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Critical Literature Review
(ANTA602)

ANDRILL: Has it accomplished all it set out to achieve?

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Abstract

ANDRILL (ANtarctic geological DRILLing) is a multinational drilling project that is drilling into sediments under the Ross Ice Shelf in Antarctica. ANDRILL are looking at sediment cores to find evidence supporting the theory of past paleoclimatic changes in the Ross Ice Shelf area (and globally). This review evaluates the ANDRILL project to see if it has met its own conditions and to see if it has added to the geological and climatic knowledge of the Antarctic Region.

ANDRILL has currently completed drilling in two sites (McMurdo Ice Shelf (MIS) Project and Southern McMurdo Sounds (SMS) Project) and has recovered 1285m of core material from the MIS project with sediments dating back to ~13 Ma, and another 1138m drill core from the SMS project with sediments dating back to ~20 Ma. Through analysis of these cores, ANDRILL has been able to locate each ice sheet retreat and advance in the vicinity of the drill sites over the past 20 million years. So far, there has been a lot of analysis on the sediment cores themselves, however there is a lack of correlation between these sediments and the dates they were deposited and how this relates to past and future climatic changes.

Contents

ANDRILL (ANtarctic Geological DRILLing) is a multinational project that includes over 200 scientists, students and educators from 7 different nations (ANDRILL, n.d.(a)). The chief objective of ANDRILL is to understand the paleoenvironmental changes that have occurred in the Antarctic Margin over the Cenezoic Era (approx. 65 MYA to present) through ice core drilling (ANDRILL, n.d.(b)). ANDRILL are aiming to retrieve information from the cores on the glacial and interglacial periods that have affected the Antarctic region, as well as gathering enough data to give an overview of the early tectonic history of the area. According to the ANDRILL Media Release, "without these reference records of sediment and fossils to be recovered in ANDRILL cores, our understanding of the global system would remain incomplete and biased towards largely non-Antarctic records" (ANDRILL SMO, 2007. Pg 6). This statement is misleading as there have been other drilling (CRP, MSSTS, CIROS) and ice core (Vostok Ice Core Drilling) projects that have started to collate scientific data on climatic changes in Antarctica. Through ANDRILL cores and data analysis, ANDRILL are going to use past climate change patterns to help understand the possibility of future climatic changes. ANDRILL are especially interested in finding comparable amounts of atmospheric CO_2 in the ice with that projected to be seen in the next century (ANDRILL, n.d. (b)). This way ANDRILL can relate what is happening to our CO_2 levels currently to that of the past and the cycles of climate change over geological history. From this, ANDRILL is to relate this to the potential response of the Polar Regions to changes in the amount of greenhouse gases, in regard to ice volumes, terrestrial and marine temperature changes and future ice sheet formation and destruction. The position of the ANDRILL drill sites was chosen due to the area being well understood in its stratigraphy (due to past drill projects) and because of its critical junction between the East and West Antarctic Ice Shelves, its proximity to TAM and the West Antarctic Rift System (Naish et al, 2007; Harwood et al, 2006).

So far, ANDRILL has drilled in two ice shelf areas of the Antarctic in the anticipation of collecting continuous stratigraphic ice records. ANDRILL has already gathered ice core data from the McMurdo Ice Shelf (MIS) Project and from Southern McMurdo Sounds (SMS) Project and are now preparing to drill at Coulman High, which is near the seaward edge of the Ross Ice Shelf. The key objectives of ANDRILL are hard to pinpoint as different publications (From the same source – ANDRILL) give slightly different objectives (ANDRILL Steering Committee, 2003; Bannister & Naish, 2002; Harwood & Florinda, 2006, Harwood & Florinda, n.d.; Henrys et al, 2001; Horgan, 2003; Naish & Powell, 2006, Naish & Powell, n.d.; Naish et al, 2001). Below are the four overriding themes for ANDRILL:

1. The history of ice sheet stability including a composite event history of glacial and interglacial events.
2. The influence of ice shelves and sea ice on the global system, including atmospheric and oceanic circulation.
3. Origins and adaptations of polar biota and their response to warm, cold and extreme environments and events.
4. To document the evolution and timing of major West Antarctic Rift System (WARS), the Transantarctic Mountains (TAM) and local volcanism and their influences on stratigraphic development of associated sedimentary basins.

