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An ice-core drilling site at Law Dome summit, Wilkes Land, Antarctica

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AN ICE-CORE DRILLING SITE
AT LAW DOME SUMMIT, WILKES LAND, ANTARCTICA

by

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ABSTRACT

Two intermediate depth, thermally drilled ice cores (382 m and 474 m) and two shallow ice cores (both 30 m) have been obtained from the Law Dome summit region. It is now proposed to drill a deep ice core (through to bedrock) for scientific analysis. This report outlines the investigations which have been undertaken in the region so far and the rationale for selecting a drilling site with a view to obtaining the best possible scientific data.

Detailed bedrock and surface topographic surveys have been conducted over an area of 100 km^2 (with 1 km grid spacing) centred on A001 at Law Dome summit. These surveys, in conjunction with a knowledge of surface snow accumulation rates, physical properties revealed by the analysis of earlier ice cores, and factors affecting the scientific analysis of the future ice core, are discussed.

A drill-site is proposed, approximately 4.3 km due west of A001, situated over a local bedrock depression. The approximate co-ordinates of the drill-site are 66°44'S, 112°44'E, elevation 1360 m. The ice thickness at this location is 1260 m.

1. INTRODUCTION

Ice-core analysis is now well established as a method of revealing the historical changes of atmospheric chemistry, past climate, and ice sheet changes (Robin 1983(a), Stauffer and Oeschger 1985, Scientific Committee for Antarctic Research 1983, Young 1982). Borehole studies and analysis of cores from the Antarctic ice-sheet have, over recent years been the focus of effort by many nations, particularly those participating in the International Antarctic Glaciological Project (IAGP). Proxy climate records obtained from oxygen isotope ratio ($\delta^{18}O$) analysis of ice-cores, have been reported by numerous scientists including Benoist et al. 1982, Dansgaard et al. 1973, Robin 1983(a) and Morgan 1985(a).

Law Dome summit is a region of near zero horizontal ice flow where the basal ice has an age thought to be in excess of 10 000 years. An ice core from surface to bedrock at Law Dome summit can therefore provide data on the history of the ice sheet and climatic changes over this time period.

Complexities involved in the intended scientific interpretation demand careful attention to site selection (e.g. Holdsworth 1984), rigorous planning of studies to be performed either on-site or in the laboratory, and development of complementary programs which could clarify the understanding of physical processes operating in the area. The scope of possible scientific investigations is well demonstrated by a comprehensive report prepared by the Committee for Science Planning in Greenland (1985).

Ice drilling techniques (Splettstoesser 1974, Holdsworth et al. 1982) have now advanced to the stage where it may soon be possible to drill through Antarctic ice up to 4500 m thick, with the possibility of obtaining a climate record over a period in excess of 200 000 years and perhaps up to 500 000 years.

Previous Australian thermal drill programs have obtained ice cores from Law Dome and the Amery Ice Shelf (Figure 1). Figure 2 shows the locations of the Law Dome drill-sites, the year in which the drilling was carried out, and the borehole depth. These boreholes have mostly been to depths less than 500 m, the limit of the Australian thermal drill winch-cable, and near the limit of dry-hole drilling in this region of Antarctica. Dry hole drilling to greater depths is impractical on Law Dome because of relatively high borehole closure rates.

For this new drilling work, an Australian version of the Danish ISTUK (electromechanical) drill is presently under development and will operate in a borehole which is fluid loaded. A mechanical coring drill is preferred to a thermal drill because, in general, a superior quality ice core is obtained for scientific analysis and the drilling method is more energy efficient. With thermal ice core-drilling, excessive core heating may result if the penetration rate is too slow, and outer layers of the core may be subject to micro-cracking and recrystallisation. Excessive heating of the ice core may also disturb the record of atmospheric gas composition contained in air bubbles, in a similar fashion to an effect reported by Pearman et al. (1986), where some ice cores were thought to have been subject to substantial heating during transportation or storage. Thermal ice cores are also prone to major cracking as a result of thermal shock.

Law Dome summit has been chosen for the next major drilling operation for scientific reasons (the relative simplicity of the ice dynamics and hence the interpretation of the environmental record), and logistic reasons (the site is relatively close to the permanent Australian station of Casey).

2. THE LAW DOME

Law Dome (previously referred to as the Wilkes Ice Cap) is approximately 200 km in diameter and situated between 110°E and 115°E, on the periphery of the main Antarctic ice sheet (Figure 1). The ice cap is approximately circular with a maximum elevation of 1389 m at A001, 66°44'S, 112°50'E (Figures 1, 2 and 3).

Early glaciological investigations on Law Dome were comprised of reconnaissance surveys which defined the ice cap shape. Later, accurate surveys over a large northern and small southern triangular route were made, and finally a survey over a 16 km grid network over the ice cap. This work established a knowledge of bedrock and surface topography and the snow accumulation regime (Black and Budd 1964, Budd 1966, Budd 1968, Budd 1970, Allen and Whitworth 1970, Carter 1976). Refer to Figure 3.

Near the centre of Law Dome, ice thickness exceeds 1200 m. The bedrock is irregular and has several high points where elevation exceeds 400 m. Figures 4 and 5 show cross-sections of surface and bedrock profiles from Law Dome summit to Cape Folger and Cape Poinsett respectively. The average bedrock elevation is about 300 m near the centre of Law Dome (which is a high point in both surface and bedrock) and falls away to several hundred metres below sea-level at the northern seaward boundary.

The ice flow from the main East Antarctic ice sheet diverges around the southern side of the Law Dome, exiting to the sea via the steep-sided trench which connects the Vanderford and Totten glaciers (Figure 1). In terms of the long term history of Law Dome ice cap, there is evidence from the oxygen isotope analysis of deep ice at Cape Folger (Budd and Morgan 1977), and from the glacial geomorphology of the Windmill Islands (Cameron 1964) to suggest that prior to 10 000 years ago, Law Dome was completely covered by the main Antarctic ice sheet. Since then, the main Antarctic ice has retreated and Law Dome has become an ice cap with a largely independent flow regime.

Surface ice velocities and strain rates were first measured using conventional survey techniques from the centre of Law Dome to the coast, around the large triangle shown in Figure 2. Budd (1970) referred to this surface work combined with theoretical studies of the ice-mass thermodynamics, as the first stage of the Wilkes Ice Cap project, after which phase 2, consisting of ice core drilling, followed. The first stage established basic properties of the ice sheet and the first estimates of the current state of balance. Core drilling has since provided information on the interior properties of the ice sheet and on past changes of the ice sheet and climate.

Law Dome surface temperatures were investigated by Cameron (1964) as part of the study of the mass balance of the ice sheet margin, and by Battye (1964) as part of a larger study of the inland ice sheet. By measuring 10 m firn temperatures, Cameron (1964) found the characteristic surface lapse rate for Law Dome to be 1.02°C/100 m, for elevations above 400 m.

Temperature profiles within the ice cap, were investigated by Budd et al. (1976). It was suggested that measured profiles conformed closely to computed 'steady state' temperature profiles. However, temperatures measured in BHD (Figure 6) during 1977 indicate some discrepancy with the colder profiles (measured in the borehole at A001) of Budd et al. (1976). Below the 474 m depth the temperature profile is unknown.

Budd (1970) suggested, on the basis of net budget and flux divergence calculations, that Law Dome is not in balance, but lowering at a rate roughly equal to the accumulation rate. Pfitzner (1980) also suggested, on the basis of preliminary surveys, that there appeared to be a net ice cap lowering of about 0.2 ma^{-1}.

More recent studies of ice-flow based on the analysis of Law Dome ice-cores and borehole measurements have been described by Russell-Head and Budd (1979), Morgan and McCray (1985), Young et al. (1985), and Etheridge and McCray (1985).

Law Dome is an accessible and conveniently located ice cap which is well suited to modelling studies. Data collection is continuing and, in addition to the interest in ice-core drilling, includes surface ice-velocity measurements which are being extended and improved using satellite doppler positioning equipment.

3. THE LAW DOME SUMMIT

Analysis of satellite doppler surveys from 1973 to 1984, indicates that at A001 the horizontal surface ice movement is 0.54 $\pm$ 0.2 ma^{-1} at 232^{o} $\pm$ 15^{o} (Young, personal communication 1986). No detectable vertical surface movement is apparent from the same satellite doppler results; the movement is less than the measurement error although the magnitude of the error is unknown due to complicating factors in the interpretation of the satellite doppler data.

Morgan (1966) reported the 1964 elevation of Law Dome summit to be 1370 $\pm$ 10 m. This elevation was determined barometrically and immediate comparisons with recent satellite doppler height determinations should be treated with caution. However the small change (1370 m measured in 1964 and 1390 m measured in 1984) is evidence contrary to the conclusions of a net ice cap lowering suggested by Budd (1970) and Pfitzner (1980). Recent changes in the surface level are difficult to judge at Law Dome summit because of the interference to the snow accumulation regime caused by passing tractor trains and field equipment, particularly those associated with core drilling activities.

Another issue subject to speculation is the variation in the location of the summit with time. Johnson (1982) suggested that recent increases in the surface snow accumulation may be circumstantial evidence suggesting a gradual migration (from west to east) in the exact position of the Law Dome summit.

Continuous meteorological measurements have not yet been gathered from the summit of Law Dome although an automatic weather station was installed in February 1986 near the drill-site to complement ice core drilling. The only 'long term' meteorological information concerning Law Dome climate comes from meteorological observations (Cameron 1964) collected at S2 between March 1957 and January 1958 and from Wilkes and Casey climate data. Because of the proximity of S2 (245 m lower in elevation and 40 km in distance) to Law Dome summit, the climatological description of S2 is currently the best information available.

Bromwich (1976) showed that at both Wilkes and Casey, and S2, mean monthly wind speeds have characteristic maximums in spring, although wind speeds at Wilkes and Casey are mostly light with calms occurring 14% of the time. At S2, calm winds occur only 1% of the time and winds have one preferred direction throughout the year; 82% of the winds come from the east to south-east. Bromwich (1976) also showed similar sastrugi direction and katabatic streamlines for both S2 and Law Dome summit. Apparently the centre of katabatic circulation is offset to the south-east of the summit.

Mean monthly temperatures at S2 are typically 8 to 11^{o}C cooler than at Wilkes and Casey, due mainly to the elevation difference. The mean annual temperature for Law Dome summit (-21^{o}C), was first calculated using the adiabatic lapse rate with respect to the mean annual temperature at Casey. This theoretical figure has since been supported by the measured firn temperature (-21.3^{o}C) in the A001 borehole, at a depth of 20 m.

Snow accumulation is non-uniform throughout the year, with most precipitation occurring in spring, winter and autumn. In winter, the deposited snow surface becomes eroded by wind and snowdrift and is transformed into hard ridge-like formations of sastrugi. In summer, the action of light winds and low 'ground-drift' redeposit snow over the rough and irregular sastrugi, converting the surface back into a soft, level and smooth snow cover.

