Report

A Workshop Aimed at Advancing our Understanding of Cretaceous Ocean Dynamics by Scientific Ocean Drilling

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INTRODUCTION

Marine environmental conditions during the middle Cretaceous (Barremian through Turonian; 125-85 Ma) provide insights into the state of future oceans influenced by globally increasing temperatures. This preview includes ocean dynamics driven by reduced thermal gradients and episodic ocean acidification together with hypoxia, anoxia and euxinia. The Paleogene interval holds many of the same clues to the future and has been targeted by a number of highly successful Ocean Drilling Program and Integrated Ocean Drilling Program expeditions over the last decade. However, only one leg during this time has recovered extensive middle Cretaceous sediments (Leg 207, Demerara Rise). Other legs, for example, Leg 198 (Shatsky Rise) and Leg 342 (Newfoundland Rise) recovered only short records of the Cretaceous. Yet high profile and novel research has demonstrated that the middle Cretaceous oceans were in many ways as representative of future marine environments as those of the Paleogene and indeed record the 'end-member' condition of a ocean–atmosphere system forced by rapid and extreme climate change (e.g., Erba et al., 2010; Jenkyns, 2011). In particular, the middle Cretaceous was characterized by CO_2 levels likely higher than any time in the last 150 million years (e.g., Berner et al., 1993; Royer et al., 2004), equivalent to or higher than those forecast for the future. This interval of elevated CO_2 involved some of the most significant chemical perturbations in the marine realm including major changes in oxygenation and pH levels. Thus, understanding Cretaceous climate and ocean circulation is central to the *Science Plan for the International Ocean Discovery Program 2013 – 2023.*

Considerable progress in our understanding of Cretaceous oceans derived from the early stages of ocean drilling, especially the Deep Sea Drilling Project (Schlanger and Jenkyns, 1976; Ryan and Cita, 1977; Arthur and Fischer, 1977; Jenkyns, 1980; Bralower and Thierstein, 1984). However, at the present time, advancing the state of knowledge of middle Cretaceous oceanic environments is severely limited by a lack of material to which new proxies and techniques can be applied. The limitations are both geographic and stratigraphic in scope. For example, there are few oceanic records from the high latitudes, particularly in the Northern Hemisphere, and the Pacific Ocean is under-represented, especially given its significant geographical area, essentially half the planet, in the Cretaceous. Many 'classic' Cretaceous sites drilled during the early DSDP expeditions, such as those that recovered thin Pacific black shales atop large basaltic plateaus (e.g. Legs 32 and 33), were only spot-cored before the development of the extended core barrel (XCB) and other techniques that improved recovery substantially. Furthermore, early DSDP drilling was largely exploratory and so sites were not located with specific paleoceanographic hypotheses to test. Consequently, we have very few well-designed depth transects through the Cretaceous ocean.

This paucity of material from all oceans has limited our understanding of rapid paleoceanographic change such as expansion of the oxygen-minimum zone during Oceanic Anoxic Events (OAEs), injection of isotopically light carbon into the ocean–atmosphere system, movement of the Calcite Compensation Depth (CCD), fluctuations in nutrient loads and composition of planktonic biota - and hence prevented the high-resolution studies that have led to significant breakthroughs in studies of the Paleogene (e.g., Bains et al., 1999; Thomas et al., 2002; Zachos et al., 2003; Nunes and Norris, 2006). Finally, knowing that the deep biosphere includes active heterotrophic microbes along with preserved organics and possibly cells, ancient organic rich sequences are an interesting place to examine the potential long-term maintenance of the deep biosphere. The potential for reexamination of deposited cells by diffusing shales present a unique opportunity for exploration into survival and evolution questions.

The workshop funded by ECORD/ICDP Magellan Plus, IODP-MI and Ocean Leadership was held April 15-17, 2013 at University College London, attended by a multidisciplinary group of 46 scientists from six countries (Appendix A). These scientists represent multiple key disciplines including geocehmistry, microbiology, micropaleontology, sedimentology, climate modeling, and tectonics and have a working knowledge of the geographic range of potential Cretaceous drilling targets.

The central workshop goal was to instigate new drilling legs designed to further our understanding of middle Cretaceous climate and ocean circulation. The program (Appendix B) included plenary talks, but most of the workshop was devoted to regional breakout groups designed to address the fesability of individual drilling targets in addressing the key themes. The following broad questions arose from these themes.

(1) How sensitive was the Cretaceous climate to high levels of CO_2?
(2) How did warm Cretaceous climate and low thermal gradients impact the intensity and patterns of ocean circulation?
(3) What is the evidence for ice in the Cretacous, and, in ita absence, how can higher freqency sea level cycles be explained?
(4) How does the opening of major ocean gateways impact climate, ocean circulation and the deposition of organic-reich sediments?
(5) What were the triggers for oceanic anoxic events (OAEs), and what was the geographic and bathymetric extent of anoxia? How does the distribution of organic rich sediments differ between Atlantic and Pacific oceans?
(6) What are the processes that lead to recovery after climatic perturbations such as OAEs?
(7) What is the geochemical and paleontological record of ocean acidification both at the surface of the ocean and at depth? How does the calcite compensation depth dffer between different ocean basins?
(8) How do anoxia and acidification affect the origination, extinction, composition and diversity of plankton and benthos assemblages?
(9) How faithful are the major paleotemperature proxies?
(10) How does the occurrence of organic carbon impact the long-term maintanence of the deep biosphere?

These questions are highly relevant to key challenges in the Science Plan for the International Ocean Discovery Program 2013 – 2023. In particular, they address the following challenges:

- Climate and Oceans Challenge 1: How does Earth's climate system respond to elevated levels of atmospheric CO_2?
- Climate and Oceans Challenge 2: How do ice sheets and sea level respond to a warming climate?
- Climate and Oceans Challenge 4: How resilient is the ocean to chemical perturbations?
- Biosphere Frontiers Challenge 5: What are the composition, origin and biogeochemical mechanics of deep seafloor communities?
- Biosphere Frontiers Challenge 6: What are the limits of life in the subseafloor realm?
- Biosphere Frontiers Challenge 7: How sensitive are ecosystems and human societies to environmental changes?

A wide range of potential drilling targets have been proposed to address these questions. These targets include traditional leg- and APL-length expeditions. However, many of these questions will require multiple expeditions to be addressed. The report includes a more detailed description of the major scientific questions followed by descrptions of the potential drilling targets.

SCIENTIFIC RATIONALE FOR DRILLING

Cretaceous Climate and its Impact on Ocean Circulation

The Mesozoic Era is classically considered as a 'greenhouse' interval in the Phanerozoic climatic history of the Earth (Fischer, 1982) although whether or not polar ice developed during the relatively warm Cretaceous Period is still under debate. In particular, there is a range of isotopic and biotic evidence that favours the concept of discrete 'cold snaps', or at least cooler intervals, marked particularly by migration of certain biota towards lower latitudes. However, TEX_{86} data from the Southern Ocean indicate that relatively warm sea-surface conditions (26–30°C) existed throughout Early Cretaceous time, albeit indicating an overall cooling trend (Littler et al., 2011; Jenkyns et al., 2012). Indeed, high-latitude cooling at the end of the Cretaceous is indicated by TEX_{86} data from the Arctic Ocean, giving sea-surface temperatures of 15–19°C (Jenkyns et al., 2004), but still well above freezing point. The evidence from plant fossils and dinosaurs also chimes more with subtropical polar climates than with the presence of polar ice (Nathorst, 1911; Rich, 2002), but 'greenhouse glaciologists' still represent a substantial proportion of the community. Given that low-latitude sea-surface temperatures have been estimated to be as high as 37°C (e.g. Forster et al., 2007; Bornemann et al., 2008; Littler et al., 2011) when Southern Ocean sea-surface temperatures were 10°C cooler, such relatively low Equator–pole gradients during parts of the Cretaceous imply the existence of very different forcing functions from those that controlled ocean circulation during 'icehouse' intervals. Were deep waters even generated at the poles during the Cretaceous or was the density structure of the oceans largely governed by latitude-dependent insolation? Recent work using DSDP and ODP materials suggests that deep-water ventilation mechanisms varied in both time and space through the Cretaceous. Neodymium isotopes are emerging as a powerful proxy for reconstructing Cretaceous intermediate and deep-water circulation and have provided evidence for bottom water production at low-latitudes during the mid-Cretaceous driven by evaporation (e.g. MacLeod et al., 2008, 2011; Jimenez-Berrocoso et al., 2010) and at high latitudes in the Late Cretaceous driven by long-term cooling (e.g. Robinson et al., 2010; Murphy and Thomas, 2012; Robinson and Vance, 2012). The inferences drawn from Nd are complementary to those from traditional stable isotopic measurements in benthic foraminifera (e.g. Frank and Arthur, 1999; Friedrich et al., 2008, 2012) but can be applied to a greater range of palaeowater depths and lithologies. However, interpretation of Nd-isotopes would benefit greatly from strategically placed depth transects.

The rationale for drilling should include the following considerations, discussed extensively at the workshop. (1) Interpretation of proxy sea surface temperature (SST) data is undergoing some recent changes (e.g., Hollis et al., 2012). For example, the TEX_{86} proxy likely need require different calibrations for warmer and cooler waters and even then might still be overestimates. As a result wherever possible, SST estimates should be based on more than one proxy. (2) Our understanding of deep ocean circulation is limited by the paucity of systematic profiles of water column properties in the different ocean basins. Thus, proposed expeditions should incorporate a depth transect wherever possible to determine water column structure and the properties of deep water masses. (3) Cretaceous ocean circulation was impacted profoundly by the opening of ocean gateways especially at both ends of the South Atlantic. This gateway theme was recognized as high priority for furthering our understanding of several aspects of Cretaceous climate.

Origin of Ocean Hypoxia

The level of oxygen content in seawater is a major determinant of the diversity, abundance and nature of life in the oceans, and controls respiration, thereby determining the amount of nutrient recycling and carbon sequestration in sediments and the deep ocean. Under future global warming, it is predicted that low oxygen regions will expand, potentially creating widespread hypoxic and anoxic waters, loss of diversity and a reduction in the sustainability of coastal economies and pelagic fisheries (e.g. Stramma et al., 2008, 2012). Examples of warming-driven anoxia from the geological record could potentially provide additional constraints on the mechanisms and feedbacks associated with these conditions. The Cretaceous oceans were subject to periods of extremely low oxygen conditions that resulted in the accumulation of organic-carbon-rich sediments, many of which are now important hydrocarbon reserves. The discovery of geographically widespread, synchronous ‘black shales’ during the early years of the DSDP led to the concept of ‘oceanic anoxic events’ (OAEs; Schlanger and Jenkyns, 1976), which are now recognised as important responses of the Earth system to global environmental perturbations. However, the processes by which hypoxia was established, maintained and terminated are not fully resolved. Paradoxically, in order to maintain high surface productivity (and hence organic carbon supply) a dynamic nutrient recycling mechanism must have existed, yet vigourous circulation would tend to promote oxygenation rather than diminish it (e.g. Hay, 2008). Furthermore, whilst the temporal links between OAEs and perturbations to other aspects of the climate system, ocean chemistry, biogeochemical cycling and the solid earth (e.g. large igneous province volcanism, tectonic gateways) have been explored, many ideas remain untested or untestable with the currently available materials. Depth and geographic transects are required to determine the spatial and temporal variability in oxygen minimum zones and, in particular, to address why some areas of the Cretaceous ocean (e.g. the southern North Atlantic) appear to have been hypoxic for long-periods of time whilst other regions (e.g. the equatorial Pacific) only experienced transient anoxia during the OAEs. Continuous, high-resolution stratigraphic records would allow clear documentation of the relative timing of events as OAEs progress, in turn allowing different mechanistic hypotheses to be tested. Of course, the OAEs occurred against an evolving set of boundary conditions as paleogeographies and climates shifted through the Cretaceous, and so consideration of these events within the broader context of the other themes of the proposed workshop (such as mid-Cretaceous climate and ocean acidification) is key.

As discussed at the workshop, there is a paucity of OAE records from the expansive Pacific Ocean, especially ones with adequate recovery. For example we have only one of two records of OAE1a and OAE2 in the Pacific. Moreover, even though the oxygen minimum zone model (e.g. the modern Peru Shelf) has been discussed as representative for the Cretaceous for many years (e.g., Ryan and Cita, 1975; Thiede and Van Andel, 1977), the model has never been proven as applicable. Thus the rationale for drilling to investigate Ocean Hypoxia should include: (1) depth transects as for the other themes, and dedicated campaigns in the Pacific Ocean.

Ocean acidification: Causes and Consequences:

Predicting the consequences of Ocean Acidification (OA) is at a very early stage (Blackford 2010), due to the complexity of system drivers and of responses within and among different organisms. OA is significantly impacting the upper oceans that have already assimilated almost 50% of all the CO_2 emitted since 1800 (Sabine et al. 2004) causing a pH drop from 8.0-8.3 (pre-Industrial Revolution) to present 7.9-8.1 units. At current CO_2 emissions and OA rates, the ocean pH is expected to drop 0.3-0.5 pH units by year 2100 (Ridgwell & Zeebe 2005).

While oceanic uptake of CO_2 will lessen global warming, acidified oceans might be adverse for many calcifying organisms and alter the survival, growth, development, metabolism, and pH-balance of marine biodiversity and trophic interactions (Royal Society 2005; Kleypas et al. 2006). Chronic exposure to increased CO_2 has long-term, largely unknown implications for calcification rates. In the long run, decreased calcification might compromise the fitness of marine calcifiers and make non-calcifying competitors more successful. Some planktonic calcifiers may be able to adapt via natural selection, but those unable to adapt are likely to experience reductions in their geographic ranges or could even disappear, inducing major changes in calcification and primary productivity, altering the oceanic global biodiversity and ultimately affecting foodwebs through pH-dependent speciation of nutrients and metals (Huesemann et al. 2002; Fabry et al. 2008).

Even small changes in CO_2 concentrations in surface waters may have large negative impacts on calcifiers and natural biogeochemical cycles of the ocean (Gattuso et al. 1998; Wolf-Gladrow et al. 1999; Langdon et al. 2000; Riebesell et al. 2000; Marubini et al. 2001; Zondervan et al. 2001; Reynaud et al. 2003). Understanding of the Earth system at time scales longer than human observations has became imperative, because anthropogenic activities are likely to telescope by an order of magnitude the rates of climatic change that usually result from geologic processes. Research groups assessing the ecosystem responses to current excess-CO_2, global warming and OA recognize that geological records are instrumental for evaluating future long-term trends (e.g. Kleypas et al. 2006) and the associated response of marine calcification. Geological examples of paleoenvironmental perturbations partially share characteristics of anthropogenic warming and OA (Honisch et al 2012), although rates and durations are substantially different.

Under excess CO_2 and greenhouse conditions, the Cretaceous deep ocean became depleted of oxygen promoting the accumulation and burial of massive amounts of organic matter during Oceanic Anoxic Events (OAEs) (Schlanger & Jenkyns 1976). Although global anoxia and enhanced organic matter burial are the most striking and intriguing paleoceanograhic phenomena, OAEs can be studied also to decipher the oceanic ecosystem response to (sequence of) CO_2 pulses (e.g. Turgeon & Craser 2008; Mehany et al 2009), and OA (Weissert & Erba 2004, Kump et al 2009; Erba et al. 2010).

Compared to the PETM, the Aptian OAE1a has been demonstrated to be a similar CO_2 perturbation of the atmosphere-ocean system (Leckie et al. 2002; Weissert & Erba, 2004; Mehay et al. 2009; Erba et al 2010). It is taken as a geological example of volcanicCO_2-induced OA with evidence of a geologically rapid warming (increase of 5-6°C) and decreased carbonate saturation in surface and deep waters at global scale. Erba et al. (2010) demonstrated that calcareous nannoplankton were extremely sensitive to OA associated to OAE1a, allowing separation of most-, intermediate-, and least-tolerant taxa. After a major calcification failure of heavily calcified forms, ephemeral coccolith dwarfism and malformation represent the most remarkable species-specific adjustments to survive surface water acidity. Data from the Tethys also show that deep-water acidification induced a 1-2km CCD shoaling just prior to onset of global anoxia. Repetitive abundance peaks of peculiar heavily-calcified nannoliths trace intermittent alkalinity recovery alternating with OA peaks marked by coccolith dwarfism and malformation. In addition to OAEs, another potential long-lasting episode of OA is the Aptian/Albian boundary interval characterized by major failures in planktonic foraminifera (Huber & Leckie 2011) and calcareous nannoplankton (Erba 2004).

As discussed at the workshop, data from the open oceans are severely biased by the low recovery and/or spot-coring of early DSDP Legs. However, based on DSDP/ODP sites we know that complete sequences exists in the oceans to allow a quantitative study of ocean acidification at global scale. Continuous, high-resolution stratigraphic oceanic records (expecially from the Pacific) would allow documentation and modeling of the impact of OA on calcifiers and ocean chemistry. Sites at low, middle and high latitudes will provide data to quantify OA in surface watermasses with different temperature (and salinity) values. Also we want to compare oligotrophic to eutrophic conditions and marginal to open ocean settings. In analogy to the "PETM experiments" (e.g. Zachos et al 2005), depth transects along plateau flanks will allow to trace the CCD shoaling through the OA onset as well as the CCD deepening after OA climax. The recovery of pelagic biogenic sediments at oceanic sites will be the only means of understanding response, adaptation and/or failure of marine calcifiers to OA at large scale and medium to long term.

Impact of Environmental Change on Plankton

The mid Cretaceous saw the establishment of the modern plankton ecosystem, with coccolithophores, dinoflagellates and radiolaria being joined by the emerging planktic foraminifera and diatom groups (Leckie et al. 2002). There is evidence that climate and oceanographic change played important roles in the evolution of all of these groups, and the OAEs, in particular, appear to have caused very significant extinction and radiation in the radiolaria and planktic foraminifera (Leckie et al. 2002) and major assemblage shifts in coccolithohores (Erba, 2004; Bown et al., 2004). However, whilst we have a broad brush understanding of these evolutionary trends many outstanding questions and details still remain, including: (1) at high resolution, do plankton diversity and abundance records vary in unison and how does this relate to the attendant carbon cycle shifts; (2) do plankton morphometric, shell weight and shell geochemistry data correlate with carbon cycle and other palaeoceanographic data; (3) does selectivity in plankton extinction or origination provide information concerning causal mechanisms; (4) can we use these different plankton data types (abundance, diversity, morphometry, calcification/weight, selectivity) to address and deconvolve the roles of temperature, carbonate saturation and nutrient levels through these mid Cretaceous environmental change events; (5) the planktic foraminiferal evolutionary record through the mid Cretaceous appears to have been particularly sensitive to carbon cycle shifts and in a number of cases saw near total turnover, and yet we still do not fully understand why this was the case, and why other plankton groups were relatively unaffected (e.g. Huber & Leckie, 2001); moreover, the times of significant foraminiferal assemblage turnover (e,g, the Aptian/Albian boundary) do not always correspond to times of the most singificant nannplankton turnover (e.g., the early Aptian).

In every case these questions require integrated palaeontological and palaeoceanographic data from new, high quality cores/sites with good microfossil preservation. The identification of appropriate sites is especially important for these events, which often coincide with low carbonate sediments with poor microfossil preservation. At the workshop strategies were discussed to obtain transects of important biographic boundaries, especially those in temperate and high latitude locations. In addition, the significance of siliceous plankton was discussed. Both of these priorities can be addressed by drilling ocean gateways in the South Altnaitc.

DRILLING STRATEGIES

A compresive strategy is required to address the themes described above. Most of the workshop was devoted to addressing drilling targets from around the oceans as well as the characteristics of the ideal sections. For the scientific goals to be achieved, a number of critical elements were ephasized: (1) expanded sections must be recovered that will allow processes to be studied at millenial resolution; (2) superior microfossil and organic matter preservation are required for modern proxies to be applied successfully; and (3) where possible, depth transects will provide key information such as the precise elevation of the changes in the CCD in critical intercvals and the existence of oxygen minimum zone.

The reports of the regional working groups are presented in the following with each report containing descriptions of potential drilling targets.

REFERENCES CITED

Arthur M. A., and Fischer A.G., 1977. Upper Cretaceous-Paleocene magnetic stratigraphy at Gubbio, Italy. I. Lithostratigraphy and sedimentology. *Geol. Soc. Am. Bull.*, 88:367-371.

Bains, S., R.M. Corfield, R.N. Norris, Mechanisms of climate warming at the end of the Paleocene, *Science*, *285*, 724-727, 1999.

Berner, Robert A., et al. (1983). "The Carbonate-Silicate Geochemical Cycle and Its Effect on Atmospheric Carbon Dioxide over the Past 100 Million Years." *American J. Science* **283**: 641-83.

Blackford, J.C. (2010), Predicting the impacts of ocean acidification: Challenges from an ecosystem perspective. *Journal of Marine Systems, 81*, 12–18.

Bornemann, A., et al., 2008, Isotopic Evidence for Glaciation During the Cretaceous Supergreenhouse, *Science* 11 January 2008: Vol. 319 no. 5860 pp. 189-192 *DOI:* 10.1126/science.1148777.

Bown, P.R., Lees, J.A, and Young, J.R., 2004, Calcareous nannoplankton evolution and diversity through time, *in* Thierstein, H., and Young, J.R., eds., Springer, 481-508.

Bralower, T. J., and Thierstein, H. R., Low productivity and slow deep-water circulation in mid-Cretaceous oceans: *Geology*, v. 12, p. 614-618.

Erba, E. (2004) - Calcareous nannofossils and Mesozoic Oceanic Anoxic Events. *Marine Micropaleontology*, *52*, 85-106

Erba, E., et al. (2010), Calcareous Nannoplankton Response to Surface-Water Acidification Around Oceanic Anoxic Event 1a. *Science, 329*, 428-432. DOI: 10.1126/science.1188886

Fabry, V.J., Seibel, B.A., Feely, R.A., and Orr, J.C. (2008), Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science, 65*, 414–432.

Fischer, A. G.: Long-term climatic oscillations recorded in stratigraphy, in Climate in Earth History, Studies in Geophysics, National Academy Press, Washington, 1982.

Forster, A., et al. 2007, Mid-Cretaceous (Albian–Santonian) sea surface temperature record of the tropical Atlantic Ocean, Geology, doi: 10.1130/G23874A.1 *v. 35 no. 10 p. 919-922.*

Frank, T. D., and M. A. Arthur (1999), Tectonic forcings of Maastrichtian ocean-climate evolution, *Paleoceanography*, *14*, 103–117, doi:10.1029/1998PA900017.

Friedrich, O., J. Erbacher, K. Moriya, P. A. Wilson, and H. Kuhnert (2008), Warm saline intermediate waters in the Cretaceous tropical Atlantic Ocean, *Nat. Geosci.*, *1*, 453–457, doi:10.1038/ngeo217.

Friedrich, O., R. D. Norris, and J. Erbacher (2012), Evolution of middle to Late Cretaceous oceans–A 55 m.y. record of Earth's temperature and carbon cycle, *Geology*, *40*, 107–110, doi:10.1130/G32701.1.

Gattuso, J-P., Frankignoulle, M., Bourge, I., Romaine, S., and Buddemeier, R. W. 1998. Effect of calcium carbonate saturation of seawater on coral calcification. *Global and Planetary Change, 18*, 37–46

Hay, W.W., 2008, Evolving ideas about the Cretaceous climate and ocean circulation: Cretaceous Research, v. 29, p. 725–753, doi: 10.1016/ j.cretres.2008.05.025.

Honisch, B., et al (2012) ,The Geological Record of Ocean Acidification.Science, 335, 1058-1063.

Huber, B.T., and Leckie, R.M. (2011) Planktic foraminiferal species turnover across deep-sea Aptian/Albian boundary sections. *Journal of Foraminiferal Research, 41*, 53–95.

Huesemann, M. H., Skillman, A. D., and Crecelius, E. A. (2002). The inhibition of marine nitrification by disposal of carbon dioxide. *Marine Pollution Bulletin, 44*, 142–148.

Jenkyns, H.C., 1980. Cretaceous anoxic events: from continents to oceans. *Geol. Soc. Lond.* 137:171-188.

Jenkyns, H.C., Forster, A., Schouten, S. and Sinninghe Damsté, J.S., 2004. High temperatures in the Late Cretaceous Arctic Ocean. Nature, 432, 888-892.

Jenkyns, H. C., Schouten-Huibers, L., Schouten, S., and Sinninghe Damsté, J. S. (2011) Middle Jurassic-Early Cretaceous high-latitude sea-surface temperatures from the Southern Ocean, Clim. Past Discuss., 7, 1339-1361, doi:10.5194/cpd-7-1339-2011.

Jenkyns, H.C., and three others, 2012. Warm Middle Jurassic–Early Cretaceous high-latitude sea-surface temperatures from the Southern Ocean. Clim. Past, 8, 215-226.

Jiménez Berrocoso, A., and four others (2010), Nutrient trap for the Late Cretaceous organic-rich black shales in the tropical North Atlantic, *Geology*, *38*, 1111–1114, doi:10.1130/G31195.1.

