# Isotopes, climate and ice sheet dynamics from core studies on Law Dome, Antarctica

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**Abstract.** Oxygen isotope studies have been carried out on surface samples and seven cores ranging in depth from 70 to 380 m from Law Dome at various elevations from 160 to 1390 m. Detailed studies of 15 years accumulation have been made to compare the isotope variations with the climatic record at Wilkes-Casey over the same period. Although strongly influenced by sastrugi and dunes the records do show some correlation with annual mean temperatures.

Two cores 12 km apart covering the most recent decades and centuries show considerable similarity in fluctuations which are considered primarily climatic.

Two deep cores reaching close to bedrock near the coast show little change from steady state since about 8000 years ago. Prior to that the ice was of much colder origin. Gas content analyses of the cores suggest the surface elevation was also considerably greater for that time period. An estimation is made of the extent of the ice during the maximum ice age period.

**Les isotopes, le climat et la dynamique de l'inlandsis révélés par les études des forages sur le Law Dome, Antarctique**

**Résumé.** On a étudié la composition isotopique (oxygène) des échantillons prélevés en surface et lors de sept forages (profondeurs de 70 à 380 m) sur le Law Dome, pour des altitudes de 160 à 1390 m. On a étudié de façon détaillée la neige déposée sur une période de 15 ans pour comparer les variations isotopiques avec les données climatiques enregistrées à Wilkes-Casey au cours de la même période. Quoique fortement influencé par les sastruggis et dunes, le profil isotopique montre une certaine corrélation avec les températures moyennes annuelles.

Deux carottes distantes de 12 km couvrant les dernières décades et siècles présentent des fluctuations semblables attribuées principalement au climat.

Deux carottes profondes atteignant presque le socle rocheux près de la côte indiquent peu d'écarts par rapport à l'état d'équilibre depuis environ 8000 ans. Antérieurement, la glace est d'origine bien plus froide. La teneur en gaz de la glace suggère que l'altitude de la surface était aussi alors considérablement plus élevée. On estime l'étendue de la glace durant le maximum de la glaciation.

## BACKGROUND

Prior to 1969 the work on Law Dome (formerly known as Wilkes Ice Cap) was concentrated primarily on studies on the ice cap surface. These studies included: ice surface movement, accumulation rates, ice surface elevation, ice thickness sounding, 10-m depth firn temperatures, and climatology.

A summary of this work has been given by Budd (1970). Some of the results are shown in Fig. 1, which has been updated by more recent measurements. The general patterns of surface elevation, ice movement and accumulation rates over the ice cap are given. Deep core drilling commenced in 1969 and was continued in 1972 and 1974. The sites of the drilling are shown on Fig. 1. Cores were obtained to the following depths: *A* 324 m, *D* 380 m, *J* 113 m, *B* 70 m, *P* 110 m, *F* 350 m.

The holes at *A* and *F* reached within about 30 m of the bed beyond which high shear and closure rates prevented further drilling with the dry hole technique. These two holes reached quite old ice, approximately 10 000–20 000 years old, whereas the rest reach ages of only a few hundred years. A preliminary coarse spacing survey of the $^{18}O/^{16}O$ ratios in the ice cores from the Dome summit (*D*) and near Cape Folger (*A*) was presented by Budd and Morgan (1973). The aim was to assess the borehole data by comparison with present-day processes and expected distributions resulting from steady state.

