BRITISH ANTARCTIC SURVEY ACTIVITIES WITH SPECIAL REFERENCE TO GLACIOLOGY

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ABSTRACT

BAS supports six science divisions covering the Atmospheric/Space Sciences, Life Sciences and Earth Sciences. Glaciology is a mainstream discipline within the Ice and Climate Division. Logistics support is provided through the Antarctic research stations (Bird Island, Signy, Faraday, Halley and Rothera, the latter being the principal focus for the deployment of glaciological field parties), aircraft (BAS operates three ski-equipped Twin Otter aeroplanes) and ships (RRS Bransfield and John Biscoe). The glaciological research is directed into two principal programmes: the Dynamics of the West Antarctic Ice Sheet and Past Climate and Environment. Current work on the Ronne Ice Shelf is concerned with the dynamics of the ice sheet system (inland ice - ice streams - ice shelves). The aim is to understand how the forces which restrain ice sheet flow react to changing boundary conditions in a changed climate. Survey stations have been established on the Ronne Ice Shelf and the Rutford Ice Stream to determine velocities and strain rates. Radio echo sounding data are also being used in conjunction with satellite imagery to decipher the physical mechanisms that control the movement of the fast flowing Rutford Ice Stream over its bed. Data are being used in the development and testing of ice sheet models. BAS glaciologists are investigating the thermal regime of temperate George VI Ice Shelf. The aim is to produce estimates of basal melt rates over the entire ice shelf and understand the physics of the processes which control their behaviour. The work involves drilling through the ice to measure temperature gradients and install instruments in the sea beneath the shelf, and oceanographic studies of the surrounding waters.

The response of the ice sheet system to past climatic change can be studied using chemical data from ice cores. BAS glaciologists have concentrated on shallow cores from the Antarctic Peninsula which give climatic information over the past 50 years which can be compared with meteorological records. This has produced improved knowledge of the relationship between stable isotope composition and air temperatures. In the future deeper cores will be drilled in Palmer Land. Global pollution is being studied by investigations of heavy metals in recent snow and comparison with older ice in which concentrations are being determined at the pg/g level.

1. INTRODUCTION : THE BRITISH ANTARCTIC SURVEY

The British Antarctic Survey (BAS) is responsible for the British Government's scientific research activity in the Antarctic, South Georgia and the South Sandwich Islands and covers a land area of some 1.1 M km^2 (Figure 1). The

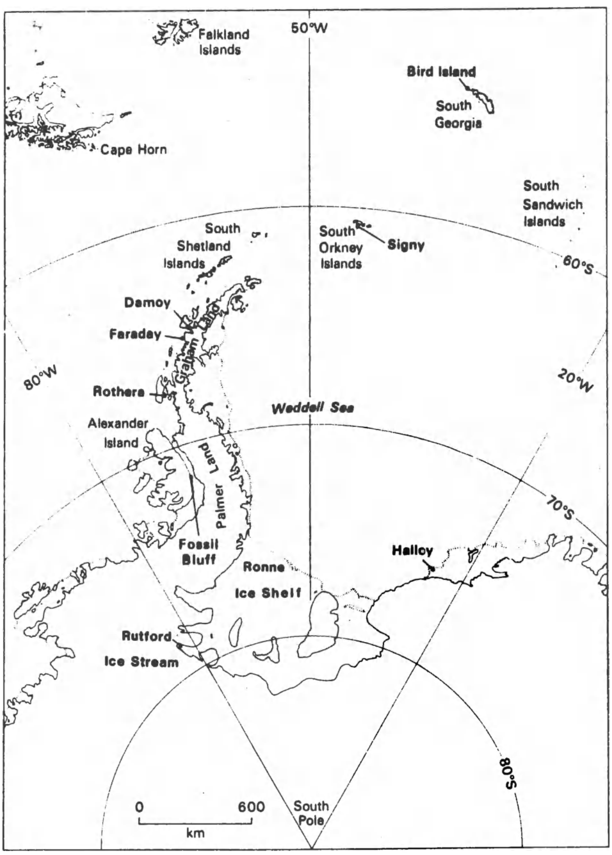

Fig. 1.
Location map for activities of British Antarctic Survey.

Survey originated as a wartime naval operation (Tabarin) in 1943 which was transferred to the Colonial Office in 1945 and was known until 1962 as the Falkland Islands Dependencies Survey. In 1967, BAS became one of the research institutes of the Natural Environment Research Council (NERC). Financial support comes through NERC from the Department of Education and Science. The total scientific and support staff totals about 400, made up of contract personnel supervised by BAS permanent staff. The Survey currently runs on an annual budget of £15 M excluding major new capital expenditure on ships, aircraft or Antarctic bases.