Kleypas, J. A., Feely, R. A., Fabry, V. J., Langdon, C., Sabine, C. L., and Robbins, L. L. (2006). Impacts of ocean acidification on coral reefs and other marine calcifiers: a guide for future research. Report of a workshop held 18–20 April 2005, St Petersburg, FL, 88 pp.

Kump, L.R., Bralower, T.J., and Ridgwell A.R., 2009. Ocean acidification in deep time. *Oceanography, 22*, 94-107

Langdon, C., Takahashi, T., Sweeney, C., Chipman, D., Goddard, J., Marubini, F., Aceves, H., et al. 2000. Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef. *Global Biogeochemical Cycles, 14*, 639–654.

Leckie, R.M., Bralower, T.J. and Cashman, R. (2002). Oceanic Anoxic Events and plankton evolution: Biotic response to tectonic forcing during the mid-Cretaceous, *Paleoceanography 17*, 10.1029/2001PA000623.

Littler, K., Robinson, S.A., Bown, P.R., Nederbragt, A., and Pancost, R., 2011, High sea-surface temperatures during the Early Cretaceous Epoch, Nature Geoscience, 4, 169-172

MacLeod, K.G., Martin, E.E., and Blair, S.W., 2008, Nd isotopic excursion across Cretaceous oceanic anoxic event 2 (Cenomanian–Turonian) in the tropical North Atlantic: Geology, v. 36, p. 811–814, doi: 10.1130/G24999A.1.

MacLeod, K.G., C. Isaza Londoño, E. E. Martin, Á. Jiménez Berrocoso & C. Basak, 2011, Changes in North Atlantic circulation at the end of the Cretaceous greenhouse interval, *Nature Geoscience* 4, 779–782, doi:10.1038/ngeo1284

Marubini, F., Barnett, H., Langdon, C., and Atkinson, M. J. (2001). Dependence of calcification on light and carbonate ion concentration for the hermatypic coral Porites compressa. *Marine Ecology Progress Series, 220*, 153–162

Mehay, S., et al. (2009) - A volcanic CO2 pulse triggered the Cretaceous Oceanic Anoxic Event 1a and a biocalcification crisis. *Geology 37*, 819-822

Murphy, D. P., and D. J. Thomas, Cretaceous deep-water formation in the Indian sector of the Southern Ocean, *Paleoceanography,* 27, PA1211, doi:10.1029/2011PA002198

Nathorst, A. G., 1911. On the value of fossil floras of the Arctic regions as evidence of geological climates, Geol. Mag. Decade V, 8, 217–225.

Nunes, F., and Norris, R., 2006. *Abrupt reversal in ocean overturning during the Palaeocene/Eocene warm period.* Nature ***439**, 60-63,| doi:10.1038/nature04386*

Reynaud, S., N. Leclercq, S. Romaine-Lioud, C. Ferrier- Pagés, J. Jaubert, and J.-P. Gattuso (2003) Interacting effects of CO2 partial pressure and temperature on photosynthesis and calcification in a scleractinian coral. *Global Change Biol.*, *9*, 1660–1668.

Ridgwell A.T,. Zeebeb R.E. (2005). The role of the global carbonate cycle in the regulation and evolution of the Earth system. *Earth and Planetary Science Letters, 234*, 299– 315.

Riebesell, U., Zondervan, I., Rost, B., Tortell, P. D., Zeebe, R. E., and Morel, F. M. M. (2000). Reduced calcification of marine plankton in response to increased atmospheric CO2. *Nature, 407*, 364–367

Robinson, S. A., and D. Vance, 2012, Widespread and synchronous change in deep-ocean circulation in the North and South Atlantic during the Late Cretaceous, *Paleoceanography,* doi:10.1029/2011PA002240, in press.

Robinson, S.A., Murphy, D.P., Vance, D., and Thomas, D.J., 2010 Formation of "Southern Component Water" in the Late Cretaceous: Evidence from Nd-isotopes, *Geology*, 38, 871-874.

Royal Society (2005). Ocean acidification due to increasing atmospheric carbon dioxide. Policy Document 12/05, The Royal Society, London. 60 pp.

Royer et al., 2004, CO2 as a primary driver of Phanerozoic climate, GSA Today, v. 14; no. 3, doi: 10.1130/1052-5173.

Ryan, W.B.F., and Cita, M.B., 1977. Ignorance concerning episodes of ocean-wide stagnation. *Marine Geology*, 23:197-215.

Schlanger, S. O., and H. C. Jenkyns (1976), Cretaceous oceanic anoxic events: Causes and consequences, Geol. Mijnbouw, 55, 179–184.

Siegenthaler, U., and J.L. Sarmiento (1993) Atmospheric carbon dioxide and the ocean. *Nature*, *365*, 119–125.

Stramma, L., Johnson, G.C., Sprintall, J. and Mohrholz, V.2008, Expanding Oxygen-Minimum Zones in the Tropical Oceans, Science, 320 (5876), 655-658. [DOI:10.1126/science.1153847]

Stramma, L., Prince, E.D., Schmidtko, S. Luo, J., Hoolihan, J.P., Visbeck, M., Wallace, D.W.R., Brandt P., & Körtzinger A., 2012, Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes, *Nature Climate Change* 2, 33–37 doi:10.1038/nclimate1304

Thomas, D. J., Zachos, J. C., Bralower, T. J., Thomas, E., and Bohaty, S., 1002. Warming the Fuel for the Fire: Evidence for the thermal dissociation of methane hydrate during the Paleocene-Eocene thermal maximum, *Geology,* v. 30, p. 1067-1070.

Turgeon, S.T., and Craser, R.A. (2008). Cretaceous oceanic anoxic event 2 triggered by a massive magmatic episode. *Nature, 454*, 323-326.

Zachos, J. C., et al. 2003. A Transient Rise in Tropical Sea Surface Temperature During the Paleocene-Eocene thermal maximum, *Science* v. 302, p. 1551-155.

Zachos, J.C., et al (2005). Rapid Acidification of the Ocean During the Paleocene-Eocene Thermal Maximum. *Science, 308*, 1611-1615.

Weissert, H. and Erba, E. (2004). - Volcanism, CO_2 and paleoclimate: a Late Jurassic-Early Cretaceous carbon and oxygen isotope record. *Journal of the Geological Society, London* , *161*, 695-702.

REGIONAL DRILLING TARGETS

Drilling the Cretaceous Pacific Ocean

Erba, Jenkyns, Tarduno, Pancost, Owens

General Rationale

Drilling Pacific plateaus, rises, seamounts and guyots (e.g. Manihiki Plateau, Magellan Rise, Mid-Pacific Mountains, Hikurangi Plateau, Meiji Guyot, Hess Rise) will address major challenges described in the Science Plan 2013-2023. Specifically:

Challenge 1: Long-term and short-term climate changes and Earth system functioning under low and high levels of CO_2.

Challenge 4: Oceanic response to chemical perturbations during OAEs as well as before and after OAEs. History of OMZ. Ocean acidification during intervals of elevated CO_2. History of CCD. Ocean carbon (organic and inorganic) chemistry, Links between ocean chemistry and (extreme) internal and external forcings.

Challenge 7: Oceanic ecosystem response to paleoenvironmental perturbations. Calcareous and siliceous plankton evolution and paleobiodiversity. Ephemeral adaptations to transient episodes of extreme climate changes, ocean fertilization and acidification. Permanent evolutionary changes (originations and extinctions): role of long-term climate change and transient hyperthermals or cooling interludes. Biota adaptations to aragonite versus calcite oceans: history-evolution of plankton biomineralization. Fertilization from the mantle?

Our understanding of the long-term Cretaceous climate history, ocean dynamics and ecosystem functioning mostly derives from Atlantic and Tethyan successions, with the associated issues of small oceanic basins, unusual ocean chemistry and some detrital/reworking impacts. Pacific Ocean “highs” are located in the largest oceanic basin that existed during the Cretaceous Period (the Cretaceous Super-ocean), whose geological record is crucial for understanding global climate change, geochemical cycling and ecosystem reactions. These topographic highs offer a unique opportunity to investigate the Cretaceous ocean in a “pure” carbonate system and in an open-marine setting, virtually unaffected by shallow-water derived material and/or detrital continental influence.

Our current state of knowledge is, however, largely based on DSDP sites, and although they document the occurrence of Cretaceous successions, including black shales deposited during OAEs, many were only spot-cored and recovery was moderate to low in critical intervals. Technology has improved, as indicated by the successful drilling on Shatsky Rise (ODP Leg 198, Sites 1207, 1213), which recovered a near-complete record of the early Aptian OAE 1a that has been successfully investigated using a range of state-of-the-art inorganic and organic parameters. Past investigations of relatively well-recovered DSDP material (e.g. Leg 62, Site 463, mid-Pacific Mountains) has demonstrated the feasibility of a multi-proxy approach, integrating micropaleontology (quantitative and morphometric analyses), with geochemistry.

Previous drilling demonstrates that at least OAE1a (early Aptian) and OAE2 (CenomanianTuronian boundary) are recorded from the Pacific Ocean, but sedimentary material is extremely limited, especially for OAE2. Indeed, no Cenomanian-Turonian organic-rich sediment is available for detailed study and acquisition of such material remains an extremely high priority. Moreover, we have as yet no sedimentary record of anoxia and organic-rich deposition in the Pacific Ocean during other Aptian-Albian OAEs (OAE1b and OAE1d), known from Atlantic sites and the Tethyan region, from ocean drilling. Accreted Cretaceous pelagic limestones found in western North America provide hints that the Cretaceous Pacific Ocean was affected by these more subdued anoxic events, providing further motivation to obtain high resolution records by drilling Pacific plate sites to test the occurrence of black shales associated to OAe1b and OAE1d.

Hence, the recovery of carbon-rich sediments from Pacific plateaus is essential to:

a) quantify spatially and temporarily the extent of anoxia outside the Tethys-Atlantic oceans during a range of time-slices;

b) characterize the type of organic matter as well as the plankton changes through such major palaeoceanographic perturbations;

c) develop models to understand oceanic correlation connections between the Pacific, the Atlantic and the Tethys Oceans as well as global ocean-atmosphere dynamics.

The palaeowater depth of the summits of these highs is <2000m. Along their flanks, they preserve a sedimentary record allowing the history of the OMZ, the CCD, the lysocline and vertical temperature structure to be traced.

Some Pacific highs are latest Jurassic to Early Cretaceous in age and therefore provide the only fully open-ocean record prior to and at the onset of the mid-Cretaceous Greenhouse. In fact, the turning point from a cool and low-CO_2 world to a warm/hot and high-CO_2 world is dated as earliest Aptian and coincides with OAE1a. While we have complete records from land sections in the Tethyan and Boreal regions, records from the Atlantic Ocean are very limited and the Pacific highs are key places to identify this major long-term climatic shift.

The proximity of Pacific highs to mid-Cretaceous Large Igneous Provinces (LIPs) such as the Ontong Java and the Caribbean Plateau (Galapagos hotspot) offers the opportunity to investigate chemical, physical and biotic changes in an area close to the emplacement of LIPs, where hydrothermal activity and submarine/subaerial weathering of basalt may have supplied a proximal source of metals to fertilize the ocean. The Tethys-Atlantic successions provide the long-distance records relative to the LIP emplacement, but near- and medium-distance records are crucial to delineate a global picture of physical, chemical and biotic changes relative to major igneous events and associated high-CO2.

The Pacific highs are also aligned along a ~30 ° N–S palaeolatitudinal transect, which can delineate the geography (latitudinal extent) and chemico–physico–biological characteristics of the paleoequatorial upwelling belt and adjacent central gyre. The palaeogeographic configuration of the highs is ideal to quantify biogeochemical cycling in oligotrophic, mesotrophic and eutrophic regions at times of “normal” and “perturbed” environmental conditions. In particular, they will provide data to separate the fertility control on the onset of OAEs and potentially differentiate between different types of planktonic material derived from different areas of the ocean before, during and after OAEs .

Pelagic sections from Pacific highs will provide the only open-ocean record of plankton evolution during the Cretaceous and will illustrate how calcareous and siliceous plankton have responded changes to ocean chemistry and climate in time and space over short and long time scales; such sections will also monitor the influence of past episodes of ocean acidification in response to changing CO_2 levels. The response, survival and demise of benthic foraminifera to changes in the OMZ (thickness and degree of oxygen depletion) as well as shallowing and deepening of the CCD) can also be investigated..

Basement Objectives

Drilling of Cretaceous sedimentary sequences is complementary with basement objectives in terms of understanding episodes of extraordinary magmatism. These aspects fall under the “Earth Connections” theme of the IODP Long Range Plan (**Challenges 8-10**).

The largest magmatic episode is that represented by Ontong Java Plateau, associated plateaus (Manihiki and Hikurangi) and adjacent Jurassic to Early Cretaceous ocean crust capped by thick sequences of younger Cretaceous volcanic flows (e.g. Nauru and East Mariana basins). Sedimentary sequences on basement highs relatively far from the plateaus (e.g. Mid-Pacific Mountains and Magellan Rise) hold clues to volcanism and potentials linkages with large-scale oceanic change. Specifically, distinct intervals of volcanic ash are found in these sediments (DSDP Sites 167 and 463), together with organic rich sediments of the Early Aptian OAE1a. More complete records of these events will allow better definition of the temporal relationships between LIP volcanism and oceanic anoxia, providing a stronger foundation to explore processes that potentially relate the two.

Drilling on the plateaus themselves provide crucial paleontological constraints on basement ages. But this is of course only the first step for basement objectives. Topical question regarding the formation of the (early Aptian?) plateaus, include their paleolatitude of formation, geometry (i.e. did they once constitute a single feature?), emplacement age and mantle source region, will require basement penetration to obtain pristine samples for radiometric-age, paleomagnetic and geochemical analyses. Among these, Manihiki and Hikurangi plateaus are of special importance because the former is represented by only a short basement hole (DSDP Site 317A) and the latter has not been drilled.

Drilling Meiji Guyot (the northernmost available site on the Cretaceous Pacific plate potentially recording OAE2) addresses a different basement objective: the pre-81 Ma drift history of the Hawaiian hotspot in Earth’s mantle.

Magellan Rise

Erba, Jenkyns, Tarduno, Owens

The **Magellan Plateau** is a small structure, with a crest just below 3000m water depth, located near the paleo-spreading centers that defined the small latest Jurassic Pacific plate within the Pacific Super-ocean. Its topography and location make it unique as a repository of Pacific basin ocean history. Specifically, it represents the southernmost record of Jurassic/Early Cretaceous pelagic carbonate sedimentation, potentially recording a complete sedimentary record of the entire Cretaceous capturing the paleoenvironmental perturbations termed oceanic anoxic events (OAEs). A new, high resolution record from Magellan Rise will thus allow for a more complete paleolatitude temperature reconstruction prior to and throughout the Cretaceous greenhouse climate.

Magellan Rise is also proximal to Ontong Java Plateau (OJP), making it an ideal location to investigate the history of volcanism that formed the plateau and the greater OJP large igneous province (LIP, composed to Manihiki Plateau, Hikurangi Plateau and adjacent magmatism of Nauru and East Mariana Basins). Specifically, Magellan Rise sediments can be used to examine hypotheses linking oceanic anoxia and large igneous provinces (e.g. oceanic fertilization and acidification).

Magellan Plateau was drilled previously at DSDP Site 167 which penetrated an 1185m through a sedimentary section that bottomed in the Jurassic/Cretaceous boundary (~142 Ma).
Biogenic chert was encountered sporadically throughout the Albian-Aptian section, but it clearly is not as serious a problem as other sites (e.g. Shatsky) that may have been closer to the paleoequatorial upwelling belt (the estimated paleoposition of Magellan Rise at 120 Ma is in the Southern Hemisphere, greater than 15 degrees from the paleoequator). Chert appears to be a more serious problem for the earliest Cretaceous sediments (very poor recovery at Site 167), when the site may have been closer to the paleoequator. High organic carbon sediments were not recovered at Site 167, but a thick interval of volcaniclastics were recovered in sediments correlative to OAE1a. These contain altered volcanic ash; it has been postulated that this ash originated from OJP.

Goals

General goals are described in the “Rationale for drilling Pacific Highs”

Specific goals are:

- A complete Cretaceous section (to uppermost Jurassic) in the open Pacific Ocean.
- In addition to mid- Cretaceous OAEs, recovery of the Mid-Cenomanian, the Mid-Barremian Event and the Valanginian Event.
- Depth transects for OMZ and CCD histories
- preservation vs production of organic rich deposits at a central Pacific site
- depth transects will provide an ideal location to understand variations in the redox landscape of the central Pacific Ocean, currently unconstrained.
- Response of calcareous and siliceous plankton to perturbations preceding OAE1a.
- Presence/absence of calpionellids in the Pacific Ocean
- Reconstructions of plate motions through the Cretaceous and implication for sedimentation relative to the paleoequatorial upwelling belt.
- Testing the hypothesis that Magellan Rise records proximal volcanic debris from the Ontong Java Large Igneous Province
- Testing the hypothesis that anoxia of OAE1a is correlative with emplacement of the OJP LIP
- Characterization of ocean dynamics prior to OAE1a, that is before the onset of the mid-Cretaceous greenhouse. Climate, circulation, productivity, biomineralization history and evolution related to Early Cretaceous perturbations, including the Valanginian “high-CO_2” event.

- Functioning of the ocean/atmosphere systems during the mid-Cretaceous “supergreenhouse”
- Open ocean recovery at the end of the mid-Cretaceous “supergreenhouse”: long-term cooling.
- Evolution of calcareous and siliceous plankton prior to the onset of the mid-Cretaceous “supergreenhouse”.
- Testing of hypotheses linking OAEs to large igneous province emplacement.

Locations

Rotary drilling will be required for Cretaceous objectives. Prior seismic survey data used for DSDP Leg 17 appear sufficient to locate 2-3 additional sites near Leg 167. Sites should be offset from Site 167 to avoid sedimentary sliding detected in the Aptian and older sediments.

Manihiki Plateau

Erba, Jenkyns, Tarduno, Uenzelmann-Neben

The **Manihiki Plateau** is a large structure rising just above 3000m depth, located east of the Ontong Java Plateau. It is composed of two general highs, separated by a deep NNE-trending canyon (the Danger Island Trough). Manihiki Plateau is linked with Hikurangi Plateau (now offshore New Zealand) through the paleo-spreading fabric in the western South Pacific Ocean. Hence the southern edge of Manihiki Plateau represents a rifted margin. The physical linkage of Manihiki (and Hikurangi) Plateau to Ontong Java into a once contiguous structure is more speculative.

The southern high (also called the High Plateau) was drilled during DSDP Leg 33. At Site 317A, the oldest carbonate sediment recovered is Early Aptian, which is underlain by volcanic sandstones that contain a horizon with high organic carbon that is possibly equivalent to the Selli Level (OAE1a). Basalt underlying the volcaniclastics sandstone has an Ar-Ar radiometric age of 123.7 Ma.

Goals

- At ~120Ma Manihiki was at ~ 40°S, in oligotrophic waters, faraway from the palaeoequatorial upwelling belt. Coring the sedimentary cover of Manihiki Plateau will allow tracing of the extent of anoxic waters in the paleo-South Pacific during OAE1a, OAE1b, OAE1d, OAE2.
- Characterization of organic matter at an open-ocean, oligotrophic location in the tropical to mid-latitude paleo-South Pacific.
- Understanding global geochemical cycling in the Cretaceous ‘Super-Ocean’.
- Plankton adaptation and evolution in a “stable” environment. This study is particularly relevant for understanding evolutionary patterns and responses of both k-strategists (calcareous nannoplankton and planktonic foraminifera) and r-strategists (diatoms and radiolarian).
- investigate reactions and adaptations of the ocean/atmosphere system, as well as geochemical fluxes and compositions of particulates in an area close to emplacement of LIPs.
- The Manihiki Plateau might be the fragmented remains of a much larger structure together with the Ontong Java (the “Greater Ontong Java”) LIP. Compare petrology, and radiometric ages and paleomagnetism of Manihiki and Ontong Java basalts to test the hypothesis that they are part of the same igneous-tectonic event.
- Volcanic construction history and subsidence of Manihiki Plateau. Did Manihiki emerge to an “island stage”, as predicted by some mantle plume models.
- Characterization of OAE1a at a very proximal site relative to Ontong Java, and testing potential causal relationships between oceanic anoxia and LIP emplacement.
- Characterization of OAE2, which is possibly related to emplacement of the Caribbean Plateau.
- Climate variability during and in between major events: cooling interludes during OAEs, immediately following OAEs and during global warming through the mid-Cretaceous Greenhouse.
- History of CCD and ocean acidification.
- Extent of anoxia, onset and recovery rates.
- *Response of calcareous and siliceous plankton to perturbations related to OAEs, including excessCO2, warming, ocean acidification, fertilization.
- The thick volcaniclastic section at DSDP Site 317A suggests that Manihiki was built to shallower depths than Ontong Java.
- Recovery of a significant depth of basement (10-15 time-independent cooling units, ~150-200 m) at several sites on the Manihiki plateau will greatly advance our understanding of this plateau-forming event. Recovery of subaerially-erupted lavas would address concerns about missing uplift and

subsidence predicted by plume head models. Paleomagnetism will constrain paleolatitudes and potentially help in testing models of continuity with Ontong Java Plateau.

Locations

Paleo –water depth transects from sites selected on the highs north and south of Danger Trough; seismic data exist to place sites.

Parsing sea-floor spreading in the Cretaceous Quiet Zones (ParseKQZ)

Kent, Cande, and Gee

The initial global correlations of the M-sequence magnetic anomalies (Larson, 1991) produced estimates of elevated rates of ocean crust production during the Cretaceous Quiet Zone (KQZ), which were soon used to explain various estimates of very high sea levels in the Cretaceous and possibly related environmental and biotic effects (Hays and Pitman, 1973). The Cretaceous Greenhouse has become closely associated with the concept that CO2 outgassing is directly related to ocean floor production rate, which were presumed to be unusually high during the KQZ, and that the outgassing rate for pre-Cretaceous times can be estimated from inversion sea-level curves. Variations in the tectonic degassing parameter thus constructed drive the BLAG/GEOCARB family of carbon cycling models (Berner, 1994, 2004)

As advocated by (Larson, 1991), the evidence for a Mid-Cretaceous pulse in ocean-crust formation -- for a mantle superplume -- is mainly in Pacific ridge and Pacific oceanic plateau production, which began relatively suddenly at 120-125 Ma, and waned over a long period to about 70 Ma. Using a time scale that happened to be very close to current age estimates for at least the beginning and end of the KQZ, Larson found that spreading rates during the Cretaceous lie within the present-day range, although average Pacific rates were higher. Figure 1 summarizes various parameters associated with the superplume concept.

High crust production rates, particularly related to faster rates of sea-floor spreading calculated for the KQZ, have not gone unchallenged from the outset (e.g., (Baldwin et al., 1974)) and continue to be revised using updated time scales and plate reconstructions (e.g., (Cogné and Humler, 2006)), bearing in mind that less than 1/2 of oceanic crust older than 55 Ma is preserved (Rowley, 2002). What remains undetermined is whether spreading rates during the ~40 Myr-long KQZ was constant or varied systemtaically, for example, higher in the older part than in the younger part on different ridge systems. Such information would provide useful constraints on models of overall ocean crust production and can only be obtained by drilling into the KQZ.

We propose that drilling be undertaken on an opportunistic basis to obtain bottom-hole ages (from biostratigraphy of immediately overlying sediments) in the KQZs of major spreading systems in places where the bounding magnetic anomalies (C33/34 and M0) and flow lines from facture zones are reasonably well defined. There are virtually no DSDP, ODP or IODP holes in any KQZ to date. Recovery of ocean basement in the KQZ would also be important to establish if there are peculiar petrologic or geochemical characteristics that might be associated with KQZ magnetized crust, which often has high-amplitude magnetic anomalies even though it is a time interval of no geomagnetic reversals. A search for correlatable magnetic anomalies could be conveniently conducted during drilling operations at each of the KQZ drill sites by cesium-vapor magnetometer equipped drones that can be launched and recovered from the drill ship (Gee et al., 2008). Potential sites are illustrated in Figure 2.

ParseKQZ-NPac

Between Mendocino and Murray Fracture Zones about half way between Anomalies C33/34 and M0. This is the largest extant KQZ and thus important in setting the pace of overall global spreading within the KQZ.

ParseKQZ-Agulhas

South of Agulhas FZ and north of Agulhas Plateau, between mapped C33/34 and M0. A good opportunity if ship is in Indian Ocean and there is a drilling leg in vicinity.

ParseKQZ-SAtl

Either in eastern basin (north of Agulhas FZ or conjugate in western basin (north of Falkland FZ) between mapped C33/34 and M0.

ParseKQZ-NAtl

Either in eastern or western basins between Atlantis and Kane FZ between mapped C33/34 and M0.

References

Baldwin, B., P. T. Coney, and W. R. Dickinson, 1974, Dilemma of a Cretaceous time scale and rates of sea-floor spreading: Geology, v. 2, p. 267-270.

Berner, R. A., 1994, GEOCARB II: A revised model of atmospheric CO2 over Phanerozoic time: American Journal of Science, v. 294, p. 56-91.

