu.au or mgee@cyllene.uwa.edu.au
Stuart Henrys	Basin studies, structural geology, gas hydrates GNS Science, Wellington	s.henrys@gns.cri.nz
Gary Huftile	Active tectonics, structural geology, geophysics Queensland University of Technology, Brisbane	g.huftile@qut.edu.au
Anna Kaksonen	Microbiology CSIRO Exploration and Mining, Perth	Anna.Kaksonen@csiro.au
Helen McGregor	Palaeoceanography ANSTO, University of Wollongong	mcgregor@uow.edu.au
John Moreau	Microbiology University of Melbourne	jmoreau@unimelb.edu.au
Louis Moresi	Plate kinematics Monash University	Louis.Moresi@sci.monash.edu.au
Jody Webster	Carbonate sedimentology University of Sydney	jody.webster@usyd.edu.au
Gary Wilson	Paleomagnetism Otago University, Dunedin	gary.wilson@otago.ac.nz
Raphael Wüst	Inorganic geochemistry, sedimentology James Cook University, Townsville	raphael.wust@jcu.edu.au

Other important contributors to this document are listed on the next page.

Other key contributors:

30 delegates at the COGS Conference in Perth, July 2009. Numerous scientists across Australia and New Zealand by e-mail questionnaire in March 2009.

Bradley Opdyke - carbonate sedimentology
Australian National University, Canberra, Bradley.Opdyke@anu.edu.au

Shannon Johns - sea bed exploration, ore geology
CSIRO Exploration and Mining, Perth, Shannon.Johns@csiro.au

Chris Yeats - sea bed exploration
CSIRO Exploration and Mining, Perth, Chris.Yeats@csiro.au

Dietmar Muller - plate kinematics, tectonics
University of Sydney, d.muller@usyd.edu.au

Alina Hale - plate kinematics, tectonics
University of Sydney, a.hale@usyd.edu.au

Gabriele Morra - plate kinematics, tectonics
University of Sydney, gabrielemorra@gmail.com

Ana Gibbons - plate kinematics, tectonics
University of Sydney, a.gibbons@usyd.edu.au

Maria Seton - plate kinematics, tectonics
University of Sydney, maria.seton@usyd.edu.au

William Howard - microfossils, palaeoceanography
University of Tasmania, Hobart, Will.Howard@acecrc.org.au

Patrick Quilty - foraminifera, Antarctic geology
University of Tasmania, Hobart, p.quilty@utas.edu.au

Giuseppe Cortese - microfossils, paleoceanography
GNS Science, g.cortese@gns.cri.nz

Cornel de Ronde - hydrothermal systems
GNS Science, cornel.deronde@gns.cri.nz

Chris Hollis- microfossils, paleoceanography
GNS Science, c.hollis@gns.cri.nz

Richard Levy - Antarctic paleoclimate, integrated stratigraphy
GNS Science, r.levy@gns.cri.nz

Rupert Sutherland - tectonics
GNS Science, r.sutherland@gns.cri.nz

APPENDIX CT1: POTENTIAL IODP TARGETS - CO-EVOLUTION OF LIFE AND PLANET

CT1.1-1.6 Co-evolution of Life and Planet

ANZIC microbiologists would be interested in contributing to several currently pending Deep Biosphere and Subsurface Ocean IODP drilling proposals, particularly 547 (Juan de Fuca Ridge/Plate), 601 (Okinawa Trough), 673 (Moroccan Margin), 677 (Mid-Atlantic Ridge), 689 (Moroccan Margin), 701 (Great Australian Bight see below, here perhaps including consideration of the Stansbury Basin and/or Kanmantoo Trough), 739 (Bering Sea), 743 (Gulf of Mexico), 744 (Rodriguez Triple Junction), 745 (northwest Pacific off Japan), and/or 749 (Guaymas Basin). We also support new sites such as those nominated in other sections of this paper (***Appendix CT4.2a-e Active and extinct hydrothermal systems***). For example, hydrothermal circulation zones in the Fiji Basin, hydrothermal vents in the Lau and Manus Basins, and the Tonga-Kermadec subduction zone, which could all incorporate objectives similar to those discussed in currently pending proposals. Hydrocarbon-rich regions along the Northwestern Australian margin (e.g. Yampi Shelf), as well as gas seeps in the offshore portion of the Otway Basin (southwest of Victoria, Australia) would provide additional sites. All of these potential IODP target areas could comprise research relating to all of the topics under the **CT1: Co-evolution of Life and Planet** theme.