2. ORGANIZATION OF SCIENTIFIC RESEARCH AND LOGISTICS

Research is organized from the BAS headquarters in Cambridge within the framework of six scientific divisions - Geology, Geophysics, Upper Atmospheric Sciences, Ice and Climate, Terrestrial and Freshwater Life Sciences and Marine Life Sciences. In addition, a seventh division is responsible for administration and logistics - co-ordinating the supply and rebuilding of Antarctic stations, air and ship operations, staffing and finance.

BAS maintains five permanently-manned stations (Figure 1). Bird Island is located in the sub-Antarctic off the western tip of South Georgia. It is the smallest station with a summer complement of 8 scientists and 3 overwintering personnel. Research is focussed upon the biology of the higher predators of the Southern Ocean ecosystem - the numerous birds and seals which frequent the islands. Signy Island in the South Orkney Islands also concentrates on a wide range of biological research, principally marine, freshwater and terrestrial programmes. Upwards of 30 persons may work at Signy during the summer. BAS maintains two research stations along the west coast of the Antarctic Peninsula, the most southerly is at Rothera on Adelaide Island. This is the centre for extensive earth science operations supported by aircraft and has a summer complement of 70. Geological, geophysical and glaciological programmes are deployed from Rothera to field camps or advance summer-only bases such as Fossil Bluff on Alexander Island. Faraday is a geophysical observatory undertaking work on geomagnetism and upper atmospheric physics. The latter is also the principal activity at Halley, the most remote BAS station at 75°S and located on the floating Brunt Ice Shelf in the south-eastern Weddell Sea.

The bases are re-supplied each year by two BAS vessels, the RRS Bransfield and RRS John Biscoe. The Bransfield is the larger of the two at 100 m length and ice-strengthening allows her to enter the pack ice of the Weddell Sea to reach Halley. John Biscoe was modified in 1979 to undertake scientific cruises for about 100 days each year, principally in support of marine geophysics and geology and the Offshore Biological Programme. Built in 1956, she is to be replaced in the 1990-91 season by a new dual role (science/cargo) ship of about 95 m length.

Three ski-equipped de Havilland Twin Otter aircraft (a fourth will be acquired in 1988) are used to deploy scientists to field camps and bases, operating out of Rothera, where a snow/ice runway is maintained, and undertake a variety of remote sensing projects - radio echo ice thickness sounding, aeromagnetics and aerial photography.

3. GLACIOLOGICAL RESEARCH

The BAS supports a large scientific Division to investigate glaciological and related climatic phenomena, recognizing that ice plays a major role in the global ocean/atmosphere system. Antarctica, still firmly in the grip of an ice age, provides a useful analogue for the ice sheets that covered northern continents 12,000 years ago. The size of the ice sheet is regulated by climate, and one of the key unsolved questions concerns the response of the ice sheet to climate change induced by human activity - especially the greenhouse warming effect. The investigation of the issues associated with this problem are of prime concern to BAS and have led to the development of two principal research programmes.

3.1 Dynamics of the West Antarctic Ice Sheet

The West Antarctic ice sheet, which rests on bedrock below sea level, is believed to be particularly vulnerable to climate change and could shrink significantly over periods as short as a few centuries, leading to significant rises in sea level world-wide, with consequent social and economic damage.

A strategic BAS programme is looking at all the active elements in the ice sheet system (the inland ice sheet, outlet glaciers/ice streams and floating ice shelves) with the aim of producing a coherent account of the interactions between each of the different parts. Each element has its own distinctive set of boundary conditions and physical processes that govern its flow, but they must all be coupled together in a realistic fashion to understand present day behaviour and to predict consequences of any changes in the environment.

3.1.1 Ronne Ice Shelf - Rutford Ice Stream - flowline study

Rutford Ice Stream drains about 36,000 km^2 of the West Antarctic Ice Sheet into Ronne Ice Shelf (Figure 2). The BAS have been operating over the drainage basin, ice stream and adjacent ice shelf since 1975 in a variety of groundbased and airborne surveys.