Berner, R. A., 2004, The Phanerozoic Carbon Cycle: Oxford, Oxford University Press, 150 p.

Cande, S. C., J. L. LaBrecque, R. L. Larson, W. C. Pitman, X. Golovchenko, and W. F. Haxby, 1989, Magnetic Lineations of the World's Ocean Basins: AAPG, Tulsa OK.

Cogné, J. P., and E. Humler, 2006, Trends and rhythms in global seafloor generation rate: Geochemistry, Geophysics, Geosystems, v. 7, p. Q03011, doi:10.1029/2005GC001148.

Gee, J. S., S. C. Cande, D. V. Kent, R. Partner, and K. Heckman, 2008, Mapping geomagnetic field variations with Unmanned Airborne Vehicles: Eos, v. 89, p. 178–179.

Hays, J. D., and W. C. Pitman, 1973, Lithospheric plate motion, sea level changes and climatic and ecological consequences: Nature, v. 246, p. 18-22.

Larson, R. L., 1991, Geological consequences of superplumes: Geology, v. 19, p. 963-966.

Rowley, D. B., 2002, Rate of plate creation and destruction: 180 Ma to present: Geological Society of America Bulletin, v. 114, p. 927-933.

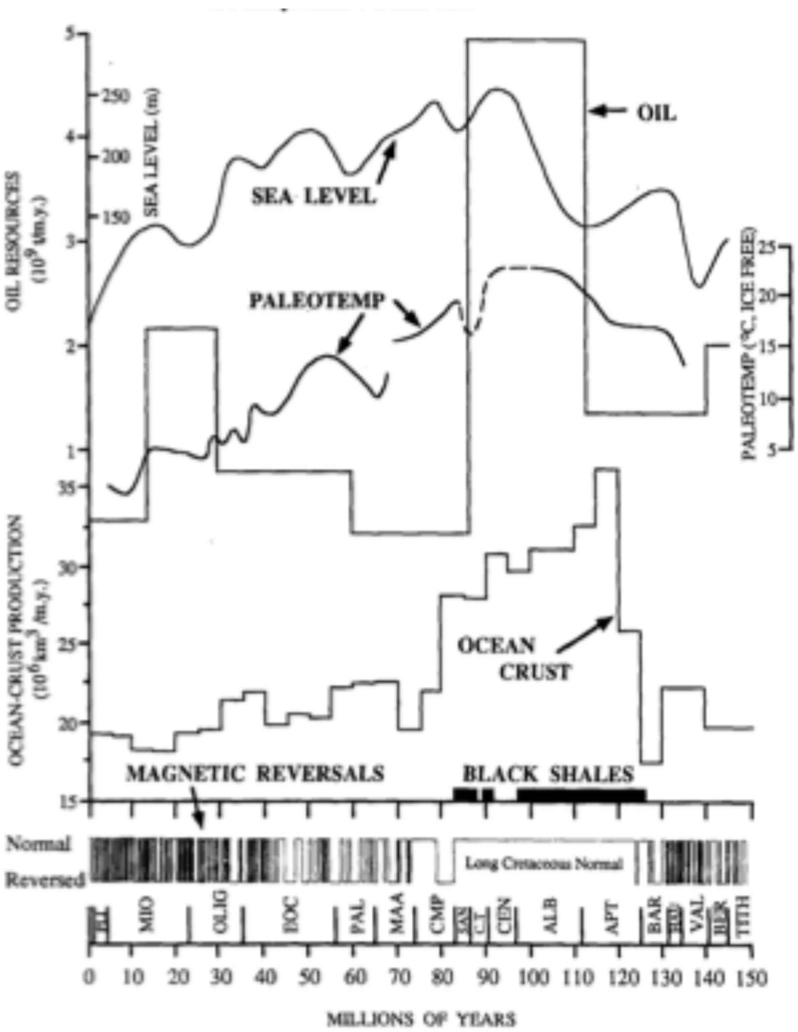


Figure 1. Plots of geomagnetic polarity time scale, global ocean crust production rate, sea-level, ocean paleotempratures, times of black shale deposition, and world hydrocarbon resources (Figure 1 in Larson (1991)).

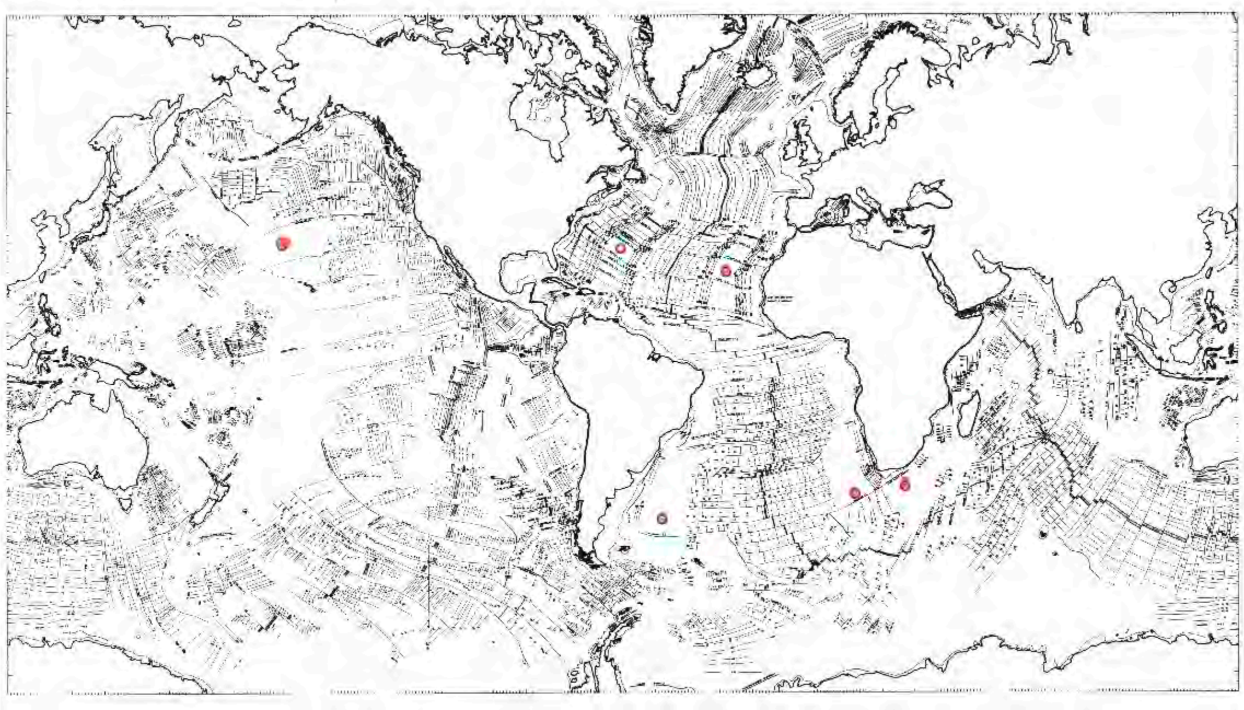


Figure 2. World magnetic lineation chart (Cande et al., 1989) showing locations of preliminary sites for drilling in Cretaceous Quiet Zones (between magnetic anomalies C33/34 and M0).

Cretaceous oceanic events in the NW Pacific and climate reaction on East Asian continent (CONPEAC): Off-Sendai fore-arc basin drilling

Hasegawa and Moriya

This proposal addresses:
Challenge 1. How does Earth's climate system respond to elevated levels of atmospheric CO_2?
Challenge 2. How do ice sheets and sea level respond to a warming climate?
Challenge 3. What controls regional patterns of precipitation, such as those associated with monsoons or El Niño?
Challenges 4. How resilient is the ocean to chemical perturbations?

Paleoceanography in the Pacific that occupied majority of the world ocean during the Cretaceous has largely remained uncertain. Appreciating knowledge from climate models of less meridional thermal gradient in the Cretaceous than today, extensive equator-to-pole heat transport with intensified western boundary currents (WBCs) and deep and/or intermediate water formation at the NW high latitudes would have played an essential role for the Pacific paleoclimate, or even in the global paleoclimate. Since nearly all the late Cretaceous oceanic sediments in the NW Pacific have been subducted, sediments comprising forearc basin sequence appear to be an exclusive target to study flow history of the WBC of the NW Pacific. In addition to this geographical advantage, extremely high sedimentation rate of 30 cm/kyr potentially allows us to resolve millennial scale climate variability in the Cretaceous greenhouse, which offers unique physical data sets for climate models. Because of its proximity to land, in addition to oceanic materials, forearc sediments contain terrigenous detritus as well. Using these forearc sediments, terrestrial response to each C-cycle perturbation, which is poorly understood in comparison to the growing knowledge of the Cretaceous oceanic events including OAE2, will be analyzed.

Major goals: (1) Elucidating flow history of the North Pacific WBC as a heat carrier. Atmospheric CO_2 concentration and climate oscillation in the modern ice age are expected to be linked with a position of the Westerlies, hence, a position of northern end of the north Pacific subtropical gyre. In analogous to this idea, the flow history of WBC will be discussed in association with major chemical oceanic perturbations (i.e. OAEs), and orbital cycles climate variability. (2) Understanding continental climate evolution. Terrestrial signatures obtained with marine proxy data provide unique opportunity for study on East Asian monsoonal variability and its linkage with marine environment during the Cretaceous, which allow us to evaluate how it coupled/decoupled with oceanic C-cycle perturbations.

How to achieve the science: On the basis of outcrop- and borehole-based analyses hitherto conducted, thermally immature organic compounds (i.e. <0.4 Ro%), and extremely well preserved glassy foraminifers should be collected in abundance with minimum stratigraphic gaps (Fig. 1). We propose triplicate or even quadruplicate coring at Off-Sendai forearc basin by Joides Resolution that fulfills the condition above. Gently dipping structure (Fig. 2) of the sediments allow us to obtain a series of age transect of shallow buried sediments.

Owing to the high sedimentation rate of approximately 30 cm/kyr, complete sequences from the onset to the termination of OAE1d, and OAE2 will be explored. Lead and rag between volcanic degassing, C-cycle perturbation, negative feedback cooling, biotic turnover, etc. and their causality would be resolved in less than kyr time resolution. Paleoceanographic proxies including planktic/benthic foraminiferal δ^{13}C and δ^{18}O and TEX_{86} provide physical condition of surface/intermediate water of the NW Pacific, including putative glaciation in the greenhouse world. Terrestrial organic biomarkers including hydrogen isotope of long chain *n*-alkanes would show dry/wet fluctuation on the East Asian continent. Detailed correlation between each site can be achieved with carbon isotope stratigraphy of terrestrial organic carbon. Biostratigraphy of planktonic foraminifers and calcareous nannoplankton offers age anchoring and calibration. Radiometric ages of volcanic deposits could help establishing age model.

Our science can only be achieved with ocean drilling. Exquisitely preserved materials were found only sporadically on land because of diagenetic alteration with meteoric water. Majority of region that yields well-preserved Cretaceous materials on land is protected by national government.

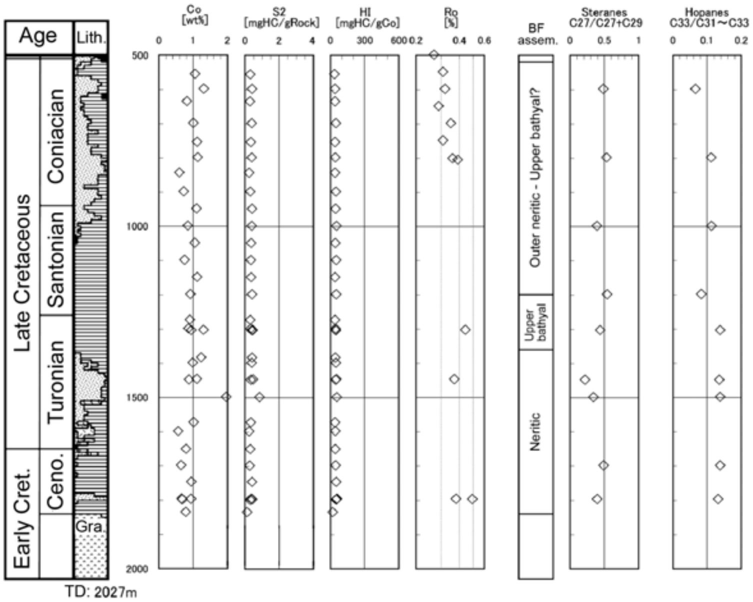


Fig. 1. Organic geochemical stratigraphy of the borehole drilled by Japan Oil, Gas and Metals National Corporation (MITI Off-Kesennuma, in Inaba et al., 2009; Jour. Jap. Ass. Per. Tech, 74, 560-572). Depth is denoted by meter below sea level. Water depth is 230m. Shadings with horizontal lines and dots in lithology represent mudstone and sandstone, respectively. BF assem.; Benthic foraminiferal assemblages. Cret.; Cretaceous. Gra.; Granite. Lith; Lithology. TD; Touchdown depth.

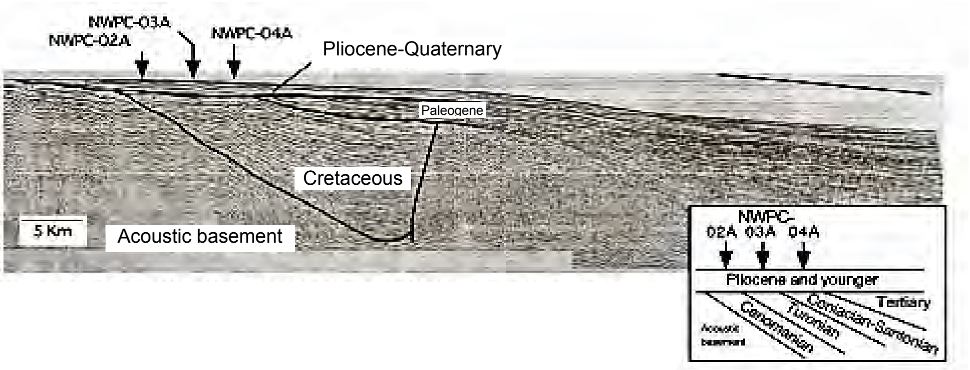


Fig. 2. Seismic profile (M86-4) of off Sendai showing a latitudinal section from West (left) to East (right) reported by Japan Oil, Gas and Metals National Corporation. NWPC-02A, 03A, and 04A represent potential sites for the non-riser drilling. Inset on bottom right shows a schematic drawing of a seismic interpretation (After IODP Pre-606 by Hasegawa et al.).

J-Anomaly Ridge

Bornemann, Junium, and Bown

Here we propose re-drilling IODP Site U1403 (39°56.5997'N, 51°48.1998'W; 4944.3 mbsl) with two holes as an APL expedition to recover a unique sequence of Late Cretaceous and older sediments from a relatively deep pelagic environment (> 2 km water depth at the Lower-Upper Cretaceous boundary) in the mid-latitudes of the western North Atlantic Ocean (J-Anomaly Ridge).

IODP Expedition 342 recovered Cretaceous sediments spanning the Aptian/Albian to the Cretaceous-Paleogene (K-Pg) boundary interval from the Southeastern Newfoundland Ridge (IODP Site U1407; 3073 mbsl). At this relatively shallow site a complete sequence, including a well-developed Cenomanian-Turonian boundary interval (OAE 2), possibly the latest Albian OAE 1d and the top of the Aptian/Albian reef that forms the basement in this region, was drilled.

IODP Site U1403 formed the deepest site of the J-Anomaly depth transect drilled in June 2012. The sediments are carbonate poor since this site was positioned below the calcite compensation depth (CCD) for most of the Cenozoic, however, around the K-Pg boundary this site moved above the CCD resulting in a pelagic carbonate-rich facies with abundant calcareous microfossils for the Cretaceous. At Site U1403 drilling was stopped after reaching the Campanian at 253 m CSF-A, but around 250 m of older sediments lie below this on top of a seismic reflector representing the top of the a mid Cretaceous reef. Seismic reflectors also suggest an increasing thickness of the remaining (not drilled) Aptian-Albian to Campanian sediments indicating enhanced sedimentation rates compared to the rather condensed nature of the latest Cretaceous and the Cenozoic. Along the Newfoundland margin in the target area of IODP Expedition 342 Upper Cretaceous sediments can be recovered from different water depths, thus, this area has also a high potential to drill a new depth transect to reconstruct Late Cretaceous CCD fluctuations.

This APL addresses key Climate and Ocean Change and Biosphere Frontiers of the 2013-2023 IODP Science Plan, specifically Challenges 1, 4 and 7. Main scientific objectives are:

1) Providing a pelagic perspective of the Late Cretaceous, specifically of OAE2 and maybe older OAEs, in the North Atlantic.
2) Biotic and ecosystem response to a high CO_2 world during key events that can be compared to the general background variability.
3) Generating long-term climate records: SSTs, bottom water temperatures, water column gradients; proxies: TEX_{86}, alkenones; relatively shallow burial (< 500 m).
4) Reconstruction of Late Cretaceous CCD changes in the North Atlantic.
5) To better constrain the Cretaceous subsidence history of the eastern North American margin.

The Mesozoic of Southern Tethys (MOST): Moroccan Margin and Mazagan Plateau

Leckie, Martin, Poulsen, Trabucho-Alexandre, Nishi

Mesozoic strata of the southern Tethys margin have not been drilled since 1981. DSDP Legs 41, 50, and 79 recovered an uppermost Triassic through Cretaceous composite section off Morocco that records the breakup of the central Atlantic, development of Jurassic carbonate platforms, foundering of the carbonate margin, followed by the deposition of thick hemipelagic sediments during the Cretaceous and Cenozoic. The Cretaceous sections record multiple Oceanic Anoxic Events, evolution of Atlantic ocean circulation, climate change, and sea level history. We propose a depth transect of five or six sites that build off the knowledge gained by the earlier DSDP legs. Improved drilling technologies and proxy development, coupled with extensive new research on the Mesozoic, have opened new doorways of research into the greenhouse world and have identified fresh perspectives to drive investigations. Data-model integration also provides a new approach to testing hypotheses and reconstructing past environments.

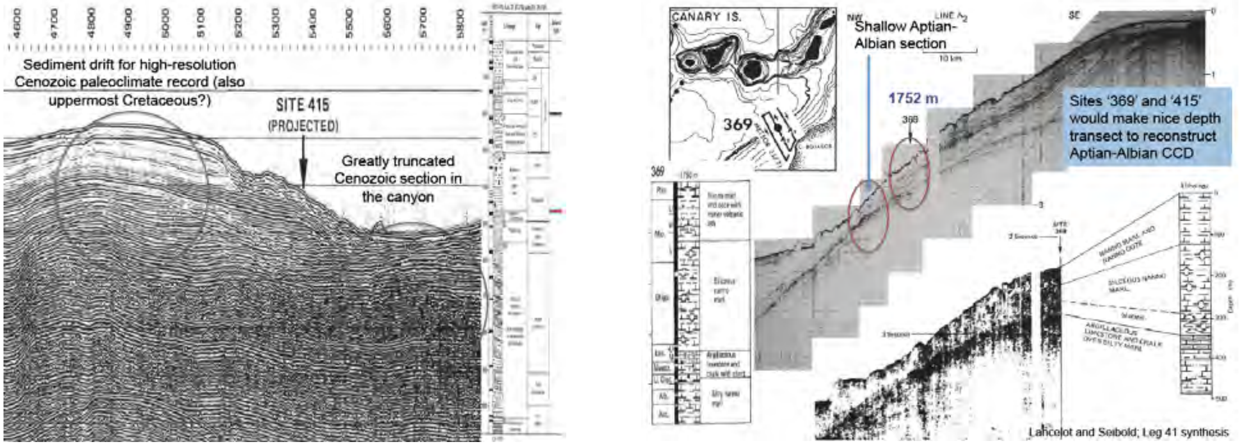
Connection with land-based sections of the Tarafaya Basin and Atlas Gulf (Agadir) in Morocco provides new opportunities to explore the Mesozoic history of coastal upwelling and productivity in the Trade Wind belt off NW Africa, define the dimensions of oxygen minima and relationship with Oceanic Anoxic Events, and reconstruct the timing and patterns of sea level change along this relatively stable continental margin to test models of the causes of sea level change during the presumed greenhouse climates of the Mesozoic. The proposed drilling will reconstruct the history of the CCD along the southern margin of Tethys and its relationship to deep-water mass sources and circulation, productivity and OAEs, ocean acidification events, and sea level change. The opening of the equatorial Atlantic gateway during the mid-Cretaceous is a likely source of subtropical deep or intermediate waters, and erosional events associated with contour currents along the MOST margin may reveal aspects of gateway development.

Cretaceous data on circulation in the eastern North Atlantic are currently limited to one Nd isotopic record from Site 367 (Leg 41) near Cape Verde (Martin et al., 2012; *EPSL*). These data suggest a connection to a Tethys or North Atlantic source in the Cenomanian, with possible evidence for introduction of warm, saline water from the Demerara region beginning in the Coniacian and peaking in the Campanian; however, this record is poorly dated and low resolution due to spot coring. Expansion of the Demerara warm, saline water mass (MacLeod et al., 2008; *Geology*; Martin et al., 2012) into this region suggests this water mass became sufficiently dense to sink to the deep sea, providing key evidence for the controversial concept of warm, saline deep water formation during a greenhouse world. In addition, the Mazagan sites fill a gap in the distribution of sites around the North Atlantic that will be important for understanding the timing of gateway connections to the South Atlantic, Tethys, and Pacific, and the flow path of intermediate and deep waters through the region. Information on the depth of the CCD derived from depth transects around the North Atlantic, including Mazagan Plateau, will also be used to test interpretations of water mass aging and therefore flow directions and water mass source regions in order to further constrain regional circulation patterns.

We propose a depth transect to address the mid-Cretaceous histories of the CCD, continental margin OMZ, OAEs, productivity, climate history, sea level, distribution of sedimentary facies, and deep water circulation related to the opening of the central Atlantic gateway. Additional targets will include the Jurassic carbonate platform, which is expected to contain the first record of the Toarcian Oceanic Anoxic Event recovered by ocean drilling, Early Cretaceous foundering of the platform, and Late Cretaceous and Cenozoic subtropical hemipelagic sediments (Figures 1 and 2).

- Two deep sites adjacent to DSDP Site 415: 1) a sediment drift where the entire tropical Cenozoic may be recovered and perhaps uppermost Cretaceous, and 2) in Agadir Canyon where Cretaceous is exposed closer to the surface than in Site 415.

- Slope site: just down slope from DSDP Site 369 the Cretaceous is exposed closer to the surface.
- Slope site: at or near Site 545 at base of Mazagan Plateau to better recover the expanded mid-Cretaceous and Jurassic section cored there.
- Upper slope site (or sites): outer edge of the Mazagan Plateau where mid-Cretaceous and older strata are shallowly buried.


Sediment drift for high-resolution Cenozoic paleoclimate record (also uppermost Cretaceous?)

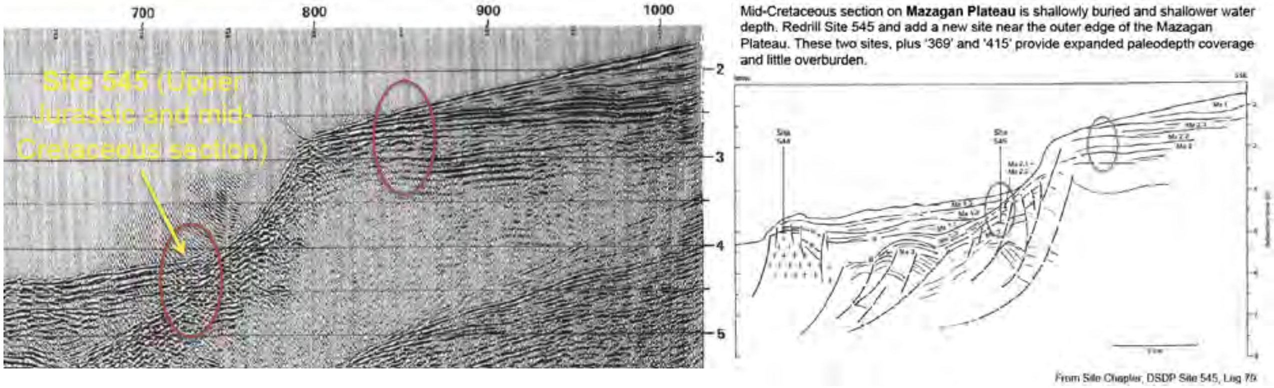
Greatly truncated Cenozoic section in the canyon

Shallow Aptian-Albian section

Sites '369' and '415' would make nice depth transect to reconstruct Aptian-Albian CCD

Lancelot and Seibold; Leg 41 synthesis

Figure 1. Proposed deep water and slope sites off Morocco. Left: Two deep-water sites adjacent to DSDP Site 415 drilled during DSDP Leg 50. Right: Slope site near DSDP Site 369 drilling during DSDP Leg 41.


Site 545 (Upper Jurassic and mid-Cretaceous section)

Mid-Cretaceous section on **Mazagan Plateau** is shallowly buried and shallower water depth. Redrill Site 545 and add a new site near the outer edge of the Mazagan Plateau. These two sites, plus '369' and '415' provide expanded paleodepth coverage and little overburden.