CT1.1 Great Australian Bight, Southern Ocean – Role of seafloor and sub-seafloor microbes in the biogeochemical cycling of crustal elements and nutrients

The Great Australian Bight contains Cenozoic sequences forming the largest cool water carbonate shelf on Earth. We strongly support IODP pre-proposal 701, which targets the extraordinary Pleistocene sequence drilled in the Great Australian Bight. The interstitial water data from the earlier ODP Leg 182 suggests unusual microbial processes. The rapidly deposited sediments contain high-salinity interstitial brines and abundant organic carbon, and up to 50% methane and 15% hydrogen sulfide in the fluids. These results challenge our current understanding of microbial sulfate reduction and methanogenesis, and raise fundamental questions about the evolution of the global biogeochemical cycles of carbon, sulfur and oxygen. Because of the water depth limitations of the *JOIDES Resolution*, no sites on the inner- and mid-shelf could be drilled during ODP Leg 182, although they were an integral part of the original proposal. Full site survey data exists and we propose that any future Great Australian Bight drilling expedition incorporates an alternative platform component, so that the original objectives of the Leg 182 proposal can be met. A dedicated microbiology leg would investigate one of the largest known active deep-biosphere ecosystems that may hold the clues for a deeper understanding of the global carbon, oxygen and sulfur cycles.

Another area of interest more generally is the Southern Ocean between Australia and Antarctica, where we propose research on the response of microbiological communities to highly variable primary productivity and nutrient cycling.

CT1.5 Southern Ocean – Antarctica, geomicrobiology and climate change

Exploration of areas around Antarctica where long-term sediment accumulation may have led to stable stratification would be of interest for exploring microbial activity in the context of biogeochemical zonation and climate change.

APPENDIX CT2: POTENTIAL IODP TARGETS - EARTH'S INTERIOR, CRUST AND SURFACE INTERACTIONS

CT2.1a-c Passive margin formation

The passive margins surrounding Australia encompass the range of types of passive margins and thus provide a prime opportunity to develop a model of passive margin evolution that covers all cases.

CT2.1a Australian Southern Margin, Wilkes Land Margin: Non-volcanic, symmetric margin

The continent-ocean transition zone with linearly magnetised crust variously proposed to be exhumed mantle/anomalous seafloor/stretched continental crust. A prime example occurs in the Great Australian Bight and has a symmetrical conjugate on the Antarctic Wilkes Land margin.

CT2.1b Western Australian Margin: Volcanic passive margin

It is unknown whether the West Australian volcanic passive margin has a different break-up process as compared to the non/low volcanic Southern Margin. If there are extensive volcanics along the western margin, it is unknown if they are associated with a mantle plume. If so, would they be related to extension rates, mantle temperature, or small-scale convection. Although the Kerguelen plume has been proposed as the source of much of this volcanism many of the volcanics are located outside the plume head radius. There are two main hypotheses for the formation of massive volcanic constructions on continental margins: mantle plume and non-mantle plume scenarios. On the Valanginian Cuvier margin off Western Australia, rifting and breakup (~130 Ma) has formed such a margin.

Globally the Western Australian margin is well-suited for testing the nature of volcanic margin formation, partly because its igneous basement is easily accessible. Proposal 717 aims to drill a transect across the southern Cuvier Margin and Wallaby Plateau in an area with voluminous Seaward Dipping Reflectors (SDRs) and oceanic plateaus, aiming to determine the mechanism of continental breakup. The strategy is to drill breakup volcanics; Wallaby Plateau volcanics/basement; and surrounding normal oceanic crust for shallow reference sites. The geochemical signature of recovered basalt would determine the mantle source of magmas, melting conditions, and contamination of magmas by continental lithosphere. Dating of the samples would constrain the temporal and spatial information.

