Antarctica New Zealand

New Zealand Antarctic Institute

NEW ZEALAND'S ANTARCTIC RESEARCH:

a companion to the Antarctica New Zealand Annual Report 2001 – 2002

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Antarctica **New Zealand**

New Zealand Antarctic Institute

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Front cover: Lieutenant Evans surveying with theodolite used by Scott to locate the South Pole. *Herbert Ponting, Antarctica New Zealand Pictorial Collection.*

Back cover: Map of Antarctica showing the route of the *Discovery. Courtesy – C. R. Ford Lantern Collection, Auckland War Memorial Museum, reference C15 079.*

NEW ZEALAND'S ANTARCTIC RESEARCH

New Zealand's Antarctic Research is the inaugural companion science document to Antarctica New Zealand's Annual Report. This document highlights a portion of the research undertaken with the support of Antarctica New Zealand over the last four years. We are excited about this addition to our suite of Antarctic publications and hope you find this document informative and useful.

The projects described have been funded by highly competitive national science funding bodies such as the Foundation for Science, Research and Technology, the Marsden Fund and Vote: Education. These projects have also secured logistics support from Antarctica New Zealand through a competitive peer-review bidding round.

In 1998 Antarctica New Zealand published the *New Zealand Science Strategy for Antarctica and the Southern Ocean*. The Strategy began a new era of New Zealand Antarctic research with a focus on five science themes relating to Antarctic and global processes. The Science Strategy reaffirmed New Zealand's commitment to Antarctic and Southern Ocean research and provided a basis for managing and enhancing New Zealand science activities in Antarctica and the Southern Ocean.

Five Antarctic science themes were developed for the Science Strategy, to focus science undertaken in Antarctica around broad outcomes rather than narrow disciplines of research. The themes have provided a guide for the presentation of science proposals, as well as creating a framework through which New Zealand Antarctic science can contribute to answering important questions on the global and Antarctic environment.

The five Antarctic science themes in the science strategy are:

1. Antarctica as a Global Barometer
2. The Southern Ocean
3. Life in Extreme Environments
4. Human Influences In/On Antarctica
5. The Connections between Antarctica and New Zealand

New Zealand's Antarctic Research presents accounts of four research projects that have been completed recently by a diverse group of New Zealand Antarctic researchers from Universities and Crown Research Institutes in collaboration with a number of international scientists under the support of Antarctica New Zealand. The projects described reflect a wide range of research areas and cover all five science themes.

There have been many scientific achievements by researchers supported by New Zealand in Antarctica and the Southern Ocean over the past four years. There have been a total of 391 publications in refereed journals by New Zealand authors, six PhD degrees and six MSc degrees between 1998 – 2001. Over the past few years not only have the number of publications grown, but the quality of the research articles has increased. A measure of this quality is the number of scientific articles in pre-eminent international journals. Two journals with such distinction are *Science* and *Nature*. We are proud to say that over the last two years there have been six papers authored by New Zealand researchers published in these two journals. Two of these papers have made the front cover of each journal.

New Zealand also maintains a high profile internationally through representation on the Scientific Committee on Antarctic Research (SCAR). Dr Clive Howard-Williams from the National Institute of Water and Atmospheric Research Ltd., has recently been elected SCAR Vice-President. Professor Bryan Storey, Director of Gateway Antarctica at the University of Canterbury, is the Secretary of the new Geo-sciences Standing Science Group of SCAR and I have been elected Chair of the Joint Committee on Antarctic Data Management of SCAR.

A government review of New Zealand's strategic interests in Antarctica and the Southern Ocean, in May 2002, has reaffirmed our involvement in the Antarctic. The revised statement states that New Zealand is committed to "conservation of the intrinsic and wilderness values of Antarctica and the Southern Ocean, for the benefit of the world community and for present and future generations of New Zealanders. This will be reflected in active and responsible stewardship, under the Antarctic Treaty System that promotes New Zealand's interests in:

- National and international peace and security through a commitment to keeping Antarctica peaceful, nuclear free, and its environment protected;
- Continued influence in Antarctic governance through maintaining an effective role in the Antarctic Treaty System, and maintaining its long term interest, commitment to and credible presence in the Ross Dependency;
- Conserving, protecting, and understanding the biodiversity of Antarctica and the Southern Ocean, in particular the biodiversity of the Ross Sea region, including promotion, protection and management of representative special areas, and enhancing biosecurity;
- Conservation and sustainable management of the marine living resources of the Southern Ocean, and in particular the Ross Sea, in accordance with CCAMLR and the Antarctica Environmental Protocol, and within the context supporting strong environmental standards and sustainable economic benefits;
- Supporting and where appropriate leading, high quality Antarctic and Southern Ocean science that benefits from the unique research opportunities provided by Antarctica;
- Demonstrating and advocating for best practice in environmental stewardship and all other activities throughout Antarctica, and in particular the Ross Sea region;
- Ensuring that all activity is undertaken in a manner consistent with Antarctica's status as a natural reserve devoted to peace and science."

Antarctica New Zealand is currently leading the process of creating a new Antarctic and Southern Ocean Science Strategy for New Zealand. The revised strategic interests will be taken into account in the new strategy. Therefore, research in the future will be built around these interests.

In this companion document you will find an article describing an international investigation in Antarctica's past response to climate change. The article entitled "An Antarctic Perspective on Climate Change", relates to the three science themes, Antarctica as a Global Barometer, Human Influences In/On Antarctica and The Connections between Antarctica and New Zealand. The second article looks at direct human impacts in Antarctica, in particular human impacts on ice-free regions of the Antarctic. "Impacts of Hydrocarbon Spills on Antarctic Soils" is closely aligned with the science theme Human Influences In/On Antarctica. The third article gives a summary of the research New Zealand and international collaborators are conducting to understand the role Antarctic sea ice has in Southern Ocean and world climate. This article relates to the science themes, The Southern Ocean and Antarctica as a Global Barometer. The final article describes our research into the understanding of "extremophiles" in the Antarctic inland waters. This research is under the science theme Life in Extreme Environments. I truly hope you enjoy reading this document and come away with a better understanding of what has been accomplished in Antarctica by these and all New Zealand researchers.

Dr Dean Peterson
Science Strategy Manager
Antarctica New Zealand

AN ANTARCTIC PERSPECTIVE ON CLIMATE CHANGE

Professor Peter J Barrett
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This is an updated article, which first appeared in *New Zealand Science Review Vol 58* (1), 2001. References to information in the article can be found in "Antarctic Cenozoic Paleoenvironments – a review", *Terra Antartica*, Volume 3 (2), 1996, 103 – 119.

Global Warming Considered More Likely

In January 2002 the Intergovernmental Panel on Climate Change's (IPCC) third assessment announced that the latest modelling projects a rise in average global temperature from CO_2 emissions of between 1.4 and 5.8°C by the end of this century. This is up from the 1 to 3.5°C of the second IPCC assessment five years previously.

Where does this fit among the many pressing priorities of modern life? In this article I put this prospect of future climate change in the context of what we know of past climate in Antarctica, a region of high climate sensitivity. To do this I will outline some recent studies on what Antarctica was like 20 to 30 million years ago when the earth's temperature was last 3 to 4°C warmer, as is now expected by the end of the century.

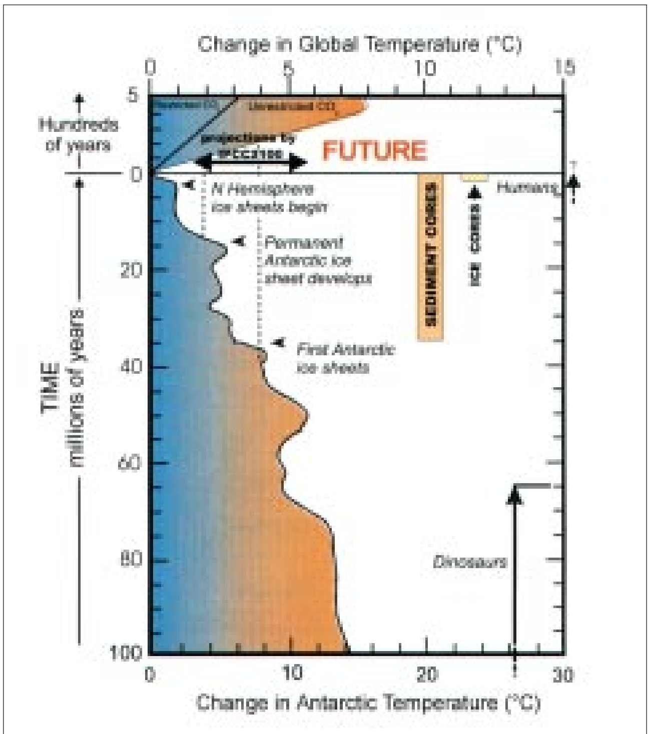


Figure 1. Comparison of past changes in temperature with that expected from future greenhouse warming (curves from Crowley and Kim, 1995). The curve for the past 100 million years shows a more or less continuous decline of 7°C in global temperature (equivalent to 14°C in the Antarctic – see text). The curve into the future shows the projected increase in temperature for a "restricted" scenario, where atmospheric CO_2 emissions are limited to 1990 levels (5 GT/year), and an "unrestricted" scenario, in which no constraints are made. The latter path, which we are currently following or worse, can be expected to give us an atmosphere like that of 12 – 13 million years ago by 2100 AD and one like that of around 35 million years ago by 2200 AD. However, the mid-point of the IPCC 2001 projection indicates this could happen by the end of this century.

Overview

Figure 1 shows the decline of around 7°C in global temperature over the last 100 million years, estimated from oxygen isotopic ratios measured in calcareous microfossils from cores of deep-sea sediment. We believe that the first Antarctic ice sheets formed around 34 million years ago with a sharp cooling when the global temperature was 4 to 5°C warmer than today. This is thought to represent the change from ice sheets that grew and collapsed to the permanent Antarctic ice sheet like we see today. Another significant cooling is inferred at around 14 million years ago, when the global temperature was 2 to 3°C warmer than today. Throughout these tens of millions of years, however, glacial-interglacial cycles have been superimposed on the decline in global temperature.

Our present civilisation has really only developed since sea level stabilised around 6500 years ago after the most recent of many glacial periods. Our current interglacial period has been characterised by climate (and sea level) stability. This now seems threatened with CO_2 levels having risen 30% higher in the last century, higher than during any of the last three interglacials, and with global average temperatures having risen by ~0.6°C over the same period.