From Site Chapter, DSDP Site 545, Leg 79

Figure 2. Proposed sites off the Mazagan Plateau. Site 545 was drilled during DSDP Leg 79

South Atlantic Margin of Brazil (SAMBa)

Junium, Biddle, Wagner, Leckie, Koutsoukos, Pancost, Chiessi

The geologic record of the Cretaceous Ocean-Climate system provides a unique laboratory for defining the range of climate variability during Earth's warmest intervals. The evolution of the Atlantic Basin plays an integral role in Cretaceous climate as a regulator of ocean circulation and as a locus for carbon sequestration.

This project constitutes a revision of targets proposed in IODP Preproposal 801 (Junium and Biddle) that focused on the Brazil and Argentina Margins with diverse Paleogene, Cretaceous and deep biosphere targets. On the basis of this meeting we have narrowed our focus and propose an expedition that will access Mesozoic age sediments following a north-south transect of the Brazilian Margin as a part of a larger endeavor to better understand the Mesozoic of the Atlantic Basin. This drilling area is of great paleooceanographic interest because it contains record of the expansion of the South Atlantic Ocean basin, Oceanic Anoxic Events, and dissection of Equatorial and Rio Grande/Walvis Ridge gateways. The Eastern Margin of South America has been relatively underexplored in the Ocean Drilling Era and has yet to be revisited during the ODP-IODP programs.

The distribution of sites will be focused on the north and south sides of the Rio Grande/Walvis Rise ridge systems in the Campos and Pelotas Basins. Specific targets include reoccupations of DSDP Sites 356 and 515 with goals of accessing black shales and extending the record of these sites to basement that is of Aptian age. Challenges to advancing this work include the deep burial depth of known Cretaceous sequences. Accessing these records will require significant time to multiply core deep sites unless overlying sediments can, in some cases, be drilled through.

Exciting possibilities of shallowly buried Late Cretaceous in the Campos Basin suggests that there are shallow targets that will allow unprecedented access to Cretaceous sequences with the possibility of pristine preservation. For this approach to be successful we need the collaboration and imaging data provided by industry partners and the Brazilian Government.

With common interest in accessing the ancient record of black shales the paleoceaographic community finds a natural partner with deep biosphere. We are proposing that this expedition be a joint-venture between the paleoceanography and deep biosphere communities. This expands the range of science to address the *Climate and Ocean Change* and *Biosphere Frontiers* of the 2013-2023 IODP Science Plan. The proposed region is of of interest for subsurface microbiology for two broad reasons. First, subsurface microbiology of the South Atlantic is presently unexplored, and second, organic-rich horizons may fuel a unique subsurface habitat. Organic rich margins have previously been shown to contain abundant subsurface Archaea, and recent results have suggested that archaeal signatures are correlated to total organic carbon content of sediments.

Niger Transform Margin

Wagner, Head, Hubert, März, Martin, Flögel, Hofmann, Biddle, Junium, Owens, Sepulveda

The South Atlantic basin acted as a primary site of carbon production and burial throughout large parts of the early and mid-Cretaceous, manifested by prolific petroleum systems along the conjugate continental margins (Cameron et al., 1999 and references therein) with black shale reported from marginal and central parts of the both sub-basins (Wagner et al., 2013 and references therein). Recent modeling (Flögel et al., 2011; McAnena et al., 2013) shows that the South Atlantic basin experienced a disproportionately high rate of excess carbon burial during the early to mid Cretaceous, estimated to account for ~16% of the total global carbon burial, which at that time represented only ~1% of the global ocean surface. For comparison, the Southern Ocean and the combined North Atlantic and the eastern Tethys region, comprising 4% and 12% of the global ocean area, added another ~19% and ~13 % to the global burial in combination, emphasizing the crucial role of the young evolving ocean basins that developed in the wake of Pangaea break-up.

The South Atlantic sub-basin on both sides of of the Rio Grande-Walvis Ridge remained particularly prone to ocean anoxia and carbon burial until tectonic opening progressively separated the two ridge systems in the subtropics and the connection between Africa and S America in the tropics, changing large scale ocean circulation and ultimately leading to more homogenous conditions across both Atlantic basins with termination of widespread black shale formation once the Equatorial Gateway was sufficiently established in the upper Cretaceous (e.g., Wagner and Pletsch, 1999).

This proposal identifies the **Niger Transform Margin (NTM)** as a strategic region for drilling where major contributions will be made to target central questions identified in the IODP Future Science plan, including ‘climate systems and elevated CO2’, ‘regional patterns of precipitation’, ‘resilience of the ocean to chemical perturbations’, and ‘deep biosphere’.

This proposal addresses core aspects of earth-ocean history and deep biosphere, while at the same time directly linking with other proposals aiming to drill Cretaceous sediments from the Rio Grande Rise off Brazil (SAMBa, Junium et al.) and the Mazagan Plateau off NW Africa (Leckie et al.).

The NTM is a promising drilling target for a wide range of reasons, including:

- Cretaceous strata in the NTM are buried as deep as 1000 m in the subsurface with thicknesses of a few hundreds meters, generally expanding towards distal marine settings. This configuration makes the region a valuable drilling target, enabling continuous marine sediment sections and active processes within them to be studied across a spectrum of thermal maturity, which will be integral to studies of deep biosphere.
- The NTM is one of the most prolific petroleum system worldwide, ranking among the top ten producers at the global scale. It is actively charged from expanded Cretaceous source rocks covering large areas of the eastern equatorial Atlantic region, some of which have been drilled before (e.g. Leg 159) generating fundamentally new understanding of how the tropical Cretaceous Ocean acted as a biogeochemical hotspot that closely responded to environmental change at geological to sub-orbital time scales, closely linked to the evolution of the Equatorial Atlantic Gateway.
- The unique geologic boundary conditions of the NTM, with low thermal gradients (<19°C per km) created by continuous rapid burial since the early Cretaceous, have generated a strongly compartmentalized (stacked pay) system that is characterized by high pressure but low temperature. These rare conditions create very steep compositional gradients at regional and sub-reservoir scales. While these remain unconstrained, they are probably indicative of intensive and large-scale carbon cycling via subsurface microbial activity (e.g., Morono et al 2012; Røy et al 2012), suggesting potentially novel deep biosphere communities could be metabolizing this pool of buried carbon.

Given the absence of large non-HC gas (CO_2 and H_2S) accumulation, the fate of the mineralized carbon in the NPS is poorly understood and remains contested.

The central scientific objectives to be addressed at the NTM are:

- To recover expanded and continuous thermally immature sediment sections from the NTM to reconstruct the opening history of the Cretaceous Equatorial Gateway, ideally complementing earlier work from the semi-restricted Deep Ivory Basin (Leg 159, e.g. Wagner and Pletsch, 1999; Wagner 2002). Large uncertainties still remain to be addressed, in particular about the exact timing of surface, intermediate and deep water exchange between both Atlantic basins that can be addressed with water mass tracers, including Nd isotopes (MacLeod et al., 2008; Robinson et al., 2010; Martin et al., 2012; Robinson and Vance, 2012).
- To provide unique high resolution records of paleo-monsoonal forcing in a core tropical setting demonstrating the highly dynamic processes and feedbacks that linked tropical hydrology, land-ocean coupling, marine biogeochemical cycling including ocean anoxia, and marine ecosystems in response to orbital forcing along gradually changing levels of past greenhouse condition.
- To study active microbiological and geochemical processes, microbial reaction kinetics, the spatial distribution of microorganisms (e.g., Kallmeyer et al., 2012), and the hydraulics of effective nutrient transport in the deep subsurface. One overarching goal is to constrain the petroleum deep biosphere system end-members substrates, i.e. source and reservoir vs fluids by drilling immature Cretaceous/Tertiary successions in the shallow offshore area to obtain source/reservoir/fluid (non HC's) reference calibration data as one critical end member. The later means to drill outside of the working HC system.

Drilling strategy

- The drilling strategy will be to double/triple core using APC/XCB to refusal. Recovering Cretaceous sections at the NTM will require deep drilling given subsurface depths of the targeted section below 1000 m. This drilling strategy will require limiting the number of drill sites, probably 2-3, however will build on excellent data and a comprehensive understanding of subsurface distribution of Cretaceous and younger strata from 50 years of intense petroleum exploration, continuously moving seaward into deeper waters.

References

Cameron, N., Bate, R., Clure, V. (1999), The Oil and Gas Habitat of the South Atlantic. The Geological Society of London, London, Special Publication 153.

Flögel, S., Wallmann, K., Poulsen, C.J., Zhou, J., Oschlies, A., Voigt, S., Kuhnt, W., 2011. Simulating the biogeochemical effects of volcanic CO_2 degassing on the oxygen-state of the deep ocean during the Cenomanian/Turonian Anoxic Event (OAE2). Earth and Planetary Letters 305, 371-384.

Kallmeyer, J., Pockalny, R., Adhikare, R.R., Smith, D.C. & D'Hondt, S., Global distribution of microbial abundance and biomass in subseafloor sediment. *PNAS*, **109**, 16213-16216 (2012)

McAnena, A., Flögel, S., Hofmann, P., Herrle, J.O., Griesand, A., Pross, J., Talbot, H.M., Rethemeyer, J., Wallmann, K., Wagner, T., 2013. Atlantic cooling associated with marine biotic crisis during the mid-Cretaceous period. Nature Geosciences, in press.

MacLeod, K.G., Martin, E.E., & Blair, S.W., Nd isotopic excursion across Cretaceous oceanic anoxic event 2 (Cenomanian–Turonian) in the tropical North Atlantic. *Geology,* **36***,* 811-814 (2008)

Martin, E.E., MacLeod, K.G., Jiménez Berrocoso, A., & Bourbon, E., Water mass circulation on Demerara Rise during the Late Cretaceous based on Nd isotopes. *Earth Planet. Sci. Lett.,* **327-328**, 111-120 (2012)

Morono, Y., Terada, T., Nishizawa, M., Ito, M., Hillion, F., Takahata, N., Sano, Y. & Inagaki, F., Carbone and nitrogen assimilation in deep subseafloor microbial cells, *PNAS*, **108**, 18295-18300 (2011)

Murphy, D.P., & Thomas, D.J., , Cretaceous deep-water formation in the Indian sector of the Southern Ocean, *Paleoceanography*, **27**, doi:10.1029/2011PA002198 (2012)

Robinson, S.A., Murphy, D.P., Vance, D., & Thomas, D.J., Formation of 'Southern Component Water' in the Late Cretaceous: evidence from Nd-isotopes. *Geology,* **38***,* 871-874 (2010)

Robinson, S.A., & Vance, D., Widespread and synchronous change in deep-ocean circulation in the North and South Atlantic during the Late Cretaceous, *Paleoceanography*, **27**, PA1102, doi:10.1029/2011PA002240 (2012)

Røy, H. Kallmeyer, J., Adhikari, R.R., Pockalny, R., Jørgensen, B.B. & D'Hondt, S. Aerobic Microbial Respiration in 86-Million-Year-Old Deep-Sea Red Clay, *Science*, **336**, 922-925 (2012)

Wagner, T., Pletsch, T., 1999. Tectono-sedimentary controls on Cretaceous black shale deposition along the opening Equatorial Atlantic Gateway (ODP Leg 159), in: Cameron, N., Bate, R., Clure, V. (Eds.), The Oil and Gas Habitat of the South Atlantic. The Geological Society of London, London, pp. 241-265.

Wagner, T., 2002. Late Cretaceous to early Quaternary organic sedimentation in the eastern equatorial Atlantic. Palaeogeography, Palaeoclimatology, Palaeoecology 179, 113–147.

Wagner, T., Hofmann, P., Flögel, S., 2013. Marine black shale deposition and Hadley Cell dynamics: A conceptual framework for the Cretaceous Atlantic Ocean. Marine Petroleum Geology 43, 222-238.

The Cretaceous Arctic

Tarduno, Flögel, Brassell, Fillippelli, Holbourn, Jarvis, Kuhnt, Macleod, Naafs, Oakes, Poulsen, Sepulveda

Motivation

Introduction The northern polar region is highly sensitive to climate variability and, for this reason, can serve as a dipstick for global climate change. The modern Arctic region is undergoing rapid change primarily in response to anthropogenic forcing, making the future of the Arctic a fundamental concern. Our knowledge of the sensitivity of the Arctic region to elevated CO_2 concentrations, particularly to those projected for the end of this century is limited to what we have learned from paleoclimate records. The high atmospheric CO_2 levels found in the Cretaceous provide a case study for understanding the sensitivity of the northern polar region under greenhouse conditions, and its linkages to global ocean and atmospheric circulation. At present, only one marine temperature record from the Cretaceous Arctic exists (Jenkyns et al. 2004). However, it is restricted to the Maastrichtian, based on a single proxy, and its extrapolation to the mid Cretaceous remains debated. Therefore, there is a dire need for additional data and an extension of the record back in time to the thermal maximum.

Predictions of future climate change rely upon earth system models (ESM). Here, paleoclimate records are crucial to validating these models. Climate proxies from the Cretaceous provide evidence of extreme polar warmth and a reduced equator-to-pole temperature gradient (e.g., Wolfe and Upchurch, 1987; Jenkyns et al. 2004; Tarduno et al., 1998). ESMs of the Cretaceous, however, fail to reproduce these thermal features without invoking greenhouse gas concentrations substantially higher than proxy estimates (Bice et al., 2002; Poulsen, 2004; Spicer et al., 2010). However, existing proxy data are sparse and based mainly on terrestrial data. Furthermore, it is unclear whether the mismatch is due to inadequacies of the models, or uncertainties and limitations of the proxy data. Additional proxy data from the Arctic are critical to resolve this issue.

The hydrological cycle is expected to intensify in a warmer world, but the magnitude and spatial changes in net precipitation are highly uncertain. The most direct evidence for changes in the Cretaceous hydrologic cycle comes from isotopic analyses of paleosol carbonates. Cretaceous equator-to-pole precipitation $\delta^{18}O$ gradients are steeper than those for the modern climate system (Ludvigson et al., 1998; Ufnar et al., 2002; Suarez et al., 2011), an observation that has been interpreted to indicate intensified poleward transport of moisture but is at odds with paleoclimate model simulations (Poulsen et al., 2008). Proxy data from the Arctic can provide important constraints on the origin and transport of moisture to the high latitudes.

How important is the Arctic region to global climate? In addition to resolving the thermal state of the Cretaceous Arctic, the circulation of the Arctic basin, its stratification, and its connectivity to the global ocean are open questions that can be investigated through ocean drilling. Climate modeling, for example, suggests that gateways between the Arctic and Pacific Ocean are critical to driving high-latitude climate variability (Poulsen and Zhou, 2013). The timing of the opening/closing of various gateways with the Arctic and their climatic consequences are uncertain, but may be identified through paleoceanographic records.

What role did the Arctic Ocean play in global biogeochemical cycling, both on long timescales and in response to shorter time scale perturbations during OAEs? It is uncertain whether the Arctic acted as a passive or active component of global biogeochemical cycles, and also how the various components of the Arctic ecosystem responded to such perturbations and how they were expressed in the basin.

Locations for Study

While there are a number of sites that merit exploration, we concentrate of two areas were prior work indicates drilling could result in significant advances: the Colville River of northern Alaska and the Alpha-Mendeleev Ridge of the Amerasian Basin. The former would be a continental scientific drilling object, whereas the latter falls under the objectives of IODP. Details on potential drilling in these areas are contained as separate sections of this report. Below, we outline the general approaches (including use of proxies and modeling) common to both projects, that address the special challenges and opportunities of Cretaceous Arctic sites.

Approach & Objectives

We intend to take a multi-disciplinary approach by combining biogeochemical and numeric modeling tools. An ideal strategy is to use a broad spectrum of proxies: however, in the Arctic this strategy is constrained by the absence of carbonate. Below we summarize the range of approaches that we propose to employ.

Temperature Proxies

Temperature estimates can be provided by analysis of microfossil fish debris (teeth, scales, and bone fragments; MacLeod, 2012) and the TEX_{86} index based on the distribution of archaeal membrane lipids (Schouten et al., 2002). TEX_{86} has proven to be a valuable tool in temperature reconstructions for the Cretaceous (e.g., Schouten et al., 2003; Dumitrescu et al., 2006; Forster et al., 2007) and was successfully applied to Maastrichtian samples from the Fletcher Ice Island cores (Jenkyns et al., 2004), the only TEX_{86} results published from the Cretaceous Arctic. Confidence in TEX_{86} values will be heightened if redox and nutrient conditions can be constrained. Thus, this proxy will be evaluated in the context of the full range of GDGTs and other biomarker constituents to assess other environmental controls on organic proxies. The same cores contain fish debris (e.g., Clark et al., 1986), which can provide an independent estimate of temperature modified by the isotopic composition of ambient waters. Oxygen isotopic ratios in phosphates can be used as a thermometer with the same temperature response as carbonate-$\delta^{18}O$ thermometers, although analytical error is 0.3‰ (approximately ±1.5°C) and the water depth range provided by fish debris represents an integrated signal given that fish are more mobile than calcareous plankton. The proxy has been successfully applied for the Cretaceous (Pucéat, 2007) and analyses can be made on small samples (300 - 500 μg), quickly, cheaply, and accurately to provide high-resolution records. Tooth enamel and enamaloid scales are resistant to diagenetic alteration and would be preferred targets both for paleotemperature and paleoecological studies (MacLeod, 2012 and references therein). Use of these proxies will be complemented by micropaleontological and palynological analyses including diatoms and dinocysts (e.g., Byers et al., 1986; Sluijs et al., 2006; Davies et al., 2009).

Hydrological Indicators

Changes in the hydrological cycle (continental precipitation and sea-surface salinity) will be evaluated using compound-specific stable hydrogen isotopes in aquatic- and terrestrial-derived biomarkers (e.g., Pagani et al., 2006), which can be preserved in Cretaceous sequences (Pedentchouk et al., 2006). This will be complemented with plant- and soil-derived biomarkers, as well as palynological (spore, pollen, dinocyst) records to constrain changes in terrestrial and freshwater input in response to varying continental runoff (e.g., Brinkhuis et al., 2006; Pagani et al., 2006). Also, in comparison with organic and phosphate-$\delta^{18}O$ paleotemperature estimates, we expect to provide constraints on the isotopic composition of seawater.

Sedimentological/Geochemical Measures of Ocean/Atmosphere Circulation

Constraining the source area(s) of terrigenous material via composition, geochemistry and mineralogy and their variation over time is an important way to determine major marine circulation patterns. Additionally, careful analysis of size-fractionated terrigenous material extracted from bulk sediment has proven critical to determining wind stress fields and source region aridity. Newer techniques utilizing Nd and Pb isotopic fingerprinting of dust-sourced terrigenous material coupled with source reconstructions of marine-transported detrital material, can shed light on the interplay between atmospheric and ocean circulation patterns and their variability through time.

^{143}Nd/^{144}Nd ratios in fish debris with parallel measurements of detrital material can provide relatively direct evidence on sources waters in the Arctic including potential connectivity to other basins. Nd isotopes are a semi-conservative water mass tracer also influenced by weathering inputs, particle exchange in the water column, and boundary exchange recorded by fish debris (e.g., Goldstein and Hemming, 2003). Through the Late Cretaceous, ^{143}Nd/^{144}Nd ratios are consistently high whereas in the northern Atlantic values decrease from moderately to markedly low (e.g., Martin et al., 2012; Murphy and Thomas, 2012). Detrital values and sedimentological observation (e.g., the presence of ashes) will provide constraints on local inputs.

Ecological & Environmental Proxies

In the absence of carbonates, lipid biomarkers can be used to track changes in eukaryotic (algae) and prokaryotic (cyanobacteria, methanotrophic bacteria, green sulfur bacteria, and archaea) plankton ecology and productivity (e.g., Boon et al., 1979; Summons and Powell, 1987; Summons et al., 1999; Kuypers et al., 2001). Variations in the occurrence and distributions of biomarkers record biotic assemblages and changes in environmental conditions such as nutrient availability and redox conditions. The presence of organic-walled and siliceous microfossils can provide independent, complementary evidence for plankton communities and their response to environmental perturbations.

The combined use of organic and inorganic redox indicators will allow us to track changes in water column stratification and redox potential in response to greenhouse conditions in the Arctic Ocean. Biomarkers provide measures of photic zone euxinia (Summons and Powell, 1987), redox change at the sediment-water interface (e.g., Peters and Moldowan, 1991) and water column stratification (gammacerane index; Sinninghe Damsté et al., 1995). Similarly, inorganic geochemical tools provide evidence for redox conditions via framboidal pyrite size distribution, iron speciation, trace-metal concentrations (e.g., Mo, V, U), and their stable isotope systems (e.g., Brumsack, 2006; Lyons et al., 2009). Also, the stable isotopes of nitrogen and sulfur record changes in their biogeochemical cycles in response to varying oxygenation of the water column (e.g., Rau et al., 1987; Wilkin and Arthur, 2001).

Stratigraphic Controls

Use of standard biostratigraphic tools can be complemented by carbon isotope profiles for organic matter excursions, which offer a basis for stratigraphic correlations based on the evidence of systematic variations, especially major excursions in d^{13}C$_{org}$ (e.g., Erbacher et al., 2005; Jarvis et al., 2011). Palynological-based stratigraphy (dinocysts, pollen, spores) will be critical in constraining chemostratigraphy, in combination with magnetostratigraphy for the Campanian-Maastrichtian.

ESM modeling

Earth system modeling provides a tool for both testing the sensitivity of the climate system to changes in forcing and boundary conditions, and for evaluating the feasibility of hypotheses based on proxy records (e.g., Poulsen et al., 2007, 2013: Zhou et al., 2008; Flögel et al., 2011a,b). Climate model experiments will be developed to evaluate the sensitivity of the Arctic climate (e.g. temperature) and atmospheric and oceanic circulation to new and/or uncertain boundary conditions (paleogeography, CO_2, CH_4, orbital forcing). In particular, earth system model experiments will be constructed to determine how details of gateway connections between the Arctic and adjacent basins affect both Arctic and global climate, and for constraining potential climate mechanisms.

References

Bice, K.L., Norris, R.D., 2002. Possible atmospheric CO_2 extremes of the Middle Cretaceous (late Albian-Turonian). Paleoceanography, 17,doi:10.1029/2002PA000778.

Boon, J., Rijpstra, W.I., De Lange, F., De Leeuw, J.W., 1979. Black Sea sterol – a molecular fossil for dinoflagellate blooms. Nature 277, 125-127.

Brinkhuis, H., et al., 2006. Episodic fresh surface waters in the Eocene Arctic Ocean. Nature 441, 606-609.

Brumsack, H.J., 2006. The trace metal content of recent organic carbon-rich sediments: Implications for Cretaceous black shale formation. Palaeogeography, Palaeoclimatology, Palaeoecology 232, 344–361.

Clark, D. L., Byers, C. W., Pratt, L. M., 1986, Cretaceous black mud from the central Arctic Ocean. Paleoceanography 1, 265–271.

Davies, A., Kemp, A.E.S., Pike, J., 2009. Late Cretaceous seasonal ocean variability from the Arctic. Nature 460, 254-258.

Dumitrescu, M., Brassell, S.C., Schouten, S., Hopmans, E.C., Sinninghe Damsté, J.S., 2006. Instability in tropical Pacific sea-surface temperature during the early Aptian. Geology 34, 833-836.

Erbacher, J., Friedrich, O., Wilson, PA, Birch, H., Mutterlose, J., 2005. Stable organic carbon isotope stratigraphy across Oceanic Anoxic Event 2 of Demerara Rise, western tropical Atlantic. Geochemistry, Geophysics, Geosystems 6, doi 10.1029/2004GC000850.

Flögel, S., Wallmann, K., Poulsen, C. J., Zhou, J., Oschlies, A., Voigt, S., & Kuhnt, W., 2011a, Simulating the biogeochemical effects of volcanic CO2 degassing on the oxygen-state of the deep ocean during the Cenomanian/Turonian Anoxic Event (OAE2). Earth and Planetary Science Letters, 1–14. doi:10.1016/j.epsl.2011.03.018

Flögel, S., Wallmann, K., & Kuhnt, W., 2011b, Cool episodes in the Cretaceous — Exploring the effects of physical forcings on Antarctic snow accumulation. Earth and Planetary Science Letters, 307(3-4), 279–288. doi:10.1016/j.epsl.2011.04.024

Forster, A., Schouten, S., Moriya, K., Wilson, P. A., Sinninghe Damsté, J.S., 2007. Tropical warming and intermittent cooling during the Cenomanian/Turonian Oceanic Anoxic Event 2: Sea surface temperature records from the equatorial Atlantic. Paleoceanography, 22, PA1219.

Goldstein, S.L., Hemming, S.H., 2003. Long lived isotopic tracers in oceanography, paleoceanography, and ice sheet dynamics. In: Elderfield, H. (Ed.), Treatise on Geochemistry. Elsevier, New York, 453–489.

Jarvis, I., Lignum, J. S., Gröcke, D. R., Jenkyns, H. C., Pearce, M. A., 2011. Black shale deposition, atmospheric CO2 drawdown, and cooling during the Cenomanian-Turonian Oceanic Anoxic Event. Paleoceanography 26, PA3201, doi:10.1029/2010PA002081.