CT2.1c Eastern Australian Margin, Western Lord Howe Rise: Asymmetric passive margin

It is currently unknown if the New Caledonia Basin is underlain by oceanic or stretched continental crust and the time of its formation (Cretaceous or Tertiary). Within the Norfolk Basin, what is the composition of the crust underlying the basin is also unknown. Proposal 729 addresses some of these questions.

CT2.3 Argo Abyssal Plain – Origin of reflecting interfaces within oceanic crust

A key place to investigate these enigmatic reflecting features within oceanic crust is the Argo Abyssal Plain on the northwest Australian margin.

CT2.4 Tonga-Kermadec, Lord Howe-Norfolk Ridge – Subduction initiation

The Tonga-Kermadec subduction system, as it occurs on the boundary south of New Zealand (Hjort-Macquarie-Puysegur), is an ideal location to study how subduction zones initiate and develop. This site is ideal because the plate motions are relatively well-understood and there are very few alternative sites in the world. The relatively high temperatures and low viscosity that are inferred for mantle beneath the Tonga-Kermadec region have affected the formation (and possibly led to superior preservation) of backarc basins, such as the South Fiji Basin and Norfolk Basin. There is also a good synergy between the study of the older subduction boundary in the Lord Howe-Norfolk Ridge region with subduction initiation occurring within the Tonga-Kermadec system. Both these areas would be ideal for IODP drilling.

APPENDIX CT3: POTENTIAL IODP TARGETS - CLIMATE CHANGE - RECORDS OF THE PAST, LESSONS FOR THE FUTURE

CT3.1a-h Charting ocean and climate change in shelf to continental margin settings

CT3.1a Australian Margin - oceanographic change in shelf to shelf margin settings

The thick shelf and shelf margin sequences around Australia are not well sampled by the IODP. This is primarily because they were beyond the reach of the *JOIDES Resolution*. However they have now become accessible with the *Chikyu* and other drilling platforms. Several ODP legs have sampled the shelf including ODP Sites 1126-1134 in the Great Australian Bight, and Sites 1192-1199 and 811-826 off the Great Barrier Reef. The Great Barrier Reef will be drilled soon (Expedition 325) and there is a proposal to drill the Northwest Shelf (Proposal 667) under consideration. However, these proposals miss some of the thickest sections of Cretaceous to Cenozoic age along the Australian margin that have not yet been fully cored. These regions are critical as they are likely to preserve a record of detailed climate and oceanographic evolution.

CT3.1b Southeast Australia - a record of Cenozoic Southern Ocean change

The Gippsland and Otway Basins in southeast Australia have abundant hydrocarbon exploration seismic data, and contain many exploration, production and site engineering wells. This database fulfils many of the site investigation requirements needed for successful IODP drilling proposals that are forwarded to the SSEP and SSP. The quality of the well samples is limited to minor coring and many cuttings. However, the well-data usually includes a suite of wireline data and can readily be tied to seismic. The existence of a huge hydrocarbon dataset that samples these strata makes the Australian margin prime territory for fine scale paleoclimate and palaeoceanographic studies. There are near-continuous sequences of Late Cretaceous and Eocene to Recent shelf to bathyal strata. These strata reveal strong signals of Cretaceous marine dysoxia and climate variability. In addition, evidence of the Eocene thermal maximum and Oligocene glacial induced cyclicity is well-preserved. Miocene and Pliocene climate optima are superbly represented in thick sequences, but the transition to Pleistocene icehouse is more fragmentary.

CT3.1c Gulf of Papua - Early Miocene climate history

Recent exploration of the Gulf of Papua has revealed a number of Early to Mid- Miocene age pinnacle reefs. These pinnacle reefs jut very steeply from a depth of about 1500 m to 800 m and the drilling targets are not covered by other sediments. Samples recovered from the top of the reef revealed tightly cemented beachrock with beautifully preserved benthic foraminifera. The state of preservation indicates minimal diagenesis has taken place. The location, having subsided beneath the waves in the Early-Middle Miocene, may preserve an unparalleled record of Early Miocene climate and represents a safe target for approximately 700 m of coring.