ANDRILL: The origins and adaptations of Polar Biota

Polar Biota has been an integral part of dating the sediment layers of the ANDRILL cores, along with indicating whether the area was open ocean, ice proximal or ice grounded (Scherer et al, 2007; Di Vincenzo et al, 2010; McKay et al, 2011). This has not been the only way of dating sediment as Ar-Ar dating (Zattin et al, 2012), magneto-stratigraphic dating and radio dating have also been used (Florindo et al, 2008).

Through diatomaceous sediment layers (foraminifera were rare, therefore not used in dating the sediment (Scherer et al, 2007)), it has been inferred that these time periods were when the ANDRILL drill site was in open water and where ice influences were minimal (Konfirst et al, 2011). This suggests that the Ross Ice Shelf was smaller than it is today. Depending on the researcher, the number of diatomaceous layers in the ANDRILL cores are 13 (Scherer et al, 2007; Konfirst et al, 2011) or 14 (Di Vincenzo et al, 2010), with the largest layer being up to 76m thick in the Early to Mid-Pliocene (5 – 3 Ma) (Konfirst et al, 2011), indicating a long warm period where ice was limited. Scherer et al (2007) found that the diatomaceous layers were mainly found in the upper 600m of the ANDRILL core which is dated to about the Late-Pliocene, however his data is tentative and further investigations are needed to clarify these findings. The layers that contained diatoms showed little diversity (Scherer et al, 2007), which indicated high productivity of the few species that existed within each time frame. Within these diatom layers there are three distinct ecological diatom groups that are based on their adaptations and tolerance for differing water temperatures. These three groups can be seen in stratigraphic records, moving from one dominant group to the next. The changes in these dominant groups show the changing ice shelves, as 'Sub-Antarctic diatoms' can be found in the sediment cores during open water environments in the area (warm climatic period with limited ice) through to 'polar open ocean and sea ice tolerate' (transitional periods between glacials and interglacials) and the final group being 'sea ice' species which are tolerate of persistent sea ice (McKay et al, 2012(a)). Time periods when ice shelves persisted (like today) or have been grounded, there are no diatoms found in the sediments as diatoms are photosynthetic pelagic species that need a water body that has sunlight filtering through it.

ANDRILL: The history of ice sheet stability including a composite event history of glacial and interglacial events

Through ANDRILL, the knowledge of the Early to Mid-Miocene record has been expanded (Paulsen et al, n.d.). ANDRILL has collected the first direct evidence of oscillating marine ice sheets, where temperatures and carbon dioxide levels were higher than today (ANDRILL, n.d.(c)). There is clear evidence that there have been ice advances and retreats over the drill site area over the past 20 Ma (Fielding et al, 2011) and this is composed of approximately 74 short-order glaciomarine sequences that can be correlated into 13 long-order sequences of climate warming and cooling (Fielding et al, 2011). These 13 lithofacies show changes from ice minimal and shallow marine time periods (indicated by high levels of diatomaceous sediments), to ice-contact time periods (indicated by diamictite and sandstones), through to grounded ice (indicated by shear planes, sediment distortion (Di Vincenzo et al, 2010) and unconformities (Acton et al, 2008; Di Roberto et al, 2010)). Grounded ice has covered the drill site at least three times (19.4 mya, 18.6 mya and 17.6 mya) and the Ross Ice Shelf has been stable for the past 14 Ma according to Zattin et al (2012), The RIS has retreat approximately 1300km since the Last Glacial Maximum (LGM) though(McKay et al, 2012(b); McKay et al, 2012(a)), which was ~14.3 mya, as there was rapid cooling between 15 and 13 Ma (Hauptvogel & Passchier, 2011). Through the data collected from the drill cores of ANDRILL there is evidence that many of the ice advances where rapid but short-lived, as there is little evidence of erosion (from grounded ice) on many of the layers (ANDRILL, n.d.(c)).