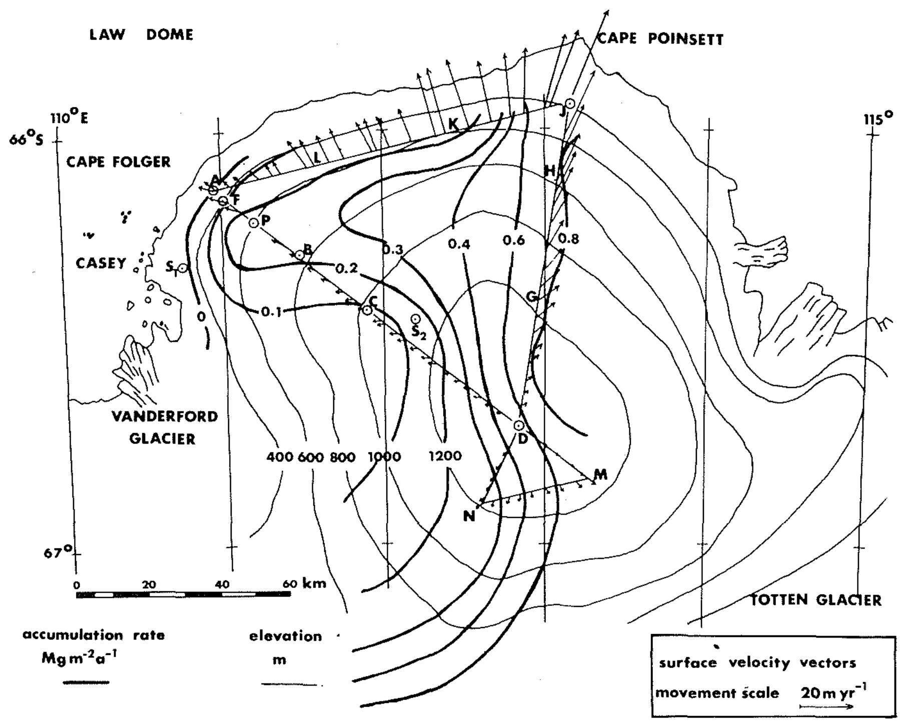


FIGURE 1. Map of Law Dome showing contours of elevation and net accumulation rate, surface velocity vectors, and the drill sites. Those discussed here are at *A, F, P, B, D* and *J*.

Deviations from steady state could then be examined in terms of climatic type changes and changes in the ice sheet. The climate type changes involve temperature, precipitation, wind speed and circulation. The changes of the ice sheet involve primarily the surface elevation, the ice velocity, the accumulation rate.

In order to derive the steady-state isotope distribution surface samples over the ice sheet surface were obtained. These showed an approximate linear relation with elevation [$1\,\delta(^{18}O)\,^0/_{00} \equiv 200$ m] and with temperature, since in this region, the surface mean temperature decreases by approximately 1°C/100 m.

Computed particle paths and ages using measured velocities, accumulation rates and ice thickness allowed the steady-state isotope profiles to be derived from the surface values. By comparison with the measured profile it is apparent that the deviations are generally small back to about 8000 years ago, but prior to that a considerably colder origin of the isotopes was indicated. However, the amount this colder origin is due to climatic temperature change or elevation change of the ice sheet still needs to be determined. Thus a programme to determine the gas volumes in the ice as an indicator of the elevation of the origin of the ice was commenced.

For the short-term changes, i.e. over periods of years to decades, the ice sheet changes are small, hence for these time intervals the mean isotope deviations are primarily due to climatic factors. In order to calibrate the isotope deviations in terms of climatic effects two cores from the detailed study 'flowline', Dome summit to Cape Folger, at positions nearest to Casey station, were analysed in great detail back to the period when the Wilkes-Casey climate record began in 1957.

This analysis over the short term then provided a calibration of $\delta(^{18}O)$ and temperature variations which allowed an evaluation of the medium-term changes in $\delta(^{18}O)$—from decades to centuries—to be assessed in terms of possible past temperature changes.

## SHORT-TERM ISOTOPE-CLIMATE CALIBRATION

The cores from *B* and *P* were obtained in early 1972 but because of the crumbly upper firn the latest few months' accumulation was not obtained intact. Hence the detailed studies were carried out over the equivalent time span of 1957–1971. The accumulation rate along the Dome-Folger line has been measured since 1964. The mean rate at both sites is about 0.5 m year$^{-1}$ of snow with a density of approximately 0.4 Mg m$^{-3}$. Hence samples were taken at 4 cm spacing so that about 12 per year could be expected on the average. The detailed plot of the $\delta(^{18}O)$ record is shown in Fig. 2. Gaps represent lost and damaged cores.