CT3.1d Sahul Shoals region of the Timor Trough - Sea level and climate history

The Sahul Shoals are sub-sea mesas that rise from the southern margin of the Timor trough. The area subsided below sea level in the latest Miocene, about 6 million years ago. These carbonate buildups, located in a relatively dry region on a subsiding margin, offer an important opportunity to test the "dip-stick" model of sea level change. Most of the sea level "highs" of the past 6 million years should have been captured on this margin and it is likely the preservation of the coral is very good. These banks vary in thickness from 400 to 600 m thick.

CT3.1e Scott Plateau - Quaternary paleoceanography

The Scott Plateau offers an ideal site to look at the Quaternary history of the Indonesian Through-Flow waters. The water depths are ideal for coring as they range between 1500m and 2500 m, and the area has reasonably high sedimentation rates, between 10 and 20 cm/ka. Given the extensive work that has been done in the South China Sea, this area would offer a good end-member comparison.

CT3.1f Scott Plateau - Cenozoic paleoceanography

On the margins of the Scott Plateau, at water depths of approximately 2000 m, there are out-crops of Late Cretaceous to Eocene pelagic sections. Given the shallow depth and the good chance of recovering relatively fresh material from this important time interval of the latest Greenhouse Earth (as shown by little altered Cretaceous forams in a piston core), these sections are a target of interest for Paleogene paleoceanography.

CT3.1g Gulf of Carpentaria - Marine/lacustrine facies

The marine to lacustrine strata of the Gulf of Carpentaria may provide a high-resolution record of sea level and climate change.

CT3.1h Fly River Delta - Paleoenvironment

The high-accumulation rate sediments in the marginal marine Fly River Delta may provide a record of paleoenvironmental change and variability in fluvial sediment supply.

CT3.2 Southern Ocean – Evolution of boundary currents and zonal asymmetries in Southern Hemispheric circulation

A way to address longitudinal variability in the Antarctic Circumpolar Current in the Southern Ocean would be to recover records from both western and eastern sides of basins that are key to Southern Hemisphere heat transport and gyre circulation, and can provide constraints on circulation mechanisms, like the heat transported by the East Australian Current. Other examples of strongly different circulation systems are the ocean basins on both sides of New Zealand, with an eastern side dominated by a strong boundary (the Subtropical Front) between high-latitude and low-latitude circulation/climatic processes, and a western side (the Tasman Sea) with a much more uniform climate, and less well constrained frontal systems/warmer surface currents. It would therefore be particularly interesting to analyse "transects" of sites from the Tasman to the Canterbury/Chatham Rise side (including the results of IODP Expedition 317, Canterbury Basin), and at the same time integrate the existing and forthcoming information available from terrestrial records (e.g., lacustrine, moraine retreat history and age determinations) on the climate evolution of the South Island of New Zealand. The study of these opposing patterns could also be addressed by targeting drill sites in areas under the influence of western and eastern boundary currents, such as the Agulhas and East Australian Current.

CT3.3 Northeast Australia – Australasian records of early Eocene hyperthermals

The diverse and well-preserved Paleocene and Eocene sections off northeastern Australia suggest that continuous sections through the Paleocene-Eocene transition exist in the area. This is a critical region to test the relative importance of ocean heat transport and greenhouse gas levels in amplifying high latitude temperatures during hyperthermal episodes, such as the Paleocene-Eocene thermal maximum (PETM), as it is likely to record changes in characteristic in surface and intermediate water flow in the region. Northeast Australia data would document the evolution of the contrast between Cenozoic surface and deep water characteristics. Drilling for the PETM record in this region should provide a record in carbonates from the Early Tertiary to the present day. The study of isotopes (C, O, Sr) of benthic and planktonic foraminifera should permit documentation of the change between surface and deep waters as global circulation changed with time (assuming good preservation of planktic foraminifera). Differences between surface and deep water should have developed, as Antarctic Bottom Water formation developed and varied depending on the strength of AABW flux. This southwest Pacific Ocean section would have been influenced by changes as Australia/New Zealand and all the island groups (including now-submerged continental fragments) evolved. Any drilling results will also influence understanding of tectonic evolution and questions, such as how colonisation of new islands was affected.