It is difficult to avoid seeing a few problems for future generations. These include the direct effects of warming, which will be pleasant for those in cold climates, but lead to the migration of climatic belts, along with plants, animals and diseases. Other predicted consequences are regional changes in precipitation patterns and the prospect of rising sea level from thermal expansion (tens of cm) and ultimately the melting of polar ice. About 6m of sea level equivalent is at present locked in the Greenland Ice Sheet, 6m from the relatively small and unstable West Antarctic ice sheet and 60m from the huge East Antarctic Ice Sheet (Figure 2). Of course the melting takes a while, even millenia in the case of the whole East Antarctic ice sheet, but there is still much uncertainty on processes, rates and feed-back effects.

Figure 2. The present day Antarctic ice sheet, showing ice drainage patterns (adapted from Drewry, 1983) and the main geographic regions of the continent. The ice sheet is divided by the Transantarctic Mountains into two parts – a large East Antarctic ice sheet with an ice volume of 60m of sea level equivalent (SLE), and a small West Antarctic ice sheet (6m SLE). The latter is inherently less stable and more vulnerable to changes in climate.

Past Antarctic Climate from Ice Cores

But how do we check on the likely consequences of the projected warming for the Antarctic ice sheet and for global sea level? One way is to study past climate records from ice cores in the region. Ice cores provide a detailed record of temperature, precipitation and

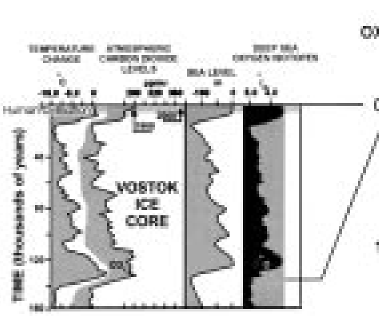


Figure 3a

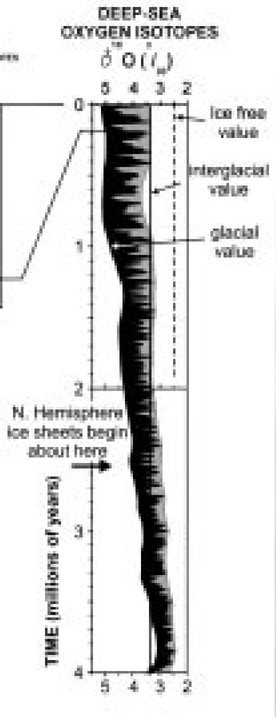


Figure 3b

Figure 3. Cyclic variation in past temperature, CO_2 and sea level for the last glacial cycle from ice core measurements (a) and the last 4,000,000 years from measurements of deep-sea sediment cores (b). The ice core record is limited to the last half million years, the age of the oldest ice, whereas the deep sea record can be taken back over 100 million years or more, though beyond 10 million years there are problems in calibration, resolution and missing intervals.

a. Patterns for the last glacial cycle from measurements of ice cores from Vostok Station in the middle of the East Antarctic ice sheet (Fig. 2), compared with sea level change recorded by a rising coastline in New Guinea, and the isotope measurements of marine microfossils in deep sea sediment. They show the close association between CO_2, temperature and sea level in the past. Ice cores almost to the base of the ice sheet have recently extended the measurements for a further 3 glacial cycles (to 400,000 years back in time – the oldest ice cored thus far) and confirmed the pattern. Atmospheric CO_2 values for this century have been added to illustrate the rapid rate of increase.

b. Deep-sea isotope record, showing the c.100,000 year cycles for the last 800,000 years, and the c. 40,000 year cycles prior to this (only the last 4 million years is shown). Cycles prior to the formation of the Northern Hemisphere ice sheets are presumed to be largely a consequence of variations in Antarctic ice volume.

composition of the atmosphere in the past, with layers in the central parts of the East Antarctic ice sheet going back over 400,000 years, or 4 glacial-interglacial cycles. These cycles themselves represent a remarkable record of climate change, with global temperatures slowly decreasing over many tens of thousands of years and then returning rapidly to the present over a few thousand years.

The last "100,000 year" glacial cycle is shown in Figure 3a, with isotopic analyses from the deep drill hole at Vostok Station providing local temperature variations. This shows a temperature depression of 10°C, twice that of the 5°C global temperature depression for the last glacial cycle. This confirms climate modelling results that point to changes in polar temperatures being double those of average global temperature. Analyses of gas bubbles in the ice core show a strong association between temperatures and carbon dioxide levels, which declined to a low of 30% below the 1900 levels 18,000 years ago. This coincided with a global sea level minimum around 120m below present sea level, and the maximum size and extent of the ice sheets of North America and Europe (ice margins reached New York and London).

Climate from ice core records, however, can help climate change prognosis only in a limited way, because global climate even in 50 years time may be warmer than the earth has experienced in the last 12 million years (Figure 1), and there is no polar ice sheet thick enough to preserve ice much older than 400,000 years. However, the cyclic pattern can be traced back in time from the detail of oxygen isotopic measurements in deep-sea cores (Figure 3b). Oxygen isotopic composition of carbonate in marine shells depends on a mix of temperature (roughly 1/3) and global ice volume (2/3) for the recent geological past. Hence they are commonly taken as proxies for ice volume. This cycle of glacial advance and retreat linked with sea level fall and rise has dominated climate, continents and coastlines most strikingly for the last 800,000 years, with the 100,000 year cycles, but prior to this time there is a persistent 40,000 year cyclicity that is now known to extend back into the distant past. These two frequencies are now generally accepted as having been controlled or more correctly, forced, by predictable cycle variations in solar radiation reaching the earth's surface due to the obliquity and eccentricity of the earth's orbit (Milankovitch cycles).

Past cyclic variations in the deep-sea oxygen isotope record are widely presumed to reflect changes in global ice volume, but where, since the Northern Hemisphere ice sheets first formed around 2.5 million years ago? Before this time, the cycles were about 1/3 of their recent amplitude (implying variations of ~40m of SLE), but they are still well defined, and have been recognised in deep sea sediments more than 20 million years old. This has been regarded as at least circumstantial evidence for the regular growth and collapse of at least a significant part of the Antarctic ice sheet well into the distant past.

Past Antarctic Climate from Sediment Cores – Cape Roberts Project

Today the Antarctic continent is almost completely ice-covered with a mean annual temperature at the coast of around -15°C. However, 200 million years ago it was covered with forests and swamps, as shown by the fossil leaves, tree stumps and coal seams now preserved in the strata capping the Transantarctic Mountains. Antarctic temperatures at this time were at least 15°C warmer (with global temperature around half of this value). What was the history of this massive shift in climate, and why did it happen?

A relatively direct record of past Antarctic climate lies in the layers of sediment eroded over millions of years from the continent and deposited in sedimentary basins around its margin. These have been cored by a succession of drilling projects since the Dry Valleys Drilling Project in the McMurdo Sound area in 1970 – 74 and the Deep Sea Drilling Project ship *Glomar Challenger* in the Ross Sea in 1973. Since then there has been further drilling on the margin on the other side of Antarctica (Prydz Bay), as well as more drilling in McMurdo Sound, most recently with the Cape Roberts Project (Figure 4).

The Cape Roberts Project grew out of earlier New Zealand-led initiatives to use the fast sea-ice off the Victoria Land coast as a drilling platform to core strata beneath the sea floor. The aim was to core through the recent glacial sediments and into layers deposited before Antarctica was covered with ice. The project, a co-operative venture between scientists, administrators and Antarctic support personnel from Australia, Britain, Germany, Italy, Netherlands, New Zealand and the United States of America, cored for three field seasons (1997 – 1999) with a team of 55 scientists and 20 drilling and support staff. The result has been virtually complete and continuous core through the western margin of the Victoria Land Basin, a sedimentary succession 1500 m thick, dating from 34 to 17 million years ago, and 100m into the floor of the basin, Beacon sandstone of Devonian age (~350 million years old).

The cores provide a nearshore marine sedimentary record, continuous and detailed for some intervals but with a number of significant time breaks for others due to erosion or non-deposition

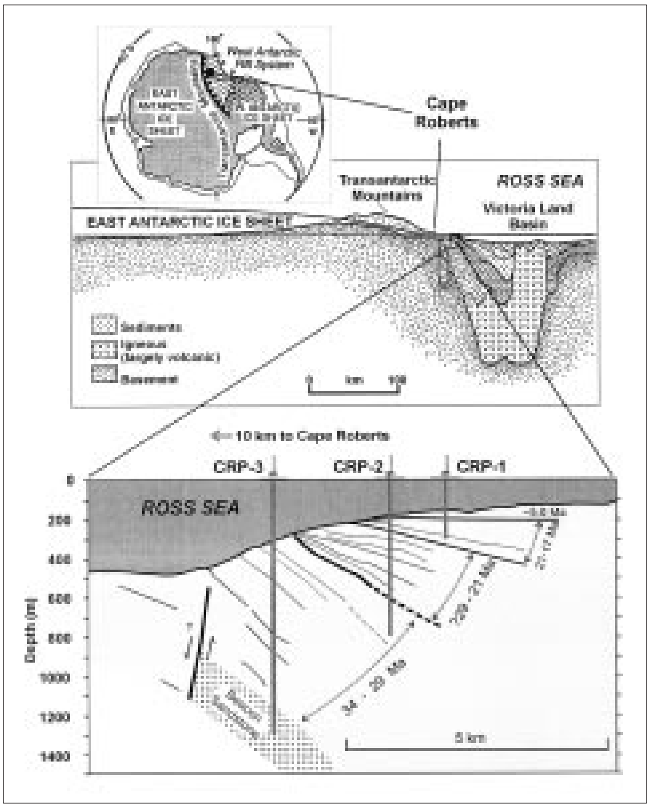


Figure 4. Cross-section through the Antarctic Ice Sheet, the Transantarctic Mountains and the Victoria Land Basin, showing how sediment that has accumulated offshore can record the advance and retreat of the ice sheet margin. The expanded cross-section shows the detail of the strata off Cape Roberts and the position of the three drill holes used to core the entire sedimentary section.

(Figure 5). The oldest Cenozoic sediments cored show that the Ross Sea coast of East Antarctica had a cool temperate climate with a low woodland vegetation (*Nothofagidites*, podocarps and palms) from 34 to 25 million years ago. These imply coastal summer monthly temperatures of around 12°C or even a little warmer, in striking contrast to the present summer temperature of -5°C. Nevertheless the oldest cores still include occasional boulders and striated stones that record glacial activity and ice-rafting at this time. The younger strata cored, representing the period from 25 to 17 million years ago, record a low-growing sparse tundra on the adjacent mountains, along with periods in which the ice sheet margin reached offshore beyond the drill site. Coastal summer monthly temperatures were significantly lower, around 5 to 7°C, but still much warmer than today.