Stratigraphic observations (Han, personal communication 1985) have been made on two (mechanically drilled) shallow cores from nearby sites (BHR, 24 km towards Cape Folger, depth 61 m; BHDE08, 16 km east of A001, depth 45 m). At BHR, where the accumulation rate is about 180 kgm^{-2}a^{-1}, numerous crusts of less than 1 mm thickness were observed throughout the 61 m length of core. Only a few infiltration ice layers and lenses 1-2 mm thickness were observed. At BHDE08, where the accumulation rate is 1685 kgm^{-2}a^{-1}, only two infiltration ice lenses and a number of crusts were observed in the total core length of 45 m. The 20 m depth snow temperature is -19.5^{o}C at BHDE08 and -20.2^{o}C at BHR, respectively 1.8^{o}C and 1.1^{o}C warmer than at the summit. Similar thin crusts can be expected to form on the snow surface at the summit but no significant melting is expected.

Density measurements have also been made on ice core from BHR and BHDE08, and the densities have in turn been used to determine the depth at which most of the gas in the ice becomes sealed-off into discrete air bubbles. This 'close-off' normally occurs over a finite depth interval which depends on temperature and the snow accumulation rate. The time interval required for the firn to increase in density, and therefore the age-range of the entrapped gases, decreases with larger accumulation rates. It should be noted that although densities have also been measured on both the BHD and A001 ice cores, data from these ice cores are considered unreliable because both were drilled thermally, and hence subject to meltwater infiltration and refreezing in upper firn layers. Most pores in the firn layer close off between densities of 795 and 830 kgm^{-3}. BHR and BHDE08 show a density of about 800 kgm^{-3} at a depth of 40 m and 65 m respectively. Using this as a guide, it is therefore expected that the close-off depth at the new drilling site will be about 50 m.

4. PREVIOUS ICE CORE DRILLING ON LAW DOME

The first ice core drilling on Law Dome was near Cape Folger in 1969, where it was possible to penetrate a large fraction of the ice thickness and therefore investigate ice sheet flow dynamics of the high shear zones near bedrock. The first core reached a depth of 324 m, within 40 m of bedrock. Later that year another ice core (at A001) was drilled at Law Dome summit to a depth of about 382 m (about one third of the total ice thickness).

Ice core and borehole analyses were initially used to determine temperature and velocity-depth profiles (Budd 1970), and to study ice crystal structure development in ice masses (Budd 1972). Following that, the flow law for anisotropic ice in a given stress configuration (Russell-Head and Budd 1979) was examined.

The next stage was to drill a series of boreholes approximately along a flowline between Cape Folger and the summit, in order to study further the ice sheet motion and in an attempt to reveal local and global climate data (Budd and Morgan 1973 and 1977).

In 1972, BHB and BHP were drilled to a depth of 73 m and 113 m respectively (along with BHJ to a depth of 112 m at Cape Poinsett). In 1974, BHF was drilled to a depth of 348 m near Cape Folger and in 1977, BHQ (midway between Cape Folger and Law Dome summit) and BHD (at Law Dome summit) were drilled to depths of 430 m and 474 m respectively.

In addition to the two intermediate thermal ice cores (A001, 382 m and BHD, 474 m) at Law Dome summit, two shallow ice cores (BHDB and BHDC, both to 30 m) have also been obtained.

Confusion has arisen in the past by referring to the two intermediate depth ice cores from the Law Dome summit region as D-core (at A001) and BHD (1 km to the north). In this paper, the 382 m ice core drilled at Law Dome summit in 1969 will be referred to by its location - at trilateration grid survey marker 'A001', in order to clearly distinguish it from the BHD ice core drilled to a depth of 474 m in 1977.

A001 and BHD are currently being analysed for physical properties such as crystal orientation fabrics (Gao and Jacka unpublished), crystal size and bubble elongation. Since crystal orientation fabrics in an ice mass are the result of the stress configuration (for shape) and accumulated strain (for strength), one might reasonably have expected similar features between the A001 and BHD cores. However, the analysis so far shows the two cores to be significantly different in both the development of crystal fabrics (Figure 7) and in the thickness of annual increments inferred from the $\delta^{18}O$ record. The A001 core exhibits a loose fabric which approximates in shape, a small circle girdle pattern. This pattern is expected for ice in which the predominant stress configuration is vertical compression, such as at a summit point. However, at similar depths, the orientation fabrics exhibited by the BHD core are more developed than those of A001. In addition they display a single pole pattern (particularly below about 300 m) indicative of a simple shear stress configuration. These findings are supported also by the $\delta^{18}O$ analysis of annual layer thicknesses within the two cores, which demonstrates that the total strains at depth for the BHD core are significantly greater than those for the A001 core. There are also differences over small time scales which are not due to flow, but are due to variations in local accumulation. Morgan (1985(b)) commented on similar differences, in the $\delta^{18}O$ profiles of the upper section of BHD and the (shallow) BHDB ice-cores.

Oxygen isotope analysis of the BHD core (Figure 8) has shown clear annual layering patterns to a depth of 474 m, corresponding to a calculated age of about 2000 years. The age of the ice at Law Dome summit indicated by recent calculations from annual layering seem to suggest it is much older than earlier estimates given for example, in the particle path diagrams of Russell-Head and Budd (1979). It is most likely that the limitation in detecting annual oscillations in the future Law Dome summit ice core, will be the physical ability to separate thin annual layers into enough (normally ten) segments. With present techniques and equipment, it is expected that annual δ oscillations should continue to be detected with confidence in annual layers as thin as 30 mm, corresponding to an age of about 7000 years and a probable depth of 700 m (Figure 9). However it may be possible to detect annual cycles in layers as thin as 20 mm (corresponding to an age approaching 10 000 years and a depth (indicated by Figure 9) of about 800 m.

Johnsen (1977) has shown mathematically that annual δ oscillations in ice cores from central Greenland are likely to survive diffusion for at least 10 000 years and a similar (or greater) figure could be expected for this region of Antarctica because of the higher snow accumulation rates. Therefore, diffusion is unlikely to be a limiting factor in dating of the ice core because, in addition, ice which is older, (according to Budd and Morgan 1977) should have originated from futher inland where, amongst other complicating factors, the surface snow accumulation rates are much smaller (hence smaller thickness of δ oscillations) and the isotope record is distorted by ice flow.

Recent analysis of the crystallography of two ice cores from Cape Folger (BHC1 and BHC2) by Thwaites et al. (1984) has shown that although borehole closure rates are highly variable, they are related to the c-axis fabric of the ice.

5. JUSTIFICATION FOR FURTHER DRILLING

An ice core from surface to bedrock at Law Dome summit is required to extend scientific data further back in time than is currently available from the relatively shallow depths penetrated so far. By sampling the deep ice it is hoped to obtain older ice which was deposited at the time when the Law Dome ice cap was over-ridden by the main Antarctic ice sheet.

In order to extract a climate record from the ice core it is necessary to know the history of past changes in the Law Dome ice cap, and the overall Antarctic ice sheet. Measurement from the surface through to bedrock, of both the physical properties of the ice core and borehole deformation, are essential for a complete understanding of ice sheet motion and determining the present and past state of balance (Budd 1972).

Equipment has been developed in recent years, to measure carbon dioxide content in entrapped air bubbles and electrical conductance of the ice core. However, these investigations depend on identification of annual layers which in turn require a continuous core. Unfortunately much of the BHD ice core has already been used by isotope studies, mechanical tests and total gas volume investigations, and a new core is therefore needed.

In addition to the long term environmental record, analysis of an ice-core from surface to bedrock should help to clarify features of Law Dome ice-flow. The differences (described previously) between the development of crystal orientation fabrics and annual layers, in the A001 core and BHD core are additional reasons why another ice core from the same general region will be of great interest.

The intended Law Dome summit drilling operation will also act as a testing and proving operation for the new electromechanical drill, before ice-coring is attempted in the deeper ice of the Antarctic interior.

6. SCIENTIFIC AIMS FOR THE LAW DOME SUMMIT DRILL PROGRAM

The major scientific interest in the next Law Dome summit ice core is the long term environmental record, which includes investigation of the past climate record.

Studies of ice core acidity from electrical conductance measurements have shown regular variations (Hammer et al. 1980, Wishart personal communication 1985) providing an independent and quicker means of dating the core by counting annual layering cycles, than is available using the oxygen isotope record. Hammer (1980) has also shown that the electrical conductance record in polar ice cores is related to past volcanic activity and may be related to internal radio reflections observed in the film record of ice thickness measurements. Therefore, the investigation of the ice conductance record will be a major priority in the analysis of the next Law Dome summit ice core.

Investigations of the climate record will include the usual meteorological parameters such as temperature and precipitation (from interpretation of the $\delta^{18}O$ record), and also the past concentration of atmospheric trace gases particularly the 'greenhouse' gases such as carbon dioxide, methane and nitrous oxide (Pearman et al. 1986).

Measurements of physical properties of the ice core will include density, crystal orientation fabrics, crystal size, total gas volume, bubble volume, elongation and length, and visual stratigraphy. Physical properties such as these are of interest in unravelling the physics of the ice sheet flow and interpreting the records of climate, atmospheric composition and impurity content.

The borehole itself will be surveyed immediately after the ice core is retrieved, and again at some time interval later (say two or five years). Borehole measurements will include the borehole diameter, inclination, orientation of the borehole, and temperature. These data will be used to investigate the ice flow regime in the Law Dome summit area.

Additional ice core studies (such as chemical analysis) may be performed by arrangement with other laboratories depending on the requirements and availability of enough ice core.

7. DETAILED SURVEY FOR THE LAW DOME SUMMIT DRILLING

To enable the selection of a specific site for the future borehole at Law Dome summit, a detailed surface and bedrock topographic survey was conducted over a grid of 100 km^2 (centred on A001, with grid lines spaced at 1 km, see Figure 10).

Surface elevations were obtained by barometric levelling from the known height of the satellite doppler station GW 31, located at A001.

Ice thicknesses were measured using 100 Mhz echo-sounding radar which records data in continuous analogue form on 35 mm film. These data were converted to digital values at 200 m intervals along the grid lines (Figures 11 to 15). Contour maps of surface elevation, ice thickness, and bedrock elevation (Figures 16, 17 and 18 respectively) were produced manually using the data. Surface snow accumulation markers at locations indicated in Figure 10, were measured in late December 1984 and remeasured in late December 1985. These data were used to prepare a snow accumulation rate contour map for the Law Dome summit survey area (Figure 19). Additionally, 5 m deep ice-cores were drilled at four points, 5 km to the north, south, east and west of A001. Snow accumulation rates were also obtained from the oxygen isotope analysis of these shallow cores (Figure 20).

Inspection of Figures 19 and 20 shows that 1984 snow accumulation rates indicated by isotope analysis are (on average) approximately 25% higher than 1985 snow accumulation rates given by stake measurements. Nevertheless, these accumulation rates, when converted from snow to water equivalent (using a mean density over the annual surface layer of 440 kgm^{-3}) agree well with the large scale accumulation pattern for Law Dome, given in Figure 2.

8. SELECTION OF DRILL-SITE AT LAW DOME SUMMIT

Priorities governing selection of a specific drilling site depend on the intended scientific analysis of the ice-core and borehole, the flow regime of the local area, and also on logistic considerations.

Internal reflections (found on radio echo sounding records) which are continuous and approximately parallel, are generally accepted as indicating isochronous layering (Robin 1983(b)) so it seems sensible to select a drilling site in areas where internal radio reflections are either parallel, or show the least amount of irregularity. Inspection of Figures 11 to 15, together with Figure 18, shows that the large flat area on the east side (bedrock elevation 100 m to 150 m) is characterised by internal reflections which are uniform and parallel. However the surface snow accumulation rate (in this eastern region) is extremely high (more than 2.0 ma^{-1}, or 880 $kgm^{-2}a^{-1}$) which would cause extreme logistic difficulties such as buildings and field equipment becoming buried.