Jenkyns, H.C., Forster, A., Schouten, S., Sinninghe Damsté, J.S., 2004. High temperatures in the Late Cretaceous Arctic Ocean. Nature, 432, 888-892.

Kuhn, G., Diekmann, B., 2002. Late Quaternary variability of ocean circulation in the southeastern South Atlantic inferred from the terrigenous sediment record of a drift deposit in the southern Cape Basin (ODP Site 1089). Palaeogeography, Palaeoclimatology, Palaeoecology 182, 287-303.

Kuypers, M.M.M., Blokker, P., Erbacher, J., Kinkel, H., Pancost, R.D., Schouten, S., Sinninghe Damsté, J.S., 2001. Massive expansion of marine archaea during a mid-Cretaceous oceanic anoxic event. Science 293, 92–94.

Ludvigson, G.A., González, L.A., Metzger, R.A., Witzke, B.J., Brenner, R.L., Murillo, A.P., White, T.S.,1998. Meteoric sphaerosiderite lines and their use for paleohydrology and paleoclimatology. Geology 26,1039-1042.

Lyons, T., et al., 2009. Tracking Euxinia in the Ancient Ocean: A Multiproxy Perspective and Proterozoic Case Study. Annual Reviews Earth Planetary Sciences 37, 507-534.

MacLeod, K.G., 2012. Conodonts and the paleoclimatological and paleoecological applications of phosphate d^{18}O measurements, *in* Ivany, L.C. and Huber, B.T. (eds) Reconstructing Earth's Deep-Time Climate – The State of the Art in 2012. Paleontological Society Papers, 18, 69-84.

Martin, E.E., MacLeod, K.G., Jiménez Berrocoso, Á., Bourbon, E., 2012. Water Mass Circulation on Demerara Rise During the Late Cretaceous Based on Nd Isotopes. Earth and Planetary Science Letters, 327-328, 111–120.

Murphy, D.P., Thomas, D.J., 2012, Cretaceous deep-water formation in the Indian sector of the Southern Ocean, Paleoceanography, 27, PA1211, doi:10.1029/2011PA002198.

Pagani, M., et al., 2006. Arctic hydrology during global warming at the Palaeocene/Eocene thermal maximum. Nature 442, 671-675.

Peters, K.E., Moldowan, J.M., 1991. Effects of source, thermal maturity and biodegradation on the distribution and isomerization of homohopanes in petroleum. Organic Geochemistry 17, 47–61.

Pedentchouk, N., Freeman, K., Harris, N., 2006. Different response of δD values of n-alkanes, isoprenoids, and kerogen during thermal maturation. Geochimica et Cosmochimica Acta 70, 2063 – 2072.

Poulsen, C.J., 2004. A balmy Arctic. Nature 432, 2.

Poulsen, C. J., Pollard, D., White, T.S., 2007. General circulation model simulation of the δ18O content of continental precipitation in the middle Cretaceous: a model-proxy comparison. Geology 35, 199-202.

Poulsen, C.J., Zhou, J., 2013. Sensitivity of Arctic climate variability to mean state: Insights from the Cretaceous. Journal of Climate, doi: 10.1175/JCLI-D-12-00825.1.

Pucéat, E., Donnadieu, Y., Naveau, P., Cappetta, H., Ramstein, G., Huber, B. T., Kriwet, J., 2007. Fish tooth δ^{18}O revising Late Cretaceous meridional upper ocean water temperature gradients. Geology, 35, 107-110.

Rau, G.H., Arthur, M.A., Dean, W.E., 1987. ^{15}N/^{14}N variations in Cretaceous Atlantic sedimentary sequences: implication for past changes in marine nitrogen biogeochemistry. Earth and Planetary Science Letters 82, 269–279.

Sinninghe Damsté, J.S., Kenig, F., Koopmans, M.P., Köster, J., Schouten, S., Hayes, J.M., de Leeuw, J.W., 1995. Evidence for gammacerane as an indicator of water column stratification. Geochimica et Cosmochimica Acta 59, 1895–1900.

Schouten, S., Hopmans, E., Schefuß, E., Sinninghe Damsté, J., 2002. Distributional variations in marine crenarcheotal membrane lipid: a new tool for reconstructing ancient sea water temperatures? Earth and Planetary Science Letters 204, 265-274.

Schouten, S., Hopmans, E.C., Kuypers, M.M.M., van Breugel, Y., Foster, A., Sinninghe Damsté, J.S., 2003. Extremely high sea water temperatures at low latitudes during the middle Cretaceous as revealed by archaeal membrane lipids. Geology 31, 1069-1072.

Sluijs, A., et al., 2006. Subtropical Arctic Ocean temperatures during the Palaeocene/Eocene thermal maximum. Nature 441, 610-613.

Spicer, R. A. and Herman, A. B., 2010, The late Cretaceous environment of the Arctic: A quantitative reassessment based on plant fossils. Palaeogeography, Palaeoclimatology, Palaeoecology, 295(3-4), pp.423–442.

Stancin, A.M., Gleason, J. D., Hovan, S.A., Rea, D. K., Owen, R.M., Moore, T.C., Jr., Hall, C.M., Blum, J.D., 2008. Miocene to recent eolian dust record from the southwest Pacific Ocean at 40° S latitude. Palaeogeography, Palaeoclimatology, Palaeoecology, 261, 218-233.

Suarez, M.B., González, L.A., Ludvigson, G.A., 2011. Quantification of a greenhouse hydrologic cycle from equatorial to polar latitudes: The mid-Cretaceous water bearer revisited. Palaeogeography, Palaeoclimatology, Palaeoecology 307, 301-312. doi:0.1016/palaeo.2011.05.027.

Summons, R.E., Jahnke, L.L., Hope, J.M., Logan, G.A., 1999. 2-Methylhopanoids as biomarkers for cyanobacterial oxygenic photosynthesis. Nature 400, 554–557.

Summons, R.E., Powell, T.G., 1987. Identification of aryl isoprenoids in source rocks and crude oils: biological markers for the green sulphur bacteria. Geochimica et Cosmochimica Acta 51, 557–566.

Tarduno, J.A., Brinkman, D.B., Renne, P.R., Cottrellm R.D., Scher, H., Castillo, P., 1998. Evidence for extreme climatic warmth from Late Cretaceous Arctic vertebrates. Science 282, 2241-2244.

Ufnar, D.F., González, L., Ludvigson, G.A., Brenner, R.L., Witzke, B.J., 2002. The mid-Cretaceous water-bearer: isotope mass balance quantification of the Albian hydrologic cycle. Palaeogeography, Palaeoclimatology, Palaeoecology 188, 51-71.

Wilkin and Arthur, 2001. Variations in pyrite texture, sulfur isotope composition, and iron systematics in the Black Sea: Evidence for Late Pleistocene to Holocene excursions of the O2-H2S redox transitions. Geochimica et Cosmochimica Acta, 65, 1399-1416.

Wolfe, J.A., Upchurch, G.R. Jr., 1987. Leaf assemblages acress the Cretaceous-Tertiary boundary in the Raton Basin, New Mexico and Colorado. Proceedings of the National Academy of Science USA 15, 5096-5100.

Zhou, J., Poulsen, C.J., Pollard, D., White, T.S., 2008. Simulation of modern and middle Cretaceous marine δ18O with an ocean-atmosphere GCM. Paleoceanography, doi:10.1029/2008PA001596.

Ziegler, C.L., Murray, R.W., Hovan, S.A., Rea, D.K., 2007. Resolving eolian, volcanogenic, and authigenic components in pelagic sediment from the Pacific Ocean. Earth and Planetary Science Letters 254, 416-432.

Alpha-Mendeleev Ridge

Tarduno and Bono

Note: Prior to the workshop Rudiger Stein (AWI, Bremerhaven) contacted the convenors and provided details of existing plans for site survey at this location in 2014 and the desire to submit an IODP proposal after the site survey is conducted (likely April 2015). These details were shared with the attendees at the workshop. The report below is not intended to supercede the efforts of Stein and colleagues, but hopefully to provide additional impetus and support for drilling of Cretaceous sediments in the Arctic Ocean in the next phase of IODP.

Introduction

Alpha-Mendeleev Ridge is a broad high cutting across the Amerasian Basin (Figure A1). Alpha Ridge extends from offshore Ellesmere Island of the Canadian High Arctic to its juncture with Mendeleev Ridge near the center of the basin. Mendeleev Ridge extends to the Siberian shelf.

The crust of Alpha-Mendeleev Ridge is exceptionally thick, reaching 40 km (Jackson et al., 1986), and thought to be dominantly oceanic in nature, although the inclusion of continental blocks seems likely. In the High Canadian Arctic, Late Cretaceous flood basalts occur (the Strand Fiord volcanics), and these have been proposed to be on-land representations of magmatism that formed Alpha-Mendeleev Ridge. Because of the nature of the Alpha-Mendeleev Ridge crust, and its potential association with continental flood basalts, parallels have been drawn between Arctic Cretaceous magmatism and Cretaceous oceanic plateaus of the Pacific and Indian Oceans. Collectively, the on-land and offshore volcanics have been considered to represent a High Arctic Large Igneous Province (Tarduno, 1996). Although the “High Arctic Igneous Province” term has been applied by subsequent workers to encompass all Cretaceous volcanism spanning the earliest Cretaceous to the Paleogene, in the context of future drilling we consider the original definition of the province, restricted to Alpha-Mendeleev Ridge and volcanics on the adjacent Canadian Arctic Islands.

The basement age of Alpha-Mendeleev Ridge is not well known and hence a major drilling objective. A determination of basement age would provide key insight into the tectonic evolution of the Amerasian basin as a whole. This history, of course, also provides the boundary conditions for understanding the Cretaceous paleoceanography of the Arctic Ocean. For example, were episodes of fresh surface waters common in the Cretaceous, as observed in the Eocene (Brinhuis et al., 2006)? Were parts of Alpha-Mendeleev Ridge subareal (Vandermark et al., 2009; Bruvoll et al., 2012) dividing the Cretaceous Amerasian basin into two basins?

While we do not know the exact basement age of Alpha-Mendeleev Ridge, there are several lines of evidence that provide clues. Marine magnetic anomalies have been identified in part of the Amerasian basin (*i.e.* the Canada Basin), and these are thought to reflect the M-sequence and hence early Cretaceous spreading. These anomalies are lacking across and adjacent to Alpha-Mendeleev Ridge so it is thought that Alpha-Mendeleev Ridge formed sometime during the ca 37 million-year-long Cretaceous Normal Superchron (~120-83 Ma). A sedimentary core obtained from ice island T-3 in1969 yielded sediments as old as Campanian in age. Basalt obtained from the base of a core collected in 1998 has an apparent Ar-Ar age of 82 Ma, but this result has been reported only in abstract form and could represent either a late-stage volcanic event or alteration. A high-resolution Ar-Ar radiometric age of 95 Ma has been reported from continental flood basalts on Axel Heiberg Island (Tarduno et al., 1998).

Late Cretaceous sedimentary targets

If Alpha-Mendeleev Ridge magmatism is part of the same magmatic event that created the adjacent Strand Fiord volcanics, we can expect that sediments on the Ridge may extend through the Turonian and into the Cenomanian. Herein, we outline 3 specific sedimentary targets on sites atop the Ridge:

- *OAE2*. This would represent a truly oceanic north polar representation of this oceanic event, complementing continental drilling proposed for the Colville River, northern Alaska.

- *Turonian hyper-warmth*. Several lines of evidence point to extreme climate warmth in the Turonian, including TEX_{86} analyses of material from ice island cores (Jenkyns et al., 2004) and global analysis of oxygen isotope records (Huber et al., 2002). Arguably the most dramatic evidence of this warmth comes from a diverse assemblage of vertebrates from the Canadian Arctic Islands that include large body crocodile-like champsosaurs (Vandemark et al., 2007). This assemblage implies a minimum mean annual temperature of 14 degrees C at 71 degrees N (Tarduno et al., 1998; 2002), a value that is not easily achieved by Cretaceous modeling efforts.

-*OAE3*. The sedimentary sequence should represent the Coniacian/Santonian anoxic event.

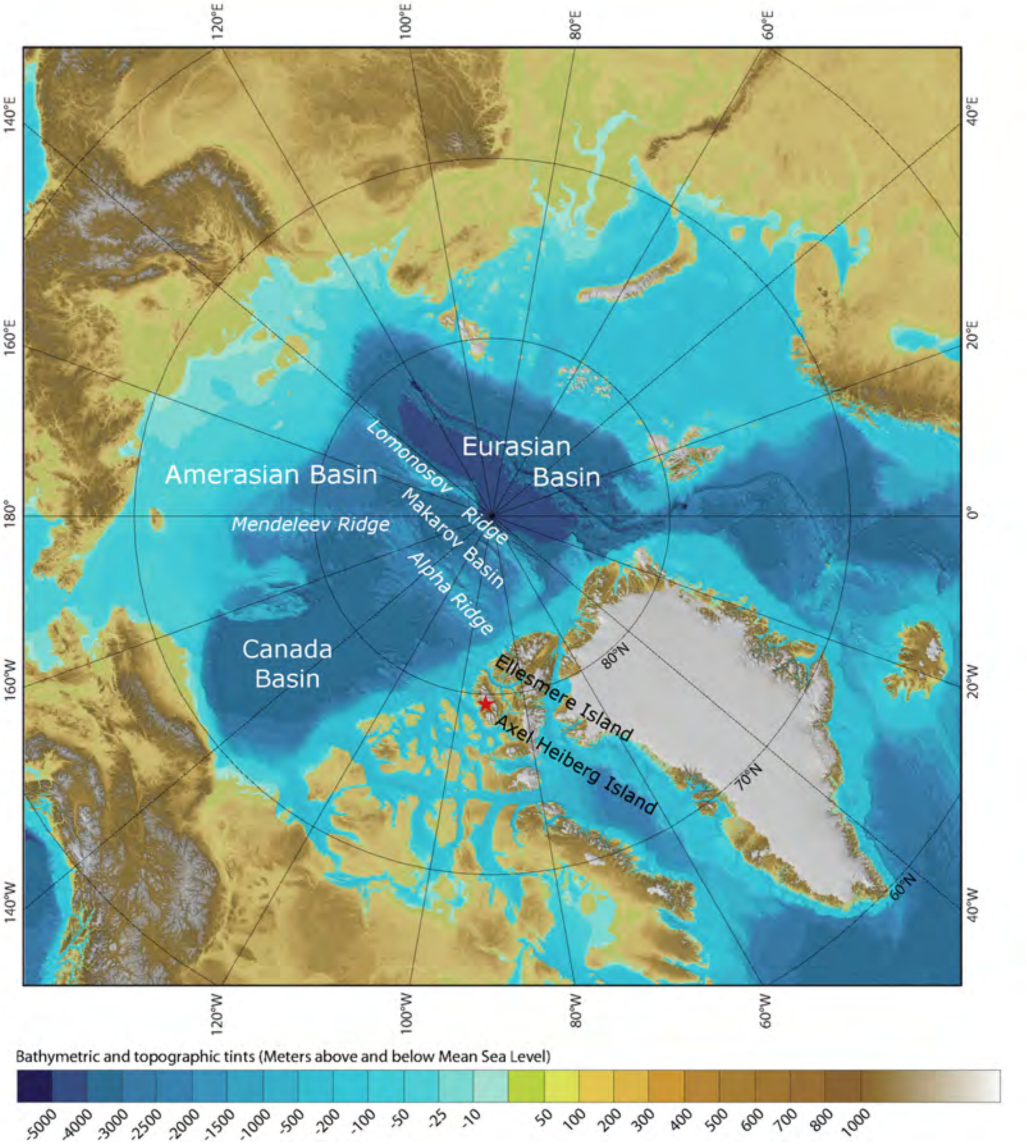


Figure A1. Alpha-Mendeleev Ridge of the Amerasian Basin. Red star highlights Late Cretaceous vertebrate locality with large bodied champsosaurs that suggests a minimum mean annual temperature of 14 degrees C.

Basement targets

Basement penetration should be 100 to 200 m at each site to obtain a sufficient number of fresh flows to assess the age and geochemical character of the Ridge.

Drilling Strategy

Drilling of Alpha-Mendeleev Ridge has been discussed at several workshops, most notably an IODP work focused on Arctic drilling (Coakley and Stein, 2009). During that conference, a drilling strategy was discussed that paralleled studies of large igneous provinces in the western Pacific Ocean. Specifically, because Alpha-Mendeleev Ridge represents such a large feature, it is necessary to obtain a first-order understanding of basement ages and sedimentary cover through drilling transects. This would be comprised of a transect along the crest of the ridge, covering as much expanse as is feasible, coupled with a perpendicular depth transect, extending from the Ridge crest to the Canada Basin floor. The latter has the potential to recover sediments older than those found on the Ridge crest.

Feasibility

Although Arctic-ice melting has now made parts of the western Arctic feasible targets with the *JOIDES Resolution*, drilling Alpha-Mendeleev Ridge is still viewed as a Mission Specific Platform endeavor. The feasibility of this approach (using, for example, a technical drilling barge or vessel, and several icebreakers) was demonstrated with tremendous success by Expedition 302 (Moran et al., 2006 Backman et al., 2006) drilling of Lomonosov Ridge.

Site Survey Data

Some site survey data exists (e.g. Jokat, 2003; Lebedeva-Ivanova, 2006; Dove et al., 2010; Bruvoll et al., 2012) (Figure A2) and efforts are underway to collect additional data. Sediment thickness of the Ridge varies between approximately 500 and 1200 m.

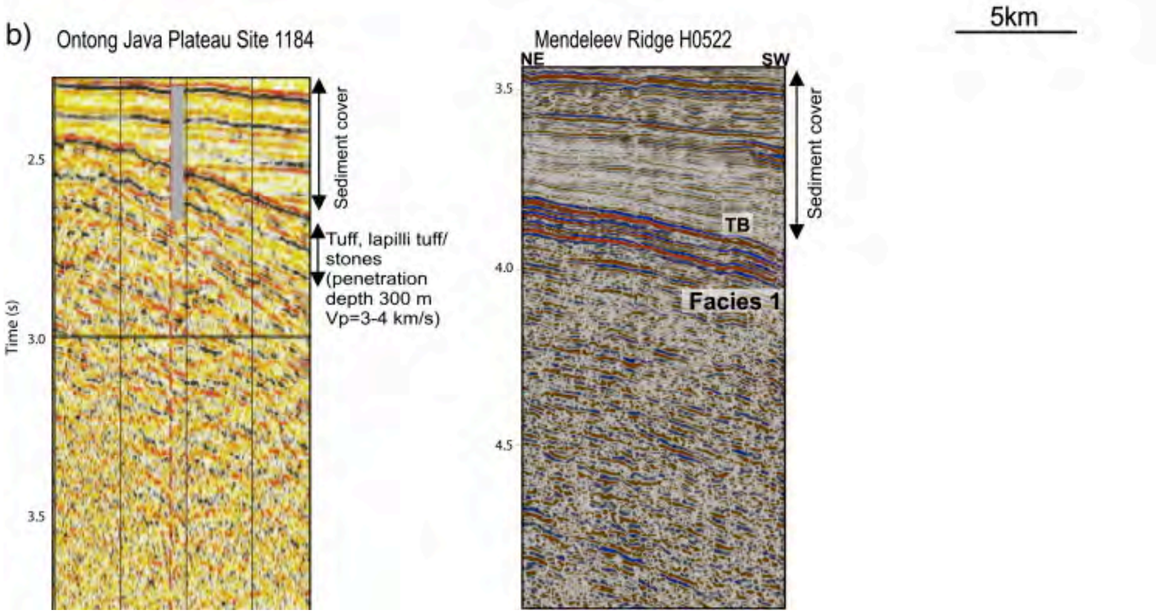


Figure A2. Comparison of seismic character of Mendeleev Ridge and Ontong Java Plateau from Bruvoll et al. (2012).

References

Backman, J., Moran, K., Mayer, L.A., McInroy, D.B., and the Expedition 302 Scientists, 2006. Proceedings IODP, 302, College Station TX (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.302.104.2006.

Bruvoll, V., Y. Kristoffersen, B.J. Coakley, J.R. Hopper, S. Planke and A. Kandilarov, The nature of the acoustic basement on Mendeleev and northwestern Alpha ridges, Arctic Ocean, Tectonophysics, 514-517, 123-145, 2012.

Coakley, B., and R. Stein, 2009, Investigating Arctic Ocean History: From Speculation to Reality, Eos Trans. AGU, 90(13), 112-113, doi: 10.1029/2009EO130005.

Dove, D., Coakley, B., Hopper, J., Kristoffersen, Y., the Healy 2005–03 Geophysics Team, 2010. Bathymetry, controlled source seismic, and gravity observations of the Mendeleev Ridge; implications for ridge structure, origin, and regional tectonics. Journal of Geophysical Research 183, 481–502.

Huber, B.T., R.D. Norris, and K.G. MacLeod, Deep-sea paleotemperature record of extreme warmth during the Cretaceous, Geology, 30, 123-126, 2002.

Jackson, H.R., D.A. Forsyth, and G.L. Johnson, 1986, Oceanic affinities of the Alpha Ridge, Arctic Ocean, Marine Geology, 73, 237261, 1986.

Jenkyns, H.C., A. Forster, A. Schouten and J.S. Sinninghe Damsté, High temperatures in the Late Cretaceous Arctic Ocean, 432, 888-892, 2004.

Jokat, W., Seismic investigations along the western sector of Alpha Ridge, Central Arctic ocean, Geophysi. J. Inter., 152, 185201, 2003

Lebedeva-Ivanova, N.N., Y.Y. Zamansky, A.E. Langinen, and M.Y. Sorokin, Seismic profiling across the Mendeleev Ridge at 82 degrees N: evidence of continental crust, Geophys. J. Inter.,165, 527544, 2006.

Moran, K., Backman, J., Brinkhuis, H., Clemens, S.C., Cronin, T., Dickens, G.R., Eynaud, F., Gattacceca, J., Jakobsson, M., Jordan, R.W., Kaminski, M., King, J., Koc, N., Krylov, A., Martinez, N., Matthiessen, J., McInroy, D., Moore, T.C., Onodera, J., O'Regan, A.M., Pälike, H., Rea, B., Rio, D., Sakamoto, T., Smith, D.C., Stein, R., St. John, K., Suto, I., Suzuki, N., Takahashi, K., Watanabe, M., Yamamoto, M., Frank, M., Jokat, W., Kristoffersen, Y., 2006. The Cenozoic palaeoenvironment of the Arctic Ocean. Nature 441, 601-605.

Tarduno, J.A., Arctic flood basalt volcanism; examining the hypothesis of Cretaceous activity at the Iceland hotspot Eos, Transactions, American Geophysical Union, 77, p. 844, 1996.

Tarduno, J.A., D.B. Brinkman, P.R. Renne, R.D. Cottrell, H. Scher, and P. Castillo, Evidence for extreme climatic warmth from Late Cretaceous Arctic vertebrates, Science, 282, 2241-2244, 1998.

Tarduno, J.A., R.D. Cottrell and A.V. Smirnov, The Cretaceous Superchron Geodynamo: Observations near the tangent cylinder, Proceedings National Academy of Sciences, 99, 14020-14025, 2002.

Vandermark, D., J.A. Tarduno, and D.B. Brinkman, A fossil champsosaur population from the High Arctic: Implications for Late Cretaceous paleotemperatures, Palaeogeography, Palaeoclimatology, Palaeoecology, 248, 49-59, 2007.

Vandermark, D., J.A. Tarduno, D.B. Brinkman, R.D. Cottrell and S. Mason, New Late Cretaceous macrobaenid turtle with Asian affinities from the High Canadian Arctic: Dispersal via ice-free polar routes, Geology, 37, 183-186, 2009.

Drilling a high-latitude climate archive through Oceanic Anoxic Event 2 in North Alaska (re-drilling of Umiat No. 11 exploration well in the Colville Basin)

Kuhnt, Holbourn, Flögel, Huber

Justification for drilling

Recover the first complete high-latitude (~80°N) climate archive through Oceanic Anoxic Event 2 (OAE2) from a shelf setting with potential to:

- assess the role of the Arctic Ocean as a carbon sink under greenhouse climate conditions to better understand changes in the global carbon cycle during extreme anoxic events
- provide high latitude multiproxy paleotemperature records to constrain meridional temperature gradients and to evaluate changes in the hydrological cycle and redox conditions during the Cenomanian-Turonian super-greenhouse
- reconstruct sea level variations during OAE2 in high temporal resolution.

Scientific strategy

- Establish detailed age models, mainly based on Ar/Ar analysis of abundant bentonites and δ13C in organic carbon.
- Integrate TEX86, δ18O in phosphate (fish debris) and carbonate (planktonic and benthic foraminifers, inoceramids), Mg/Ca and clumped isotopes to reconstruct temperature variations across OAE2 at ~80°N paleolatitude
- Combine high resolution, continuous organic geochemical records across OAE2 in organic-rich shales of low maturity (rock-eval characterization of organic carbon type and accumulation, biomarkers) to evaluate the role of the Arctic Ocean as a carbon sink
- Investigate variability of Nd isotopes in fish debris to assess changes in Arctic Ocean surface and shallow/intermediate water circulation.