The drill records from the Southern McMurdo Sounds Project (SMS), show levels of sustained global warmth during the Mid-Miocene Climatic Optimum (17 – 14 Ma) (ANDRILL, n.d.(d)). This correlates with prolonged periods of ice retreat found in the sediment cores, however ANDRILL were unable to show glacial variability at levels of atmospheric carbon dioxide presumed to have existed in the Miocene (ANDRILL, n.d.(d)). Further study will need to occur to make this connection, if there is one.

On a smaller scale, McKay et al (2011) looked at the past 2 million years and found that subglacial to grounded ice (ice sheet advances and retreats) have occurred at least 7 times in the last 780 ka, giving rise to the theory of the influence of the Milankovitch orbital cycles on ice dynamics.

Some modelling has been done by Pollard & DeConto (2009), looking at the past 5 Ma and the transitions between glacial and interglacial periods. The model shows rapid transitions of ice retreat, a theory that is supported by ANDRILL (n.d.(c)). The modelling fits well with the MIS 31 collapse (1.08 – 1.06 Ma), however has not always matched other collapses (Pollard & DeConto, 2009). As with many other publications, definitive data is limited and more investigation is needed.

ANDRILL: The influence of ice shelves and sea ice on the global system

It is well known that ice sheets are important to global climate, mainly due to the high albedo of ice reflecting the suns heat and the influence of ice shelves on ocean circulation and salinity (Hauptvogel & Passchier, 2011). There is limited direct discussion about the effect ice shelves have on the global system in regard to ANDRILL sediment core data. In most circumstances, it is too early in the investigations of the cores to make definitive statements about the influence of ice shelves. Naish & Powell (2006) state that ice shelves are sensitive to changes in atmospheric and oceanic temperature changes and the collapse of the RIS could affect the thermohaline oceanic circulation. It has been stated by Hauptvogel & Passchier (2011) that the ANDRILL cores allow continuous data collecting at an ice proximal site that will give valuable information about the global system. Fielding et al (2011), has incorporated sea-level estimates in their figures, however do not outline directly, the changes in the sea levels during glacial and interglacial time periods. ANDRILL's cores are giving, for the first time, direct evidence of the WAIS collapses and these can be aligned with sea level changes and benthic δ^{18} O levels, which indicate changing temperature (ANDRILL, n.d.(c); DeConto et al, 2012).

Konfirst et al (2011) has modelled the ice shelf demise between 5 – 3 Ma with carbon dioxide levels 30 – 100% higher than Pre-industrial levels. The thermohaline circulation was affected and this inhibited the growth of sea ice increasing ice shelf melt, lowering albedo and ultimately creating an ice shelve retreat. The model shows a loose correlation to the Milankovitch Orbital Cycles (Konfirst et al, 2011; ANDRILL, n.d.(c)). The main evidence for this is an 80,000 year cycle of glacial advance and retreat (with a 20,000 year unconformity at its base), which equals out to the 100,000 year cycle of the Milankovitch Orbital Cycle (Konfirst et al, 2011).

ANDRILL: The evolution and timing of major West Antarctic Rift System (WARS), the Transantarctic Mountains (TAM) and local volcanism and their influences on stratigraphic development of associated sedimentary basins

New knowledge ascertained by ANDRILL in relation to the tectonic and rift system of the Ross Embayment, along with the stratigraphic development of the associated sedimentary basins has been limited at this point. Before ANDRILL there was knowledge of the subsidence due to the Mt Erebus Province and the associated accumulation of sediments. Through the sediment cores of ANDRILL, a new eruption has been dated through Ar-Ar dating. This eruption was in the Late Eocene / Early Oligocene and its actual location is at this point unknown. It is thought to be a subglacial volcano under the WAIS and be located approximately 100km off shore of Ross Island (based on a magnetic anomaly in that area) and be the approximate area of Mt Erebus (Zattin et al, 2012). This time setting coincides with rifting in the area.