Although sastrugi at Law Dome summit are not likely to exceed a height of 0.5 m, even this small micro-relief can make it difficult to detect annual layering in the δ profiles if the snow accumulation rate is not significantly higher (as described by Morgan(1985(b)). In the Law Dome summit survey area, the minimum snow accumulation rate is about 1.2 ma^{-1}, (i.e. 528 $kgm^{-2}a^{-1}$) occurring on the western side of A001. A snow accumulation rate of this magnitude is considered adequate for the scientific analysis of an ice core, therefore in terms of logistics, it seems sensible to choose the drilling site on the western side of the summit, which in addition, has been studied more thoroughly with respect to flow dynamics.

The future drill-site should be located over a bedrock depression, and preferably in the thickest part, to ensure that the oldest possible ice is sampled.

It is preferable that the new drilling site is at least 1 km away from previous locations to avoid contamination and disturbance of the natural snow accumulation rate (due to residual snow drifts around the earlier sites of field caravans and equipment).

9. CONCLUSION

Review of published glaciological literature about Law Dome, combined with the most recent survey and ice core data, demonstrates that Law Dome summit is an excellent site for the recovery of long term climatic and environmental data, although some of the dynamics of the ice cap (in the summit region) are as yet, not fully understood. In order to further investigate both of these issues, a continuous mechanically drilled ice core (from surface to bedrock) is required.

The proposed Law Dome summit drill-site, which appears to be the most suitable in terms of the criteria discussed above, is the area over the 100 m bedrock contour (Figure 18), approximately 4.3 km due west of A001 (refer to Figure 10). The proposed site is situated at 66°44'S, 112°44'E, elevation 1360 m. Here, ice-thickness is near the maximum (1260 m) for the 10 km square grid and internal radio reflections are reasonably uniform and parallel (Figure 11).

The combination of high, regular snow accumulation rate (approximately 1.45 ma^{-1}), small surface micro-relief (less than 0.5 m), and lack of summer melting, mean that Law Dome summit is a favourable location for retrieving a high quality record of past atmospheric gas composition from air bubbles trapped and preserved in the ice. The high accumulation rate is also advantageous for dating the core by counting annual layers in the oxygen isotope and ice conductance record. Annual layers are expected to be detectable to a depth of about 700 m.

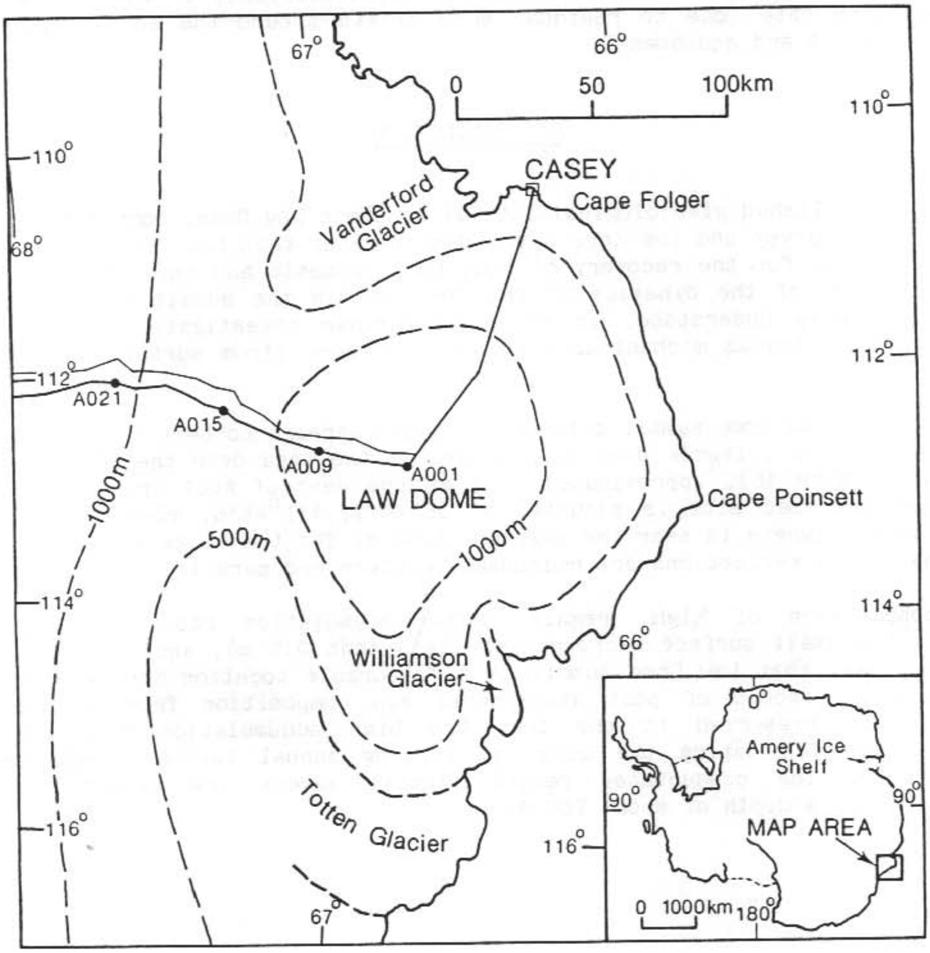

Figure 1. Map of the Law Dome and Amery ice shelf region.

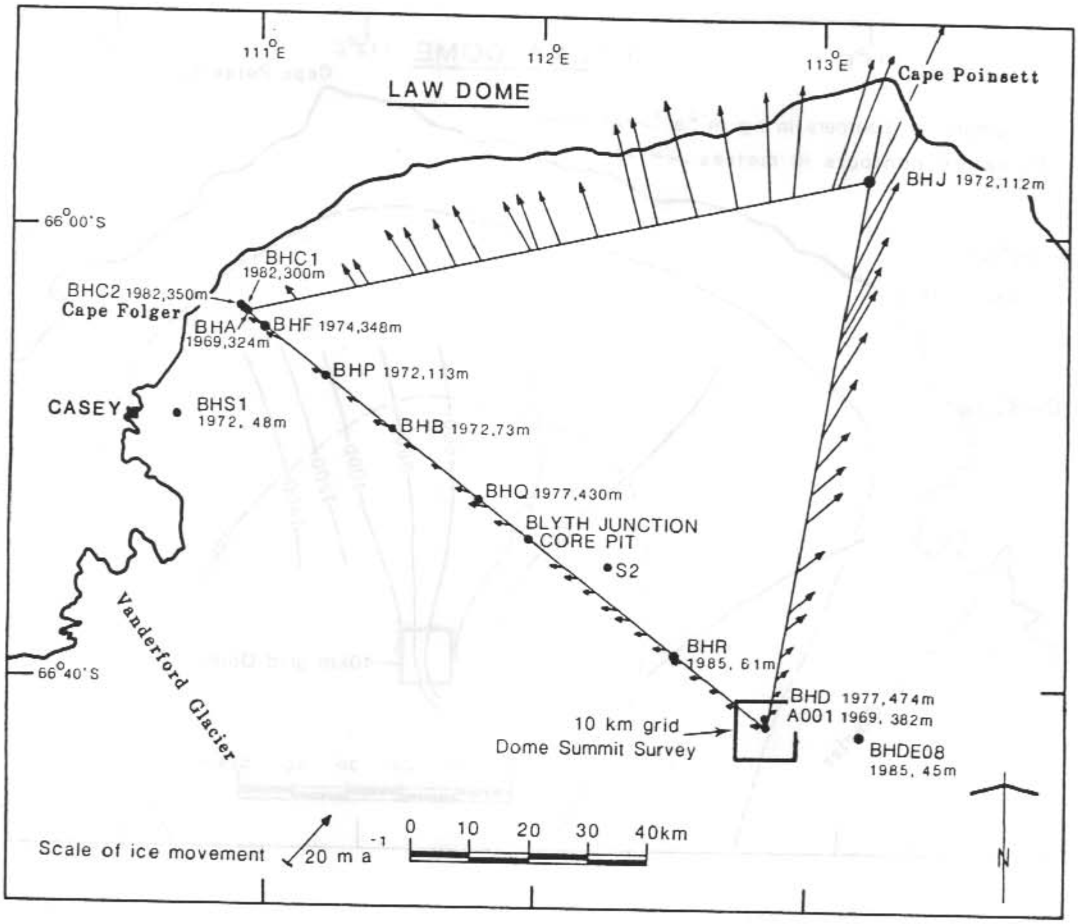

Figure 2. Law Dome survey triangle showing borehole locations and ice movement vectors (after Pfitzner 1980). BHD is located 1 km to the north of trilateration survey marker 'A001' which is located at the junction of the Law Dome survey triangle. A001 is also the same point which has been, in the past, referred to as SGD (for Strain Grid 'D') and GW31 (for satellite doppler station 31).

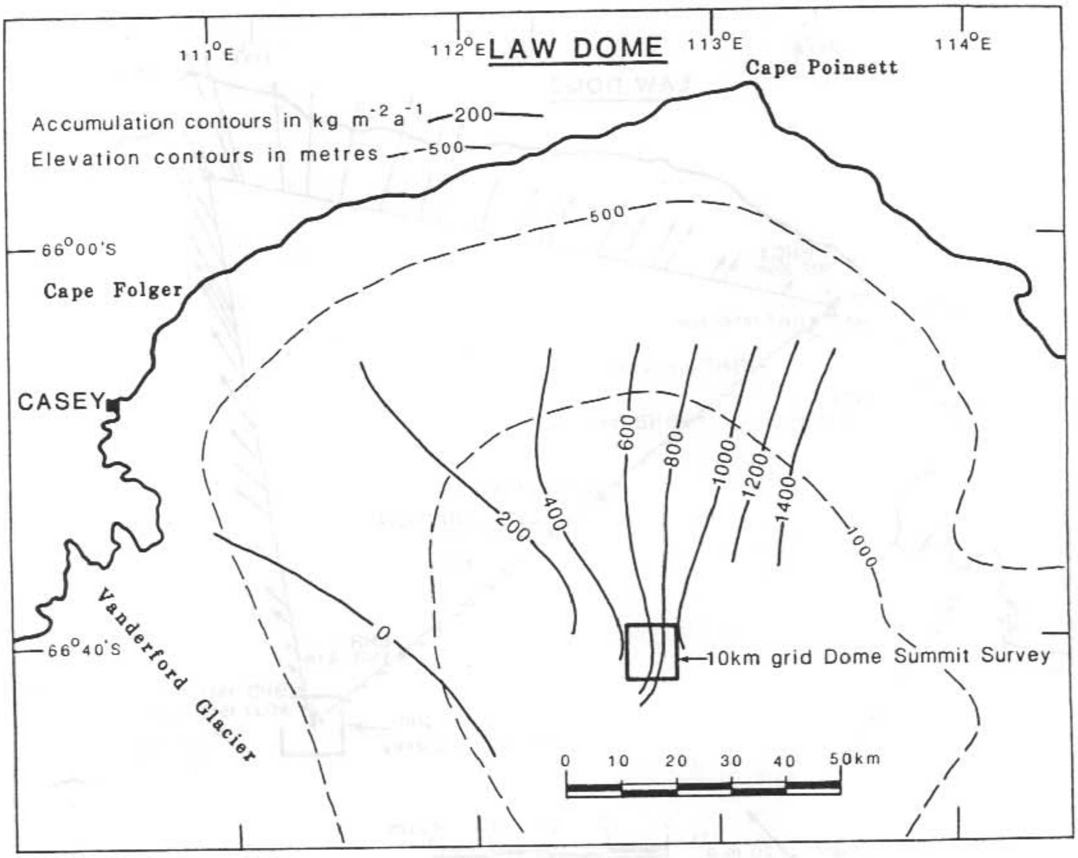

Figure 3. Law Dome surface elevation and accumulation contours. Accumulation rates are given in units of kilogram per square meter per annum of water equivalent ($kgm^{-2}a^{-1}$).