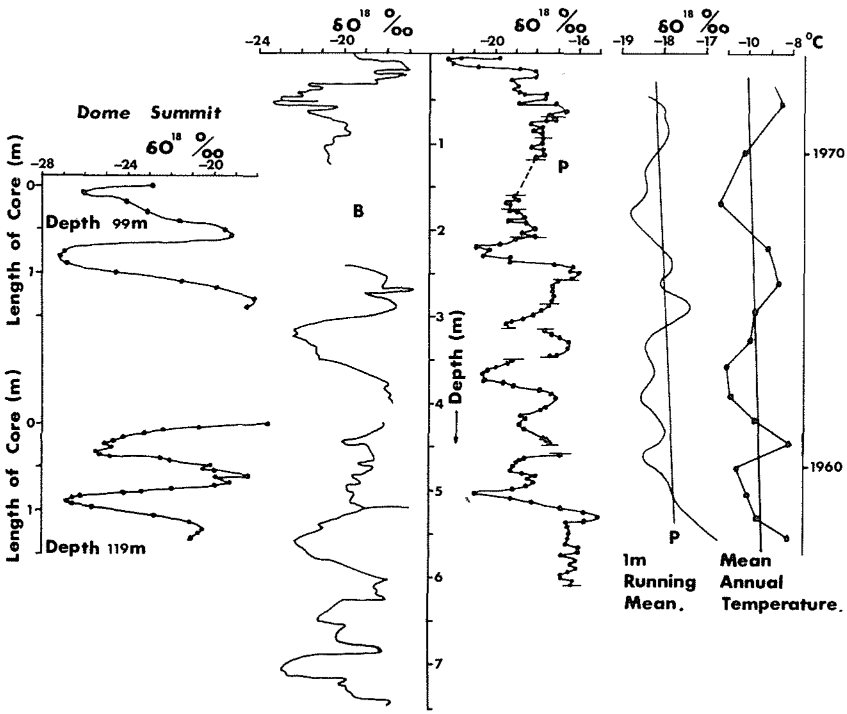


FIGURE 2. The results of the detailed analyses of the upper layers of the cores from *B* and *P* are shown together with a smoothed record for *P* and the annual mean temperature record from Wilkes-Casey. The Dome summit cores by contrast show clear annual variations.

Annual layers are not readily discernible. This is primarily due to the large dunes and sastrugi of about 0.5 m height that form from the katabatic and strong blizzard winds in this region. This results in irregular accumulation rates due to migrating dunes. These processes interact with the annual variations and confuse the record. Hence, for these two sites, only longer term average values are reliable. Hence longer term running means over 20 samples were calculated to smooth over the random noise of the dunes and sastrugi. The resultant variations are shown in comparison with the annual mean temperatures measured at Wilkes and Casey plotted on equivalent depth scale for a uniform accumulation rate and the measured density profile. In spite of the irregular accumulation rate the curves have some resemblance. Least square regression lines for the trends were also calculated. These are also shown in Fig. 2. The main trend is a shift of about $0.5^0/_{00}$ $\delta(^{18}O)$ decrease over the period. The corresponding trend in the temperature record is about 0.6°C cooling. The temperature record has larger irregular fluctuations over periods of 3–10 years. It was shown by Budd (1975) that these fluctuations have significant large-scale similarity for neighbouring stations around the Antarctic. Since 1969, high warming has developed around the Casey sector. This provides a useful critical test for future cores.

As regards annual variations it has been found that the zones of higher accumulation rate, greater than 2 m year$^{-1}$ of snow, to the west have clear annual variations as shown in Fig. 2. Even though these are a little further from Casey, since we are looking for large-scale effects, it is expected these cores will be preferable for calibrating the short-term record.

## MEDIUM TERM ISOTOPE TRENDS

To study the changes which have taken place over recent decades and centuries a coarser spaced coverage of the *B* and *P* cores were extended through the

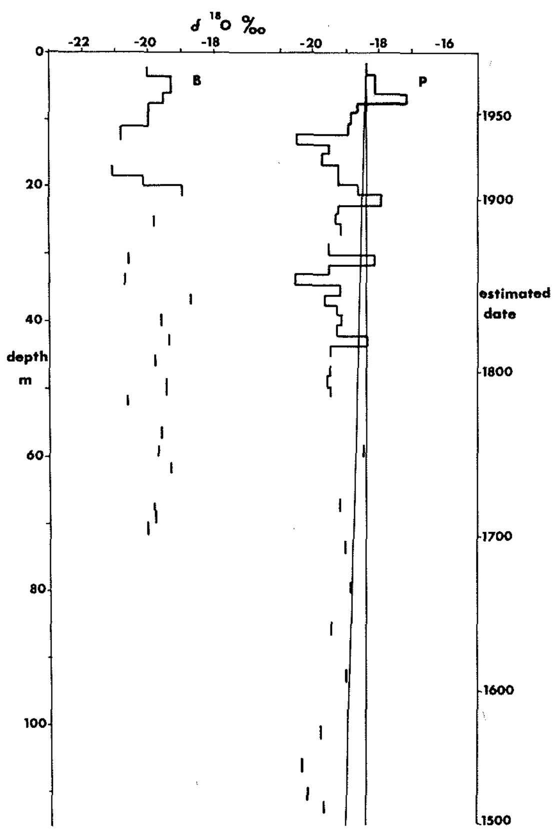


FIGURE 3. The measurements of the *B* and *P* cores averaged over individual core lengths ($\simeq$1.5 m) show some similarity in $\delta(^{18}O)$ fluctuations over the last century. The current steady-state profile for *P* is also shown by the sloping line. For *B* the steady-state flow effect is negligible.