In the 1985/86 season, a line of survey stations was established along a flowline on Ronne Ice Shelf, one of the two largest ice shelves in Antarctica (Figure 2). Some of these stations were remeasured in the 1986/87 and 1987/88

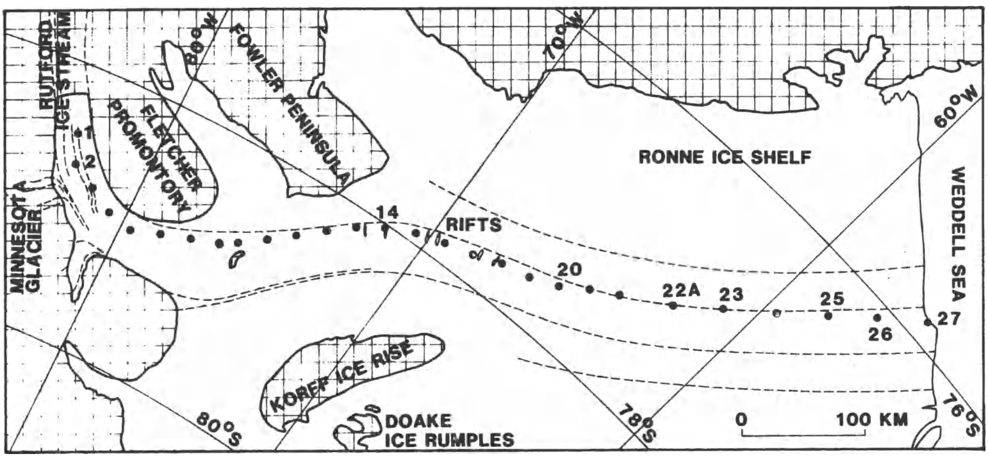

Fig. 2. Position of Glaciological Survey stations on Ronne Ice Shelf.

seasons using satellite positioning as well as optical survey equipment, to give values for ice velocity and strain rates. Additional stations were established to continue the line to the ice front. Already, it is possible to refine estimates of the basal melt rates (Doake, 1987; Jenkins and Doake, in press). It appears that within 150 km of the ice front there is a zone where saline ice is frozen onto the bottom of the ice shelf but is melted off before the ice front is reached. Ground based and airborne measurements show variations in the strength of basal radar reflections which support these results. After the flow has been successfully described by a realistic kinematic model, other estimates of physical quantities can be made, such as the forces acting on the ice shelf.

The inland end of the BAS ice shelf network joins a more intensive survey network on Rutford Ice Stream. Stake networks covering more than 140 km extend along an approximate flowline and across a grounding line that has been located on the downstream side of a small knoll by using tiltmeters to measure tidal flexure of ice more than 1600 m thick (Stephenson, 1984). The networks have been surveyed for velocity and strain rate and sounded by radar for ice thickness (Stephenson and Doake, 1982; Doake et al., 1987). Rapid variations in radar echo strength from the basal layers contain information about the nature of the glacier bed and the possible distribution of water pockets. Patterns of echo characteristics can be compared with surface topography seen in satellite images and with velocity and strain rate data from the survey network. Correlations will help understand the physical mechanisms that control the movement of a fast flowing glacier over its bed (measurements show that Rutford Ice Stream moves at a surface rate of between 300 m a^{-1} and 400 m a^{-1}), and a subset of the survey data has been analysed to see how the various forces acting both to drive and to restrain the ice stream vary with distance from the ice shelf junction (Frolich et al., 1987). For example, flow of the ice stream over a bedrock step of 500 m has created a surface knoll, which is seen clearly in satellite images. The force arising from vertical shear stress gradients is important within distances of a few ice thicknesses of the step (ice thickness about 2000 m), and represents a 'bending' component. The local peak in the driving force seen as the ice flows over the knoll is apparently absorbed by this 'bending' term. It is also noticeable that the flow must be explained by a full three dimensional analysis; lateral strain rates increase several kilometres upstream of the surface knoll, showing diverging flow around the bedrock step.

The ice stream under investigation is a transition region between the inland ice sheet and the ice shelf. Whether this is a stable configuration, or whether a periodic oscillation occurs, perhaps triggered by internal flow dynamics or external climatic forcing, is a fundamental problem in the interpretation of the dynamic history of ice sheets. Satellite remote sensing data are also assisting investigation of these problems. For instance, comparison between a SPOT image taken on 8 January 1987 (Figure 3) and a Landsat image of 3 February 1974 shows that surface topographic patterns on