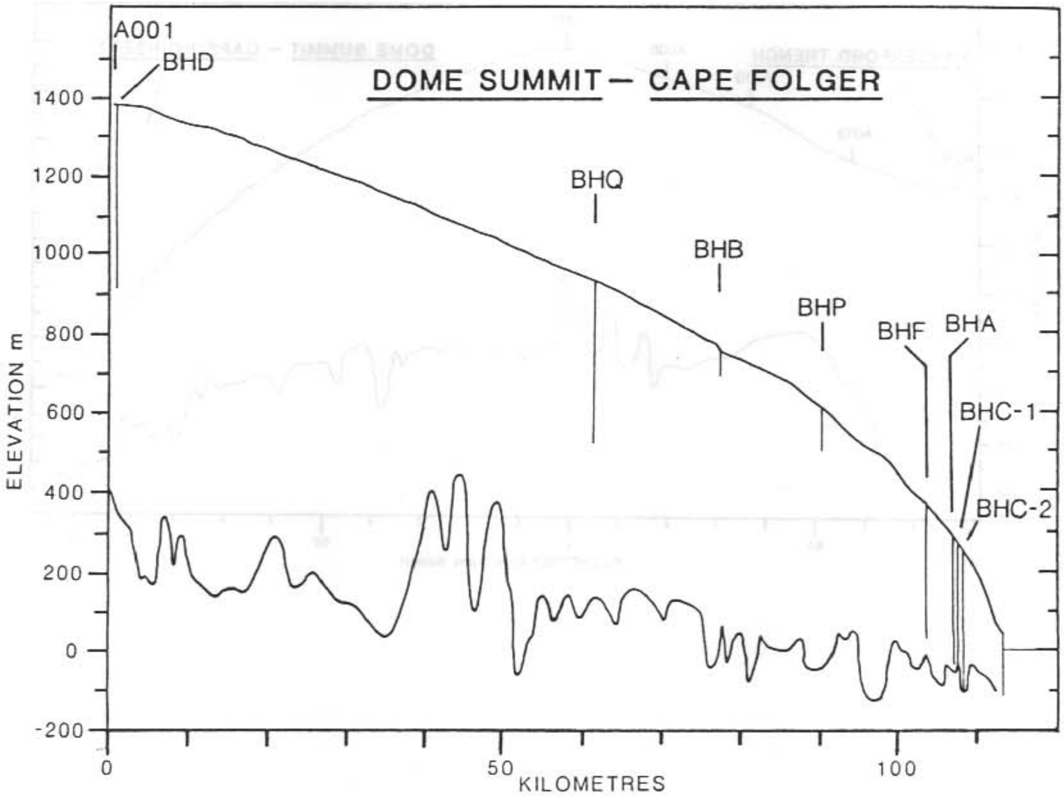

Figure 4. Ice surface and bedrock elevation profiles from Law Dome summit to Cape Folger (after Morgan and McCray 1985).

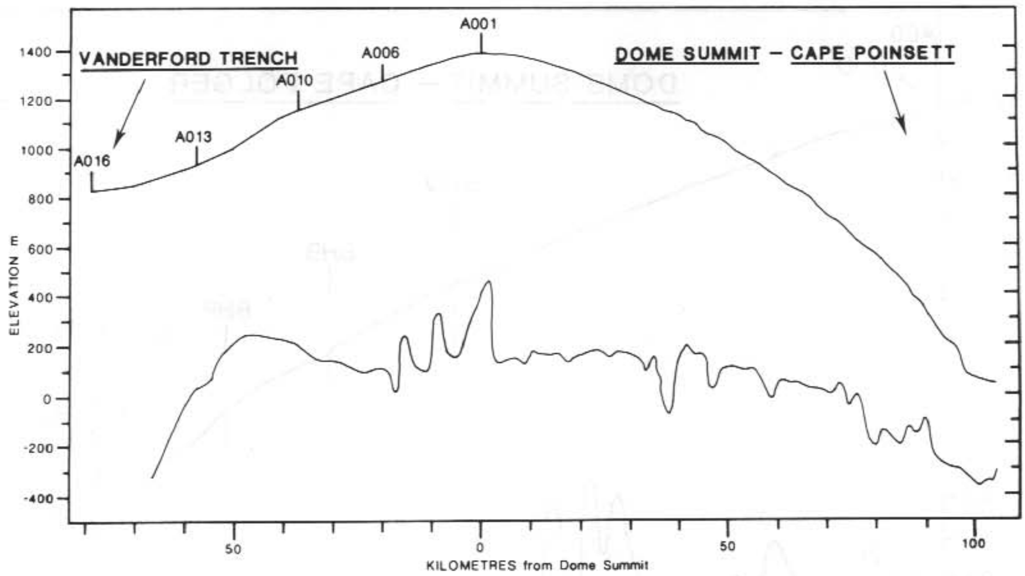

Figure 5. Ice surface and bedrock elevation profiles from the Vanderford-Totten trench to Cape Poinsett via Law Dome summit (after Pfitzner 1980).

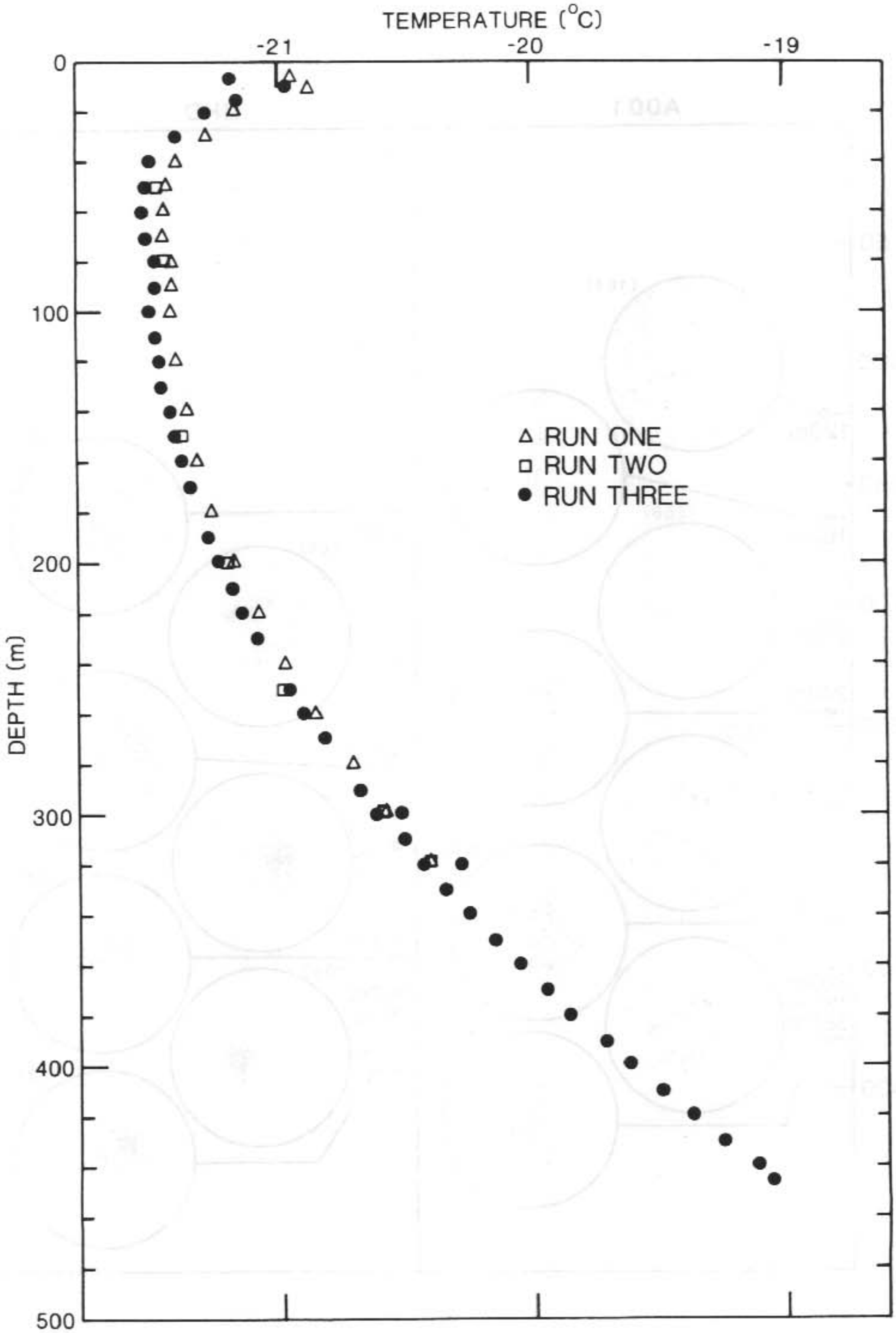

Figure 6. BHD temperature-depth profile (measured by Wilson in 1977).