This is not the only new eruption site or sequence that has been found by ANDRILL sediment core. ANDRILL has found the first rock evidence of a significant Late Miocene (6.48 Ma) submarine volcano. There were earlier eruptions - a pumice – lapilli tuff dated to approximately 22Ma by CRP (Di Roberto et al, 2010) along with more pumice layers at ~19.15 Ma and again at ~19.10 Ma (Acton et al, 2008), however this was the first rock rather than volcanic tephra found. This newly found eruption took place in an open ocean environment (therefore, less of an ice shelf than today). There is no definitive pillow lava to support this, however there are glassy rinds, flows and shears that do (Di Roberto et al, 2010). The sediment cores of ANDRILL show that the eruption started with a pyroclastic flow that provided a 70m thick sediment layer of volcanic mudstones and sandstones. This was followed by 105m thick layer of interbedded tuff that suggests a phreatic eruption, where the magma came into contact with water, producing a very large amount of tephra that settled over the ANDRILL site more than 6 Ma. A 2.8m thick tephrite lava flow sits above the tuff layer. It is thought that it was a single eruption event that may have lasted anywhere between several days to a few years (Di Roberto et al, 2010). By the time the volcano was producing lava flows it was emerging from the water. This is supported by the oxidisation of volcanic material, which must have been above water in order to react with oxygen. At the time of this eruption, Mt Erebus did not exist and therefore that subsidence would not have been there as well. This meant the volcano would not have had to have been very large to be emergent (Di Roberto et al, 2010).

Di Vincenzo et al (2010) also stated that volcanism has been nearly continuous in the RIS area since the Early Miocene and this can be seen in the multiple layers of volcanic clasts and tephra in the sediment cores of ANDRILL. Interesting, this active volcanism has progressively moved towards the Northeast (Di Vincenzo et al, 2010). Mt Morning erupted around 18.7 mya, Minna Bluff – 10 mya, White Island - 7.7 mya, Hut Point – 2 mya and Mt Erebus 1.3 mya (Di Roberto et al, 2010). This is a general trend which does not fit all eruptive sites as Mt Bird which is Northeast of Mt Erebus, erupted approximately 4 mya.

Magnetic reversals in the Ross Embayment have also been recorded through ANDRILL cores (Acton et al (2008)). The ANDRILL sediments record 23 magnetic zones – 12 reverse and 11 normal magnetisms. Through Acton et al's (2008) analysis many areas within the ANDRILL core were not conclusive in their results, therefore had many 'uncertain polarities' (Acton et al, 2008, Pg 215). Wilson et al (2007) using a different method of measuring magnetism, was able to assign a magnetic polarity to all his samples, answering a few of the 'uncertain polarities' by Acton et al (2008).

Sediments in core samples have been found to be mainly from the Discovery Accommodation Zone and not the closer Royal Society Range, which suggests that the ice shelves and glaciers have transported the material to the ANDRILL site. Problems have been found when dating sediments with volcanic clasts as many of them have been 'reworked' and transported before final deposition (Di Vincenzo et al, 2010). This means that many volcanic layers in the ANDRILL cores are of a different age than the sediment they are found in. This is based on dating and analysis of sediment. Di Roberto et al (2010) also surmised that ice from the EAIS and WAIS must have had to sweep around White Island and Minna Bluff depositing foreign volcanic clasts in the ANDRILL core site. This accounts for the knowledge of the Mt Morning volcanic histories that would not have otherwise been found at the ANDRILL sites, as Mt Morrning is far south of the drill sites.

The only reference to new information on the WARS, TAM or tectonic movements was by Acton et al (2008), where he stated that "additional breaks in section may be due to tectonic processes (Pg 211). There has been very limited documentation of new information on these geological processes in any publication read.

Summary of findings: have ANDRILL met their objectives?

According to Florinda et al (2008), ANDRILL have reached their scientific targets. This is evident in their 98% core retrieval that covers over 20 million years of sedimentary data (ANDRILL, n.d. (c)), however the published information on the analysis of this data is still lacking many details and new scientific knowledge.