CT3.4 Eastern New Zealand – East Antarctic climatic and biological evolution during the transition to glaciated state

Understanding the evolution of the East Antarctic ice sheet through the Paleogene is a key objective of the Wilkes Land IODP expedition and is also the focus of a new ANDRILL proposal to drill the Paleogene record at Coulman High, Ross Ice Shelf. It will be crucial to compare and correlate these proximal records of ice sheet evolution with far-field records of sea level change at a passive continental margin, such as the Paleogene of eastern New Zealand.

CT3.7 Scott Plateau, Southern Tasman Rise – Ocean anoxic events

The Scott Plateau and the South Tasman Rise are potential targets to investigate Cenozoic ocean anoxic events.

CT3.8 Australian Northwest Shelf – Sea level change

The Neogene carbonate and mixed carbonate/siliciclastic sequence on the Australian Northwest Shelf passive continental margin is an ideal place to study eustatic sea level changes. Proposal 667 is designed to constitute a Southern Hemisphere carbonate counterpart to coeval siliciclastic examples globally (e.g. New Jersey, Canterbury Basin off New Zealand), as well as the carbonate Great Bahama Bank, all of which have already been drilled by ODP, or will be drilled by IODP. The more complex tectonic history of the Northwest Shelf, and the presence of subordinate siliciclastic sediments, would allow for expanded study of how competing formative processes interacted with global sea-level change and tectonic subsidence to produce early Oligocene-Recent stratigraphy in this classic carbonate clastic progradational environment.

APPENDIX CT4: POTENTIAL IODP TARGETS - EARTH SYSTEM DYNAMICS, RESERVOIRS AND FLUXES:

CT4.1 Hikurangi Margin – Role of fluids in convergent margin deformation

Sites on the Hikurangi Margin potentially offer a new and unique window into deeper subduction zone processes, including slow-slip phenomena. Integrated geological, geochemical, geomicrobiological, and hydrological studies will test the role of fluids in controlling seismic behaviour on the plate interface, thus providing a powerful framework for defining the potential for earthquakes in such zones worldwide.

CT4.2a-e Active and extinct hydrothermal systems

CT4.2a Kermadec Arc – Hydrothermal fluid discharge

The hydrothermally active Brothers volcano within the Kermadec arc offshore of New Zealand is a well-studied intraoceanic arc volcano and drilling would provide crucial information into the role hydrothermal discharge from these volcanoes plays on a global scale.

CT4.2b Eastern Manus Basin, Lau Basin – Weathering and oxidation of active and extinct hydrothermal systems

The Eastern Manus Basin of Papua New Guinea and the Valu Fa spreading Ridge of the Eastern Lau Spreading Centre in the Lau Basin between Fiji and Tonga are both shallow hydrothermally active back-arc basins. These areas contain abundant hydrothermal systems which would be ideal for the study of the weathering and oxidation of the transition zones between active and extinct systems.

CT4.2c North Fiji Basin – Hydrothermal activity and subduction processes

The North Fiji Basin, northwest of Fiji, is a good location to study the interaction between subduction processes and hydrothermal systems. This region is anomalously hot (even for a back-arc) and contains abundant spreading ridges, both active and inactive. The Australian National Facility research vessel Southern Surveyor has previously visited the Hunter Fracture Zone of the North Fiji Basin, which includes an active spreading ridge.