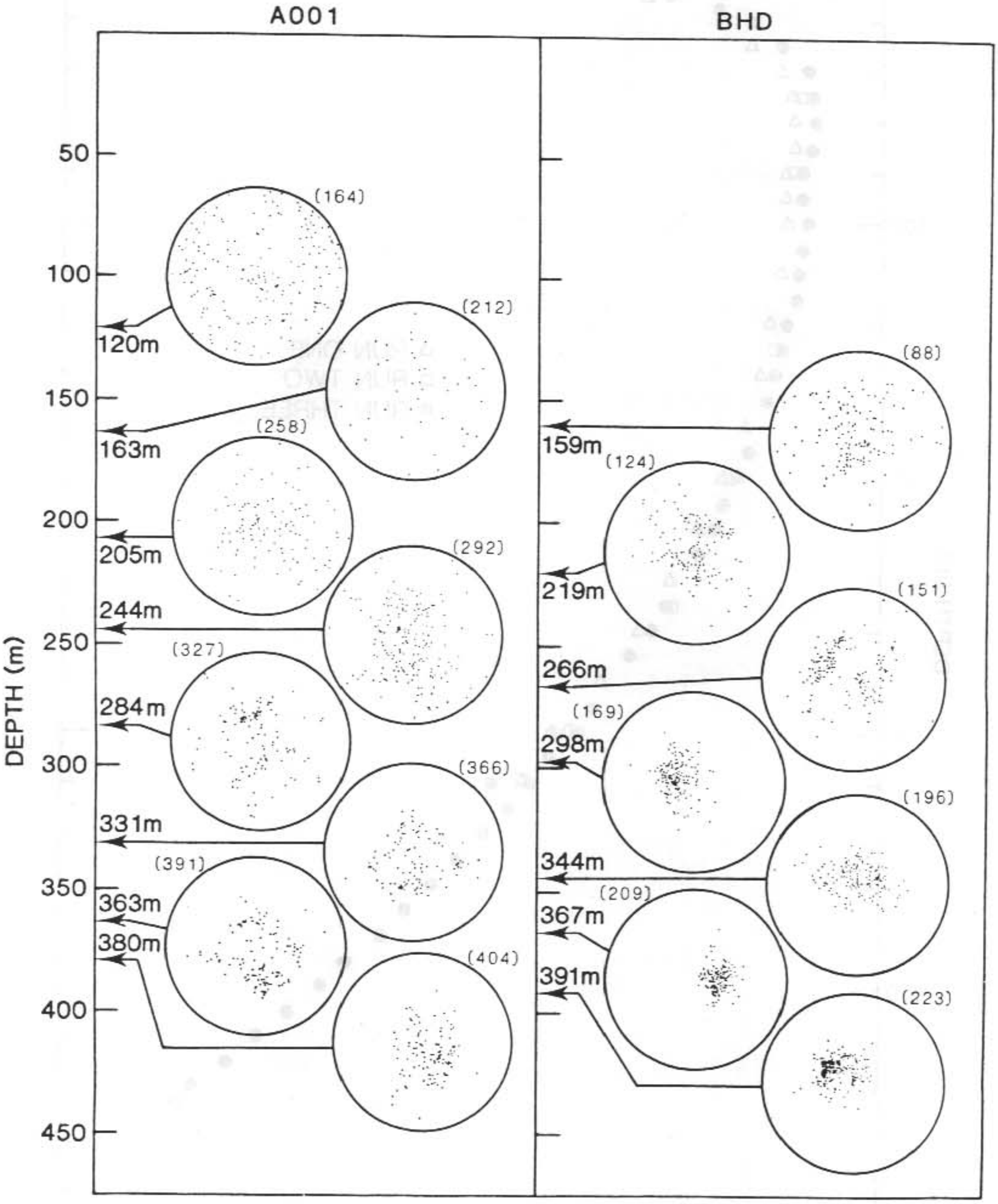

Figure 7. Crystal fabric diagrams of thin sections cut from both the A001 and BHD ice cores. Ice core depth is indicated along with the ice core number (in brackets).

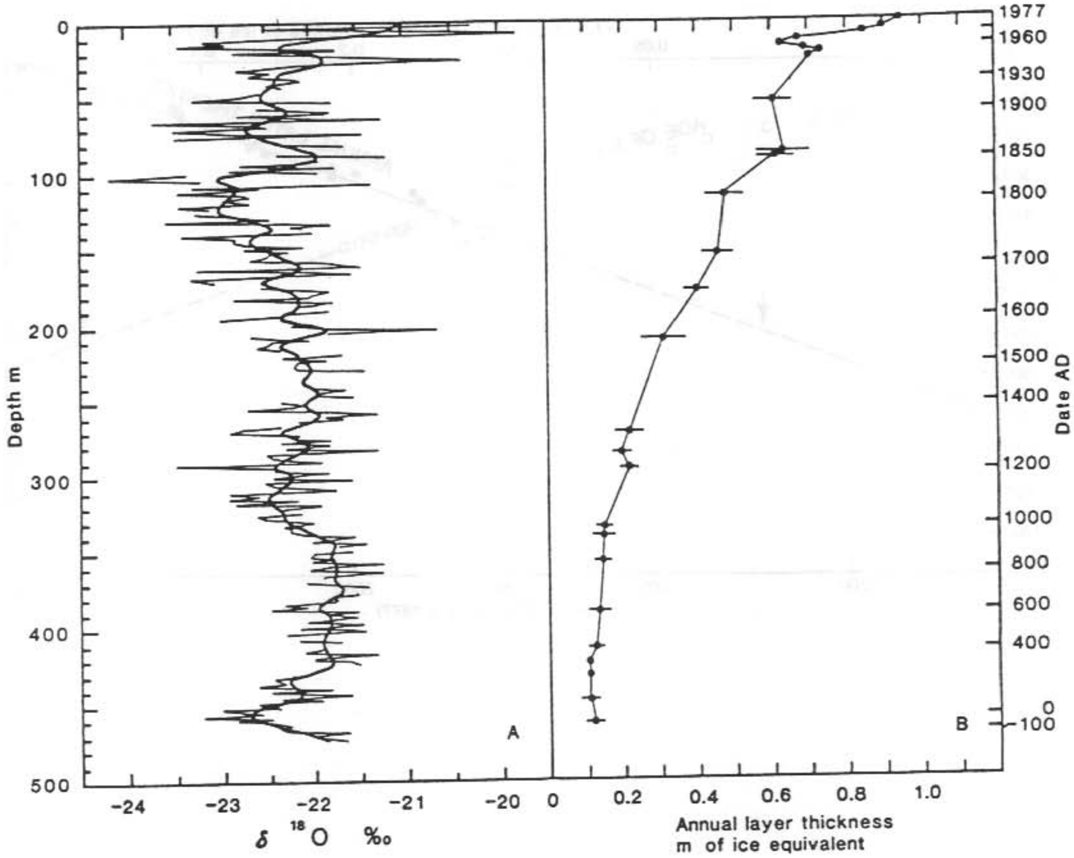

Figure 8. Oxygen isotope data for the ice core from BHD (After Morgan 1985(a)). Curve A shows average δ values over each core section, together with the same values smoothed by a gaussian weighted moving average to reduce sampling and 'accumulation' noise. Curve B shows the thickness of annual layers of accumulation at depth. Values for the upper layers are converted to equivalent thickness of ice from the measured thickness of snow using measured snow densities.

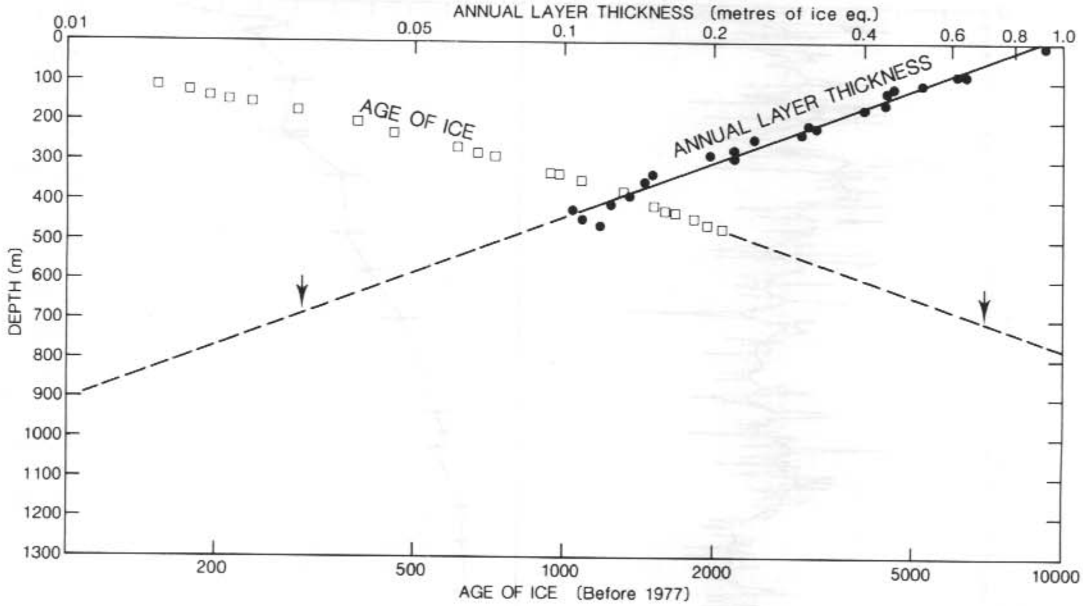

Figure 9. Annual layer thickness and age of the ice, versus depth at BHD. Arrows indicate the probable depth and age of ice at which detection of annual layers is thought to be limited.

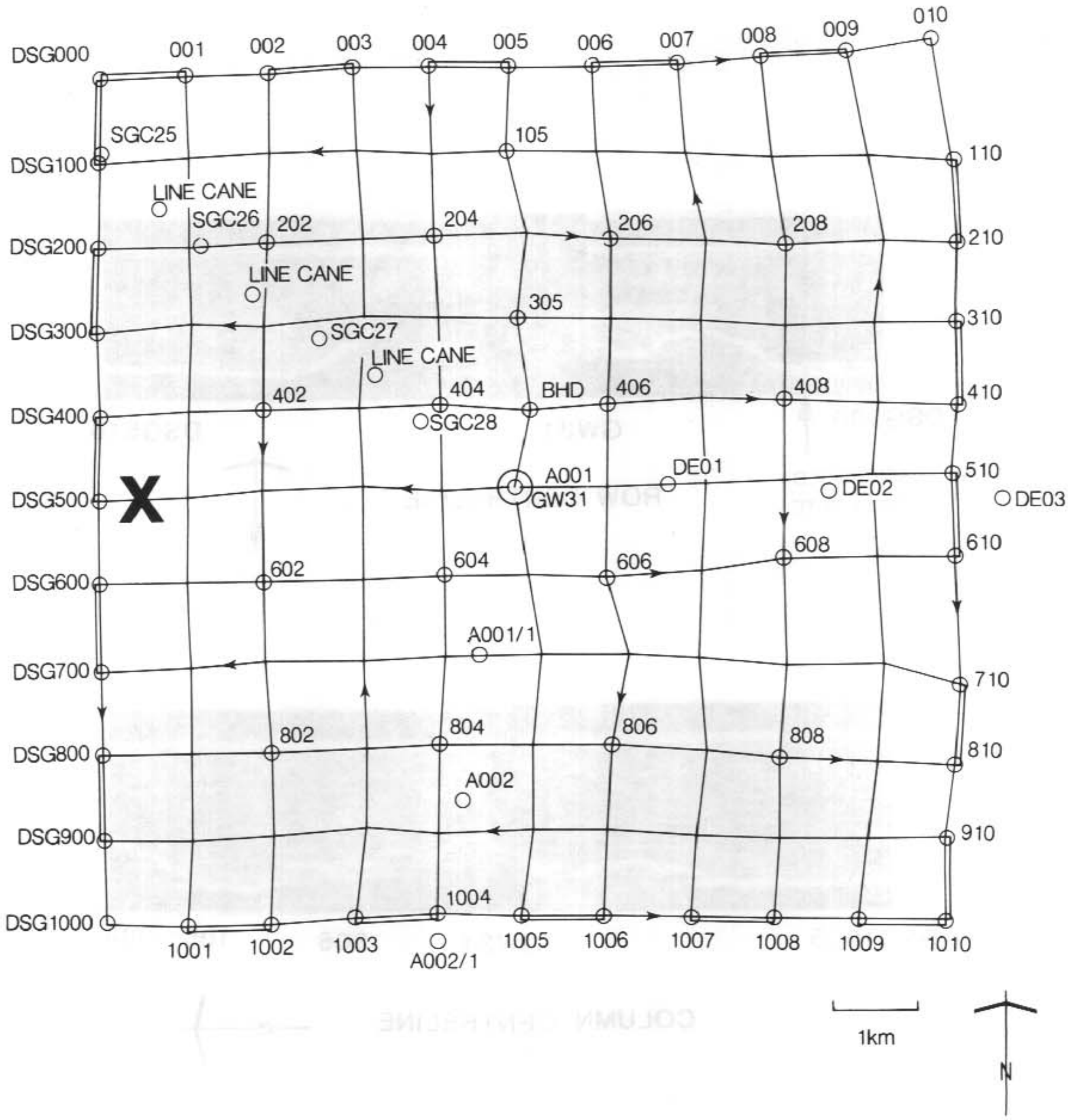

Figure 10. Law Dome summit 10 km square survey grid. Grid lines are spaced at nominal 1 km intervals and centered about A001. Grid markers are labelled DSG000 through DSG1010 (for Law Dome summit grid) and are positioned at nominal 1 km intervals around the perimeter, and at 2 km intervals in the interior of the grid. Grid markers have also been used for measurement of surface snow accumulation measurements. The proposed Dome summit drill site is marked 'X', and is approximately 4.3 km to the west of A001 (GW31/SGD).