ANDRILL publications have shown a lot of variation in the goals of ANDRILL. Depending on which publication read, there were slightly different goals outlined. This made it hard to decipher what ANDRILL's actual goals were. All publications listed goals that were in correlation with each other, however different wording, different number of goals and different focusses of goals were found (ANDRILL Steering Committee, 2003; Bannister & Naish, 2002; Harwood & Florinda, 2006, Harwood & Florinda, n.d.; Henrys et al, 2001; Horgan, 2003; Naish & Powell, 2006, Naish & Powell, n.d.; Naish et al, 2001). The final four themes that this review is based on is the amalgamation of the goals outlined by different ANDRILL publications.

The majority of papers published in relation to ANDRILL have focused on the geological and biological make up of each sediment layer and explaining the conditions that they were laid down. There is a lot of information about the glacial advances and retreats related to the sediment thickness and composition, however many publications have only gone as far as this in their conclusions. Very few publications have linked the thickness of the sediment layers or their depth within the core to the actual age that it was laid down. Acton et al (2008) was the only paper to really outline the depth of each layer and relate it to the time that it was deposited. Others only touched on certain dates rather than the overall picture.

There have been limited publications (mainly only McKay et al, 2012(a)) that focus on how this new knowledge on ice sheet advance and retreat has affected or been affected by atmospheric or oceanic circulation. The link between the global system and the sedimentary evidence is so far missing. There is already some knowledge of how ice shelves affect the Thermohaline Ocean Circulation and Bottom Water Circulation, however the links of the ANDRILL data to these processes are missing. In relation to this, the link of the ice sheet advance and retreat has not really being linked to the overlying patterns and theories (CO_2 level changes, climate change, Milankovitch Orbital Cycles). Many have touched on it (DeConto et al, 2009; Fielding et al, 2010; Konfirst et al, 2011; Pollard & DeConto, 2009McKay et al, 2012(a)), however they have not had the scientific evidence, at this point, to make overarching statements about the link between these global systems and the ANDRILL sediments. With more investigations on the ANDRILL data, more correlation and evidence will emerge.

Models are now beginning to surface (DeConto et al, 2012) that are using ANDRILL data to predict how the advance and retreat of the RIS occurred over the last 5 million years. These models are still in preliminary stages and as more data is accumulated, a more substantial model can be applied. DeConto et al (2012) admitted themselves that the model does not account for all the sedimentary evidence from ANDRILL. From there, models will need to start focusing on how the past changes in ice sheets can help us understand the future. None of the publications that were analysed discussed how this new knowledge of ice sheet dynamics can help us understand the future. As the link between CO_2 levels and ocean circulation to ice sheet dynamics become clearer, the focus needs to be on modelling future atmospheric, oceanic and cryospheric changes and what that means for the global system.

Acton, G., J. Crampton, et al. (2008). "Preliminary Integrated Chronostratigraphy of the AND-2A Core, ANDRILL Southern McMurdo Sound Project, Antarctica."

Anderson, J. B. (1999). Antarctic marine geology. New York, Cambridge University Press.

ANDRILL. (n.d.(a), 18/11/2012). "ANDRILL: Antarctic Geological Drilling; Home Page." 2006, from http://www.andrill.org/static/index.html.

ANDRILL. (n.d.(b), 18/11/1012). "About ANDRILL." from http://www.andrill.org/static/About.html.

ANDRILL. (n.d.(c)). "Post Drilling Results: McMurdo Ice Shelf (MIS) Project." from http://andrill.org/static/PostDrillingResults_mis.html.

ANDRILL. (n.d.(d)). "Post Drilling Results: Southern McMurdo Sound (SMS) Project." from http://andrill.org/static/PostDrillingResults_sms.html.

Bannister, S. and T. Naish (2002). ANDRILL site investigations, New Harbour and McMurdo Ice Shelf, Southern McMurdo Sound, Antarctica. Lower Hutt, N.Z, Institute of Geological & Nuclear Sciences.

Barrett, P. J. (1986(a)). CIROS (K014). Victoria University Antarctic Research Expedition Science and Logistics Reports 1986-87: VUWAE 31 A. Pyne. Victoria University of Wellington.