CT4.2d Eastern Manus Basin – Seafloor massive sulphides and hydrothermal systems

ODP Leg 193, which drilled the PACMANUS site on Pual Ridge in the Eastern Manus Basin in 2001, remains the ocean drilling community's only foray to a felsic-volcanic hosted seafloor hydrothermal system. Despite the technical challenges of drilling in a highly heterogeneous hard rock stratigraphy, which resulted in very poor overall core recovery, the

Leg was successful scientifically, providing important insights into the volcanic stratigraphy, subsurface alteration and hydrology, role of seawater and deeply-sourced fluids in the system, and the subsurface biosphere. However, both the PACMANUS and nearby SuSu Knolls sites remain highly attractive targets for further investigation. SuSu Knolls is a series of three porphyritic dacite domes, 1.0-1.5 km in diameter with crests 1150-1520m below sea level, forming a NNW-trending edifice. An intense hydrothermal plume, with peak transmission anomalies >40%, is sourced from the largest central cone (North Su) and active sulfide chimney mineralisation has been detected on the crest of all three volcanoes. On the crest of North Su, strongly altered porphyritic dacite is associated with acidic fluids, formation of native sulfur flanges, diffuse venting through spires, and subhalative to exhalative pyrite-fukuchilite-enargite±covellite-chalcopyrite stockwork and massive sulfide mineralisation. On the crest of Suzette, actively venting Au-Cu rich chimneys cap large sulfide mounds that are surrounded by and draped with black sulfidic silt. The field has been interpreted as the submarine equivalent of a terrestrial high sulfidation Cu-Au mineralized system.

The contrast between a relatively mature, strongly mineralized system at Suzette and a strongly hydrothermally active, less mineralized system at nearby North Su provides a unique opportunity to investigate the critical factors leading to ore formation in the submarine environment. The activities of seafloor massive sulfide explorer Nautilus Minerals in the Eastern Manus Basin have generated an enormous quantity of high-quality site survey data at SuSu, including extensive visual mapping and surface sampling by ROV, 20cm-resolution bathymetry, deep tow magnetic and electromagnetic surveys and approximately 200 shallow drill holes, to depths of ~20m below the seafloor. The company is receptive to scientific research, and the combination of scientific interest and high quality near surface data make SuSu Knolls a highly attractive target for a future IODP Leg.

CT4.2e Eastern Manus Basin – Extremophile microbial life at active and extinct hydrothermal systems

As discussed in ***Appendix CT1: Potential IODP Targets – Co-evolution of life and planet***, active and extinct hydrothermal systems within in the North Fiji, Lau and Eastern Manus Basins, and the Tonga-Kermadec arc are ideal for the study of “extremophile” biota and microbial communities present within active and extinct hydrothermal systems.

APPENDIX CT5: POTENTIAL IODP TARGETS - EARTH-HUMAN-EARTH INTERACTIONS

CT5.1 Eastern Australian Margin – Passive margin geohazards

The occurrence of massive submarine slides on the Australian eastern margin, makes this an ideal location for the study of passive margin geohazards. A program of shallow drilling off eastern Australia, for example, could better document the nature and history of slides in this location.

CT5.2 Southern Ocean – Decadal-resolution records of past ocean variability

In the Southern Ocean, along the Antarctic margin, there are opportunities to expand records of Antarctic Bottom Water flow and surface ocean characteristics by drilling the Holocene margin drift deposits. The Wilkes Land Expedition 318 intends to drill one such high resolution site in the Adelie Basin, with the potential to recover the highest resolution oceanic record to date. This may shed much-needed light onto the functioning of high-latitude climate mechanisms (sea-ice dynamics, meltwater discharges and their influence on biological systems and large-scale oceanic circulation, etc.). In order to put the importance of such highly-resolved records in perspective, one only needs to consider the enormous improvements in ^{14}C calibration and the understanding of the past behaviour of the Intertropical Convergence Zone made possible by ODP drilling in the Cariaco Basin.

APPENDIX CT6: POTENTIAL IODP TARGETS - SCIENCE IMPLEMENTATION

CT6.1 Western Australia – Bridging the continental/ocean divide IODP/ICDP

An excellent region for investigating the continental/ocean stratigraphic record of environmental change is Western Australia. The West Australian state government, at present, funds three stratigraphic wells per annum in the onshore in basins around the state. This type of supplementary drilling (independently funded outside the IODP), if linked to offshore basin drilling by the IODP, would be an extremely cost effective way of bridging the continent/ocean divide. It would lead to a better understanding of the geological history and processes on this passive margin.