Background

Exploration drilling by the U.S. Navy in the 1940s and early 1950s recovered an expanded succession (several 100 m thick) of upper Cenomanian to Turonian organic-rich shales in the Umiat 11 well, interpreted as a highstand system tract deposited within a dysaerobic outer shelf setting (Seabee Formation, Mull et al., 2003). Logging data and seismic analogs indicate multiple sequence boundaries within the shale succession, suggesting that the sealevel highstand at the Cenomanian/Turonian boundary consists of a composite of multiple depositional sequences (Housknecht and Schenk, 2004) including a a prominent lowstand in the center of OAE2, possibly corresponding to the „Plenus Cold Event“ or eustatic sequence boundary TU1. Earlier micropaleontological work (Tappan, 1961) on outcrop material from the Umiat area indicated the presence of planktonic foraminifers, suitable for isotope analysis. A pilot study of material from the Umiat wells, which is curated in the core repository of the Alaska Geological Survey at Anchorage, revealed rare but well-preserved benthic foraminifers mainly of the genera *Praebulimina* and *Neobulimina* and extremely rare planktonic foraminifers (*Heterohelix globulosa* and *Hedbergella loettrli*). However, the scarcity of microfossils may be an artefact of preferential spot-coring of siltstone and sandstone layers during oil exploration drilling.

Operations

Re-drilling of Umiat 11 well with modern wireline coring techniques to ~ 600 m depth

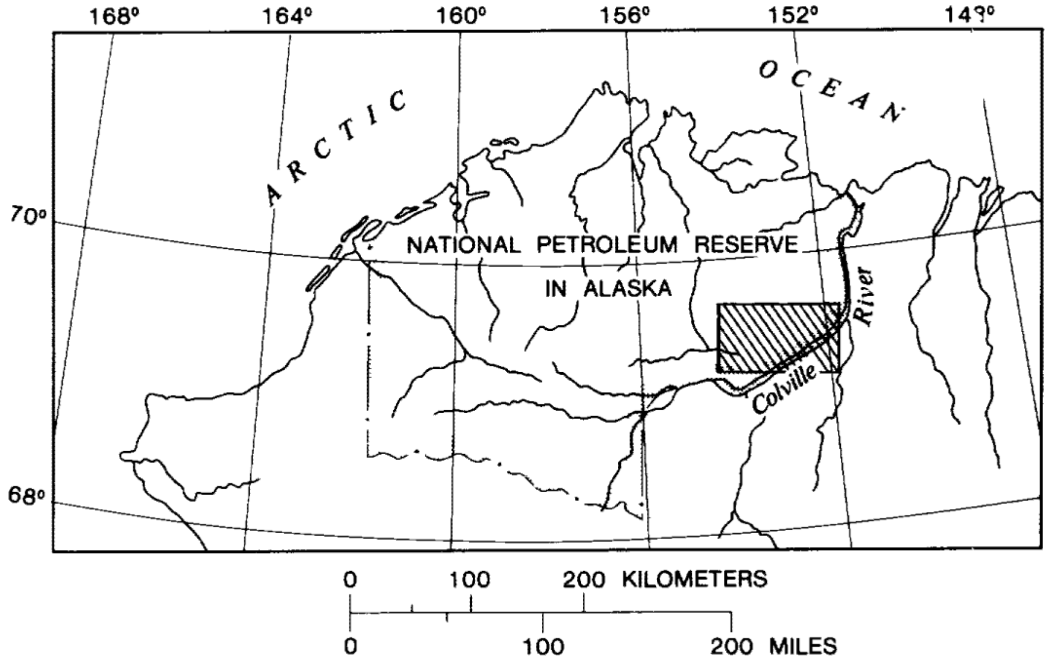
References

Tappan, H., 1961. Foraminifera from the Arctic Slope of Alaska. Part 3, Cretaceous Foraminifera. U.S. Geological Survey Professional Paper 236-C. 1-203.Geological Survey Professional Paper 1673, 1-51.

Mull, C.G., Houseknecht, D.W., and Bird, K.J., 2003. Revised Cretaceous and Tertiary Stratigraphic Nomenclature in the Colville Basin, Northern Alaska. U.S. on Umiat Mountain, North-Central Alaska. U.S. Geological Survey Professional Paper 1709-B, 1-18.

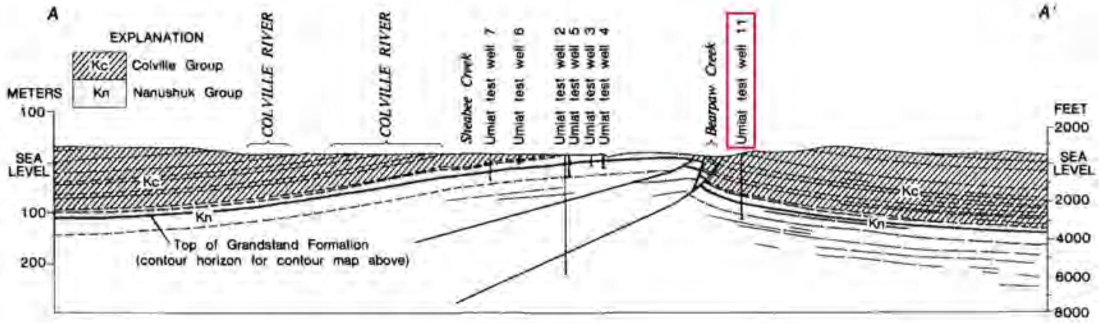
Houseknecht, D.W. and Schenk, C.J., 2004. Sedimentology and Sequence Stratigraphy of the Cretaceous Nanushuk, Seabee, and Tuluvak Formations exposed Petroleum Reserve in Alaska. US Geological Survey Circular 820, p. 1-47.

Fox, J.E., Lambert, P.W., Pitman, J.K., and Wu, C.H., 1979. A Study of Reservoir Characteristics of the Nanushuk and Colville Groups, Umiat Test Well 11, National

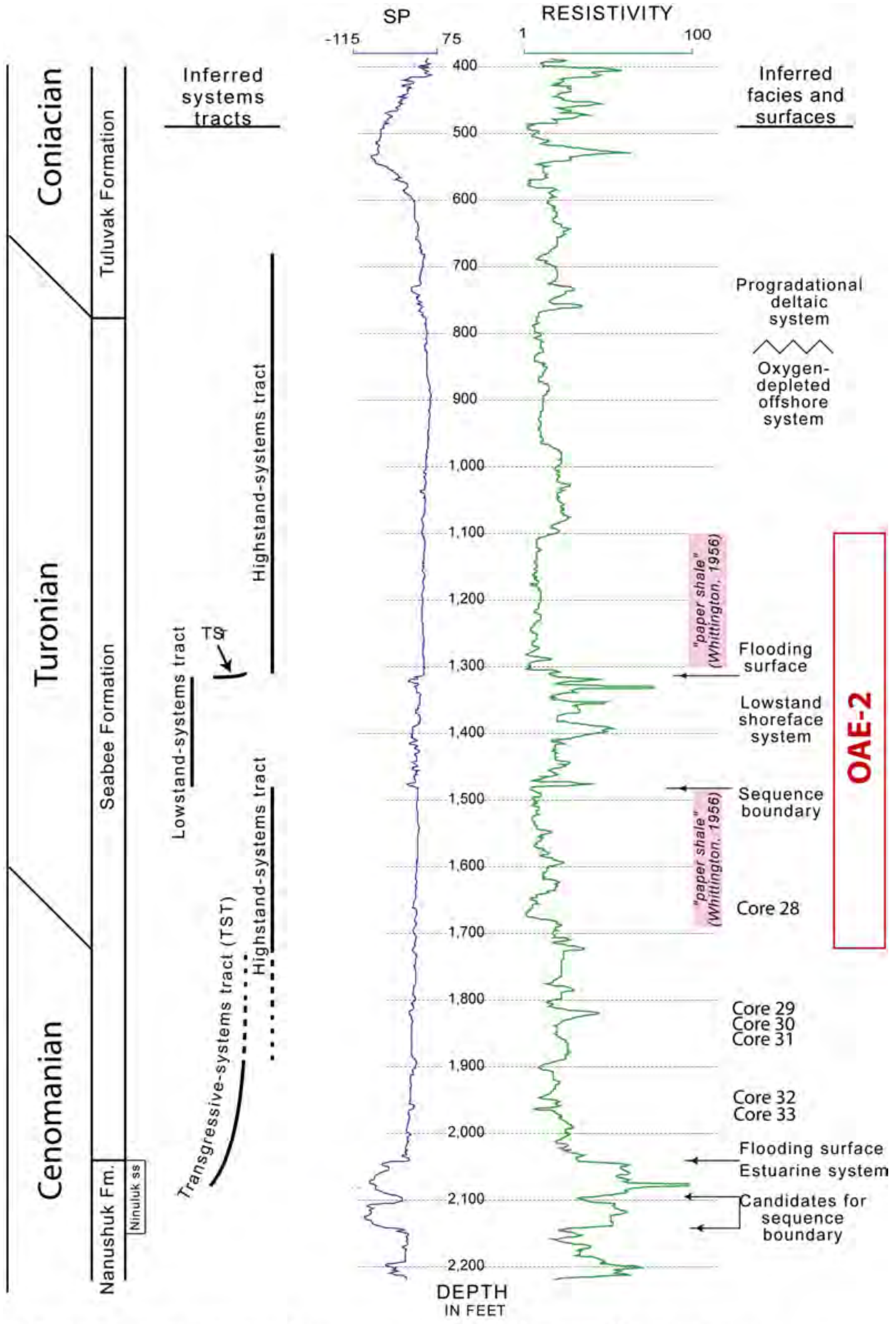


Location of the Umiat Anticline in North Alaska (from Fox et al., 1979)

S N



Cross section of the Umiat Anticline in North Alaska (from Fox et al., 1979)



Wireline log from the Umiat No. 11 well in North Alaska, gamma-ray profiles collected from Umiat Mountain outcrop section, and summary of sequence stratigraphic interpretations. Curves: blue, spontaneous potential (SP); green, resistivity. TS: transgressive-systems tract (modified from Houseknecht and Schenk, 2004).

Southern Oceans

Uenzelmann-Neben, Thomas, Whiteside, Williams, Voigt, Wise, Kulhanek, Lowery, Wagreich, Lees, Bralower

1. Climatic context

Predicting the effects of anthropogenic climate change on Earth's future climate stability requires an understanding of the physical and biogeochemical processes operating under high-temperature, high-atmospheric greenhouse gas concentration conditions. The Cretaceous was one of the longest periods of sustained warmth in Earth history. Several fundamental questions about the mechanics of Cretaceous climate remain unanswered. Data for the middle and high latitudes are critical for deciphering inter–hemispheric climate synchronicity, but are notably scarce (e.g., Friedrich, 2012); filling in these latitudinal gaps is essential. Oxygen isotope sea surface temperature reconstructions suggest peaks of 32°C (Huber et al., 2002) in the southern high latitudes during the Cenomanian-Turonian climate maximum; how does deepwater form in high latitudes in such warmth? How did water mass movements change with the opening of gateways (particularly the South Atlantic), and what affect did this have on the climate system? Is this the cause of the cooling of the Late Cretaceous? Did short-lived glaciations punctuate mid-Cretaceous warmth?

Answering these questions offers opportunities to understand the climate system of a sustained hothouse world that complements the recent advancements made in understanding the more ephemeral hyperthermals of the Paleogene. The Cretaceous witnessed several episodes of widespread anoxia that caused massive perturbations in the chemistry of the ocean, both in nutrients and pH, which had a profound affect on marine biota. Black shales presumed to be associated with OAEs are known from the Southern Ocean, and undoubtedly contain a rich archive on physical and chemical conditions in a hothouse ocean and biotic response, but have yet to be the focus of comprehensive study.

2. Biotic context

Studying the Cretaceous greenhouse world enables unique insights into the interaction of biota and biogeochemical cycles. During the Mesozoic, the global carbon cycle changed fundamentally through the evolution and proliferation of pelagic calcifiers, which made deposition of $CaCO_3$ on the deep-sea floor possible. In particular, planktonic foraminifera, which originated in the Jurassic, proliferated during the Cretaceous. The calcium-carbonate compensation depth originated only with the proliferation of pelagic calcifiers, and the saturation state of the deep ocean became buffered as long as pelagic biogenic production of $CaCO_3$ was greater than the river flux of $[Ca^{2+}]$ and $[CO_3^{2-}]$ (Zeebe & Westbroek, 2003; Ridgwell, 2005; Erba, 2006). The buffering of the deep-ocean's saturation state might have been a factor in the Cretaceous evolutionary radiation of hyaline deep-sea benthic foraminifera. Quantifying this carbonate flux from open-ocean calicfiers and preserved on the deep ocean floor is of prime importance for understanding changes in sea water chemistry over the Mesozoic. More completely recovered and globally distributed carbonate records of the Late Jurassic through Early Cretaceous are necessary to develop novel proxies for calcification such as Ca isotopes and stable Sr isotopes, which can be measured over this critical interval in time (Blaetttner et al., 2012). Such records are also needed to evaluate the timing and rates of changes in Mg/Ca in the oceans (e.g., Dickson, 2002), and whether such changes are related to the evolution of pelagic calcifiers, which may have caused increased preservation of low Mg/Ca calcite.

The silica cycle is also profoundly affected by biotic evolution during the Cretaceous. With the evolution and proliferation of diatoms, Si secretion changed from a predominance of sponges and zooplankton (radiolarians), to being dominated by diatom primary producers. Diversified floras of diatoms occurred by the early Aptian (~ 120 Ma) in the polar regions, the oldest well-preserved diatoms described from anywhere in the world (Gersonde and Harwood, 1990; Harwood and Gersonde, 1990).

Early floras of diatoms may have been restricted to shallower neritic environments because none have been recovered from deep-water oceanic sites, but they certainly were present across low to high latitudes by the Late Cretaceous (99-65 Ma; Davies et al., 2009). Tracing the early evolutionary history of diatoms, which are the most highly productive extant phytoplankton in the oceans and form the foundation of the oceanic food chain as well as a major component in the oceanic silica cycle, is only possible through drilling at high latitude locations. The presently available records are short and isolated, but longer-term high resolution records of diatom evolutionary history are possible when more material becomes available. ODP Site 693 recovered a few meters of early Albian diatom ooze in the Weddell Sea that contained over 40 undescribed species, suggesting a major diversification of siliceous microflora during a period of dynamic carbon cycle changes and perhaps showing the impact that biosphere evolution can have on global change.

3. Targets

Discussion in the Southern Ocean breakout group addressed the extent to which potential targets were most likely to yield records to accomplish key questions related to climate and biotic evolution of the Cretaceous.

Only one Cretaceous proposal currently exists with the system (813-Full) which is discussed in detail below.

The following drill targets were discussed:

3.1 Triangle in the Cretaceous Southern Ocean
  Agulhas-Plateau-Transkei Basin Transect
  Weddell Sea
  Falkland Plateau
3.2 Naturaliste Plateau
3.3 Australian Bight
3.4 George V Land

3.1 *A Triangle of Sampling in the Cretaceous Southern Ocean*

Cores from three oceanic basins that were in close proximity during the Early Cretaceous (~130 Ma, M10, Hauterivian) (Koenig and Jokat, 2006) but had diverged considerably by Turonian times (~90 Ma) will provide unique insights into temperature gradients as well as the evolution of both planktonic and benthic microorganisms that profoundly changed the Earth's carbon, silica and calcium cycles. By elucidating environmental and biotic evolution in these three basins from their origin through divergence via plate tectonics, we can study the effects of formation of the ocean gateways of most importance in the present oceans, these around the Antarctic continent, as they developed with the breakup of Pangaea.

We will be able to trace the evolutionary history of these organisms over times when climate varied between cooler and warmer conditions, and when oceanic environments varied between more and less oxygenated, thus addressing challenges in the Science Plan, namely: Challenge 4: how resilient is the ocean to chemical perturbation?; and Challenge 7: how sensitive are ecosystems and biodiversity to environmental change? Biotic and environmental change impacted of proposed LIP formation in the area will be addressed using three sites separated by 25+ degrees latitude today. Drifting of study sites in time resulted in crossing what are today key paleoceanographic fronts gives results on the dynamic response of ecosystems. This will be used to understand the connection between ocean chemistry and extreme internal forcings to Earth's surface by this LIP.

The Cretaceous greenhouse Earth experienced increasing global temperature and major changes in atmospheric inventories of greenhouse cases, thus our research will provide unparalleled insight into Challenge 1: how does Earth's climate system respond to elevated levels of atmospheric CO_2? By providing novel information not only on past environments during greenhouse conditions and high atmospheric pCO_2 levels, but also oceanic biota, we can directly ask and answer how the oceanic biosphere responds to such conditions through long-term adaptation and evolution. The Weddell Basin moved southward to higher latitudes during the Cretaceous, so that comparison between biota in the Weddell Basin, the Agulhas Plateau, and Falkland Plateau during this separation and motion into different climate zones will provided unparalleled insights into the response of the biosphere to variable oceanic conditions along a latitudinal gradient, and to the development of latitudinal diversity gradients during a hothouse world. Such studies will enable us to evaluate the influence of latitudinal temperature (which are hypothesized to be considerably lower than today's gradients) and seasonality gradients (dark conditions over several months prevailed even in a warm world) on diversity gradients, a controlling factor in extant marine ecosystems. Looking at Southern Ocean diversity gradients and variability of microfossils along depth transects and multiple sites along a palaeolatitude gradient will help to understand biological and ocean chemistry responds to major environmental perturbations and resulting biogeochemical-climate feedbacks. Multiproxy approach on depth transects will give results on water masses and climate sensitivity during the Cretaceous. The biological response not only on fossil ecosystems but also on the evolution of microfossil groups, especially siliceous microfossils, will be addressed.

There is considerable debate whether polar ice sheets could have existed in a Cretaceous greenhouse world (Bornemann et al., 2008), with direct impacts on climate sensitivity to atmospheric pCO_2. Recovering sediment from the Antarctic region, where such ice sheets must have been sourced, will enable us to find convincing evidence for the presence or absence of continental ice sheets at sea level, such as ice rafted debris, determine how any polar ice might have changed in extent through time, and provide evidence for significant sea-level changes in combination with proxies for SSTs, thus addressing Challenge 2: how do ice sheets and sea level respond to a warming world?

These data on environments and pelagic ecosystems across latitudinal gradients will enable us to improve not only general paleoclimate models, but also earth system models including a marine ecosystem component. Recovery of sediment across multiple Oceanic Anoxic Events (OAEs) in three different ocean basins, which originally were parts of a single small restricted basin, will enable us to evaluate contributions of basin isolation on oceanic anoxia versus other factors, including primary productivity. We address the long-term biological responses to ocean hypoxia by investigating the southern expression of OAEs and their resulting unique high-latitude black shales. The evolution of restricted basins fostering anoxia to open basin systems and its environmental and biological affects will be addressed.

Only through a coordinated drilling program targeting sediments of the same age at different bathymetric and geographic locations will we be able to take forward our understanding of the earth-life system interactions during the Cretaceous greenhouse world.

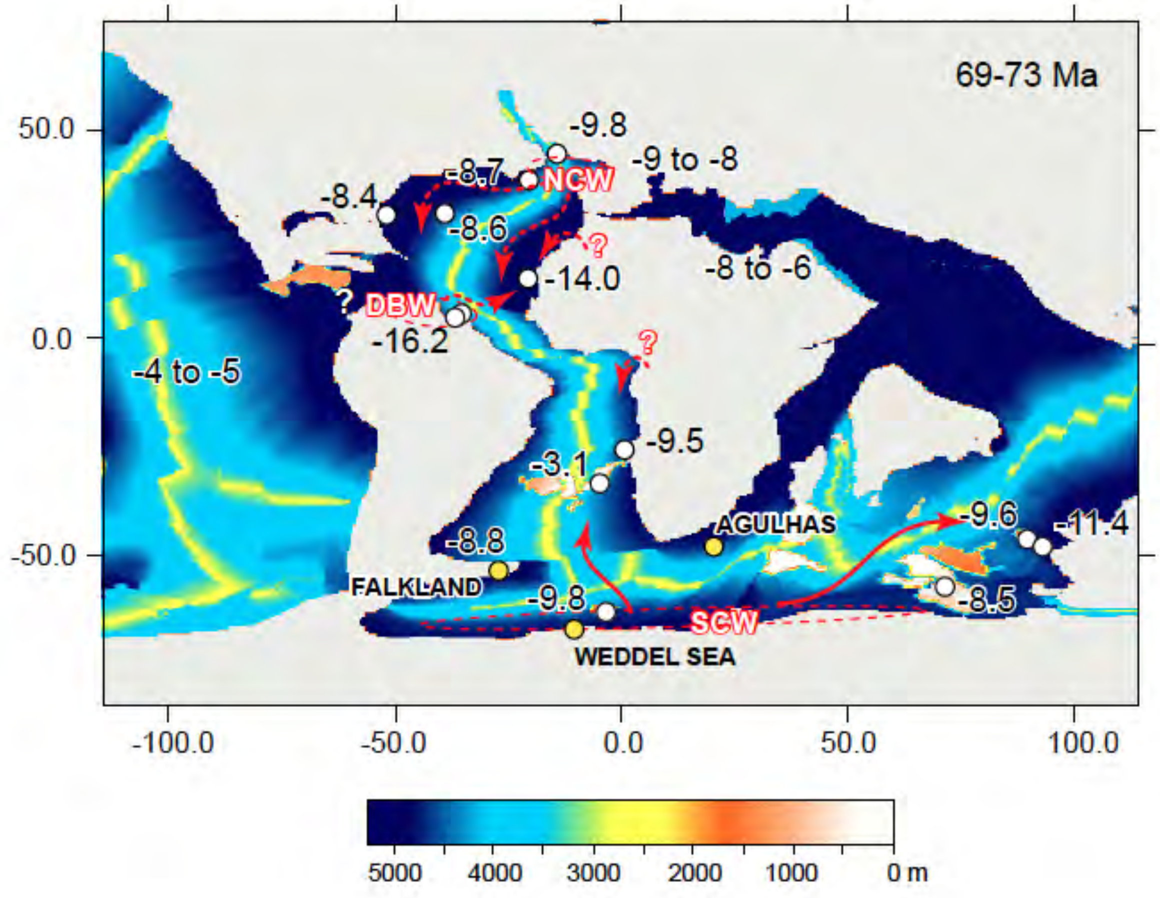


Figure 1. Palaeobathymetric reconstruction of the Pacific, North- and South Atlantic, Southern and proto-Indian oceans at ~71 Ma (late Campanian-early Maastrichtian) without shelf seas (after Müller et al., 2008). The consecutive opening of the basins constituting the modern Southern Ocean played a crucial role in the global linkage of oceanic deep-water reservoirs and the establishment of global thermohaline circulation system similar to the modern one, during which changes in seafloor topography and the magmatic-tectonic development of this Southern Ocean gateway played an important role.
Values indicate average intermediate- to deep-water Nd isotope data at different sites and water depths from the late Campanian through early Maastrichtian (69-73 Ma). Neodymium isotope data are from Voigt et al. (2013), Frank et al. (2005), MacLeod et al. (2011), Martin et al. (2012), Puceat et al. (2005), Robinson and Vance (2012), and Robinson et al. (2012). Arrows schematically mark the supposed flow of different deep-water masses (Voigt et al. 2013). NCW – Northern Component Water, SCW – Southern Component Water. Yellow circles show approximates locations of sites to be drilled in a suite of three proposals with Lower Cretaceous objectives in the Agulhas Plateau/Transkei Basin region, the Weddell Sea, and the Falkland Plateau.

References

Bornemann, A., Norris, R.D., Friedrich, O., Beckmann, B., Schouten, S., Sinninghe Damste, J. S. Vogel, J., Hofmann, P., Wagner, T., 2008. Isotopic evidence for glaciation during the Cretaceous supergreenhouse. *Science*, v. 319, 189-192.

Davies, A., Kemp, A.E.S., and Pike, J. 2009. Late Cretaceous seasonal ocean variability from the Arctic. *Nature*, vol. 460, p.254-258.

Dickson, J.A.D., 2002. Fossil echinoderms as monitor of the Mg/Ca ratio of Phanerozoic oceans. *Science* vol. 298, p. 1222–1224.

Erba, E., 2006. The first 150 million years history of calcareous nannoplankton: Biosphere–geosphere interactions. *Palaeogeography, Palaeoceanography, Palaeoecology* vol. 232, p. 237-250.

Fassell, M.L., and Bralower, T.J., 1999, Warm, equable mid-Cretaceous: Stable isotope evidence, *in* Barrera, E., and Johnson, C., eds., Evolution of the Cretaceous ocean-climate system: Geological Society of America Special Paper 332, p. 121–142.

Frank, T.D., Thomas, D.J., Leckie, R.M., Arthur, M.A., Bown, P.R., Jones, K., and Lees, J.A., 2005, The Maastrichtian record from Shatsky Rise (northwest Pacific): A tropical perspective on global ecological and oceanographic changes: *Paleoceanography*, v. 20, PA1008, doi: 10.1029/2004PA001052.