Barrett, P. J., C. Cape Roberts Project. International Steering, et al. (1997). Cape Roberts Project science plan: coring for Antarctic tectonic and climatic history. Wellington, N.Z., Antarctic Research Centre, School of Earth Sciences, Victoria University of Wellington.

Barrett, P. J., B. C. McKelvey, et al. (1986). Stratigraphy Antarctic Cenozoic history from the MSSTS-1 drillhole, McMurdo Sound. Wellington, N.Z, Science Information Publishing Centre, Dept. of Scientific and Industrial Research. 237: 9 - 52.

Barrett, P. J., S. New Zealand. Dept. of, et al. (1986(b)). Introduction Antarctic Cenozoic history from the MSSTS-1 drillhole, McMurdo Sound. Wellington, N.Z, Science Information Publishing Centre, Dept. of Scientific and Industrial Research. 237: 5 - 8.

Committee, A. S. (2003). Future antarctic margin drilling: developing a science program plan for McMurdo Sound : report of a workshop, Oxford, UK, April 5-7, 2001. Lincoln, NE, ANDRILL Science Management Office.

DeConto, R. M., D. Pollard, et al. (2012). "Modeling Antarctic ice sheet and climate variations during Marine Isotope Stage 31." Global and Planetary Change 88-89: 45-52.

Di Roberto, A., M. Pompilio, et al. (2010). "Late Miocene submarine volcanism in ANDRILL AND-1B drill core, Ross Embayment, Antarctica." Geosphere 6(5): 524-536.

Di Vincenzo, G., L. Bracciali, et al. (2010). "Ar-40-Ar-39 dating of volcanogenic products from the AND-2A core (ANDRILL Southern McMurdo Sound Project, Antarctica): correlations with the Erebus Volcanic Province and implications for the age model of the core." Bulletin of Volcanology 72(4): 487-505.

Fielding, C. R., G. H. Browne, et al. (2011). "Sequence stratigraphy of the ANDRILL AND-2A drillcore, Antarctica: A long-term, ice-proximal record of Early to Mid-Miocene climate, sea-level and glacial dynamism." Palaeogeography, Palaeoclimatology, Palaeoecology 305(1): 337-351.

Florindo, F., D. Harwood, et al. (2008). "ANDRILL's Success During the 4th International Polar Year." Scientific Drilling.

Gamble, J. A., P. J. Barrett, et al. (1986). Basaltic clasts from Unit 8. Antarctic Cenozoic history from the MSSTS-1 drillhole, McMurdo Sound. Wellington, N.Z, Science Information Publishing Centre, Dept. of Scientific and Industrial Research. 237: 145 - 152.

Harwood, D., J. Cowie, et al. (2006). "Deep drilling with the ANDRILL program in Antarctica." Scientific Drilling.

Harwood, D. and F. Florindo (2006). "ANDRILL southern McMurdo Sound project scientific prospectus." ANDRILL Contribution 5,.

Harwood, D. and F. Florindo. (n.d.). "Southern McMurdo Sound (SMS) Project." from http://andrill.org/static/sms.html.

Hauptvogel, D. W. and S. Passchier (2012). "Early-Middle Miocene (17-14 Ma) Antarctic ice dynamics reconstructed from the heavy mineral provenance in the AND-2A drill core, Ross Sea, Antarctica." Global and Planetary Change 82-83: 38-50.

Henrys, S. and G. N. S. Science (2006). ANDRILL 2005: site investigations/seismic surveys, McMurdo and Southern McMurdo Ice Shelf, McMurdo Sound, Antarctica. Lower Hutt, N.Z., GNS Science. 2006/13.

Henrys, S. A., C. J. Bücker, et al. (2001). "Correlation of seismic reflectors with the CRP-3 drillhole, Victoria Land Basin, Antarctica." Terra Antarctica 8(3): 127-136.

Horgan, H., G. Institute of, et al. (2003). ANDRILL site investigations/seismic surveys, McMurdo and Southern McMurdo Ice Shelf, McMurdo Sound, Antarctica. Lower Hutt, N.Z, Institute of Geological & Nuclear Sciences.