One significant outcome from studying the sediment characteristics is that the core shows cycles of advance and retreat of the ice margin. These coincide with falls and rises in sea level recognised from other core features, and presumed to be linked through changes in ice sheet volume. Over 50 of these cycles are recognised in the Cape Roberts core, though many more must be missing through erosion. Three of the thicker cycles deposited around 24 million years are of particular interest because a lucky combination of age data from volcanic ash, fossils and magnetic measurements has shown them to have been deposited within a time period of no more than 400,000 years and most likely within 120,000 years. Although the most recent ice ages are characterised by a 100,000 year cyclicity, the deep-sea record suggests that those prior to 800,000 years ago are characterised by 40,000 year cyclicity. The Cape Roberts record is the first physical confirmation of cyclicity on these time scales for ancient ice sheets, indicating that the Antarctic ice sheet in the distant past was being modulated at Milankovitch frequencies like the more recent Northern Hemisphere ice sheets.

Integration of Geological Data and Climate Modeling

In addition to showing how much Antarctic climate has changed in recent geological times, a useful contribution from sediment (and also ice) cores lies in the information they provide on past climate from the most sensitive part of the planet for checking global climate models. The integration of circum-Antarctic geological data with the present generation of models is being facilitated through the ANTOSTRAT sub-committee of the Scientific Committee on Antarctic Research, and was the subject of a workshop in September 2001 in Erice, Sicily. The workshop brought together geologists, geophysicists, ice sheet modelers and climate modelers, and has enabled more collaborative work following the recent spurt of drilling activity by the Ocean Drilling Program and the Cape Roberts Project.

For some time modellers have been considering the effects of different arrangements of land and oceans due to movement of the earth's plates, and different past levels of CO_2 in the atmosphere. It has long been accepted that the break-up of Gondwana land, which has led progressively to the isolation of Antarctica by deep ocean, and the formation of the circum-Antarctic current, was the primary cause of cooling of the Antarctic continent to the point where ice sheets could form. But most also agree that the warmer climate of the early Cenozoic and Cretaceous times involved high atmospheric CO_2 levels. How much CO_2 was elevated remains a question, and the separation of geographic from atmospheric influences remains a significant challenge. Plainly, it will be useful to constrain models with parameters from the Antarctic margin relating to geography and temperature for particular time periods in the past, for example, before and after the first ice sheets formed around 34 million years ago, and before and after the change in character of the ice sheet around 14 million years ago.

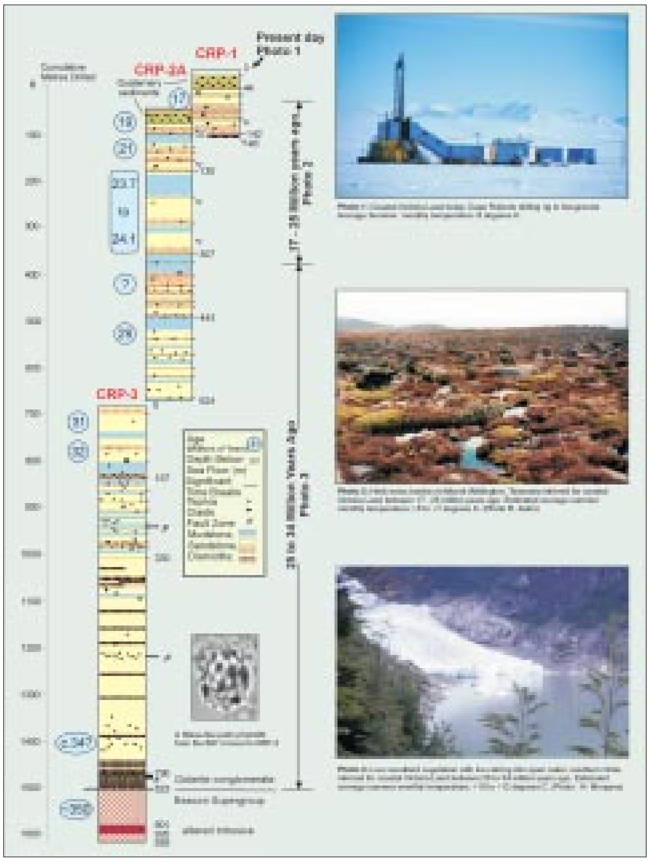


Figure 5. Log of the 1,500m of strata cored by the Cape Roberts Project, showing their ages and main features. Images on the right compare the present ice-covered landscape (with the Cape Roberts rig in the foreground), with images of the type of vegetated landscape indicated by microfossils and sedimentary features in the core. They indicate a staged decline in climate and vegetation in the region from low woodland 34 to 25 million years ago to herb-moss tundra 25 to 17 million years ago to the present ice-covered landscape.

Future work

Much remains to be done, even with the existing core. Many of the marine microfossils extracted from the 1500+ samples examined thus far are new species, and even those that are known to have significant paleoclimatic implications need confirmation. There are now plans to extend the Cape Roberts record to younger time periods, especially the unusually warm period around 400,000 years ago, when sea level was 20m higher, but also another warm period around 800,000 years ago that is less well recorded globally. A thick sedimentary sequence recording these events lies beneath the Ross Ice Shelf in Windless Bight near Scott Base, and could be cored with some new technology. Extending the Cape Roberts record back in time is also important. The sedimentary strata recording the earliest cooling 34 million years ago that preceded the first Antarctic ice sheet have yet to be cored, though their existence is known from a few scattered boulders of fossiliferous sandstone in moraines of southern McMurdo Sound. These goals are currently being developed for future ice-platform drilling in the McMurdo Sound region under the name of ANDRILL. Countries currently represented are USA, Italy, New Zealand, UK and Germany, but more are expected. The New Zealand representative is Dr Tim Naish, Institute of Geological and Nuclear Sciences. The group will also be considering prospects for this type of drilling with similar objectives in other parts of the Antarctic margin. In addition to this work a US ship-based initiative, SHALDRILL, is planning to core strata for climate history over the period from around 20 to 45 million years ago off the Antarctic Peninsula.

Final comment

These are exciting times for climate scientists with perhaps our civilisation's grandest experiment now under way. What effect will rising CO_2 levels really have on our atmosphere? And what will be the effects on the climate of various parts of the earth? The IPCC has now provided another comprehensive report on the earth's climate, its current state and recent trends, along with explanations and projections provided by modelling. Here I have offered a longer-term perspective, in which I note that the mid point projected for global temperature by the end of this century is equivalent to the global temperature at around 34 million years ago, when the coast of Antarctica was over 15°C warmer and forested. Changes in earth's climate of this speed and magnitude are unprecedented to our knowledge, aside from large meteorite impacts. While plainly the work of IPCC must continue in order to improve projections of the likely consequences of climate change, the extent and rate of change is such that understanding climate in the distant past will be of increasing interest for providing reference points – a sort of "ground truth" for climate models.

The implications of these studies are more serious, though, and suggest that if these trends continue the climate in which our civilisation developed will be significantly different by the end of this century. The amount and timing of future sea level rise is more difficult to gauge, but once underway would be even more difficult to reverse than temperature. The problem is rapidly becoming better defined – a solution is likely to become increasingly important.

Acknowledgements

I would like to acknowledge the late Professor Bob Clark for his initiation in 1957 of the Victoria University of Wellington Antarctic expeditions, which led to the work described here, and Alex Pyne, Victroria University of Wellington Expedition Manager for the last 23 years, who has kept them going. I also thank Alex for his key role in advising and supporting both science and drilling over this period, and Gillian Wratt, convener, Cape Roberts Project Operations/Management Group, Dr Fred Davey, CRP New Zealand National Science Co-ordinator, Jim Cowie, Project Manager and Pat Cooper, Drilling Manager, as well as the Cape Roberts support staff, drillers and scientists for the remarkable achievements of this project. The illustrations for the paper have a complex history but owe most to the skills of Mike Hannah and Salli Rowe.

IMPACTS OF HYDROCARBON SPILLS ON ANTARCTIC SOILS

Dr Jackie Aislabie

Landcare Research New Zealand Limited

Hamilton

Fuel spill trials at Scott Base. *Photo: Emma Waterhouse, Antarctica New Zealand Pictorial Collection.*

Introduction

Understanding the impact of human activities on the Antarctic environment continues to be a priority research area for Antarctic science programmes. As a signatory to the International Antarctic Treaty, New Zealand plays a key role in the development of environmental protection measures for the Antarctic. These measures were drafted into the Protocol on Environmental Protection of the Antarctic Treaty in Madrid in 1991, and environmental protection is an integral part of all Antarctica New Zealand activities.

The ice-free regions of Antarctica are particularly vulnerable to human activities. The ice-free areas are the most biologically active sites and contain various periglacial and geological features. They are also the focus of ever increasing human activity and infrastructure and therefore are vulnerable to impacts. The majority of the operating scientific research stations are located in ice-free regions.

Consequences of human activities in the ice-free areas are potentially many, for example local hydrocarbon pollution due to oil spills, disposal of sewage, deposition of combustion products, landscape modification due to construction, introduction of foreign organisms and disturbance to animals. So far little is known about the significance of these human impacts, although it has been suggested that the potentially adverse effects of tourism and research may be negligible relative to the effects of global climate change. Most impacts are small and confined to scientific research stations or frequently visited tourist sites.

The purpose of this programme was to determine the effects of hydrocarbon spills on the chemical, biological, and physical properties of soils of the Ross Sea region. Wherever humans go in the Antarctic, and whatever they do, be it research, tourism or fishing, they need fuel for their planes, icebreaker ships and land vehicles, and fuel to run generators. Because of this, petroleum hydrocarbons are the most likely source of pollution in the Antarctic.

Antarctic soils

The total ice-free area of Antarctica comprises less than 0.4% of the continent. The ice-free regions, of which about 10% are bare rock, are located mainly on the continental coastline, particularly on the Antarctic Peninsula and the McMurdo Dry Valleys in the Ross Sea region. The McMurdo Dry Valleys, the largest continuous expanse of ice-free ground in the Antarctic, covers about 6,000 km^2 or about one quarter of the total ice-free ground of the region.

Soils of the Ross Sea region are cold desert soils. They are characterised by extremely low soil temperatures with an average mean annual temperature ranging between -15°C and -40°C. As snowfall is low, available moisture is low, and there is minimal biological activity. The soil surface is often covered by a pebble or boulder pavement. The subsurface soil below the desert pavement includes an active layer and permafrost. The soils lack topsoil, or accumulations of organic matter and are often alkaline particularly in moister coastal regions and show wide variations in soil salinity. Some soils, particularly soils in dry environments on old surfaces may contain large quantities of salts.

The prevailing low temperatures, low humidity, freeze-thaw cycles, and salinity of the soil combine to create a harsh environment for plant and animal life. Only a few plants and animals have managed to colonise and survive in ice-free regions. Microbes however, are distributed throughout soils of the Ross Sea region with highest numbers detected in moist coastal areas compared with dryer inland soils.