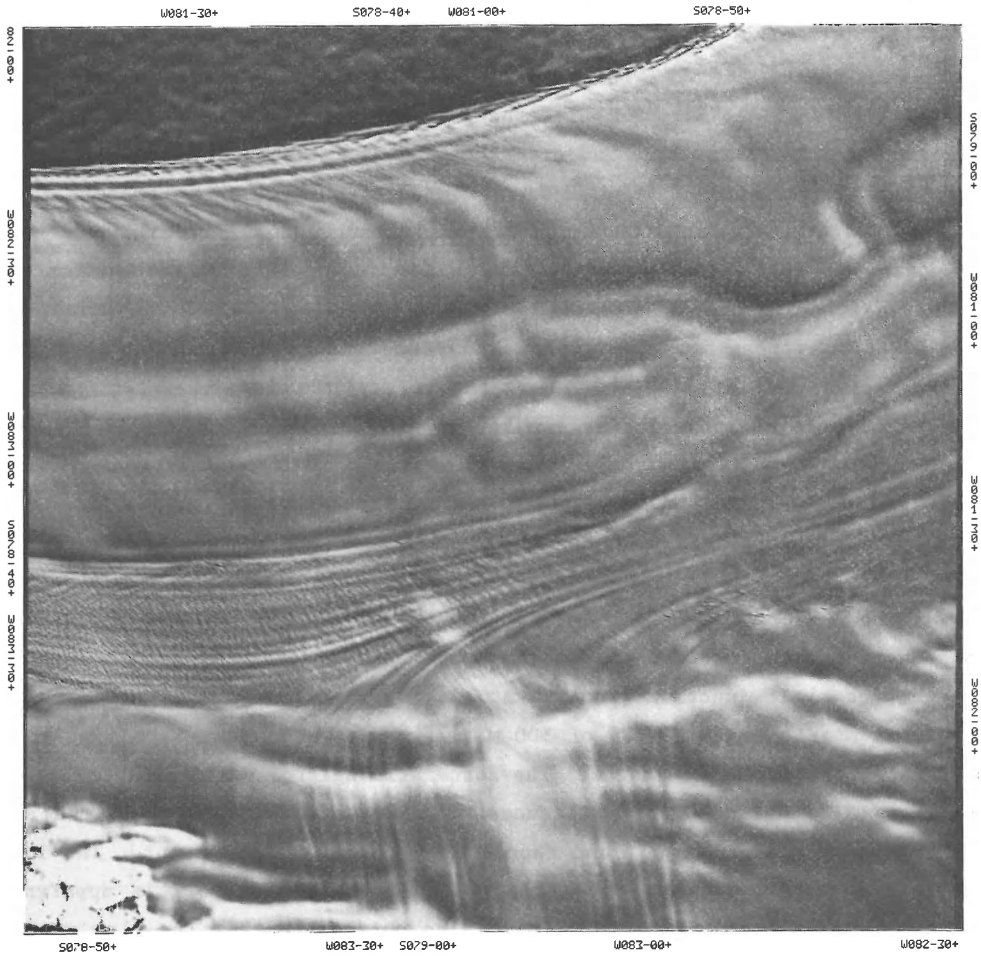

Fig. 3. Image of Rutford Ice Stream © CNES 1987 from SPOT satellite, 8.1.87. The ice is flowing from left to right in approximately south-easterly direction. Surface patterns are caused by subtle topographic relief, with height differences up to 20 m over distances of a few km.

Rutford Ice Stream have been displaced downstream by several kilometres (Vaughan, Doake and Mantripp, in press). Ice velocities derived from these movements agree with measurements made by ground based surveys in the near vicinity. Because the surface topography is thought to reflect partial grounding of the glacial sole the implication is that the substrate to the ice stream is mobile. Deformable beds to glaciers, composed of water-saturated till with effective pore pressures of near zero, have been suggested by Boulton and Jones (1979) and recognized in seismic records on Ice Stream B in Marie Byrd Land by Blankenship et al (1987). However, this is the first time that movement of a glacier bed on such a large scale has been seen and this has important implications for the dynamic behaviour of the ice stream and its reaction to climatic changes. Pixel radiance values from the SPOT images have been compared with surface slopes measured along a detailed level line by a ground based survey in February 1987. There is a strong relationship between slope and radiance, suggesting that our goal of deriving quantitative topographic data from single SPOT images is attainable.

Although a number of Landsat images of Rutford Ice Stream were acquired in 1973 and 1974, it is only fairly recently that some have been digitally enhanced by B. K. Lucchitta of the U.S.G.S. (Swithinbank and Lucchitta, 1986). The surface relief on the ice stream is only of the order of 20 m over distances of several kilometres, but the uniformity of the snow surface albedo again means that the radiance measured by the satellite sensor depends mainly on surface slope.