remainder of the depth. This reached back about 240 years in the case of *B* and about 450 years in the case of *P*. The results are shown in Fig. 3. These profiles are drawn on the same depth scale. The separation of the profiles tends to persist in spite of the large variations. The separation is a result of an elevation difference of 160 m. The short-term variations over the last century look surprisingly similar. The main effects in common to both cores suggest a cooling over the last 15 to 20 years following a warming from a cool period in about the 1930s which followed a warmer period about the beginning of the century and a colder period before that. The effects of this recent warming have also been noticed as slight anomalies at the tops of the deep temperature profiles around the dome by Budd *et al.* (1976). However, an accurate analysis of these effects on the temperate profiles has not yet been carried out. Over the longer term the *P* core suggests, in comparison to the steady variation which would be expected from the flow, a generally cooler origin period from 200 years ago and perhaps even earlier. Since the rate of change of elevation due to unsteady state processes cannot be expected to be this large it can be inferred that these are probably real climatic effects. Using the present temperature-time-isotope relation from the short-term calibration of about 1°C per $1^0/_{00}$ $\delta(^{18}O)$ the cooler periods could have been on the average about 2°C colder. Since there are no records over this period from a near enough vicinity the question first to be answered is: do other Antarctic locations show similar changes? This will have to await detailed studies from other cores.

## LONG-TERM ISOTOPE CHANGES

The first hole near Cape Folger at *A* which reached close to the bed was in a zone very near the mean firn line but where net ablation sometimes occurred. A second hole was cored about 4 km upstream at *F* in 1974. The general coarse spaced isotope profiles are very similar as shown in Fig. 4. The top of the *F* profile just shows up the warm-cool-warm variation over the last few hundred years as found in the *P* profile. The trend towards colder origin in the first 250 m is compatible in magnitude with flow effects from the present ice cap. The change below this of over $7^0/_{00}$ $\delta(^{18}O)$ is very large by comparison and occurs over a relatively short time span. Using the present isotope-elevation-temperature relation, this represents about a 14°C change over about a 2000 year period. To examine the question as to how much of this change is due to climate and how much due to changes in the ice sheet, we turn to the isotope elevation relation measured further inland as shown in Fig. 5. This would suggest that the ice would have had to come from about 1800 m a.s.l., and several hundred kilometres inland. If the elevation change were associated with a higher ice sheet then the inland and latitude effects would not be so strong hence elevation change would need to be greater, perhaps as high as 2500 m. To consider this further we turn to the gas volumes analysis.

## ANALYSIS OF ENTRAPPED GAS CONTENT

Below the level in the firn where the air spaces become closed off from the surface air they are entrapped in the ice. In spite of deformation this mass of gas per unit mass of ice remains fixed throughout the motion. Hence if the gas content varies in a systematic way over the ice cap at present then this may serve in the case of steady state to define the position of origin of the ice. In the case of non-steady state the question is much more complex involving problems of the temperature, pressure, and cut-off density at the unknown location in the past.