Hydrocarbons in soils

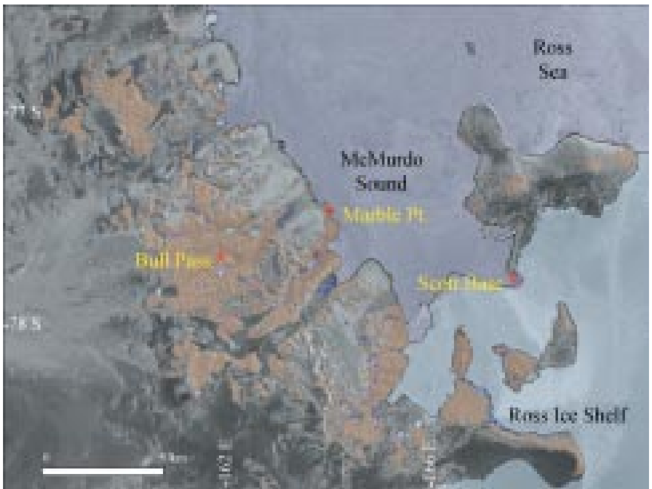
Hydrocarbons are introduced into the Antarctic environment through natural and anthropogenic sources. Natural sources include alkanes and alkenes derived from cyanobacteria or algae and polyaromatic hydrocarbons from meteorites. Most hydrocarbon contamination on land however derives from human activity concentrated around current and past research stations and field camps. Hydrocarbon contamination of soils is most often associated with the accidental spillage of fuels. Spillage occurs during storage and distribution of fuels, and leaks have been reported from storage tanks, drums, and pipelines. Spills also occurred as a consequence of drilling activities most notably the Dry Valleys Drilling Project. Hydrocarbons spilled on these soils can move into subsurface soils.

The mobility of the fuel depends on its physical characteristics. Lighter fuels such as the jet fuels JP5 and JP8, which are most commonly used in the Ross Sea region, are highly mobile and rapidly migrate down through the soil and travel along the bedrock or ice-cemented surface where present. In contrast, heavier fuels like lubricating or engine oil are less mobile and tend to accumulate in surface soils causing staining of the soil surface. Every year during the thaw hydrocarbons in soil may be mobilized in surface and subsurface runoff during snowmelt, with preferential movement of the more water-soluble compounds such as the monoaromatics and naphthalenes.

Site location and investigation

We have compared the properties of control soils with hydrocarbon-contaminated soil from three locations: Scott Base, Marble Point, and in the Wright Valley at Bull Pass (Figure 1). Soils in the Scott Base area have been impacted by the establishment and habitation of the New Zealand base continuously for 40 years, and hydrocarbon contaminated sites have been sampled from a number of locations including a former storage area for drums of mixed oils. Soil sampled from Marble Point was taken from near the old Marble Point camp, inhabited from 1957 to about 1963. Oil stains were visible on the soil surface, and are assumed to have been there for more than 30 years. The samples selected for analysis from the Wright Valley came from a spill site near Bull Pass, that occurred during seismic bore-hole drilling activities in 1985. In addition, we have conducted preliminary investigations of hydrocarbon-contaminated soil from near Lake Vanda, Cape Evans and Cape Hallett, all sites of former research stations. The hydrocarbon-contaminated areas in the Ross Sea region have been estimated at less than two hectares.

Generally pits were dug at each location and soil samples collected from a range of depths, depending on the presence of ice-cemented surfaces or bedrock. Also, control samples were collected at least 30 metres from the contaminated areas. Soil samples for microbial and chemical analysis were stored frozen until analysis in New Zealand.



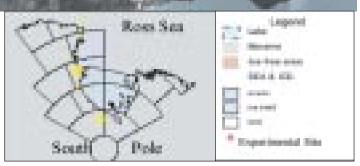


Figure 1: Map showing the three study sites and the geographical information of the area.

Hydrocarbons in soils

Levels of total petroleum hydrocarbons were elevated at all the contaminated sites and below detectable levels in control soils. Levels range from below detection limits, to about 29,000 micrograms per gram of soil. The hydrocarbons identified in the soil were predominantly n-alkanes with chain lengths from C9-C15, and mono and di-aromatic compounds, with lesser amounts of more toxic polyaromatic compounds. Naphthalenes were the predominant polyaromatic compounds detected. However polycyclic aromatic hydrocarbons (PAHs), including known carcinogens, have been detected in soils from some sites. Hydrocarbons spilled on these soils are persistent. We have recently detected hydrocarbons in soil under and around the historic fuel depots at Cape Evans.

Microbiology of contaminated soils

Hydrocarbon spills on Antarctic soils can result in increases in microbial abundance. Elevated numbers of hydrocarbon degraders and culturable heterotrophic bacteria and fungi at some spill sites indicate that hydrocarbons spilled on Antarctic soils can serve as substrates for microbial growth. Furthermore, significant rates of mineralization of radiolabeled *n*-alkanes or naphthalene detected in microcosms containing contaminated soils but not control soils indicate that the hydrocarbon degraders can be active in the soils from the Ross Sea region.

Hydrocarbon-degrading bacteria isolated from the soils were identified as *Rhodococcus*, *Pseudomonas* and *Sphingomonas* species by 16S rDNA sequence analysis. The hydrocarbon degraders were psychrotolerant because while they could grow at low temperatures, their optimum temperature for growth was greater than 15°C. Given the temperature surface soils can reach in summer, up to 20°C this result is not surprising. The *Rhodococcus* were isolated when provided with jet fuel as sole source of carbon, degraded *n*-alkanes with chain lengths from C6 to at least C20 and the branched alkane pristane, but not aromatic compounds. Recent investigations indicate that *Rhodococcus* species may be prevalent hydrocarbon degraders in cold soils world-wide. In contrast, the *Pseudomonas* and *Sphingomonas* species were isolated when provided with aromatic substrates for growth including toluene and naphthalene. Phylogenetic analysis indicates that the *Rhodococcus* and *Pseudomonas* isolates cluster with other hydrocarbon degraders isolated from cold climates. However, *Sphingomonas* Ant 17, from Scott Base soil, was most similar to a PAH-degrader isolated from soil in Germany. Detailed laboratory investigations of *Sphingomonas* Ant 17 from Scott Base soil indicate that this strain degrades the aromatic fraction of several different crude oils, jet fuel and diesel fuel at low temperatures with and without nutrient amendment. It degrades a broad range of aromatic compounds including hydrocarbons, heterocycles and aromatic acids and alcohols. More recently, we have isolated heterotrophic nitrogen-fixing bacteria from the contaminated soils. Their selection *in situ* was attributed to high soil carbon:nitrogen ratios resulting from hydrocarbon spills. Some of the nitrogen fixers were identified as *Pseudomonas* and *Azospirillum* species. In addition to fixing nitrogen some of the isolates also degraded hydrocarbons although not at the same time.

Investigations of culturable fungal populations of soil from around Scott Base and Marble Point indicate that *Phialophora* species are abundant in oil-contaminated soils whereas *Chrysosporium* dominated control soils. The ability of these fungi to degrade hydrocarbons has not been investigated, however *Phialophora* are known to degrade hydrocarbons.

Knowledge of microbes in soils has been limited by the availability of appropriate techniques. Fortunately, traditional culturing techniques are now augmented by a powerful array of DNA-based methods that allow the amplification of small subunit (SSU) ribosomal RNA (rRNA) genes directly from natural environments. This strategy has detected the presence of a wide variety of organisms which were previously unknown. We have been successfully applying these techniques to investigate bacterial diversity of soils from Scott Base, Marble Point and the Wright Valley. Preliminary investigations of oil-contaminated and control soils from around Scott Base confirm that *Rhodococcus*, *Pseudomonas* and *Sphingomonas* are prevalent in contaminated soils. Furthermore the bacterial diversity of contaminated soils is significantly reduced compared to control soils.

Effect of hydrocarbon spills on soil physical properties

In collaboration with United States Department of Agriculture (USDA) scientists, climate stations were installed at existing contaminated sites at Scott Base, Marble Point and Bull Pass and nearby control sites to make continuous measurements of soil temperature at a range of depths (Figure 2). At Scott Base the weekly maximum soil surface (2 cm depth) temperatures, in summer when soils were snow-free, were warmer, sometimes by more than 10°C, at the hydrocarbon-contaminated site than the control site. The higher temperatures at this site were attributed to the decreased surface albedo due to soil surface darkening by hydrocarbons.

- Hourly measurements all year round
- Wind speed and direction
- Temperature- air and soils
- Soil moisture- some temperature limitations
- Solar radiation
- Relative humidity
- Part of USDA Global Climate programme

Figure 2: Climate station at Marble Point and the variables it measures. *Photo: Dr Megan Balks, University of Waikato.*

Oil spillage trial

To measure how quickly soils respond to hydrocarbon spills we established an experimental spill site at Scott Base. In December 2000 we spilled JP5 jet fuel on contained soil cores. Soil moisture levels and *in situ* temperatures were monitored. The maximum daily temperature at 5 cm depth in the JP5-treated soil cores was approximately 2°C warmer than the control soils for nearly 2 weeks after fuel application. Soil cores were destructively sampled at regular intervals over 42 days and samples returned to New Zealand for hydrocarbon and microbiological analyses. Fuel was observed to have penetrated 15 cm down the soil core 10 days after fuel application, and 17 cm after one year. No differences were detected in numbers of culturable heterotrophic bacteria and hydrocarbon degraders 42 days after the spill. Hydrocarbon analysis of the soil indicated that 70% of the fuel had been lost from the soil cores after 6 weeks, with most lost during the first week (approx. 58%). Loss of hydrocarbons from the soil cores was consequently attributed to volatilisation rather than biodegradation. All contaminated soil is being returned to New Zealand for analysis and disposal.

Soils database

Descriptions and analyses of soils of the Ross Sea region are going into a Geographic Information System (GIS) and associated Antarctic soils database, managed by Landcare Research. So far, data dating back from the late 1950s has been entered, for more than 900 sites. This database, together with other research information, will eventually provide guidelines for visitors to the ice-free regions of Antarctica, so that damage to particularly fragile soils of the Ross Sea region can be avoided.

Conclusions

As Antarctic soils occur in an environment of low precipitation and severe cold, with unique biological communities, it is difficult to predict the impacts of hydrocarbon spills on these soils.

Our investigations to date of long-term hydrocarbon-contaminated sites in the Ross Sea region indicate that microbial populations in soils from Scott Base and Marble Point are more abundant in hydrocarbon-contaminated soils than control sites and that contaminated soils may be warmer on fine summer days. To measure how quickly soils respond to oil spills, we spilled JP5 jet fuel on contained soil cores at Scott Base. To assist with improved management and protection of Antarctic soils, we have collated historic and recent descriptive and analytical data, which is managed using a Geographic Information System and associated Antarctic soils database.