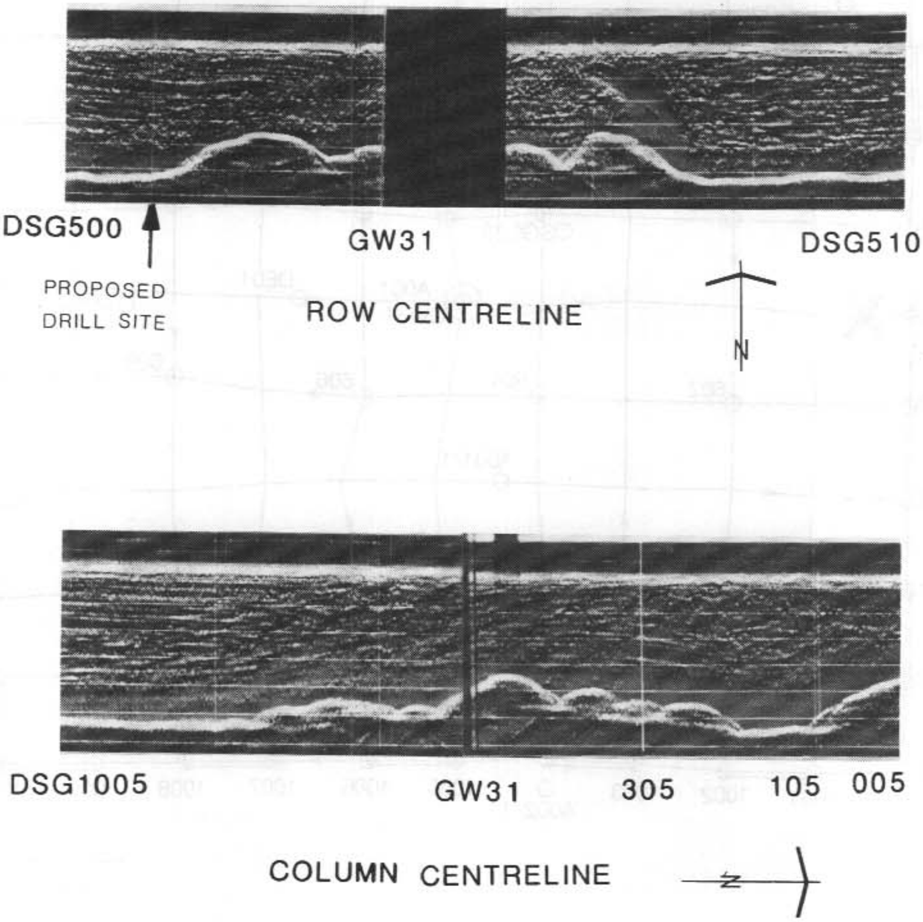

Figure 11. Radio echo sounding film record of ice thickness (centrelines only) - refer to Figure 10 for marker locations.

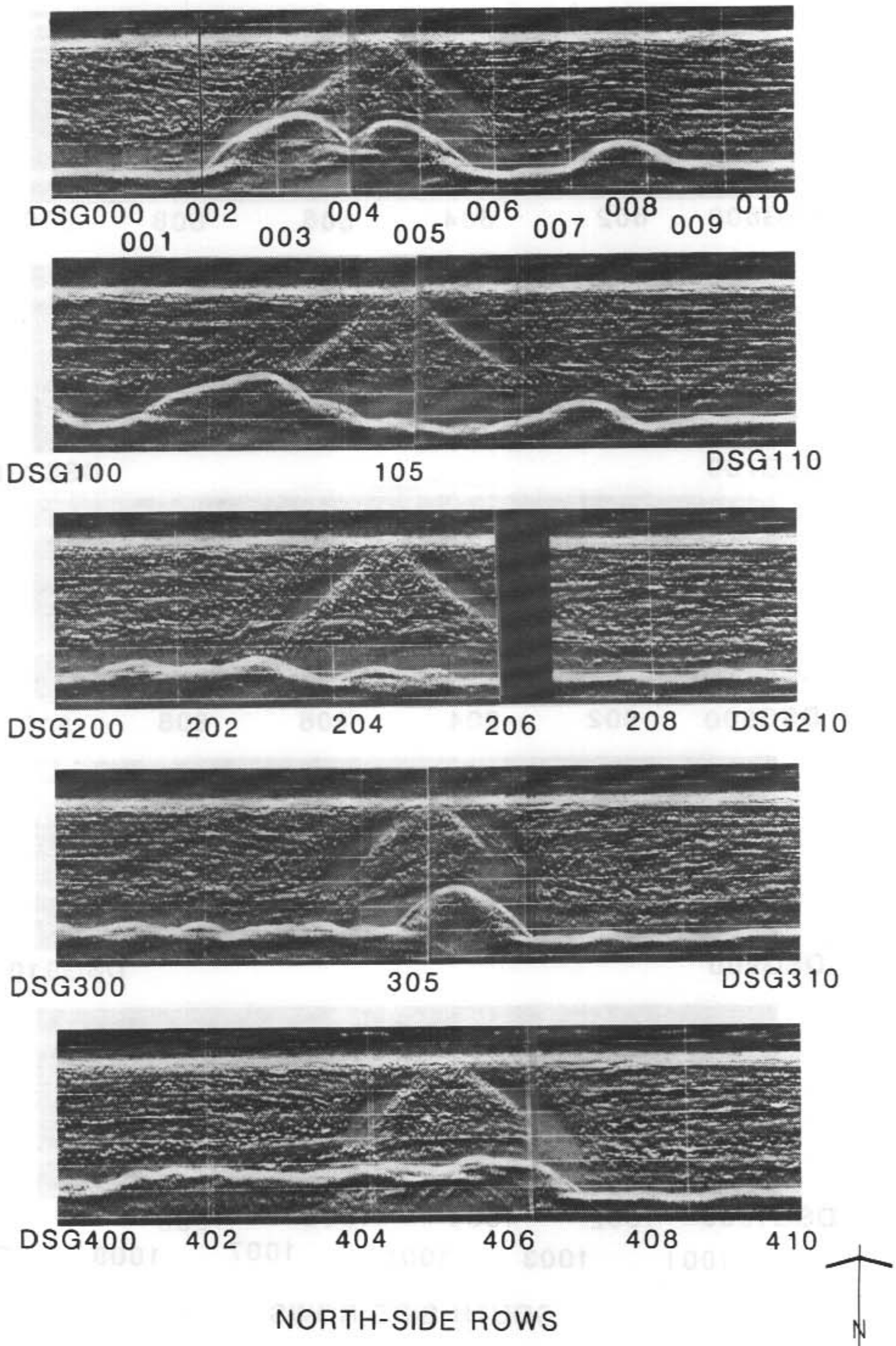

Figure 12. Radio echo sounding film record of ice thickness (north side rows) - refer to Figure 10 for marker locations.

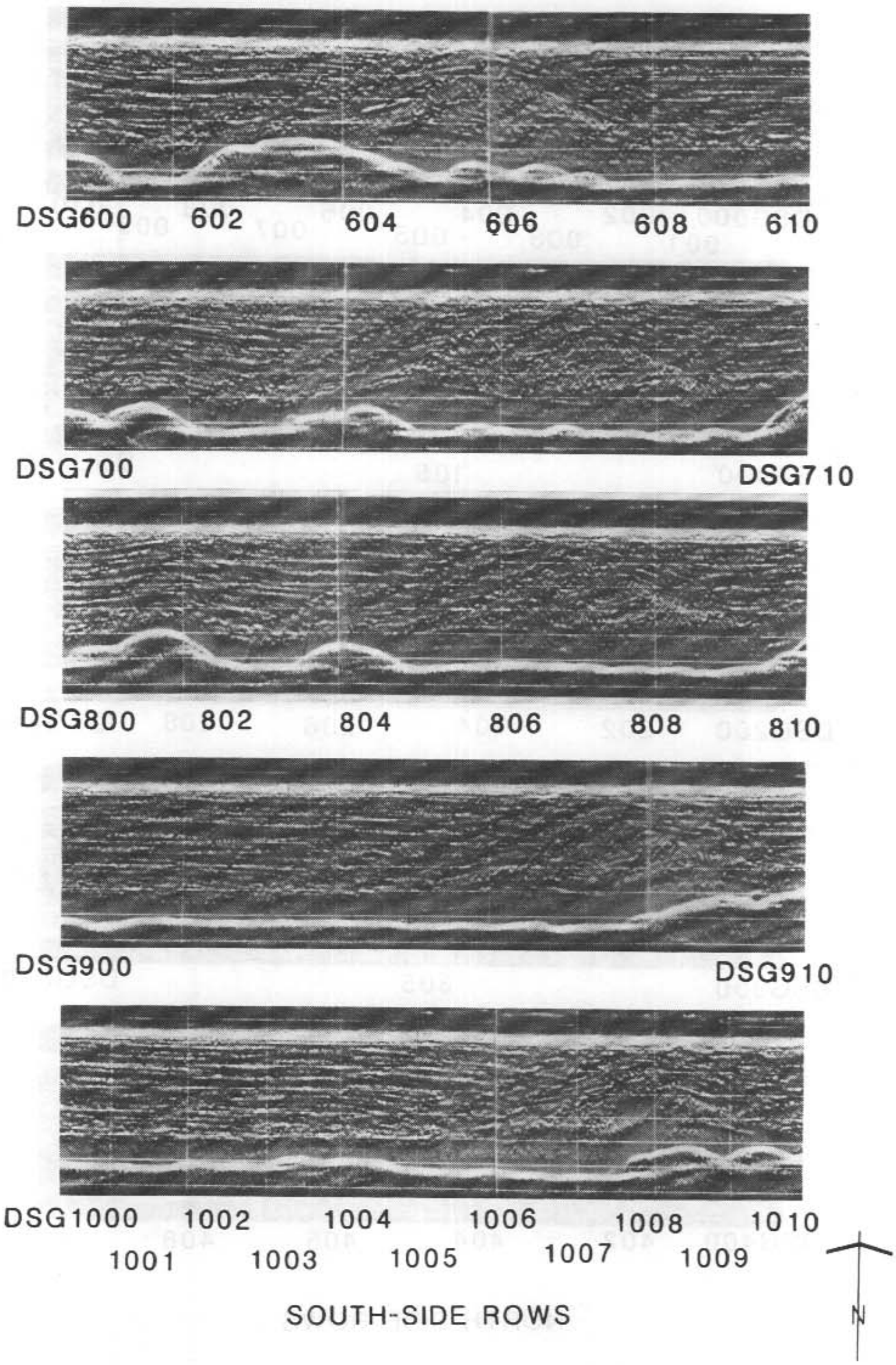

Figure 13. Radio echo sounding film record of ice thickness (south side rows) - refer to Figure 10 for marker locations.