3.1.2 Ice Shelf - Ocean Dynamics

George VI Ice Shelf, on the west coast of the Antarctic Peninsula, is unusual: unlike other ice shelves which are underlain by sea water barely above freezing the sea water here is up to three degrees above freezing. BAS glaciologists are studying the thermal regime of George VI Ice Shelf together with the oceanographic circulation beneath it. The results are important in modelling what might happen should warmer water, in a warmer climate, freely intrude beneath all ice shelves.

The channel of George VI Sound is typically 700 m deep and is overlain for most of its 500 km length by an ice shelf of around 100 m thickness at the northern ice front, increasing to 500 m thickness to the east of the Eklund Islands. Profiles of temperature (T) and salinity (S), measured in the vicinity of the northern ice front (Loynes et al., 1984; Potter et al., 1985) show a linear T/S dependence, confirming a thermodynamic model of ice melting in Circumpolar Deep Water and indicate that thermohaline convection is the principal mixing process. Oxygen isotope profiles demonstrate that the melting ice has a value of -20°/oo with respect to Standard Mean Ocean Water (SMOW). This is similar to the mean isotope ratio of present-day accumulation in the catchment (Potter and others, 1984). Since the basal ice is formed from accumulation over several millennia, it seems that there has been no significant net climatic change in the Antarctic Peninsula over this period. Measurements support a simple circulation model for the northern part of George VI Sound; Circumpolar Deep Water is advected under the ice shelf at depth, upwells transferring heat which melts the ice and then collects in a northward outflow gathered to the west by Coriolis force. The circulation is driven by the melting process which causes the upwelling of warmer water from greater depths.

Potter and Paren (1985) have inferred from T/S profiles that the northern circulation penetrates at least 160 km south but not so far as the southern ice front in the Ronne Entrance. These geographical limits constrain the basal melt to values between 1.1 and 3.6 m a^{-1}. If the ice shelf is in equilibrium it alone supplies 53 km^3 a^{-1} of ice melt or about one-sixth of the total for Antarctica.

Pedley and others (1986) have measured a year-long tidal record from beneath George VI Ice Shelf. An unusual feature of the record is a significant response in tidal species 3 to 7. Nonlinearity also occurs in the tidal motion of the Ronne and Ekstrom ice shelves but has not been reported from the Ross Ice Shelf. The tidal dynamics of several Antarctic ice shelves have therefore been modified by a region of strong nonlinear response to tidal forcing and an anelastic component in the deformation of the ice at the grounding line is tentatively proposed as the mechanism responsible.

Talbot (1987) has assembled all the available hydrographic evidence to discuss the oceanic environment of George VI Ice Shelf, and has prepared a 2800 km-long section illustrating the temperature, salinity and density structure of the sea. The transect embraces the ice shelf and extends through both its ice fronts and across the continental shelf breaks into the deep Pacific Ocean. This is an important contribution to knowledge of the oceanography of the warm Pacific sector, since hitherto all hydrographic sections have terminated at the shelf break because sea ice has curtailed shipboard surveys.

3.2 Past Climate and Environment

The Antarctic ice sheet has preserved a record both of its own evolution and of the changing climatic regime under which it is developed. The ice sheet consists of a continuous sequence of annual layers of snow, in places several kilometers thick, spanning up to several-hundred-thousand years of the Earth's history. Each layer preserves a sample of the atmospheric gases and dusts in the atmosphere at the time of the original snowfall. Analysis of the physical and chemical properties of the ice yields evidence on past climate, on factors that may have forced climatic change, on the size of the ice sheet, and in the upper part direct evidence for global pollution and human impact. Interpretation of this unique and highly detailed record is yielding quantitative information which will enable a rigorous test of computer models describing the evolution of the ice sheet, and is providing vital input data to the GCM's that are being developed for long term climate prediction.

Ice core studies are a focal point of BAS glaciological research. They aim to reconstruct the climatic history of Antarctica, both as an essential step towards understanding global climatic processes and to test theoretical models that can predict future climatic change. Furthermore, they aim to achieve a detailed record of global air pollution, revealing the importance of a human impact on the global environment.

3.2.1 Past Climate

BAS studies are presently concentrated in the Antarctic Peninsula, which cuts across the sub-Antarctic zone, bridging all the 1000 km of the gap between South America and Antarctica. It is uniquely placed to relate climatic records from the continental ice sheet with the glacial and climatic history of lower latitude continents.