Konfirst, M. A., G. Kuhn, et al. (2011). "Correlation of Early Pliocene diatomite to low amplitude Milankovitch cycles in the ANDRILL AND-1B drill core." Marine Micropaleontology 80(3-4): 114-124.

McKay, R., T. Naish, et al. (2012(a)). "Antarctic and Southern Ocean influences on Late Pliocene global cooling." Proceedings of the National Academy of Sciences of the United States of America 109(17): 6423-6428.

McKay, R., T. Naish, et al. (2012(b)). "Pleistocene variability of Antarctic Ice Sheet extent in the Ross Embayment." Quaternary Science Reviews 34: 93-112.

Melhuish, A., G. Institute of, et al. (1993). Seismic experiment Ross Ice Shelf 1990/91: characteristics of the seismic reflection data. Wellington, N.Z, Institute of Geological and Nuclear Sciences. 93/6.

Naish, T., P. J. Barrett a, et al. (2001). Report from ANDRILL New Zealand Science Workshop, 12 June, Victoria University of Wellington, Lower Hutt, N.Z, Institute of Geological & Nuclear Sciences.

Naish, T. and R. Powell (2006). "ANDRILL McMurdo Ice Shelf Project, Scientific Prospectus." ANDRILL contribution 4.

Naish, T., R. Powell, et al. (2007). "Background to the ANDRILL McMurdo Ice Shelf Project (Antarctica) and initial science volume."

Naish, T. R. and R. D. Powell. (n.d.). "McMurdo Ice Shelf (MIS) Project ", from http://andrill.org/static/mis.html.

Paulsen, T. S., M. Pompilio, et al. (n.d.). "Introduction: The ANDRILL McMurdo Ice Shelf (MIS) and Southern McMurdo Sound (SMS) Drilling Projects." Geosphere 8(3): 546-547.

Pollard, D. and R. M. DeConto (2009). "Modelling West Antarctic ice sheet growth and collapse through the past five million years." Nature 458(7236): 329-U389.

Powell, R. D., M. G. Laird, et al. (2001). "Depositional environments for strata cored in CRP-3 (Cape Roberts Project), Victoria Land Basin, Antarctica: Palaeoglaciological and palaeoclimatological inferences." Terra Antarctica 8(3): 207-216.

Scherer, R., M. Hannah, et al. (2007). "Palaeontologic characterisation and analysis of the AND-1B Core, ANDRILL McMurdo Ice Shelf Project, Antarctica." Terra Antartica 14(3): 223.

SMO), A. S. M. O. (2007). The ANDRILL Program: A Guide for the Media, the Public, and Policy Makers. U. o. Nebraska-Lincoln. USA, ANDRILL.

Wilson, G., F. Florindo, et al. (2007). "Palaeomagnetism of the AND-1B Core, ANDRILL McMurdo Ice Shelf Project, Antarctica."

Wilson, T. J. and T. S. Paulsen (2001). "Fault and fracture patterns in CRP-3 core, Victoria Land Basin, Antarctica." Terra Antarctica 8(3): 177-196.

Zattin, M., B. Andreucci, et al. (2012). "New constraints on the provenance of the ANDRILL AND-2A succession (western Ross Sea, Antarctica) from apatite triple dating." Geochemistry Geophysics Geosystems 13.

The Ross Ice Shelf and Ross Sea where ANDRILL are conducting their research is part of a rift system that has drawn Marie Byrd Land away from the Transantarctic Mountain Range. This rift system is called the West Antarctic Rift System (WARS). According to Anderson (1999), this rift system was active in the Jurassic and again in the Cenozoic, however other sources have given different time periods for rifting activity. Wilson & Paulsen (2001) has stated that the period of rifting activity was in the Oligocene, a more precise date than Anderson, while Melhuish (1993) gives a very broad and unconvincing 'Cenozoic perhaps Mesozoic'. ANDRILL's background research (Naish et al, 2007) gives the timing as the Eocene. Zattin et al (2012) has been more specific with the early rifting happening in 34 – 24 Ma and then renewed rifting 13 Ma to present. This modification of the timing of the rift system is linked to new information that has been accumulated on the subject over the decades, due to activities such as seismic reflections and drilling as ANDRILL has done (Horgan, 2003; Henrys, 2006).