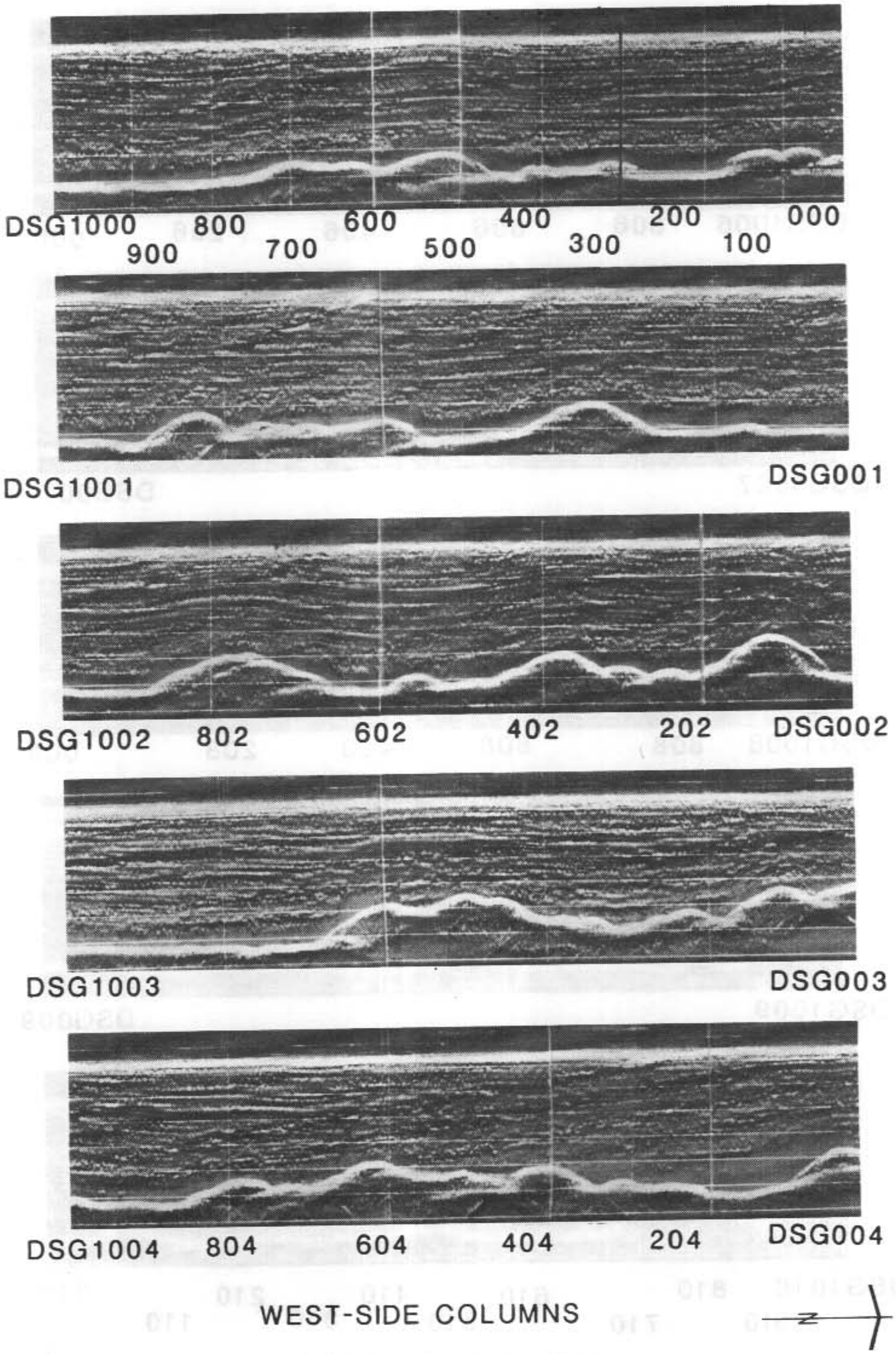

Figure 14. Radio echo sounding film record of ice thickness (west side columns) - refer to Figure 10 for marker locations.

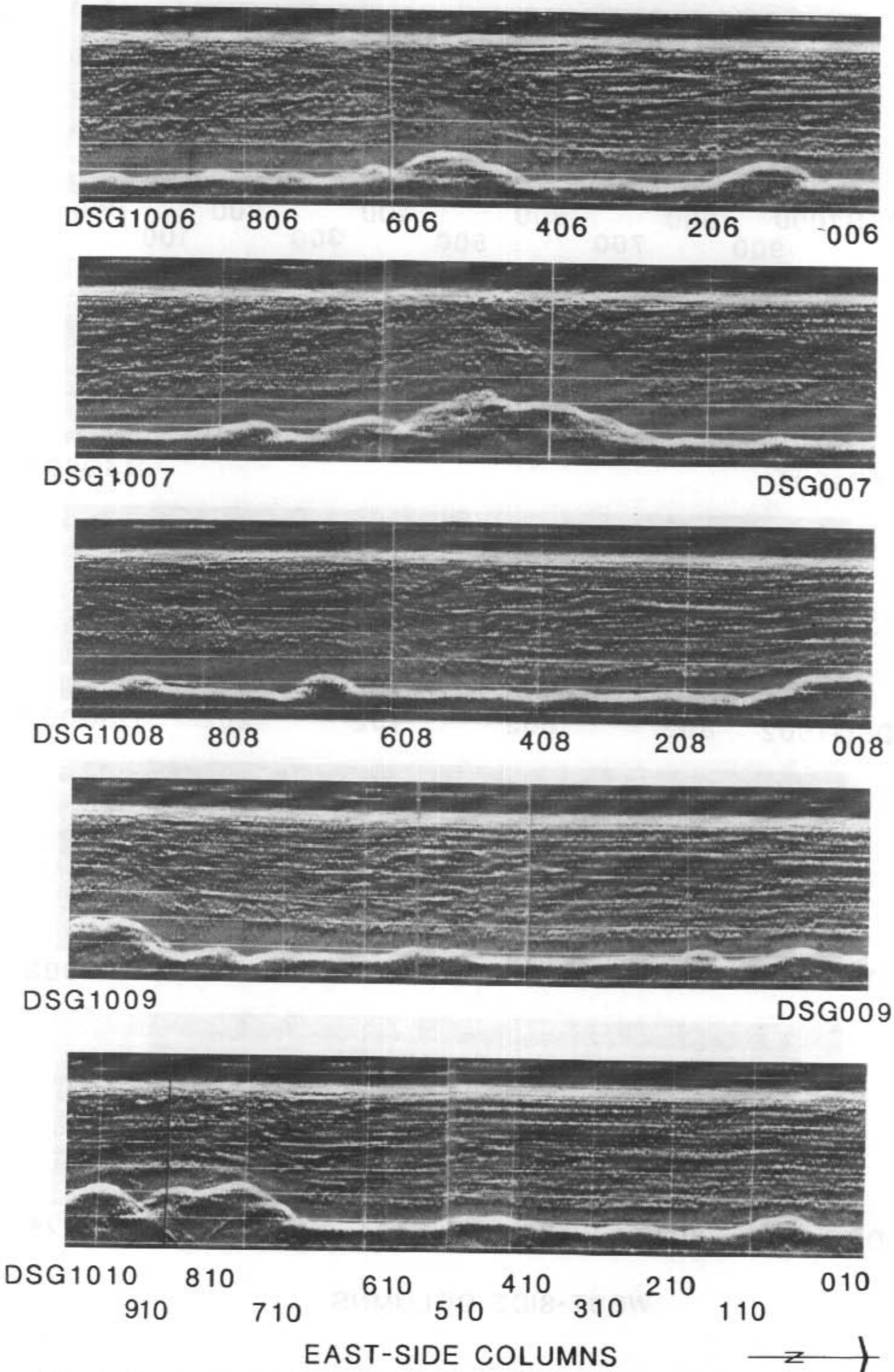

Figure 15. Radio echo sounding film record of ice thickness (east side columns) - refer to Figure 10 for marker locations.

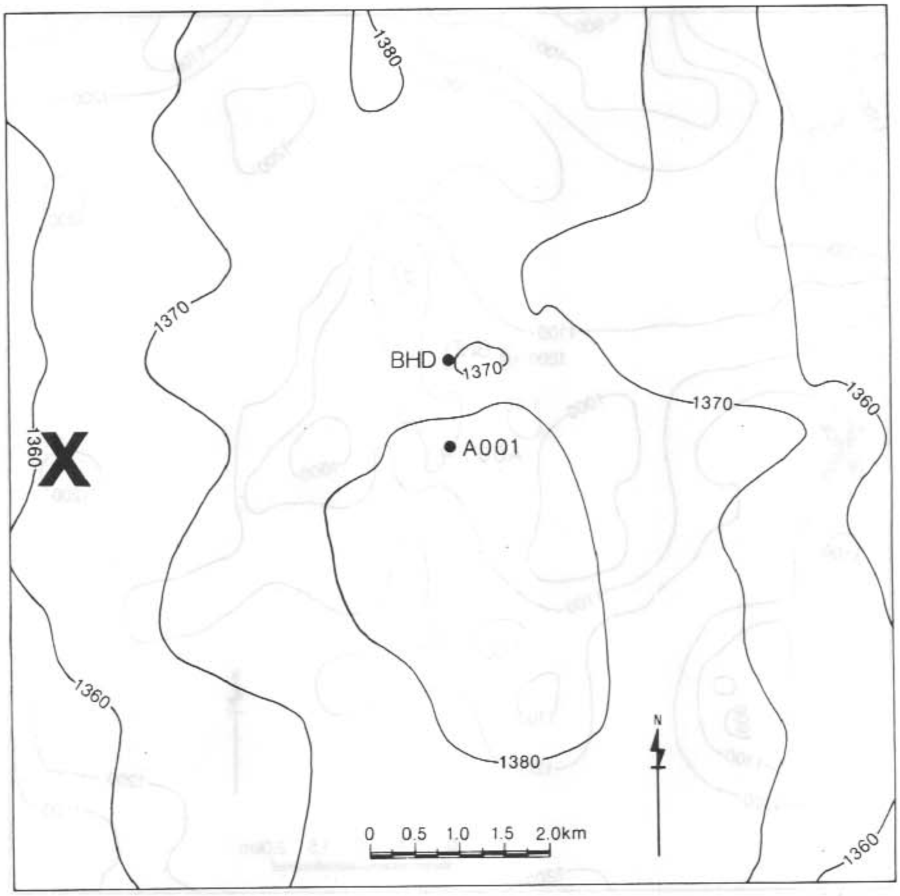

Figure 16. Law Dome summit surface elevation contour map. The proposed drill-site is marked 'X'.