The BAS effort takes advantage of the relatively long instrumental records of climate available from the region, to explore the transfer functions between climatic and ice-core parameters and essential for reliable interpretation of deep ice-core data. Studies (Peel and Clausen, 1982; Mumford and Peel, 1982) of stable isotopes, mineral dusts and dissolved salts have been made in more than 30 mainly hand-drilled, shallow cores from many parts of the region (Figure 4). They show that large areas of the Peninsula have preserved a rich geochemical stratigraphic record of climate with a regular, accurately dateable succession.

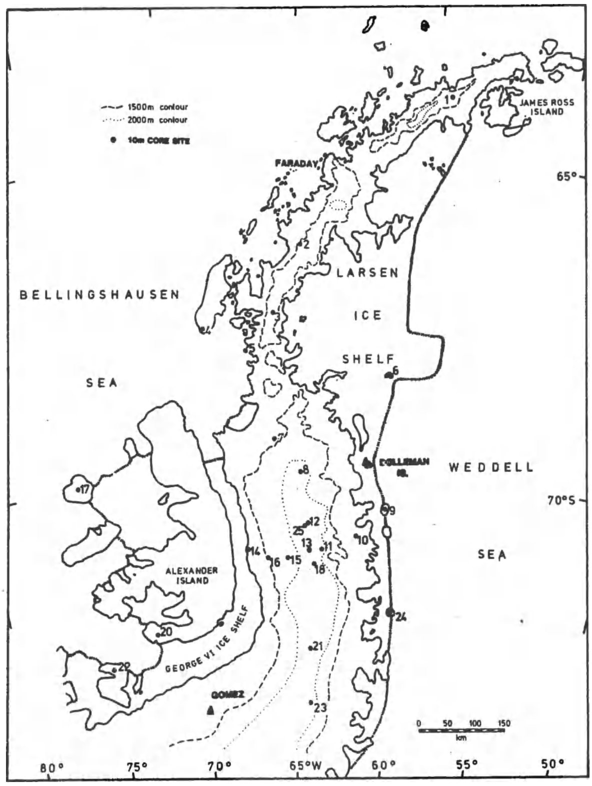

Fig. 4. Map of the Antarctic Peninsula showing the location of drilling sites and weather stations cited in this paper.

Two electromechanically-drilled cores have so far been drilled at sites chosen to represent the two principal climatic zones of the region; an 87 m core from the southern Palmer Land plateau, representing the cyclonic regime of the west coast region, and a 133-m core from Dolleman Island, representing the more continental and colder regime of the Weddell Sea sector. In collaboration with the Geophysical Isotope Laboratory, University of Copenhagen, oxygen isotope data from these cores have been used to explore the detailed relationship between the isotopic composition and air temperature records from neighbouring weather stations (Figure 5). All the major regional temperature anomalies known from climatic records are visible in the isotope profiles, including a clear temperature increase of around 1.3°C between 1960 and 1980. This is approximately 4 times greater than the average change recorded elsewhere on the Antarctic continent.

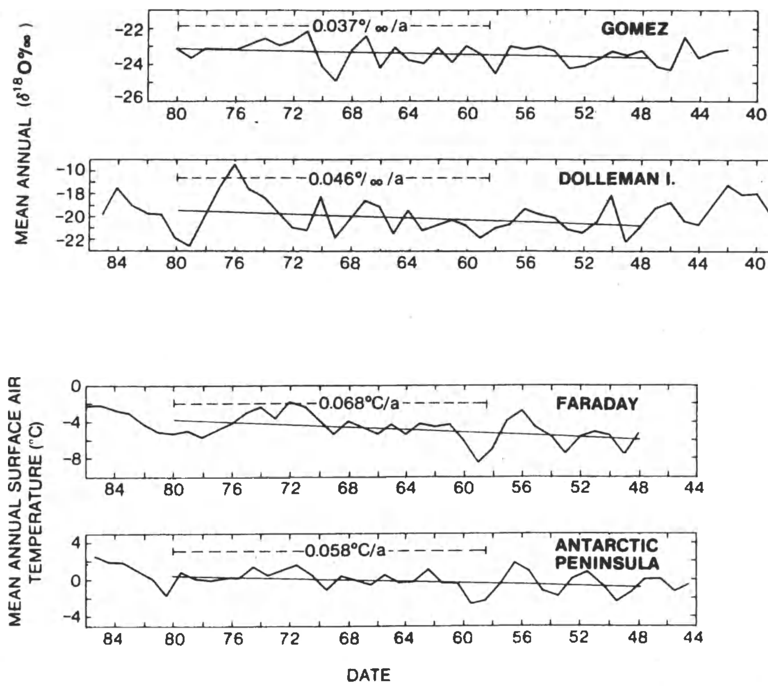

Fig. 5. Mean annual time-series of ^{18}O from Gomez and Dolleman ice cores in comparison with an instrumental record of air temperature from Faraday, and average record for the Antarctic Peninsula region.