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SEA ICE PHYSICS

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Pancake ice at Cape Adare. *Photo: Gillian Wratt, Antarctica New Zealand Pictorial Collection.*

Introduction

Climatologists now consider the sea ice to be crucial in the regulation of the planet's climate, and biologists believe it to be the driving force behind the biological productivity of the Southern Ocean. The Southern Ocean and the Antarctic pack ice, along with their associated atmosphere and biota, are part of a complex interactive system. The pack ice influences characteristics of the ocean, the atmosphere and the biosphere, yet the distribution and characteristics of the ice are themselves forced by atmospheric and oceanic variables such as temperature, wind and salinity and may also be influenced by organisms present within it. All of these potential feedback processes have the ability to play a significant part in global climate change. Sea ice on the Southern Ocean undergoes an annual change from a minimum of around 4 million sq km in late autumn to a maximum of around 19 million sq km in late spring. This is one of the largest changes on the surface of the Earth. At its maximum it can stretch as far as 2,200 km or as little as 300 km offshore depending on the local climate and sea conditions. This competition between the formation of sea ice by freezing and break-up by the violence of the Southern Ocean make the area in which this occurs one of the most active and variable regions on the surface of the Earth.

Sea ice is the complex, two-phase material formed when the polar oceans freeze. In nature it sits within a few degrees of its melting point, making its behaviour unpredictable and our understanding of it poor. At some times of year, sea ice covers up to 7% of the Earth's surface. It interacts with the atmosphere, the ocean and with ice shelves, exerting a pivotal influence on global climate. It is the physical processes that determine the extent and concentration of the ice cover that are the focus of this study.

Sea ice consists of pure ice platelets interleaved with inclusions of liquid brine. This brine may be enclosed in sub-millimetre scale pockets, or may be in channels that can extend almost right through the entire 2m thickness of the first year sea ice sheet, connecting tortuously with the underlying sea water. It is no surprise that the properties of the ice sheet depend crucially on the liquid content of the sea ice, which in turn is a strong function of temperature and salinity. Consequently all modelling and measurements on sea ice must be supported by a knowledge of the basic physical properties of the ice.

New Zealand's research effort

The New Zealand Sea Ice Group, involving personnel from Victoria, Auckland and Otago Universities (Figure 1) assisted by overseas collaborators, has existed for over 10 years. It is managed by Tim Haskell of Industrial Research Ltd. and most field work has taken place on the first year, land-fast sea ice of McMurdo Sound, Antarctica. The goal of the project is an understanding of the processes involved in the break-up of an inhomogeneous sea ice sheet. Broadly this problem splits into two parts: first we must model the strain field induced in sea ice subjected to ocean waves; second, the response of the sea ice to this cyclic forcing must be understood.

Measurements

Conventional methods of measuring sea ice physical properties involve removing the ice from its natural surroundings. To overcome this limitation, a team from Massey University led by Paul Callaghan has used a specially constructed Nuclear Magnetic Resonance (NMR)

Part of the field team from left: Tim Haskell, Eberhard Deuss, Jean-Louis Tison, Pat Langhorne, Simon Gibson, Vickey Lyttle, Dave Cochrane, Inga Smith. Missing: Vernon Squire, Colin Fox, Joe Trodahl and Paul Callaghan.

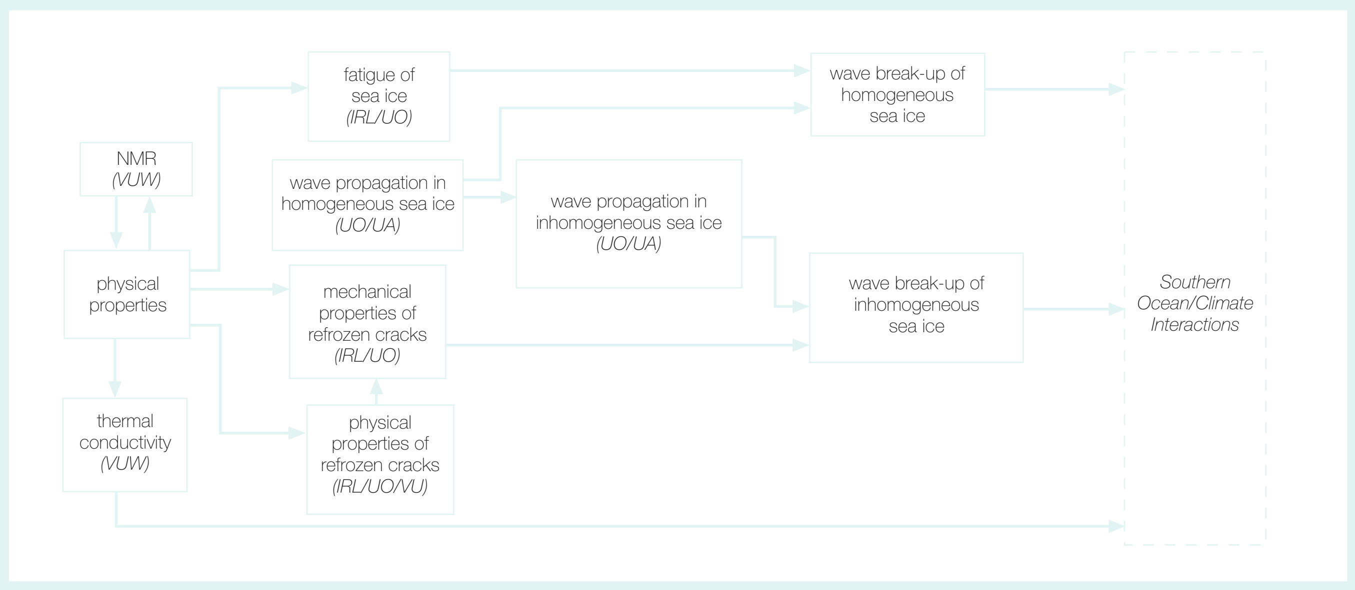


Figure 1: Structure of project showing institutional involvement in sub-projects. The New Zealand institutions taking part in the project are Industrial Research Ltd. *(IRL)*, University of Auckland *(AU)*, University of Otago *(UO)*, Victoria University of Wellington *(VUW)*.

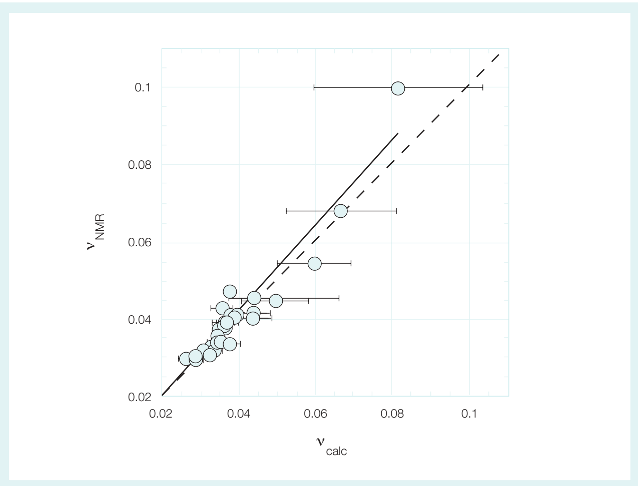


Figure 2: Brine content measured using NMR, ν_{NMR} , compared with brine content derived using conventional methods, ν_{calc} [1].

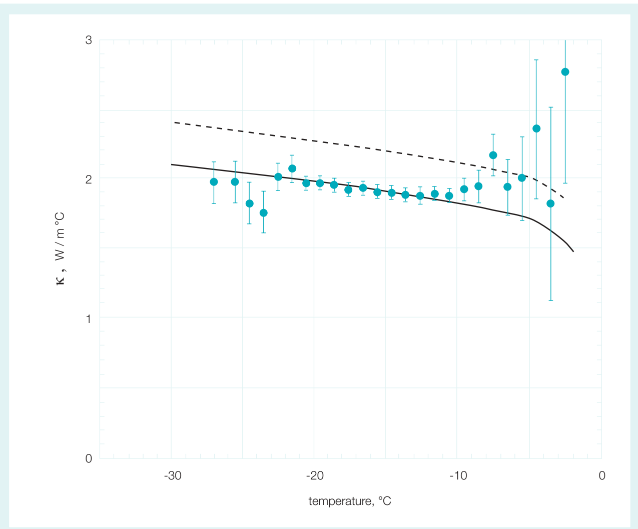


Figure 3: Dependence of thermal conductivity, **κ**, on temperature for *in situ* measurements (dots). Dashed line is the prediction used by most modellers, while the solid line is this prediction lowered by 10% to account for the scattering of phonons by crystal imperfections in the strongly disordered ice[5].

apparatus[2] to apply these techniques to measure brine content (Figure 2) and brine mobility in sea ice[1,3]. The method relies on the use of pulsed magnetic field gradients in precise analogy to well established laboratory procedures. The diffusive motion of water molecules in the brine inclusions has been found to be strongly anisotropic, and exhibits a rapidity greatly in excess of that expected for thermal equilibrium Brownian behaviour, an effect attributed to convective transport[1]. A recently improved apparatus reduces disturbance to the sea ice sheet by reducing the diameter of the magnetic field gradient coils.

In 1999 we returned to Antarctica with a new Nuclear Magnetic Resonance apparatus which was based on a specially developed compact and portable spectrometer. This system, developed for Antarctic use, has become the nucleus of a New Economy Research Fund (NERF) project in which the objective is to develop a portable NMR system for industrial use. The first application of this will be in the measurement of concrete drying, as part of a collaborative project carried out with the Building Research Association of New Zealand (BRANZ). A patent application for a magnet design associated with this project has now been lodged. It is a nice example of the unpredictable connectivity of science that Antarctic research, funded under a climate change objective, should lead to the development of R and D capability in materials technology, with the potential for generating new commercial activity.