Friedrich, O., Norris, R.D., and Erbacher, J., 2012. Evolution of middle to Late Cretaceous oceans–A 55 m.y. record of Earth's temperature and carbon cycle. *Geology*, vol. 40, p. 107-110.

Gersonde, R., and Harwood, D.M., 1990. Cretaceous diatoms from ODP Leg 113 Site 693 (Weddell Sea). Part 1: vegetative cells, *in* Barker, P.F. and Kennett, J.P., et al., 1990. *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 113: College Station, TX(Ocean Drilling Program), p. 365-402

Harwood, D.M. and Gersonde, R., 1990. Cretaceous diatoms from ODP Leg 113 Site 693 (Weddell Sea). Part 2: resting spores, chryophycean cysts, and endoskeletal dinoflagellate, and notes on the origin of diatoms, *in* Barker, P.F. and Kennett, J.P., et al., 1990. *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 113: College Station, TX(Ocean Drilling Program), p. 403-425

König, M., Jokat, W., 2006. The Mesozoic break-up of the Weddell Sea. *Journal of Geophysical Research*, vol. 111, B12102

MacLeod, K.G., Isaza-Londoño, C., Martin, E.E., Jiménez Berrocosco, Á, and Chandranath, B., 2011. Changes in North Atlantic circulation at the end of the Cretaceous greenhouse interval. *Nature Geoscience*, vol. 4, p. 779-782.

Martin , E. E., MacLeod, K.G., Jiménez Berrocosco, Á., Bourbon, E., 2012. Water mass circulation based on Nd isotopes. *Earth and Platenary Science Letters*, vol. 327-328, p. 111-120.

Müller, R.D., Sdrolias, M., Gaina, C., Steinberger, B., Heine, C., 2008. Long-term sea-level fluctuations driven by ocean basin dynamics. *Science*, vol. 319, p. 1357–1362.

Pucéat, E., Lécuyer, C., Reisberg, L., 2005. Neodymium isotope evolution of NW Tethyan upperocean waters throughout the Cretaceous. *Earth and Planetary Science Letters*, vol. 236, p. 705-720.

Ridgwell, A., 2005. Changes in the mode of carbonate deposition: Implications for Phanerozoic ocean chemistry. *Marine Geology,* vol. 217, p. 339–357.

Robinson, S.A., Murphy, D.P., Vance, D., Thomas, D.J., 2010. Formation of "Southern Component Water" in the Late Cretaceous: evidence from Nd-isotopes. *Geology,* vol. 38, p. 871–874.

Robinson, S.A., Vance, D., 2012. Widespread and synchronous change in deep-ocean circulation in the North and South Atlantic during the Late Cretaceous. *Paleoceanography*, vol. 27, PA1102, http://dx.doi.org/10.1029/2011PA002240.

Voigt, S., Jung, C., Friedrich, O., Frank, M., Teschner, C., Hoffmann, J. *In press*. Tectonically restricted deep-ocean circulation at the end of the Cretaceous greenhouse. *Earth and Planetary Science Letters*.

Zeebe, R. E., and P. Westbroek, 2003. A simple model for the $CaCO_3$ saturation state of the ocean: The "Strangelove," the "Neritan," and the "Cretan" Ocean, *Geochemistry, Geophysics and Geosystems,* vol. 4, doi:10.1029/2003GC000538

3.1.1 Agulhas- Plateau-Transkei Basin Transect

The exchange of water masses between the Indian and South Atlantic Oceans has a crucial influence on global thermohaline circulation and thus also global climate. In this context the seafloor topography of this gateway and its magmatic-tectonic development are of particular interest in reconstructing long-term climate evolution. Seafloor elevations such as the Agulhas Plateau (AP) and the Mozambique Ridge (MozR) constitute barriers for deep, intermediate, and bottom-water masses. For example, Murphy and Thomas (2012; in prep) found that the Falkland Plateau and the western flank of the Kerguelen Plateau were bathed in different intermediate-depth water-masses from ~95 Ma to 78 Ma, despite occupying similar palaeolatitudes and palaeodepths, possibly as a result of the AP and/or MozR barriers. The convergence of Falkland and Kerguelen intermediate water-masses potentially occurred due to tectonic subsidence of the intervening barriers. The evolution of Cretaceous oceanic circulation, global climate and southern high-latitude environmental conditions is archived in sedimentary structures and packages in this critical location offshore South Africa.

Gohl and Uenzelmann-Neben (2011) and Parsiegla *et al.* (2008; 2009) found geophysical evidence that the AP is an oceanic Large Igneous Province (LIP), consisting of over-thickened oceanic crust formed at 110-95 Ma. Furthermore, new seismic refraction data are interpreted as strong evidence for a LIP origin of the southern Mozambique Ridge (Gohl *et al.*, 2011) and is supported by a recent magnetic survey (König and Jokat, 2010). Plate tectonic reconstructions point towards a formation of the MozR between 146 and 120 Ma (König and Jokat, 2010), whereas the AP was formed between 100 and 94 Ma (Parsiegla *et al.*, 2008). Therefore, both these LIPs and their Cretaceous sedimentary overburden and the basin between them, the Transkei Basin, formed during the break-up of Gondwana and thus represent an archive representing the evolution of oceanic circulation and climate in this gateway location. Bright spots identified in seismic reflection data in the Transkei Basin and interpreted as black shales (Schlüter and Uenzelmann-Neben, 2008a), potentially document restricted circulation within a confined basin. The younger sediments within this basin document the transition to open-ocean intermediate and deep circulation between Tethys and the evolving Southern and South Atlantic Oceans.

The sedimentary column within the Transkei Basin is about 1800 m thick (Schlüter and Uenzelmann-Neben, 2008b), with the black shale reflector located at 300 to 800 m below seafloor.

Seismic reflection profiles across the AP indicate that sediment thickness above the rough topography of the northern third of the plateau and the more subdued topography of the southern part varies from 0 to 1 km (Tucholke and Carpenter, 1977; Uenzelmann-Neben, 2001, 2002). The attitude of the sediment reflectors reveals that the variation in sediment thickness was strongly influenced by bottom currents. Piston cores taken from across the plateau contain calcareous ooze with planktonic foraminifera ranging from Quaternary to Cretaceous in age. Maastrichtian cores were recovered from both the northern and southern regions and Turonian and Cenomanian cores were recovered from only the southern region (Tucholke and Carpenter, 1977).

Drilling a depth/latitudinal transect from the Agulhas Plateau into the Transkei Basin will allow:

- Determination of formation age and origin of the Agulhas Plateau LIP
- Determination of the role this LIP played as an obstacle to oceanic circulation at different water-depths and its concomitant impact on Southern Hemisphere to global climate evolution
- Dating of the transition from circulation within a restricted basin to open ocean circulation
- Reconstruction of Cretaceous surface-water thermal gradients in the sub Antarctic region
- Characterization of latitudinal shifts in the Austral/Transitional Biogeographic Realm boundary which in turn can be related to climate/water mass and paleocirculation history
- Age and origin of the bright spots interpreted as black shales; do they represent a mid-Cretaceous OAE?

Drilling Strategy

The drilling strategy will be to double/triple core using APC/XCB to refusal at several sites with palaeoceanographic objectives. At sites where basement will be penetrated, the sediment pile will be cored using APC/XCB to refusal, followed by rotary coring into basement. Logging at sites with deep sedimentary objectives and basement penetration will be used to aid core-log-seismic integration, obtain orientated structural measurements and make *in situ* palaeomagnetic measurements

Data availability

High resolution seismic data were gathered on the Agulhas Plateau, in the Transkei Basin and in the South African gateway in 1998 and 2005 (Uenzelmann-Neben, 1998, 2005), and more seismic data will be collected during RV *Sonne* cruise So 232 in 2014. These data are, and will be made, available for the proposal. Additionally, sediment echosound and bathymetric data are available for the Transkei Basin and in part for the Agulhas Plateau (Uenzelmann-Neben, 2005).

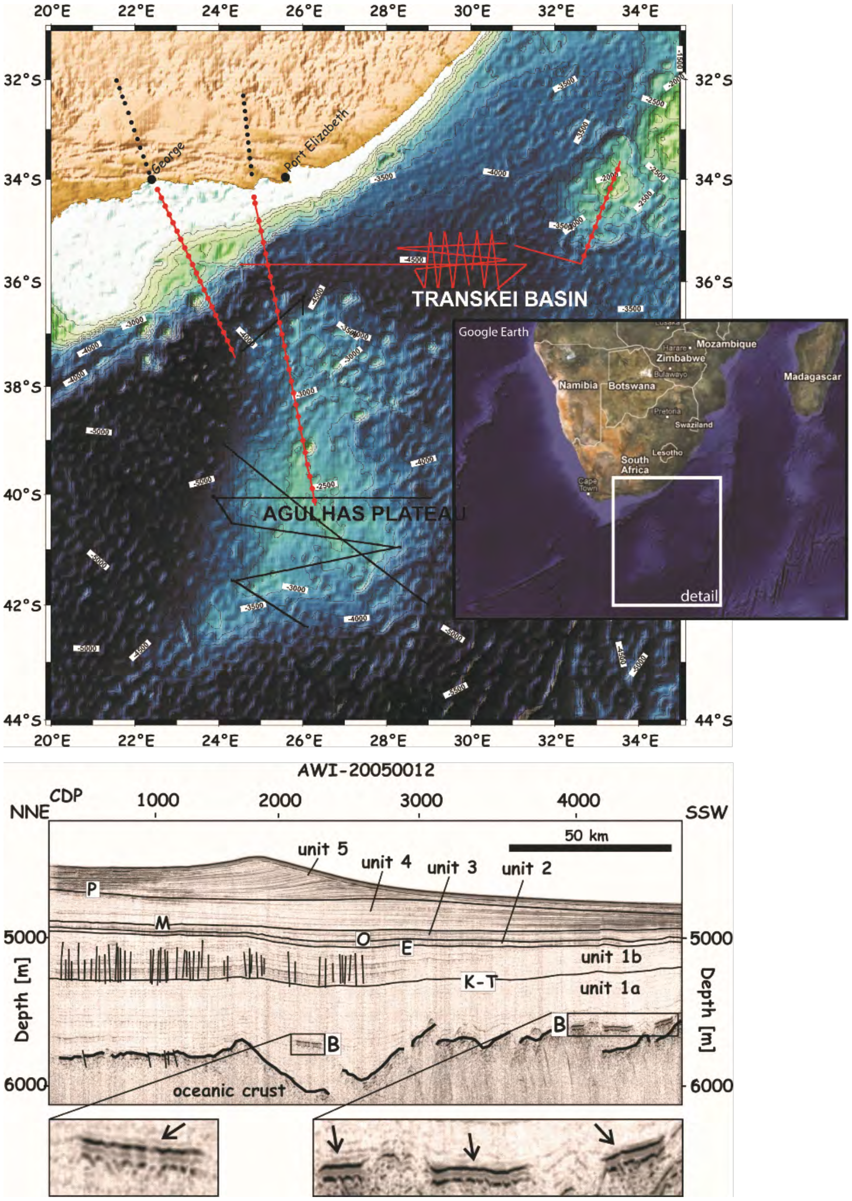


Figure 2. Agulhas Plateau and Transkei Basin location map (top) and Transkei Basin seismic data (bottom) showing interpreted Cretaceous sequence with detail of black shale intervals. P=Pliocene, M=Miocene, O=Oligocene, E=Eocene, K-T=Cretaceous-Paleogene Boundary, B=black shales. Modified from Schlüter and Uenzelmann-Neben, 2008.

References

Gohl, K., Uenzelmann-Neben, G., Grobys, N., 2011. Growth and dispersal of a southeast African Large Igneous Province South African Journal of Geology 114 (3-4), 379-386.

König, M., Jokat, W., 2010. Advanced insights into magmatism and volcanism of the Mozambique Ridge and Mozambique Basin in the view of new potential field data. Geophysical Journal International 180 (1), 158-180.

Murphy, D.P., Thomas, D.J., 2012. Cretaceous deep-water formation in the Indian sector of the Southern Ocean. Paleoceanography 27 (1), PA1211.

Murphy, D.P., Thomas, D.J., in prep. Late Cretaceous Density Driven Oceanic Circulation in the Atlantic Basins. Palaeogeography, Palaeoclimatology, Palaeoecology.

Parsiegla, N., Gohl, K., Uenzelmann-Neben, G., 2008. The Agulhas Plateau: Structure and evolution of a Large Igneous Province. Geophysical Journal International 174, 336-350

Parsiegla, N., Stankiewicz, J., Gohl, K., Ryberg, T., Uenzelmann-Neben, G., 2009. Southern African continental margin: Dynamic processes of a transform margin. Geochem. Geophys. Geosyst. 10.

Schlüter, P., Uenzelmann-Neben, G., 2008a. Conspicuous seismic reflections in Upper Cretaceous sediments as evidence for black shales off South Africa. Marine and Petroleum Geology 25, 989–999.

Schlüter, P., Uenzelmann-Neben, G., 2008b. Indications for bottom current activity since Eocene times: The climate and ocean gateway archive of the Transkei Basin, South Africa. Global and Planetary Change 60 (3-4), 416-428.

Tucholke, B.E., Carpenter, G.B., 1977. Sedimentary distribution and Cenozoic sedimentation patterns on the Agulhas Plateau. Geological Society America Bulletin 88, 1337-1346.

Uenzelmann-Neben, G., 1998. Sedimentation and tectonics of Agulhas Ridge and Agulhas Plateau. Berichte zur Polar- und Meeresforschung 273, 22.

Uenzelmann-Neben, G., 2001. Seismic characteristics of sediment drifts: An example from the Agulhas Plateau, southwest Indian Ocean. Marine Geophysical Research 22, 323-343.

Uenzelmann-Neben, G., 2002. Contourites on the Agulhas Plateau, SW Indian Ocean: indications for the evolution of currents since Paleogene times. In: Stow, D.A.V., Pudsey, C.J., Howe, J.A., Faugeres, J.-C., Viana, A.R. (Eds.), Deep-water contourite systems: Modern drifts and ancient series, seismic and sedimentary characteristics. Geological Society London, pp. 271-288.

Uenzelmann-Neben, G., 2005. Southeastern Atlantic and southwestern Indian Ocean: reconstruction of the sedimentary and tectonic development since the Cretaceous AISTEK-1: Agulhas Transect. Berichte zur Polar- und Meeresforschung, 73.

The Early Cretaceous Weddell Sea, Atlantic Sector of the Southern Ocean

Wise, Jokat, Jenkyns, Thomas

Some goals of the three ‘Triangle In the Cretaceous Southern Ocean’ proposals can be addressed only by drilling on the slope of the Weddell Sea basin, one of the earliest to form during the initial break-up of Gondwana land (Jokat et al., 2003; Leinweber and Jokat, 2012). There is a major gap in our knowledge of the opening and development of Late Jurassic and Early Cretaceous high-latitude basins, which at least during some periods were anoxic, and the relation of environments and biota to these in contemporary basins in other regions. Only drilling will determine whether the anoxic environments in the earliest Cretaceous steadily became more oxygenated as the incipient basin opened to deeper-water circulation between Valanginian and Albian, or whether anoxic conditions developed coeval with Oceanic Anoxic Events globally, or were influenced by episodes of gateway opening.

Information from the proposed Weddell Sea sites, especially as combined with information from other areas in the region (Agulhas, Falklands), which followed different geographic trajectories during basin evolution, is key to the determination of Cretaceous thermohaline circulation modes and their role in Cretaceous climate evolution as well as in evolution of oceanic biota. On the Dronning Maud Land margin of the Weddell Sea we can obtain a continuous and expanded section through the Upper Jurassic-Lower Cretaceous (up to the Lower Albian), representing the entire Antarctic region.

A Weddell Sea drilling proposal with Mesozoic objectives submitted before (Proposals 503 and 691), and a new proposal can be compiled and submitted by the October 2013 deadline. Crossing seismic lines across the proposed sites are available, and information for a small part of the sedimentary record is available through drilling on ODP Leg 113, Sites 692 and 693 (Kennett, Barker et al., 1988, 1990).

Results from previous drilling

During ODP Leg 113 Lower Cretaceous "black shales" were unexpectedly recovered at intermediate water depths at Sites 692 and 693 on the Dronning Maud Land margin of East Antarctica (Barker, Kennett et al., 1988), but most of the section (sediment package W3, Figure 3) was not drilled. Site 692 (Figure 3) recovered Valanginian to Hauterivian nannofossil claystone and organic-rich claystones with thin intercalated ash layers, and with up to 18.4% TOC (Shipboard Scientific Party, 1988a; Thompson and Dow, 1990), and common laminae and lenses of phosphorite (O'Connell, 1990). Calcareous nannofossils and calcareous benthic and foraminifera are present, and in some intervals well-preserved, as are palynomorphs (Mohr, 1990). The black shales have only a thin cover of diamicton, and outcrop along the sides of Wegener Canyon.

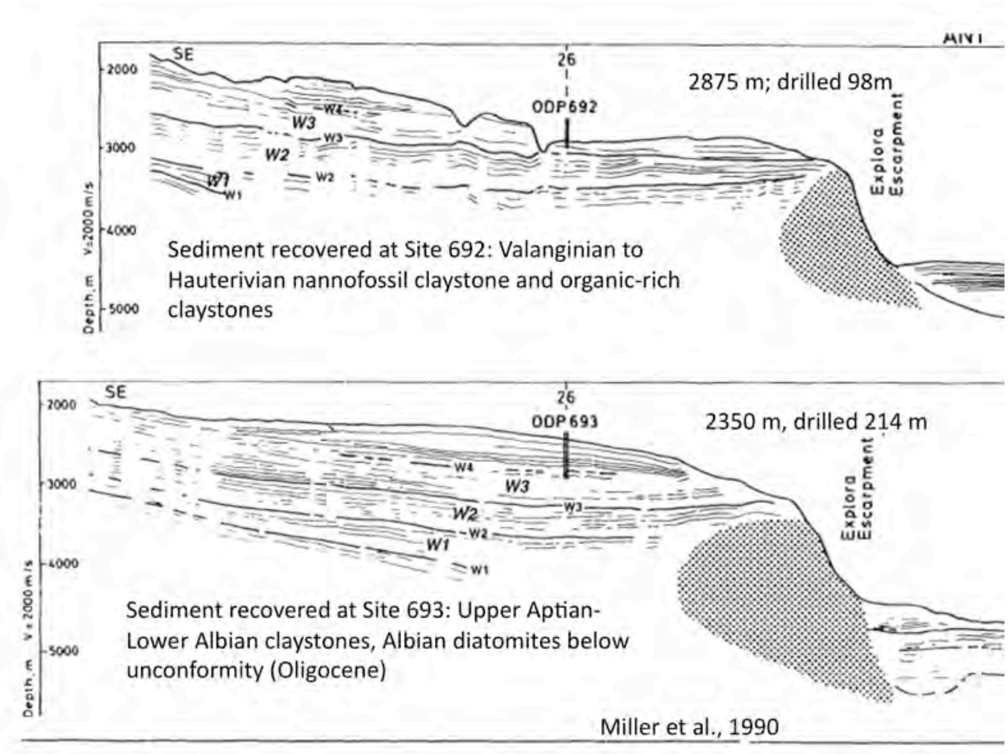
Site 693 (Figure 4) penetrated 75 m of Upper Aptian-Lower Albian claystones beneath an unconformity, overlain by ~400 m Neogene - Oligocene glacio-marine sediments. The claystones contain calcareous nannofossils and planktic and benthic foraminifera (Leckie, 1990; Mutterlose and Wise, 1990). The total organic carbon (TOC) of the claystones, largely algal-derived, averaged 2.5%, and the low Rock-Eval hydrocarbon responses of this immature kerogen indicated deposition in an environment with more oxygenated bottom waters than at Site 692. The shales grade upwards over into a greenish diatomite, the deposition of which signalled ventilation of the basin. Recovery of these diatomites transformed our knowledge of evolution of diatoms and silicoflagellates, and the 15 cm of exquisitely preserved diatom and silicoflagellate assemblages at the top of the Albian has been a virtual Rosetta Stone for interpreting the early evolution of these important microfossil groups (McCartney et al., 1990; Gersonde and Harwood, 1990; Harwood and Gersonde, 1990). Cretaceous radiolarians are also present (Ling and Lazarus, 1990).

The basin had become more oxygenated between the Valanginian-Hauterivian and the Late Aptian, but no attempt has been made to recover the sedimentary record between the recovered intervals at Site 692 and 693 (sediments W3; Figure 3), so that there is no information on conditions in the basin between these two time periods. A remarkable feature of the dark shales at both Sites 692 and 693 is the absence of macroscopically cyclicity in lithology and total organic carbon, suggesting continuous bottom water anoxia (Thompson and Dow, 1990), but this is in disagreement with the presence of benthic foraminifera (Shipboard Party, 1988).

Seismic reflection horizon (U6, Hinz & Krause, 1982; W3, Miller et al., 1990) lies ~60 m below the lowest sediment recovered at Site 692. A prominent reflector about 900 ms below W3 (U9, Hinz & Krause, 1982; W1, Miller et al., 1990) has been named the "Weddell Sea Unconformity" (W1, Miller et al., 1990), and is thought to represent a break-up unconformity. Approximately 1200 m of Upper Jurassic to Lower Cretaceous sediments lie above basement. Dredge hauls indicate that the lower part of the sedimentary sequence consists of volcaniclastic sandstones, mudstones, siltstones and coarse, poorly consolidated sandstones (Fütterer et al., 1990).

Scientific objectives

- Obtain a continuous Upper Jurassic - Lower Cretaceous record of the marine environments in this southernmost portion of Gondwanaland to study (i) the origin and evolution of the Mesozoic Weddell basin, (ii) the timing, development and intensity of anoxia in the Mesozoic Weddell Sea basin, (iii) the productivity and paleobiogeographic development of Mesozoic Antarctic faunas and floras, and (iii) the development and evolution of high-latitude Mesozoic climates. We may well recover more diatomites which may expand our knowledge of the early evolution of this group.
- Obtain records of Nd isotopes, organic biomarkers, and bulk sediment and carbonate-based isotope and trace element proxies to (i) track connections between the restricted Weddell Sea and the neighbouring ocean, and evaluate its contribution to Cretaceous deep-water formation, and (ii) determine high-latitude surface and deeper water temperatures, salinity, carbonate saturation and oxygenation levels
- Trace the history of volcanic activity in the region and synthesize the geologic data obtained by drilling and logging with regional/global geophysical studies (e.g., Jokat et al., 1996) to better understand and constrain the sequence and timing of the break-up and dispersal of the Gondwanaland continents, and reconstruct the relative plate motions that progressively isolated the Antarctic continent.



Miller et al., 1990

Figure 3: The location of ODP sites drilled on Leg 113 placed on cross-sections through the continental margin stratigraphic record. (after Miller et al., 1990.)

Two sites are proposed for drilling:

Table 2.	Latitude	Longitude	Water Depth	Penetration	Target
WS-06A	71°59'S	24°23'W	3582 m	500 m	Cenozoic/Mesozoic; redrill Site 693
WS-05A	70°46'S	14°26'W	2550 m	800 m	Mesozoic; redrill/ deepen Site 692

Falkland Plateau

A. Challenges that Falkland Plateau will address:

Climate and Oceans:

- *1. How does Earth's climate system respond to elevated levels of atmospheric CO_2?*
- *2. How do ice sheets and sea level respond to a warming climate?*
- *4. How resilient is the ocean to chemical perturbations?*

Biosphere frontiers:

- *5.What are the origin, composition, and global significance of subseafloor communities?*
- *6. What are the limits of life in the subseafloor?*

B. Justification for Falkland Plateau, as part of the Southern Ocean Development MDP:

- During the Late Jurassic–Cretaceous Falkland Plateau lies at a 'crossroads' between Southern Ocean development to the south and, later, the opening of the South Atlantic to the North
- Progressive separation between Falkland Plateau and Weddell Sea to the south, provides an opportunity to examine the development of climatic and biotic gradients across an new ocean basin
- Previous coring (e.g. Sites 511, 327) has yield extremely well-preserved planktonic and benthic foraminifera through much of the Aptian–Maastrichtian (e.g. Huber et al., 1995, Bice et al., 2003). Previous and ongoing studies illustrate the potential of Jurassic–Cretaceous sediments from Falkland Plateau to yield well-preserved organic biomarkers for SST reconstructions (Jenkyns et al., 2012; Robinson et al., unpublished data). These multi-proxy reconstructions suggest extreme warmth at ~60˚S throughout much of the mid-Cretaceous, which climate models have struggled to reconstruct (e.g. Bice et al., 2003) and have implications for the existence of 'icesheets' in the greenhouse world.
- Early and mid-Cretaceous black shales deposited during OAEs have been shown to exist at Site 511, although OAE2 was not recovered. Reconstructing both climate and oceanographic conditions across OAEs in a high latitude setting address CO Challenges 1 and 4, whilst recovery of black shales can be used to address Biosphere Challenges 5 and 6.
- Existing core materials are unsuitable for addressing the scientific objectives of the Southern Ocean Development MDP due to spot coring, poor recovery, and the failure to capture critical intervals, such as OAE2.