Mainly due to the relatively large snow accumulation rate, the Antarctic Peninsula is one of the few areas of Antarctica where sites suitable for drilling yield cores in which climatic changes averaged over only a few years can be detected (Peel and others, 1987). The most notable trend during the past 30 years is an increase of more than 30% in the snow accumulation rate which has accompanied the overall temperature increase of 0.06°C a^{-1}.

In parallel with the isotopic studies detailed analysis of the major soluble inorganic ions is being carried out - including the anions chloride, sulphate (Figure 6) and nitrate (by ion chromatography), the cations sodium, potassium, calcium and magnesium (by atomic absorption spectometry and ion chromatography) and strong acid by low level acid titration (Mulvaney and Peel, 1987). The data are being used to develop new indices of climatic (e.g. cyclonic) activity and to evaluate factors closely related to climate including sea ice extent, volcanism and atmospheric turbidity.

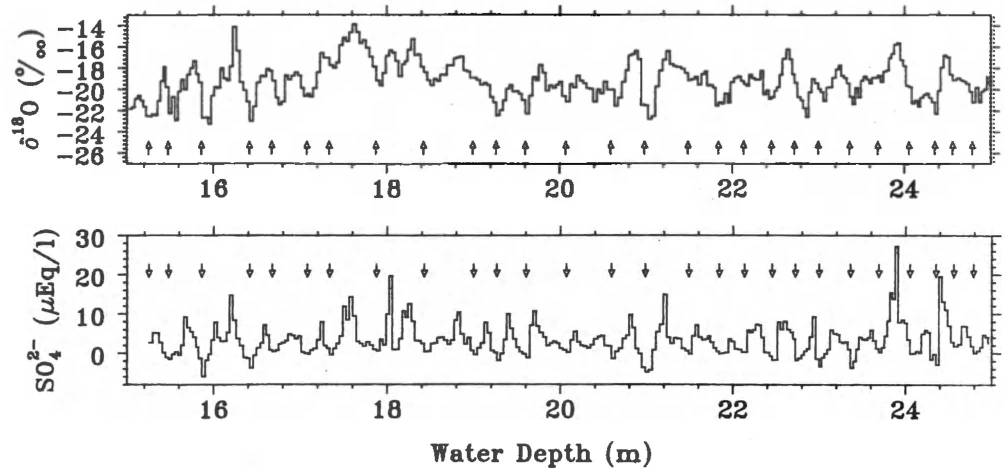

Fig. 6. Variations in sulphate and $\delta^{18}O$ in a section of the Dolleman Island ice core. Sulphate shows a clear seasonal cycle, with a maximum concentration during the austral summer.

Efforts have been made to devise new techniques for rapid and non-destructive dielectrical scanning of ice cores (Moore and Paren, 1987). These aim to identify at an early stage the most 'interesting' sections of the core for chemical analysis and could allow a core to be dated at the time of drilling. BAS glaciologists have designed and built an entirely new device for making continuous dielectric profiles along ice cores. Results confirm that the chemical content of ice is the main determinant of the electrical conductivity of ice at frequencies used for radio-echo sounding of glaciers (Moore, 1987). Thus the internal reflections seen in many radio-echo profiles are chemical in origin and can be used safely as isochrons in flow analysis.

In general the mechanisms of electrical conduction in polar ice have been poorly understood. Recently, however, BAS glaciologists have used scanning electron microscopy (SEM) to confirm a model they had proposed (Wolff and Paren, 1985) on theoretical grounds to account for DC conduction in ice. Using an X-ray microanalyzer fitted to the SEM, for the first time they showed (Mulvaney, Wolff and Oates, 1988) directly that sulphuric acid (but not sodium chloride) is localized at triple grain boundaries in an ice sample from the Antarctic Peninsula.

3.2.2 Global Pollution

Remote from industrial centres, or indeed from almost any kind of human activity, the Antarctic ice sheet has preserved a unique record of globally-dispersed air pollution (Wolff and Peel, 1985). A major advantage compared with studies elsewhere is that the human impact can be assessed directly by comparing the composition of recent snow with that of ancient ice. BAS has selected the heavy metals (lead, cadmium, zinc and copper) as a case study in view of their potential toxicity at low concentrations, and their widespread dispersal by industry.