The Transantarctic Mountains (TAM) are an uplifted rift-margin shoulder that has been uplifted due to the WARS. The basement rocks of this mountain range are metamorphic from the Pre-Cambrian Era (Melhuish, 1993) and have been intruded by granite (Zattin et al, 2012). According to Anderson (1999) these rocks were uplifted Post-Eocene which would coincide with the activity of the rift system which has cause it. Since the late Eocene, the area between Marie Byrd Land and the TAM has formed a large depression that has accumulated millions of years of sediments. This is the area in which many projects have been set up to find out about the timing of sediment deposition and in what conditions each layer was laid down.

Local volcanism is Quaternary in age and its weight on the surrounding sediments and rift system has caused local subsidence (Naish et al, 2007: Naish et al, 2006). The formation of this volcanism is in the form of Mt Erebus and Mt Terror. They were formed through a hotspot plume.

Information on the basin sediments in the area started off very broad with Melhuish (1993) stating that the Ross Sea "area had thick sequences of fluvial, glacial and shallow marine deposits of Devonian to Jurassic" (Pg. 6), however no elaboration was given to enhance our knowledge. MSSTS-1 drill project was active during 1979 and had a mission to find missing stratigraphic record in the Ross Sea area (Barrett, 1986(b)). At this time, the sediment records from the Early-Jurassic to the Early-Miocene was unknown and there was limited success from projects conducted on land to find stratigraphic records (Barrett, 1986(a)). MSSTS-1 did find sediments that relate to the time period between 30 – 24 mya, which were found to a depth of 227m, which does fill in some of the missing stratigraphy, however their conclusions are quite weak and the language used does not give confidence to their findings. MSSTS-1 found 8 'units' that relate to poor sorted mudstones, diamictite units and sandstone beds, which leads to glacial retreat and advance over this time period (Barrett & McKelvey, 1986), however the prolific use of words such as 'probably' lend the reader to have a lack of confidence in MSSTS-1's work. At the 213m mark on MSSTS-1 drill core, a 6cm thick layer was found to be containing basaltic and sandy limestone pebbles which MSSTS-1 surmised dropped out of floating ice. The sediment layer was dated to 30 Ma through mineralogy and chemical make-up, however two of the individual basaltic pebbles where big enough for K-Ar dating. These two basaltic pebbles dated at 14 – 24mya, therefore do not match the sediment layer they were found in. This also leads the reader to doubt the findings of MSSTS-1 as it is stated that the "age discrepancy is not understood" (Gamble et al, 1986. Pg 145) and only two pebbles dated, does not show scientific validity.

CIROS-1 was another project carried out in the Ross Sea area approximately 7 years after MSSTS-1. CIROS's findings are more convincing as they drilled to a depth of 702m and found that there had been at least 2 phases of glaciation recorded in the sediments from the Oligocene. The two phases were; limited ice (the evidence being sandstone and mudstone deposits deposited by floating ice) and grounded ice (the evidence being striations found on rocks from ice scouring) (Barrett, 1986(b)).

The Cape Roberts Project (CRP) added to the accumulating knowledge of the Ross Embayment, as CRP drilled to 1300m in search of tectonic, including TAM (Harwood et al, 2006) and climate history records (Barrett, 1997). Through CRP new information was gathered including 40m of dolerite breccia and conglomerate sitting on Devonian sandstones approximately 33 Ma (Henrys et al, 2001). Adding to this new knowledge Powell et al (2001), also found 9 layers that have been related to changes in sea levels and changes in ice coverage of the area. Powell et al (2001) concluded that there were at least 2 or 3 glacial fluctuations due to sandstones indicating no ice sheets where deltas occurred, to mudstones indicating glacial ice flows and then carbonates as glaciers retreated and organisms could live there again. Powell et al (2001) surmised that there was glacial advance and retreat during the early Oligocene.