C. Provisional strategy:

- Seismic data from DSDP Legs 36 and 71 suggests that there is potential for a suite of sites on Falkland Plateau that can be used to address:
    - the oceanographic development of the Southern Ocean during gateway opening
    - the record of OAEs at high latitudes

  - high latitude greenhouse climates.
- The following targets have been identified:
  - Pre-Albian black shales and early history of gateway development could be accessed by coring in the vicinity of Sites 330 and 327
  - Mid-Cretaceous OAEs and an expanded Late Cretaceous climate record could be accessed through a thinner Cenozoic interval by coring to the north of Site 511 (towards Maurice Ewing Bank).
  - A potential depth transect spanning ~1km of modern water depth may be possible in the vicinity of Maurice Ewing Bank (Site 512), where Cretaceous sediments are overlain by a relatively thin Cenozoic cover.
- More extensive depth transects may be possible but additional seismic data will be required to identify sites. There is potential here for collaboration with Industry.
- The drilling strategy will be to double/triple core using APC/XCB to refusal. For older (i.e. Late Jurassic) objectives it may be necessary to use rotary coring. Logging will be used to aid core-log-seismic integration and aid in composite depth reconstruction at deeper targets.

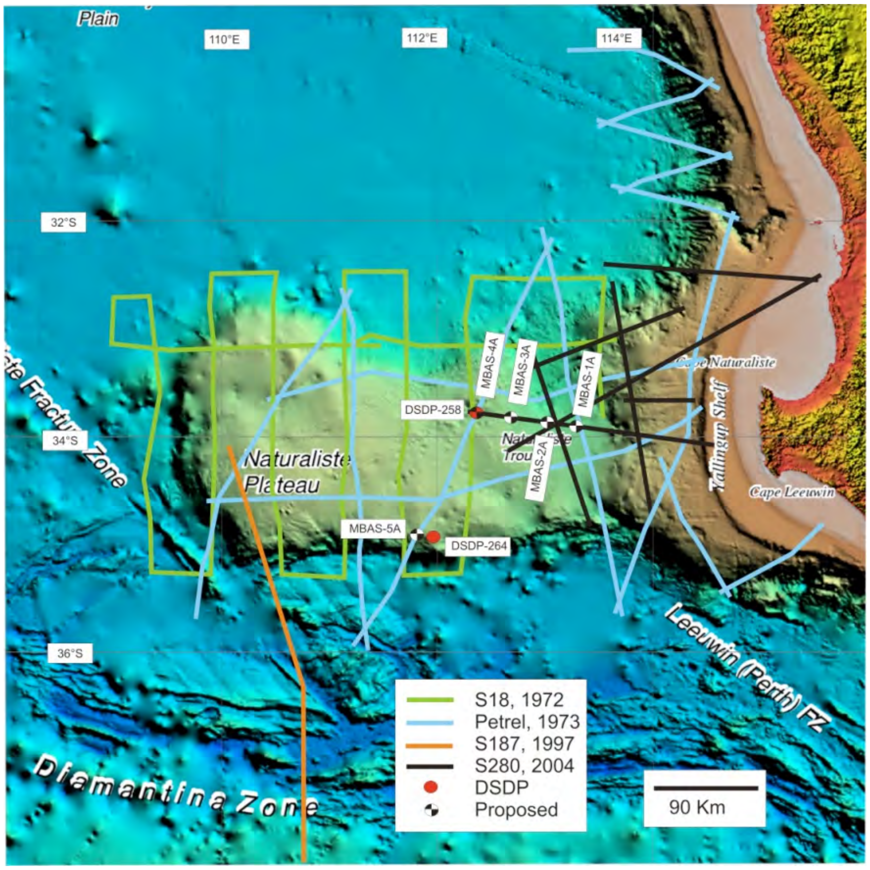


Figure 4: Seismic Profile S280-501 showing location of DSDP Site 258 , DSDP Site 264, and sites proposed for future drilling.

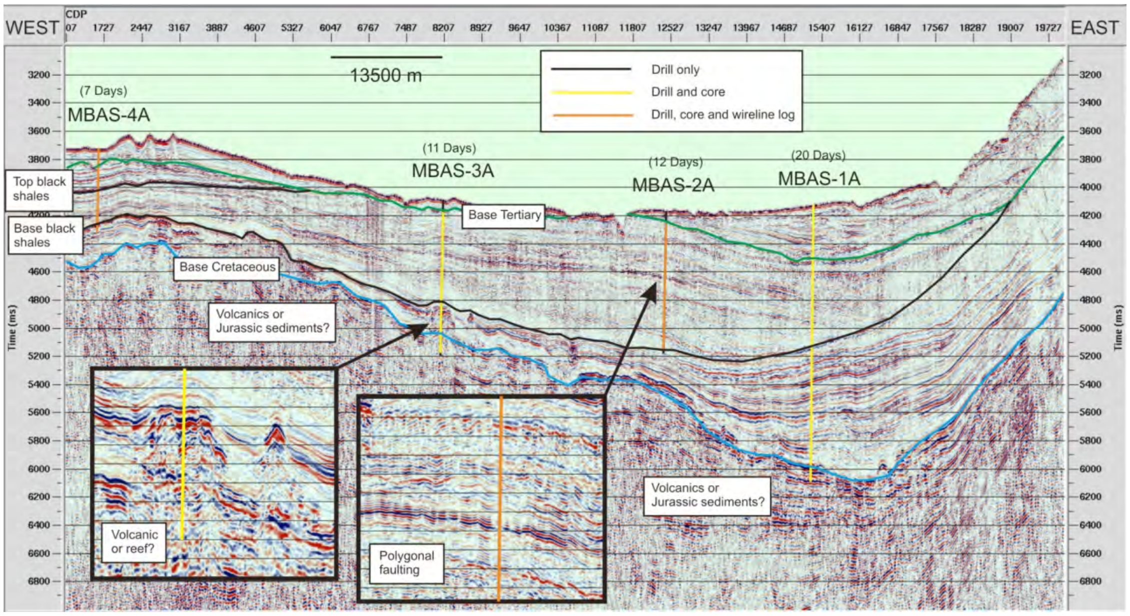


Figure 5. Seismic Profile S280-501 showing location of DSDP Site 258 and sites proposed for future drilling.

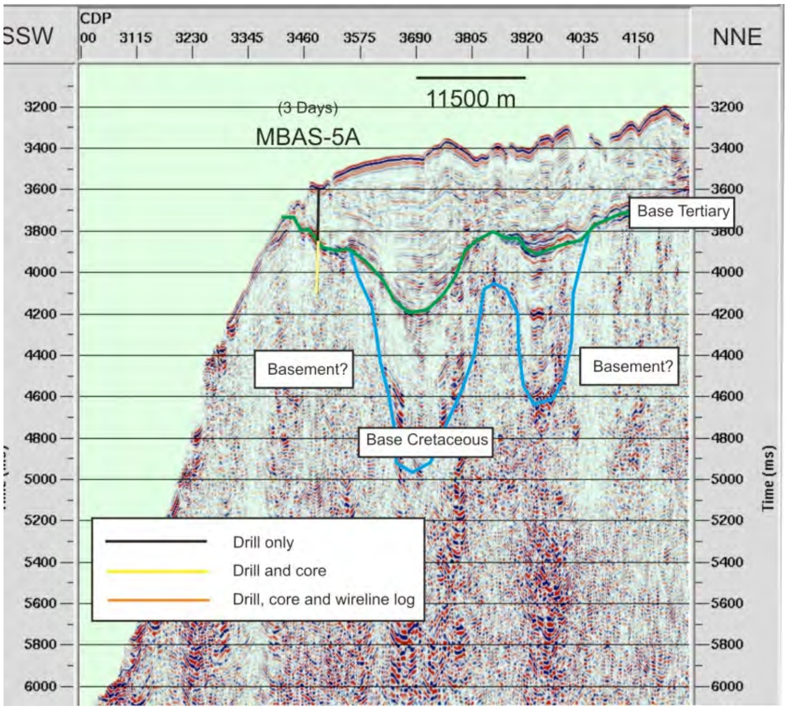


Figure 6. Proposed drilling site (MBAS-5A) to investigate the origin of the Naturaliste Plateau. This proposed site is located ~10 km west of Site 264 and thus will reproduce that coring record.

Naturaliste Plateau

A. Challenges that Naturaliste Plateau will address:

Climate and Oceans:

- *1. How does Earth's climate system respond to elevated levels of atmospheric CO_2?*
- *2. How do ice sheets and sea level respond to a warming climate?*
- *4. How resilient is the ocean to chemical perturbations?*

Biosphere Frontiers:

- *7. How sensitive are ecosystems and biodiversity to environmental change?*

B. Justification for Naturaliste Plateau Drilling

- Will provide a well resolved long-term paleotemperature history at high paleolatitudes (60-65°S) spanning the relatively cool conditions of the Albian, the supergreenhouse of the Cenomanian-Santonian and the return to cooler conditions of the Maastrichtian.
  - Previous coring (e.g., Sites 258, 264) yielded well-preserved planktonic and benthic foraminifera from the Cenomanian–Santonian (e.g. Huber et al., 1995) and moderately preserved Albian foraminifera, but because of poor core recovery the sediments are unsuitable for study of critical intervals (e.g., OAE1d, OAE2).
  - Good potential that Cretaceous and possible Jurassic sediments will yield well-preserved organic biomarkers for SST reconstructions given thermal immaturity of previously recovered material. Multi-proxy reconstructions suggest extreme warmth at ~60˚S throughout much of the mid-Cretaceous, which climate models have been unable to simulate (e.g. Bice et al., 2003).
  - Results have important implications for verifying or refuting predictions in the "greenhouse ice-sheet" model (Miller et al., 2003; Moriya et al., 2007; Bornemann et al., 2008; MacLeod et al., in press).
- The sediment record would provide a history of surface and deep water circulation in the southeast Indian Ocean during the diachronous gateway opening between the Australian and Antarctic continents, which had separated by the Turonian (Beslier et al., 2004).
- Mid-Cretaceous black shales have been shown to exist at Site 258, although OAE2 was not recovered. Reconstructing both climate and oceanographic conditions across OAEs in a high latitude setting address Climate and Oceans Challenges 1 and 4, whilst recovery of black shales and high latitude assemblages can be used to address Biosphere Challenge 7.

C. Provisional strategy:

- Seismic data from Geoscience Australia suggest that there is potential for a suite of sites on Naturaliste Plateau that can be used to address:
  - The oceanographic development of the Southern Ocean during gateway opening
  - The expression of OAEs at high latitudes
  - High latitude greenhouse climates.
- Raw shot records for the S18, Petrel and S280 seismic reflection surveys (Figs. 1-3) were provided by Geoscience Australia for re-processing. Profile S280-501 passes within 10 m of borehole Site 258 providing the only tie for the seismic interpretation.
- The following drilling strategy is considered highest priority for achieving ocean history objectives:
  - Depth transect of black-shale deposition (MBAS- 2A, 3A, 4A).
- Drilling Mesozoic sediments (MBAS-2A, 3A, 4A). Shipboard analysis of the cores from Site 258 showed a TOC value up to 2% for the mid-Cretaceous (Albian) clays, and these clays obtain a maximum thickness of ~1000 m within the Mentelle Basin. This sequence of shales would

produce one of the most expanded Albian black shale intervals from an oceanic drilling site. Based on thickness drilled through DSDP Site 258 and assuming constant sedimentation rate the Albian shales would equate 1cm to 270 years.

- Drilling into Mesozoic reefs or volcanics (MBAS-5A). During the reprocessing of the Geoscience Australia seismic data in the Mentelle Basin, significant structures were found at the base of the Cretaceous unconformity, and this study relates them to either volcanoclastic wedges or carbonate reefs. If the latter is the case then the age of these reefs will be important in determining the timing, formation and history of break-up of the Naturaliste Plateau
- The drilling strategy will be to double/triple core using APC/XCB to refusal. For older objectives it may be necessary to use rotary coring. Logging will be used to aid core-log-seismic integration and aid in composite depth reconstruction for deeper targets.

References:

Beslier, M.O., Royer, J.Y., Girardeau, J., Hill, P.J., Boeuf, E., Buchanan, C., Chatin, F., Jacovetti, G., Moreau, A., Munschy, M., Partouche, C., Robert, U. & Thomas, S., 2004. Une large transition continent-ocean en pied de marge sud-ouest australienne: premiers resultats de la champagne MARGAU/MD110. *Bulletin Societe Geologique Francaise*, v. 175, p. 629-641.

Bice, K. L., Huber, B. T., and Norris, R. D., 2003, Extreme polar warmth during the Cretaceous greenhouse? The paradox of the late Turonian δ^{18}O record at DSDP Site 511: Paleoceanography, v. 18, p. 1031, doi:1010.1029/2002PA000848.

Bornemann, A., Norris, R. D., Friedrich, O., Beckmann, B., Schouten, S., Sinninghe Damsté, J. S., Vogel, J., Hofmann, P., and Wagner, T., 2008, Isotopic evidence for glaciation during the Cretaceous Supergreenhouse: Science, v. 319, p. 189-192.

Huber, B. T., Hodell, D. A., and Hamilton, C. P., 1995, Mid- to Late Cretaceous climate of the southern high latitudes: Stable isotopic evidence for minimal equator-to-pole thermal gradients: Geological Society of America Bulletin, v. 107, p. 1164-1191.

Jiménez Berrocoso, A., MacLeod, K. G., Martin, E. E., Bourbon, E., Londoño, C. I., and Basak, C., 2010, Nutrient trap for Late Cretaceous organic-rich black shales in the tropical North Atlantic: Geology, v. 38, p. 1111-1114.

MacLeod, K. G., Huber, B. T., Jiménez Berrocoso, A., and Wendler, I., 2013, A stable and hot Turonian without evidence for a greenhouse ice-age inferred from exquisitely preserved Tanzanian foraminifera in Tanzania Geology, p. in press.

Miller, K. G., Wright, J. D., Sugarman, P. J., Browning, J. V., Kominz, M. A., Hérnandez, J. C., Olsson, R. K., Feigenson, M. D., and van Sickel, W., 2003, Late Cretaceous chronology of large, rapid sea-level changes: Glacioeustasy during the greenhouse world: Geology, v. 31, p. 585-588.

Great Australian Bight (GAB) Deep Biosphere (Pre2, Wortmann *et al.*)
Ancillary Project Letter (pre-proposal) to Proposal 701

The Bight Basin Survey found evidence of a Cretaceous source-rock in shale samples dredged from the exposed up-dip NW edge of the Ceduna Sub-basin. Geochemical analysis (Area 5, see Figure 7) has revealed good to very good organic richness (TOC 2.0-6.9%) and organic matter with a marine signature, deposited under reducing (anoxic) conditions. The samples have been dated as Cenomanian-Turonian boundary interval (CTBI) and this strongly suggests these C_{org}-rich sediments are a local expression of Oceanic Anoxic Event 2 (OAE2) (Geoscience Australia Report, 2010). Wortmann *et al.* (Pre-Proposal 701) intend to investigate biogeochemical processes in microbial communities in the deep subsea-floor of the GAB. We propose drilling one extra site (double coring) in this region to obtain this OAE2 record. [Alternatively, we could use the Mebo to drill more holes to shallower depths.]

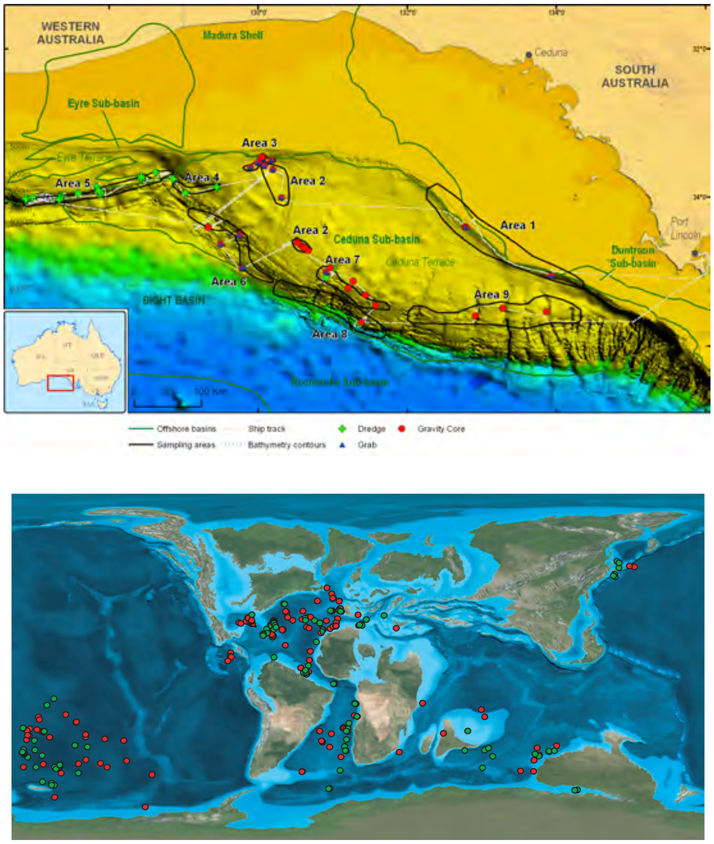


Figure 7. Australian Bight map (top) and plate tectonic reconstruction of the Cretaceous ocean basins at 90 Ma (bottom) showing drilling deep sea sites.

During the CTBI (~93Ma), the GAB was a restricted basin occupying a high southern latitude and was also a developing gateway between the high-latitude Pacific and Indian oceans, with an established marine connection to the Indian Ocean (Figure 7). The OAE2 record at this location is thus unique. Although seismic interpretations/onshore correlations suggest the Mesozoic sediments at ODP Leg 182 sites are siliciclastic (Cenomanian strata were suggested at Sites 1126 and 1134), this is apparently not the case. The reported nature of the sediments (marine shales, high TOC, ± carbonate) suggests a palaeoceanographic proxy toolbox that will potentially include $\delta^{13}C_{org}$ isotope stratigraphy, redox indicators (*e.g.* Fe-speciation, Mo-isotopes, metal ratios), biomarker assemblages, and GDGT-based palaeothermometry (*i.e.* TEX_{86}, MBT/CBT), ± planktonic foram $\delta^{18}O$ palaeothermometry. A well-constrained time-frame can be achieved using palynology (± forams/nannos, dependent on carbonate content).

Consequently, this record offers the opportunity for us to investigate:

(1) the development of OAE2 and water-column oxygenation (redox?) in a (a) restricted (euxinic, anoxic?) and (b) high southern-latitude location
(2) the nature of the primary productivity that formed these deposits
(3) the temperature record for this supergreenhouse interval at high-latitude

(4) palaeoenvironmental and palaeoecological contrasts between this OAE2 record and OAE2 records from (a) more open-ocean locations and (b) different latitudes
(5) the evolution of microfossil groups in relation to the OAE

George V Land and Adélie Land shelf sediments

IODP proposal 813-full: Greenhouse to Icehouse Antarctic paleoclimate and ice history from

Williams, Escutia, Santis, O'Brien, Pekar, Brinkhuis, Domack

Along the George V and Adélie Land (GVAL) shelf of Antarctica (~137°-148° E, south of Tasmania), shallowly-buried strata contain a record of Antarctica's climate and ice history from the Cretaceous and Eocene greenhouses to the dynamic ice sheet margins of the Neogene. This proposal seeks to drill an age transect across the GVAL shelf using 80-m deep holes drilled from the MeBo sea bed drill. This will provide age windows into high-latitude climate, including two sites targeting Early Cretaceous strata.

A short piston core east of the Mertz Glacier recovered 40-cm of Early Cretaceous (Aptian) organic-rich non-marine siltstone with a rich palynological assemblage (Domack et al., 1980). These Early Cretaceous sediments can be traced along the inner shelf as graben-fill in seismic profiles. They were likely deposited in an inland basin or a shallow seaway, before the Late Cretaceous separation of Australia and Antarctica. The organic-rich siltstone had a rich palynological assemblage and provided details of Early

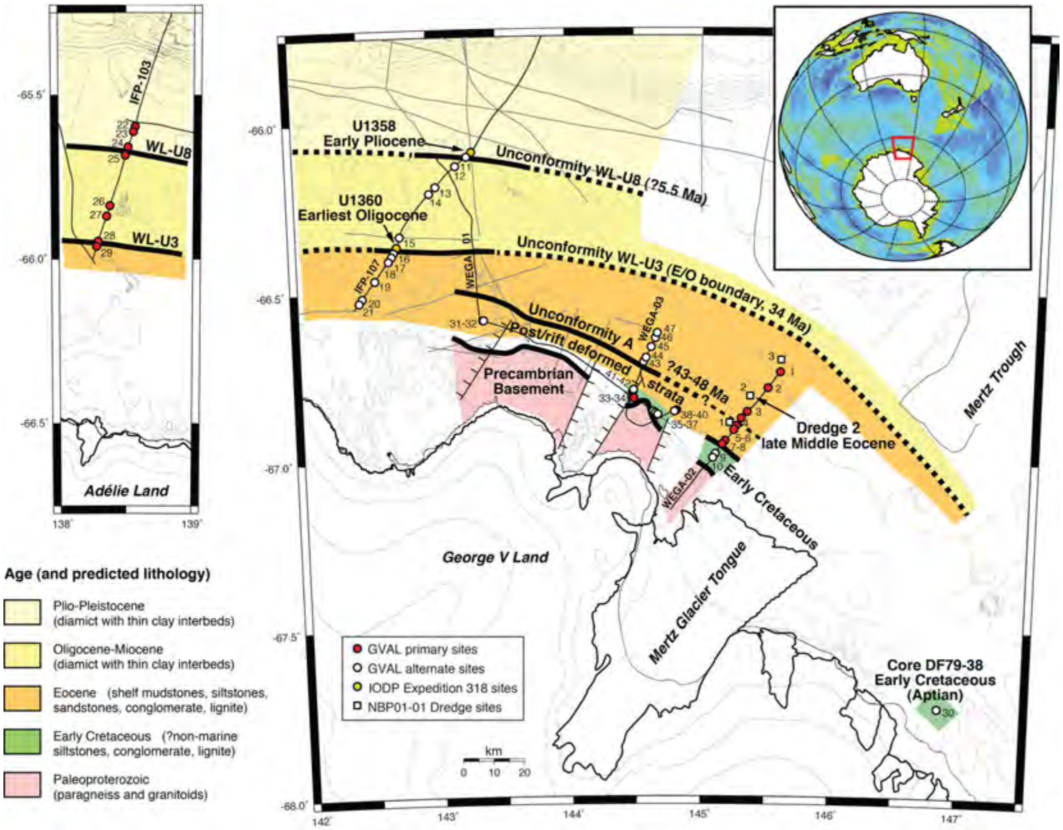


Figure 8: George V Land site location map. Cretaceous outcrop shown in green.

Cretaceous Antarctic vegetation. Organic geochemical methods should be able to provide information on paleotemperatures, although the strata could have been buried more deeply that 1 km, based on vitrinite reflectance. Lignites have also been found in dredge samples (some of which are thought to be Eocene in age). Thus we speculate that the Cretaceous succession could include alternations of varying organic content, and provide information on cycles in temperature and precipitation. The high-paleolatitude of the sites will provide constraints on pole-equator temperature gradients and their evolution. The sites on the George V Land shelf should also provide material to compare and contrast Cretaceous and Eocene Greenhouse environments. This proposal addresses the IODP science plan's challenges "How does Earth's climate respond to increased CO_2?" and "How do ice sheets and sea level respond to a warming climate?"

References

Domack, E. W., W. W. Fairchild, and J. B. Anderson (1980), Lower Cretaceous sediment from the East Antarctic continental shelf, *Nature*, *287*(5783), 625-626.

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Appendix
Workshop Timetable

Monday 15th April

Time	Event	Location
9.15	Registration	Chadwick G08
10.00	Introduction and welcome to UCL	Pearson LT
10.15	Theme 1: Cretaceous climate & circulation	Pearson LT
10.45	Theme 2: Cretaceous anoxia	Pearson LT
11.15	Theme 3: Ocean acidification and plankton response to environmental change in the Cretaceous	Pearson LT
11.45	Breakout groups to discuss themes	Breakout rooms
12.45	Lunch	Chadwick G08
13.30	Report back on Science themes	Pearson LT
14.00	Introduction to IODP proposal system	Pearson LT
14.30	Introduction to Site Survey requirements	Pearson LT
15.00	Tea and coffee break	Chadwick G08
15.30	Highlights of recent drilling	Pearson LT
16.30	Posters and reception	Chadwick G08
19.00	Close	

Tuesday 16th April

Time	Event	Location
9.00	Introduction to breakout groups	South Wing Rm 44
9.15	Breakout groups	Breakout rooms
11.00	Coffee	
11.30	Breakout groups	Breakout rooms
13.00	Lunch	
14.00	Break out groups	Breakout rooms
15.30	Coffee	
16.00	Breakout groups	Breakout rooms
18.00	Formal end to day	

Wednesday 17th April

Time	Event	Location
9.00	Breakout groups	Breakout rooms
10.45	Coffee	
11.15	Plenary - review of breakouts and identification of writing groups	Pearson LT
13.00	Lunch available and departure	