BAS glaciologists spent several years developing suitable pre-concentration procedures and clean-room techniques (Landy, 1980; Wolff and others, 1981), now known to be essential for reliable work at the pg/g concentrations of heavy metals found in Antarctic ice. For lead, results for modern snow (Wolff and Peel, 1985; Dick and Peel, 1985) from the Antarctic Peninsula have helped to form a consensus on the present-day situation, between the few laboratories capable of making reliable measurements even in modern Antarctic snow. BAS measurements of Cd, Cu and Zn represent the only reliable values to date from Antarctica, showing order of magnitude reductions on previously-reported values.

Comparison of our data on modern snow with measurements that have been made on ancient ice, suggest that pollution may be responsible for up to 90% of the present lead content of Antarctic snow (Figure 7). However, there is now an urgent need to obtain detailed time series data covering the past few hundred years from both the Antarctic and Greenland ice sheets, at sites remote from any form of human activity. BAS scientists are currently analysing a series of ultra-clean snow blocks collected from a 9 m deep pit excavated in an area of very low snow accumulation rate in Coats Land, to evaluate trends through the last century.

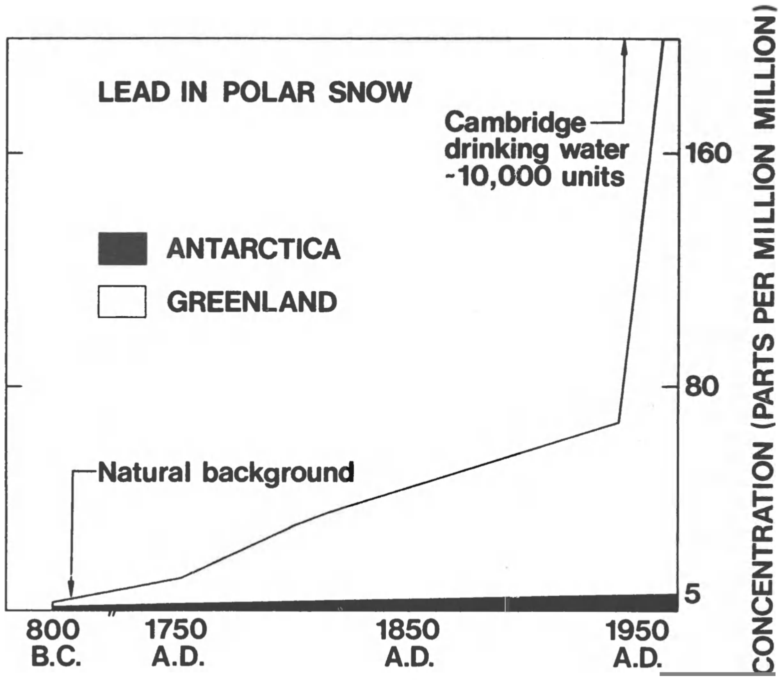

Fig 7. Contrasting trends of lead concentrations in Antarctic and Greenland snow arise mainly because 90% of pollutant emissions occur in the northern hemisphere and inter-hemispheric exchange of aerosols is limited.

In order to make a quantitative estimate of temporal changes in air pollution levels, and more generally of the composition of the atmospheric aerosol from ice-core data, it has been necessary to assume that these are uniformly related. BAS has made pioneering studies (Peel and Wolff, 1982; Dick and Peel, 1985) in the Antarctic Peninsula to explore this relationship directly by analysing aerosol and snowfall collected simultaneously at remote sites.

3.2.3 Future Plans

It is planned to conduct deeper drilling at several sites in Palmer Land in order to evaluate the inter-relationships between the dominant climatic zones and to develop further the link between palaeo climatic records from the interior of the ice sheet and those from lower latitudes. These studies will concentrate on the nature of high frequency climatic oscillation, such as those connected with the El-Nino-Southern oscillation, that are significant on the time scale of human activity. There will be a continued effort to develop empirical relationships between ice-core parameters and climatic signals and to explore the physical basis of these connections.

BAS will be keen to collaborate in larger international deep drilling activities in order to extend the time scale of its investigations and to develop a more complete understanding of the history of climatic and atmospheric processes over the West Antarctic Ice Sheet during the last glacial cycle. For example, parallel studies of cores from Berkner Island (as proposed by the European Science Foundation and the Antarctic Peninsula may help to link these latter records with the coastal strip of continental Antarctica. They should also help to resolve the role of the Weddell Sea in control of long-term climatic change over a major part of Western Antarctica.

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