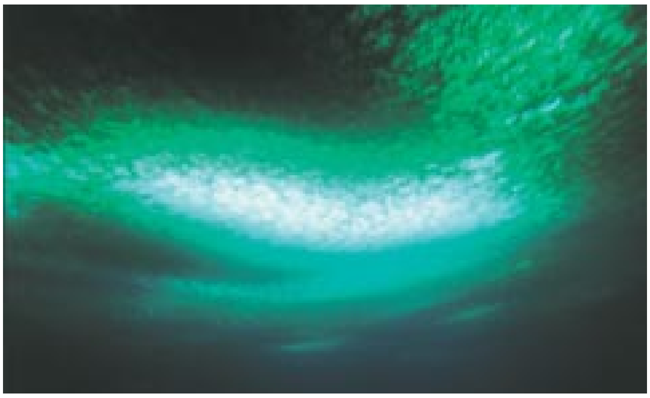
The thermal conductivity of the sea ice is a parameter of fundamental importance to heat exchange between the ocean and the atmosphere in polar waters. Surprisingly there are very few *in situ* measurements of it, with climatic models depending on calculated values. The Victoria University of Wellington group led by Joe Trodahl have been making high-resolution measurements of the temperature field in sea ice in winter and spring[4] and analyse these data to find the effective thermal conductivity of the ice-brine mixture, and its dependence on temperature (Figure 3) and structure[5]. The results are close to the values predicted thirty years ago, but limited by disordered structure near the surface and enhanced by convection in brine channels near the underlying sea water. Last year we published the first accurate measurements of the thermal conductivity of sea ice and its dependence on temperature and depth. We now have a joint NZ-USA programme seeking to provide climate modellers with an accurate parameterisation scheme to calculate the thermal conductivity. The next few years' plan is to begin an investigation of horizontal heat flow by similar techniques. The techniques developed here are being further extended with measurements and modelling being applied to heat and moisture flow in patterned ground in the Dry Valleys.

During 1985 – 2000 Bob Buckley and Joe Trodahl performed detailed studies of the random-walk transmission of light through sea ice, finally establishing the depth and seasonal dependencies of the scattering length for light in sea ice. It was necessary to develop an entirely new measurement configuration for determining the parameter without removing the ice from its environment. Based on those measurements we were able to provide a well-characterised procedure to estimate the intensity of the light field in and under sea ice, which are of interest for climatological studies and in understanding the growth of algae in the polar environment. Spot measurements of the transmission had been made in abundance, but ours were the first that specifically related the results to the ice structure, supported by such detailed measurements. As a part of the study we showed that the ultra-violet dose under the sea ice is enhanced by a factor of about two in the presence of the ozone hole. It is thus likely that under-ice algae, which provide a large fraction of the polar regions' primary production, are likely to show reduced growth rates.

The study of growth process has to date concentrated on the mechanisms of platelet ice growth. A group led by Inga Smith has collected data mainly in the Winfly period (August). Platelet ice growth is a phenomena seen mostly where cold water comes out from under ice shelves, rises and therefore super cools and sets the conditions that allow ice formation on nucleation sites. This part of the programme is being further extended to determine the relationship between the ice growth processes and the underlying oceanography of the Ross Sea.

Modelling

Refrozen cracks are a feature of most land-fast sea ice sheets. A group from the University of Otago led by Pat Langhorne is developing models for this. The refreezing of a liquid-filled crack involves heat flow in two-dimensions, upwards to the ice-air interface and laterally to the sides of the crack. This pattern of freezing is expected to effect the trapping of brine within the ice, a result confirmed by temperature and salinity measurements in artificially-formed cracks in sea ice. These features influence the strength of the refrozen material, and consequently the flexural strength of the ice sheet. In future work natural cracks will be examined, and compared with observations from the artificially formed cracks. This group has also developed a model for the fatigue failure of sea ice. This information is combined with that obtained from the modelling of wave propagation in sea ice sheets to create a model for sea ice break-up under the influence of the sea borne wave field.



Underside of sea ice. *Photo: Chris Rudge, Antarctica New Zealand Pictorial Collection.*

Vernon Squire and Colin Fox have developed mathematical methods to calculate how abrupt changes in thickness, or in the material properties of sea ice, affect the propagation of ice-coupled waves[6]. Reflection and transmission coefficients can be found for a train of waves crossing either a single crack or impinging on a region of regularly- or randomly-separated cracks in an ice sheet, allowing the amount of wave energy passing beyond the feature to be computed. Single cracks and fields of cracks favour the passage of long waves and inhibit short wave propagation[6]. A scaling law for flexural motion, and depth-integrated, mechanical indices are by-products of this modelling[7]. Ocean wave propagation, scattering, and damping in the broken pack ice of the Antarctic marginal ice zone (MIZ)[8] has been modelled in an analogous way to a composite material with two different refractive indices[9]. Energy transport velocities, dispersion relations (Figure 4) and scattering mean free paths for varying floe lengths and concentrations have been computed. Measurements, supported by the US ice breaker Nathaniel B. Palmer, have been made by a team led by Tim Haskell instrumenting floes to find the relationship between wave period and wave length[10].

Thus, it is well known that an incoming ocean swell produces a strain field in a land-fast ice sheet. In addition the number of cycles to failure for sea ice loaded at constant amplitude has been measured[11,12]. With the background work in place, the response of the land-fast ice sheet to a measured ice-coupled wave field of variable amplitude can be found. Using a cumulative damage law and stress-lifetime curves taken from field experiments, we can predict the lifetime of the sea ice sheet as a function of significant wave height and sea ice brine fraction[13,14].

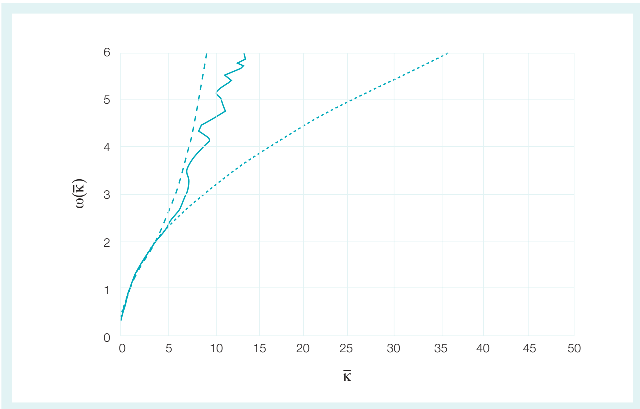


Figure 4: Dispersion relations for an ice concentration of 0.6 bounded above and below by the solid ice and open water dispersion relations respectively[9].

Conclusion

The New Zealand sea ice group is making a significant contribution to the international programmes on sea ice such as ASPECT (a part of SCAR). This is demonstrated by the number of foreign scientists who wish to join our Antarctic field parties, and also by our group receiving invitations to participate in ship cruises. We have an especially strong relationship with the United States, Australian, and European programmes. We expect these relationships to develop further in the next few years.

Acknowledgements

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ANTARCTIC INLAND WATERS: A MICROBE-DOMINATED EXTREME ENVIRONMENT

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The interest in extreme environments

There has been unprecedented interest in the study of microbes in extreme environments over the last decade. The United States National Science Foundation ran a well funded and highly competitive research grant competition in the 1990s known as LEXEN (Life in Extreme Environments) covering hydrothermal vents across the ocean floor, high mountain glaciers, subterranean rocks, geothermal hot springs and, not surprisingly, polar ice environments. Life in Extreme Environments is a central theme of New Zealand's Antarctic Research Science Strategy.

Why such interest? Life in extreme environments is dominated by microbes, now collectively called "extremophiles". They are found in deep mines, and in waters at either end of the temperature spectrum from salt waters at -20°C to hot waters approaching 100°C. They thrive in saturated brines and habitats with high metal, hydrocarbon or even radiation toxicity. The interest is spurred in large part by the understanding that survival in such conditions requires novel enzymes and genetic codes for unique biochemical processes. The biotechnology industry is particularly interested in these processes, aiming at medicine and industry. Indeed much of modern gene technology is based on a DNA-assembling enzyme discovered in a bacterium isolated from an extreme high temperature environment.

The study of extremophiles is also central to the space programmes, under the disciplines of Astrobiology and Exobiology, which are focussed on life on other planets, where average conditions may be more closely aligned with extreme conditions on earth. The similarity of the polar ice caps of Mars to those of earth, and the recently discovered wide distribution of permafrost on Mars, makes research on extremophiles in Antarctica of particular relevance to Astrobiology.

On the continent of Antarctica, physical conditions are among the harshest on earth and there are few refugia where organisms can take respite from extremes of cold and aridity. Thus, to survive at all, organisms must show extremophilic attributes. Understanding how Antarctic communities are assembled and function, how biodiversity is maintained or lost, and their vulnerability to climatic and other change, requires an understanding of the role of extreme environmental conditions in their ecology.

The Heroic Era

The biologists on the expeditions of Scott and Shackleton recognised the presence of inland life on the continent. They noted "coloured fungi" living under clear ice in some coastal ponds and the first to investigate this life was James Murray on Shackleton's expedition of 1908. With no equipment for sampling the 4m deep ponds at Cape Royds, he waited until winter when the ponds had frozen solid and then dug a pit down through the ice to the floor of the pond to retrieve samples of the organisms on the pond floor. He found that these consisted of mats of algae and associated with these were tiny animals such as nematode worms, rotifers and tardigrades. He found that these organisms were remarkably resistant to freeze thaw cycles, to changes in salinity and to desiccation. This ability to withstand such conditions is now recognised as the key to surviving in Antarctica and has been the focus of our research over the last decade. With modern sampling and analytical equipment we have been able to make considerable advances in our understanding of extremophiles.

Freezing – the biggest threat for Antarctic organisms?

Away from the sea edge, the cold of the Antarctic brings with it an environment of extreme cold and desiccation, where water is rarely available. The difference in plant and animal diversity and abundance between the relatively benign seas around Antarctica with a constant temperature of -1.8°C and the ecosystems immediately inland is very marked and, as hinted at by the early studies of Murray, reflects the requirement for tolerance of freezing and desiccation. Inland Antarctica is dominated by microbes; the few higher plants and animals that can persist are those such as mosses, nematodes and rotifers that can survive in a state of sub-zero annhydriobiosis (without water).

Freezing takes away liquid water and imposes a number of stresses on organisms. Two important stresses are "freezing" of lipid-based membranes and denaturing of proteins through water withdrawal as ice crystals form and place increasing osmotic stress on cells. Strategies employed to counter these problems include replacement of lipids in membranes by those with lower freezing points that will remain fluid at low temperatures and synthesis of intracellular osmotic protectants. Osmotic protectants act like anti-freezes in that they lower the freezing temperature of liquids, but also serve to protect the complex folding shapes of proteins during water withdrawal from cells. The exact mechanisms whereby this occurs are not fully understood, but protectants such as the sugar trehalose are thought to bind to proteins and form a glass-like substance around the sensitive proteins rather than allow them to become denatured. Antarctic microbes also appear to secrete ice-active substances into the medium in which they grow. Such ice-active substances act to restrict the growth of potentially damaging elongated ice crystals, and promote growth of benign, rounded crystals.

Where there is water there is life

Microbes are thus able, by biochemical adaptations, to reduce freezing damage at extreme low temperatures. However for active biochemical processes such as photosynthesis, respiration and cell division to take place and thus allow the development of populations and communities, there must be free water. And free water is a scarce commodity in a continent where the mean annual temperature is tens of degrees below zero. In fact, many people are surprised to learn that free water exists at all, but during a brief period in mid summer, glacier faces begin to melt and streams trickle across glacial moraine. If the relatively simple yet flexible physiology of microbes allows them to overcome the hurdle of winter freezing, it is the short period of liquid water that offers them a chance to grow and reproduce.