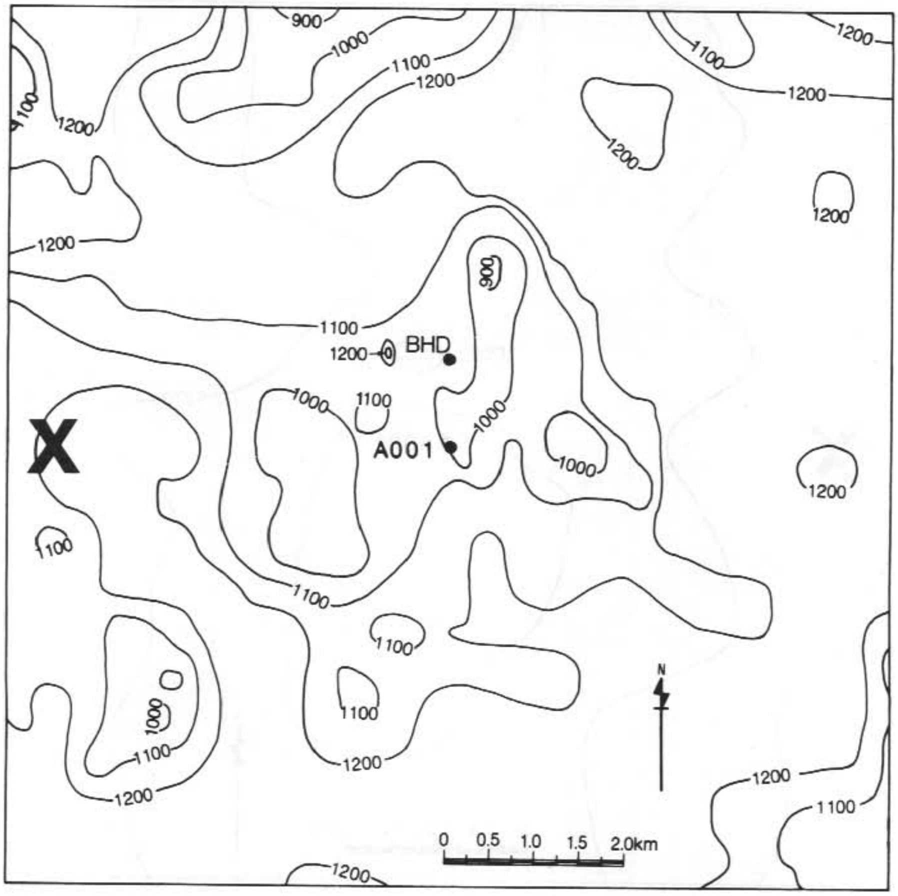

Figure 17. Law Dome summit ice thickness contour map. The proposed drill-site is marked 'X'.

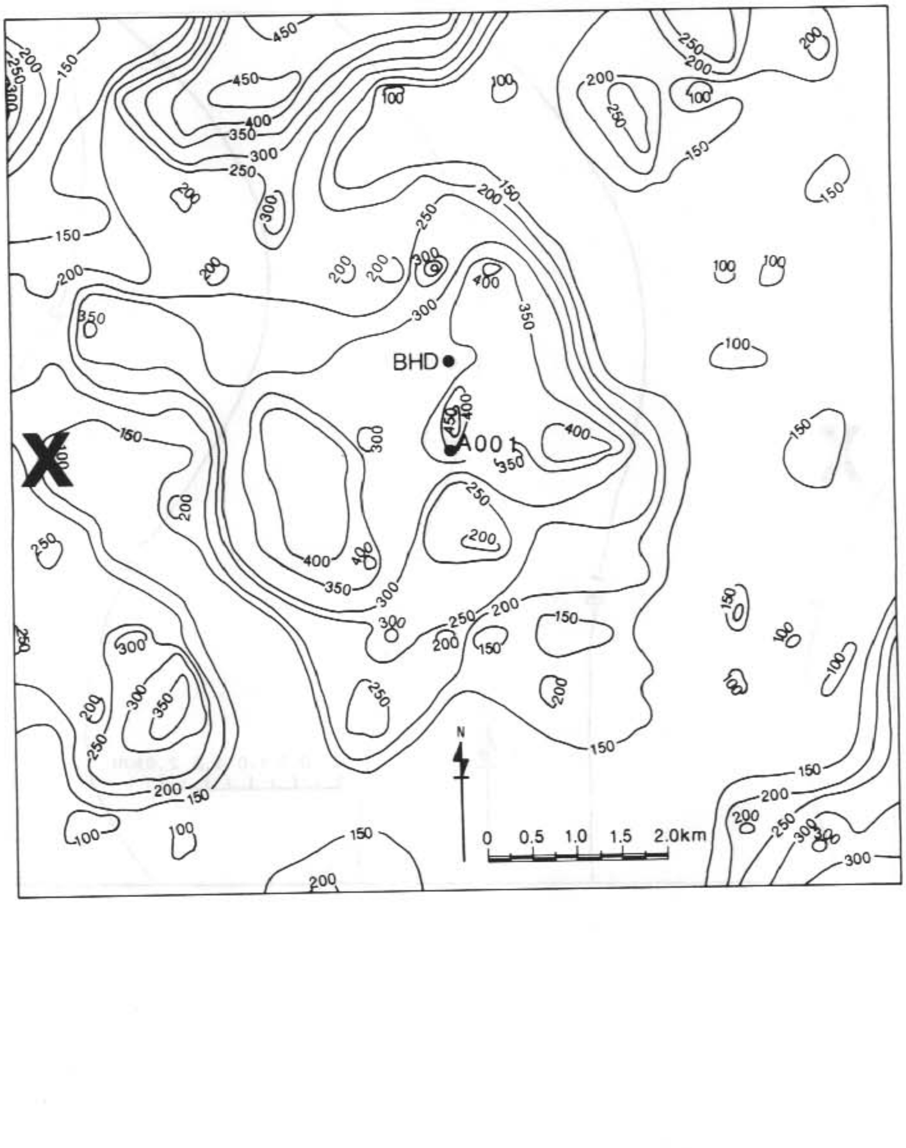

Figure 18. Law Dome summit bedrock elevation contour map. The proposed drill-site is marked 'X'.

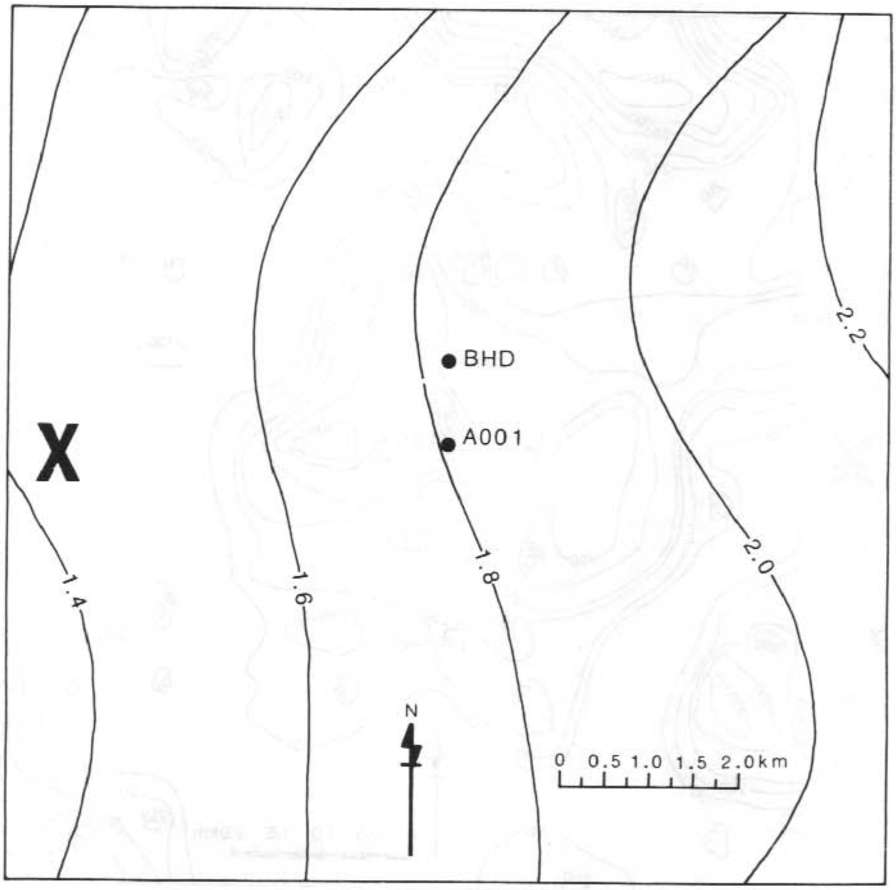

Figure 19. Law Dome summit surface snow accumulation rate, contour map (ma^{-1} of snow) from stake measurements taken at the beginning and end of the 1985 calendar year. The proposed drill-site is marked 'X'.

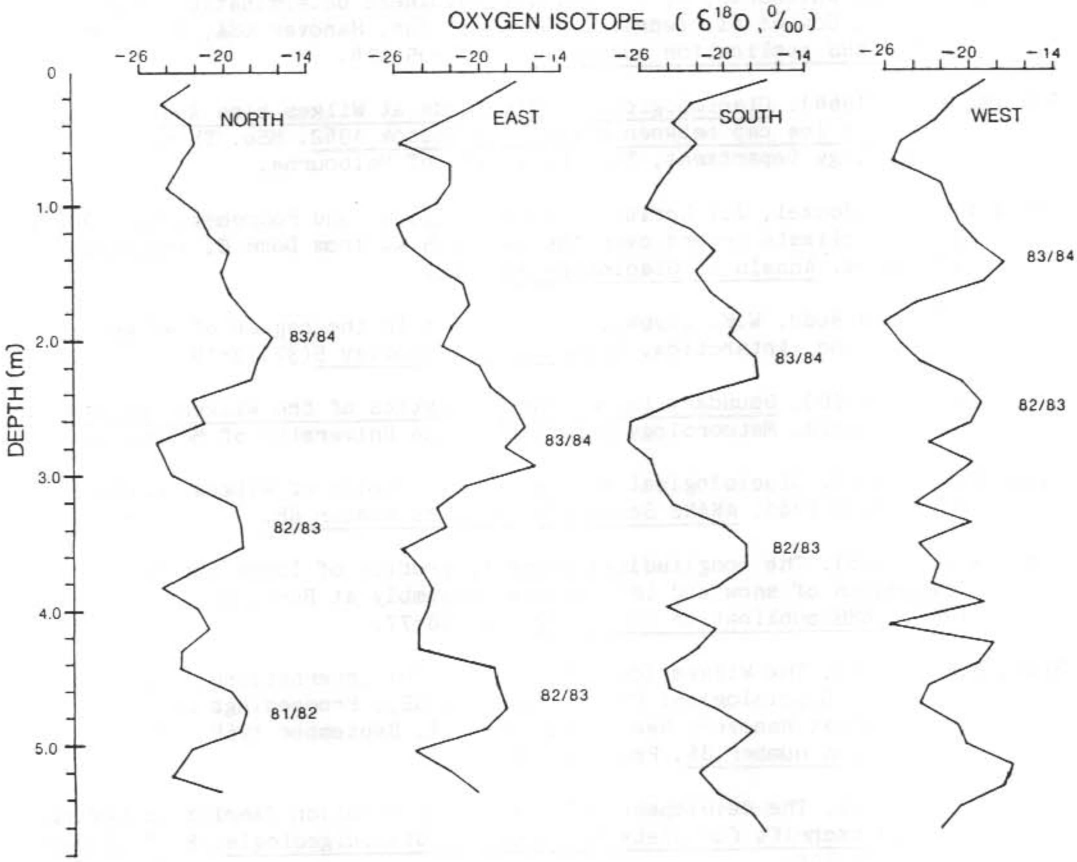

Figure 20. Oxygen isotope ratio ($\delta^{18}O$) results for four shallow ice cores obtained at points 5 km to the north, east, south, and west of A001.

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