Figure 1. Ponds on the McMurdo Ice Shelf. Upper panel shows a range of ponds across the sediment-covered surface of the ice shelf. The lower panel is a close up of a pond showing the pigmented cohesive microbial mat peeling up from the pond bottom.

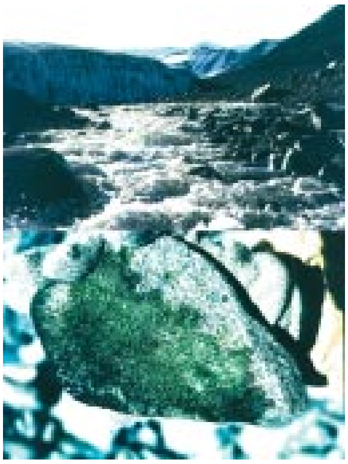

Figure 2. Glacier melt streams are common in mid-summer when alpine glacier surfaces melt. Upper panel: Adams Stream flows down to Lake Meirs from the Adams Glacier. Lower panel: a chlorophyll rich community of *Prasiola calophylla* grows in deep shade under rock surfaces in the Fryxell stream, Taylor Valley.

Water-based habitats

We have studied the aquatic systems of ice-free areas in Antarctica over the last decade. In our studies we recognise *Annual Systems*, including shallow ponds and glacier melt streams (shown in Figures 1 and 2) that are subject to winter freezing and often regular freeze-thaw cycles in mid summer. In the months of 24 hour daylight these systems are exposed to full sun (and early in the season, to increased UV-B under the ozone hole). We have also studied the *Perennial Systems*, which include the microbial communities living under the permanent ice of the deep ice capped lakes of the McMurdo Dry Valleys shown in Figure 3. These do not experience winter freezing, but are permanently under up to 5 m of ice, and light levels are very low, 1/1,000th the sunlight above. Special adaptations are needed to ensure that what little light there is, is efficiently captured. In this review we explore these environments in a bit more detail and discuss the adaptation that the organisms have made to exist here.

Shallow ponds and meltstreams

Shallow melt water ponds and streams draining glaciers or permanent snowfields are amongst the most widespread of water-based habitats in Antarctica. Nowhere in Antarctica are coastal ponds more abundant than on the McMurdo Ice Shelf (MIS) shown in Figure 1. Much of the undulating surface of the MIS is covered with a 1 – 200 mm layer of marine derived sediments, and a complex interconnected series of ponds has formed in response to melt of the ice shelf surface (Howard-Williams et al. 1990; Hawes et al. 1999). These ponds occupy an area of the MIS of over1200 km^2 and their environmental conditions and life forms are typical of other coastal ponds in Victoria Land. They are completely frozen for most of the year with a small summer period when temperatures rise above zero as shown in Figure 4.

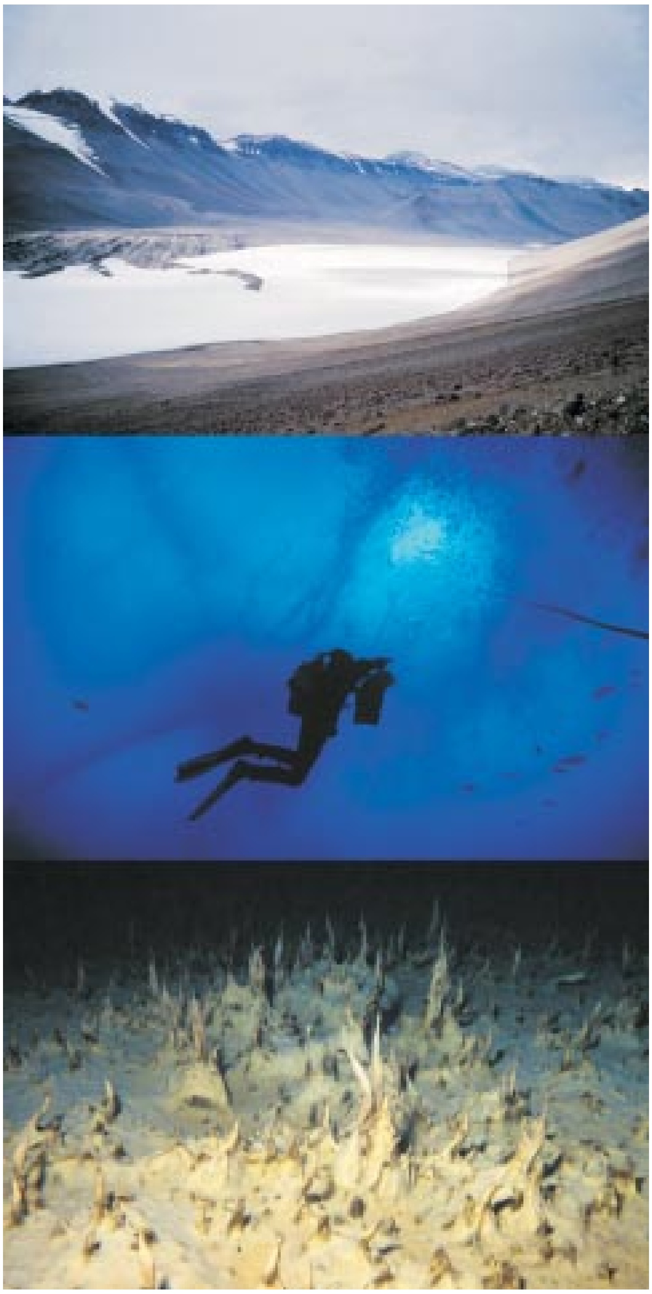

Figure 3. Lake Vanda, a permanently ice covered lake in the Wright Valley. Upper panel: view across the surface of Lake Vanda with its 4m thick ice cover. Middle panel: the clear blue water of Lake Vanda allows light to penetrate deep into the lake under the ice. Lower panel: the bottom of Lake Vanda is covered by a microbial mat dominated by cyanobacteria to depths exceeding 50 m. Unusual pinnacles extend up to the low light environment.

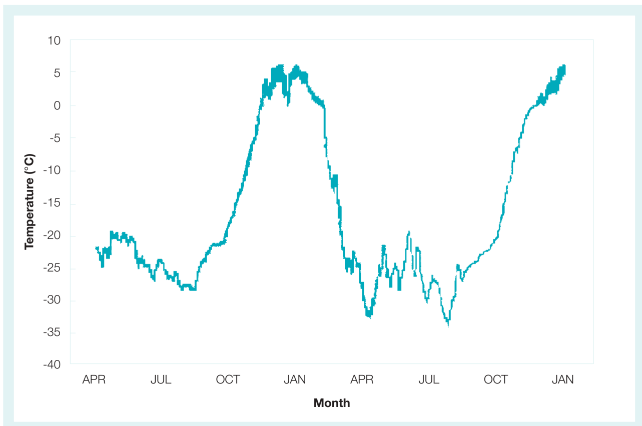

Figure 4. Communities in shallow water pond environments are subjected to temperatures of -35°C in winter and a very short growing season when liquid water occurs as the temperatures rise above zero. The graph shows the temperature record over two years for Fresh Pond on the McMurdo Ice shelf.

Minimum temperatures are close to -35°C. We have shown that as the ponds freeze, generally from the top downwards the salts in the pond water freeze out. Salts accumulate in the remaining water, resulting in formation of a salty brine which requires increasingly lower temperatures to freeze it as the salt concentration rises. In one pond, water was still liquid at -18°C in a brine more than five times as salty as sea water. A harsher environment for life is hard to imagine, and yet the pond microbial mat communities persist from year to year.

Glacier melt streams provide a somewhat different temperature regime for life. Stream channels occur off the ends of alpine glaciers in ice-free areas and for a few weeks or less each summer these channels are filled with melt water from the glacier surfaces (Vincent and Howard-Williams 1986). Unless the stream-beds are steep and unstable, microbial mats occupy stream-bed habitats either over the surfaces of the rocks, in crevices or even beneath rocks in dim light as shown in Figure 2. For most of the year the channels are dry, and the water trickles away when the glacier melt ceases. Stream life therefore freezes and desiccates until the next season's melt. Even during the melt, unusually stressful conditions occur with a daily freeze-thaw cycle. Glacier surfaces normally melt for part of the day and freeze when solar radiation decreases. Thus, even during the short growing period the microbial systems need to cope with a daily freeze and thaw and need to be well adapted to this.

One example of adaptation to the short period available for growth is seen in the extremely rapid recovery of the stream-bed microbial communities following winter darkness and freeze desiccation. These mats are comprised of an interwoven mesh of filamentous cyanobacteria that surround themselves with a muco-polysaccharide matrix giving the mat a cohesive texture (as shown, for instance, by the pond mat in Figure 1). During the winter months and up to early summer the stream-bed mats are exposed, in a dry and frozen state, on the bed of the empty stream channels. However, when the first trickle of glacial melt waters arrives, they recover extremely rapidly. Our measurements with the isotope C^{14} with which we can measure very small carbon uptake rates, showed that active uptake of C^{14} occurred in the first ten minutes after rewetting (Vincent and Howard-Williams 1986). Mats in stream channels and those on the margins of ponds may sometimes be freeze-dried for several years before rewetting. In two of these mats we found that a steady state of both respiration and photosynthesis had been achieved within two hours of rewetting from a desiccated state as shown in Figure 5 (Hawes et al. 1992).

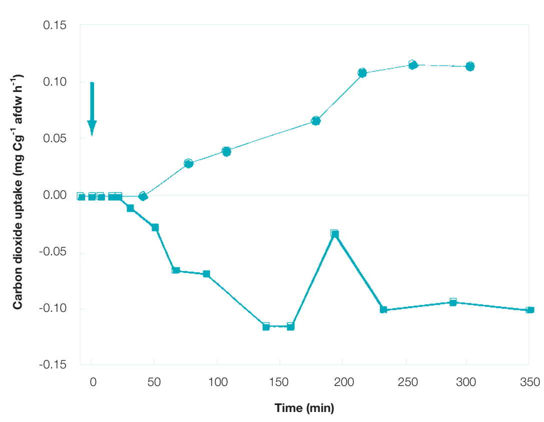

Figure 5. Microbial mat communities are able to recover rapidly from a freeze-dried state following the addition of free water. Photosynthesis and respiration begin within 40 minutes following rewetting after a dried state.

What is clear from the temperature records of ponds and the flow regimes in streams is that the summer melt period provides a very short window for growth and reproduction. It is something of a surprise to note, however, that the successful Antarctic microbes often grow extremely slowly at ambient temperatures and have temperature growth optima well above the temperatures that they ever experience in coastal ponds. Few, if any, seem to be specifically adapted to grow well at low temperature. For example, most isolates of cyanobacteria from Antarctic ponds and streams have growth optima at 15 – 30°C. This contrasts with the marine ecosystem where temperature optima for growth of diatoms and sea-ice bacteria are much lower, and close to that seen in their environment. A complete explanation of this apparent contradiction is lacking, but it may be related to the fact that the temperature in some inland systems can occasionally rise up to 10°C due to solar heating. At present, we consider that the dominance of inland waters by microbes, particularly cyanobacteria, is largely due to their ability to tolerate the extreme conditions of winter and the virtual absence of grazing or disturbance from animals. They can persist and slowly accumulate over long periods of time, as no potential competitors or predators can tolerate such conditions.

The high light environment

Microbial communties in shallow water must also tolerate extreme variations in light. During the summer there will be 24 hours of continuous high light, whereas in winter there will be continuous darkness. Too much light can be as dangerous for photosynthetic organisms as too little. When an organism is in balance, light absorbed by photosynthetic pigments is either used in photochemistry, dissipated as heat, or lost by fluorescence. There is a finite limit to the rate at which absorbed energy can be used in photochemistry, and when this limit is exceeded adverse reactions begin to occur that serve to damage the cellular machinery. Lower temperatures typically mean that these occur at lower light levels. Various inducible mechanisms help to increase the harmless dissipation as heat as light increases, but these protective measures are also slowed by low temperatures. Specific wavelengths of light, particularly UV radiation, are also directly harmful to molecules within cells, and can only be repaired by (temperature-sensitive) enzymatic processes. Thus the combination of high light, especially UV radiation, and low temperature is a potentially hazardous one.

Many shallow water communities cope with high light stress by synthesis of light screening compounds. Examples are the rock-encrusting cyanobacteria of shallow streams (e.g. *Gloeocapsa*), and *Nostoc*, a cyanobacterium charactistic of shallow waters. These protective pigments can include an array of carotenoids and scytonemins, the later of which are particularly effective at screening out UV radiation. The characteristic black/brown/orange appearances of most microbial mats in shallow waters (as shown in Figure 1), is due to the presence of these pigments. While surface layers are highly pigmented for protection from high light, most of the photosynthetic activity is located in an underlayer that is acclimated to the much lower irradiance (1 – 5%) that penetrates the upper layer. This layer is usually intensely green, and is made up of cyanobacterial trichomes that are protected from the adverse surface irradiance. In high light, suspensions of these trichomes, all of which are motile, actively clump together to protect each other from excessive light. Conversely, as light intensity decreases, the motile trichomes are able to move up through the mat until they are at the surface, thus optimising the light environment in which they operate. The dominance of photosynthesis by highly shade-adapted organisms at the base of microbial mats in the continuous bright sunlight of Antarctica is unexpected, but is clearly an effective strategy of coping with light stress at low temperature.

Deep lakes with perennial water

Deep lakes occur in the Dry Valleys of McMurdo Sound where the heat balance is such that liquid water persists all year round, under thick perennial ice cover. Cyanobacterial mats that grow under permanent lake ice face the opposite problem to those in shallow water – too little light. To offset this, lake trichomes tend to try to migrate upwards, in pursuit of more light, rather than downwards in pursuit of shade. In some situations this can result in the development of extraordinary pinnacles, many cm tall, arising from the lake floor as shown in the lower panel of Figure 3. Alternating vertical summer growth and winter stagnation also results in annual layering of the mat communities. The most active photosynthetic cells in lake mats are therefore at the mat surface, rather than at the base of the mat as in the shallow systems. The pigmentation of cells is also different, as photo-protective pigments are not needed and instead of being brown many mats are pink. This represents accumulation of the pigment phycoerythrin, which is particularly effective at harvesting the blue-green light that best penetrates the ice cover and water column. Lake mats are also acclimated to the very low light they experience by being highly photosynthetically efficient. We have estimated that 70 – 80% of the light absorbed by these mats is actually used in photosynthesis, a very high proportion for a photosynthetic system. These organisms are growing at the extreme limits of light energy for oxygenic phototrophs, and produce remarkably high biomass and near complete coverage of lake floors. Once again, however, adaptation alone is not the whole secret of success of the perennial mats. Essential too is the absence of disturbance from grazers or other larger organisms that allows the diatoms and cyanobacteria that form the mats to grow to the limits of their abilities to harvest and utilise light.

The importance of the mat as a structure

A common feature of cyanobacteria-dominated communities that survive in the extreme environments of Antarctica appears to be that they create their own "less extreme" micro-environment in the form of a layered mat. This mat also serves as a habitat for other organisms such as diatoms and a wide range of heterotrophic bacteria as well as microfauna such as nematodes, tardigrades and rotifers. Microbial mats are ubiquitous in the polar regions (and in other extreme environments such as hot springs). Why should mats be such a common growth form in these environments? Examination of the detailed structure of mats using modern micro-technology have allowed us to study structure and function of mat communities. Among their characteristics are:

- Upper layers of the mat have a "sunscreen" of photo-protectant pigments such a ß-Carotene, canthaxanthin etc.
- The mat creates a "semi-permeable" membrane between water and sediment that allows for the establishment of diffusion gradients of dissolved materials, nutrients and gasses (hours time scale).
- Trichomes are free to migrate vertically in the mat and do so rapidly to take advantage of optimum light and nutrient conditions that vary through the day.
- The mat matrix may inhibit the formation of damaging ice crystals during freeze-thaw cycles.
- The hydroscopic properties of the muco-polysaccharides in the mat matrix assist in desiccation resistance.

Layered mats such as those found on the McMurdo Ice Shelf and the Dry Valley Lakes are similar to the ancient fossil mats preserved as stromatolites in various geological formations. These are some of the oldest known microfossils, indicating that mats such as those in Antarctic inland waters have been present on earth for several billion years. When these mats were forming, the environment on earth was extremely stressful compared with that which we see today. Oxygen was absent, high concentrations of reduced metals (usually the most toxic forms) and high levels of UV radiation would have been present. It was mats such as those that we currently see in Antarctica that were probably responsible for the present oxygenated atmosphere on earth, with the resultant development of the protective ozone layer under which subsequent life could evolve. It is tempting to suggest that the ability of cyanobacterial mats to tolerate extreme conditions in Antarctica today stems from genetic lessons learnt in the early period of life on earth. As it is now, the oldest forms of life on earth, in the oldest known community structure, remain amongst the only ones capable of bringing life to the inland parts of Antarctica. Although we can look to the high profile life forms of the marine fringes, such as penguins, seals and whales, to provide the glamour to Antarctica, it is the microbes that dominate inland and provide life to the frozen continent itself. New discoveries of life forms and communities on the frozen continent will be made, and new developments of the bio-technical uses of extremophiles will ensure their study continues.

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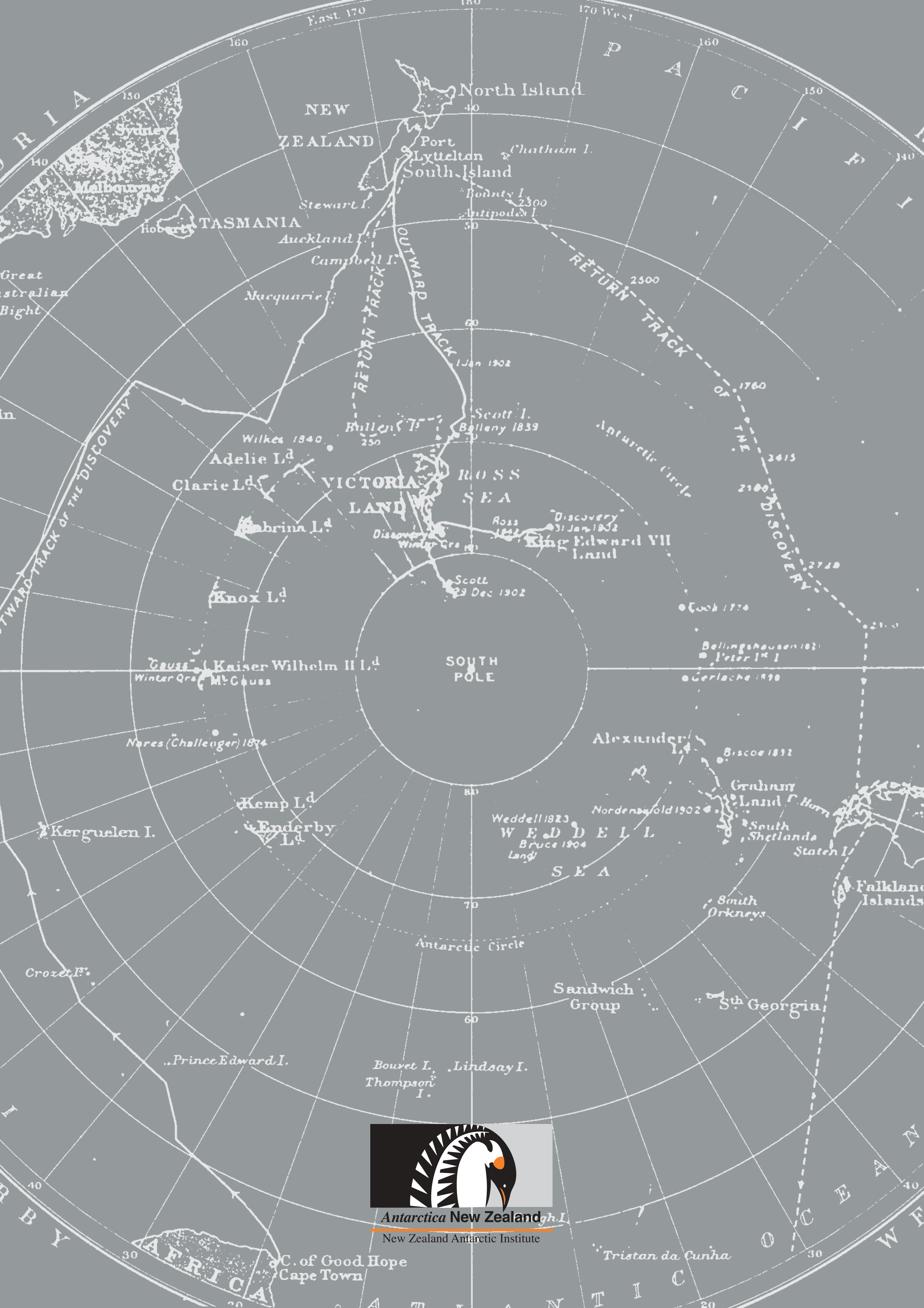

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