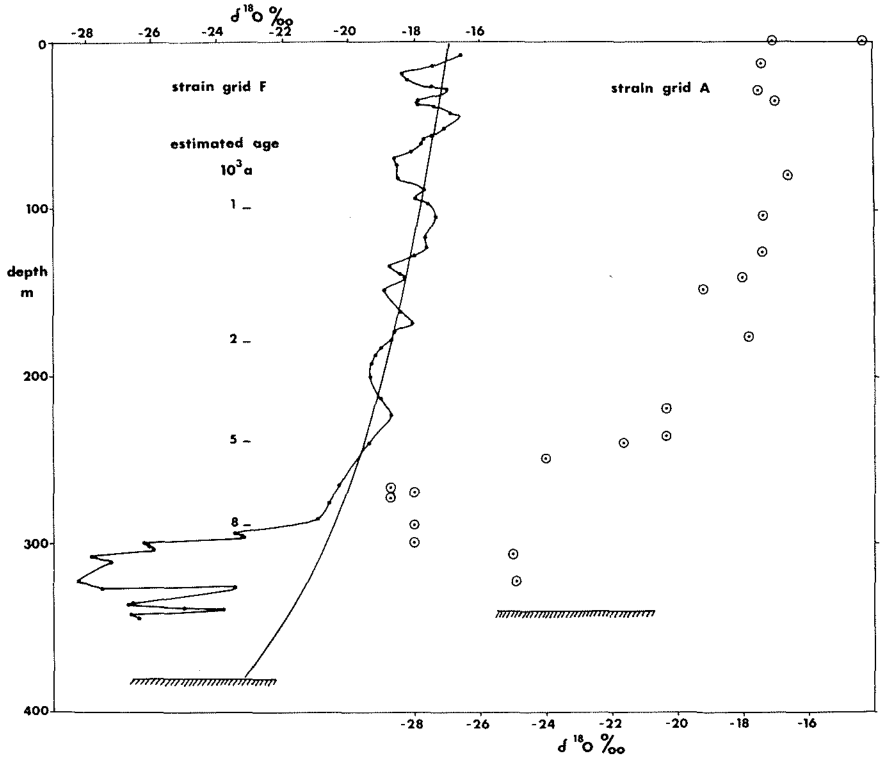


FIGURE 4. The oxygen isotope profiles for the two deep cores near the coast at *A* and *F* are shown together with a steady-state profile and estimated age scale for the *F* core.

For the Law Dome, cores from a number of sites of different origin have been examined. Even below 50 m depth there is still considerable scatter in the results. At some locations the variations are suggestive of annual variations. By making large numbers of measurements general trends become apparent. These are illustrated in Fig. 6. This shows there is a mean elevation gradient of about 15 ml/kg of ice (at STP) per km over the dome. In the Cape Folger core however, there is a gradual increase down to 200 m somewhat similar to the trend in the isotopes. Then there is a large change in the region of the isotope change from 0.11 to 0.08 ml/g. Below this level there is a small trend of increasing values towards the bed, again not unlike the isotope change.

In order to assess the magnitude of the possible elevation variations it is necessary to make some assumption about the temperature variations as the ice sheet thickness changes. This is not clear due to the effects of the large inversions. Even with no temperature effect however the elevation of origin implied would be over 3000 m.

## RECONSTRUCTION OF PAST ICE SHEET EXTENT

From geomorphological evidence Cameron (1964) inferred that the deep fjord-like trough of the Vanderford Glacier over 2000 m deep was filled by ice during the ice age maximum. To do this, the ice there would need to be more than 2000 m thicker. It also appears that the ice sheet would have reached out to the continental shelf—which is generally about 500 m below sea level in this region, and 100 km further out. Assuming base stresses to be at least of a similar

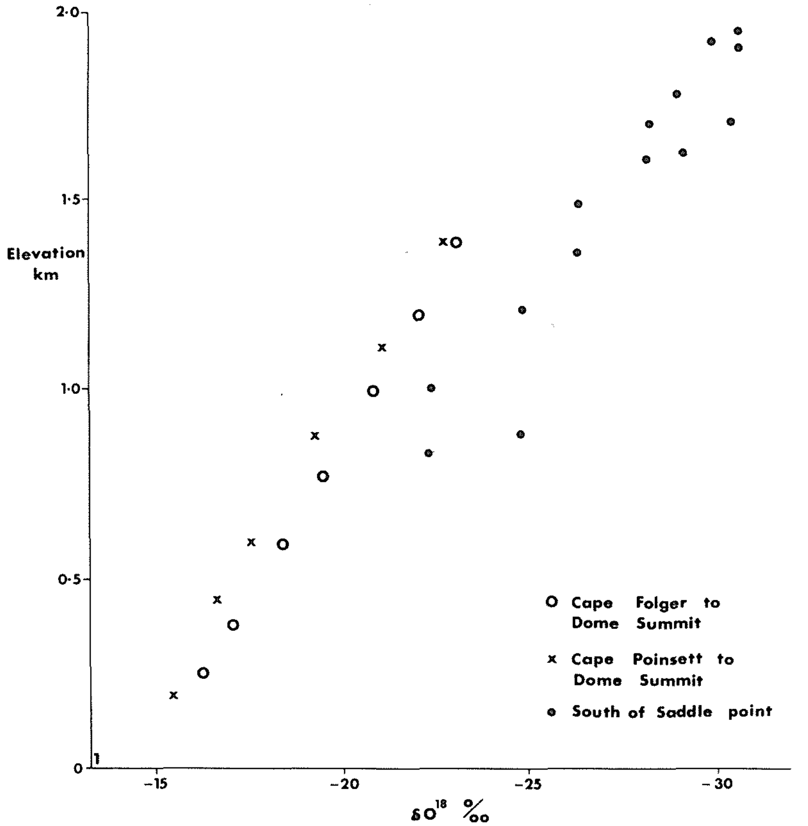


FIGURE 5. The variations of isotope ratios from surface samples are shown as a function of elevation for two lines on the Law Dome and for the main Antarctic ice sheet to the south.

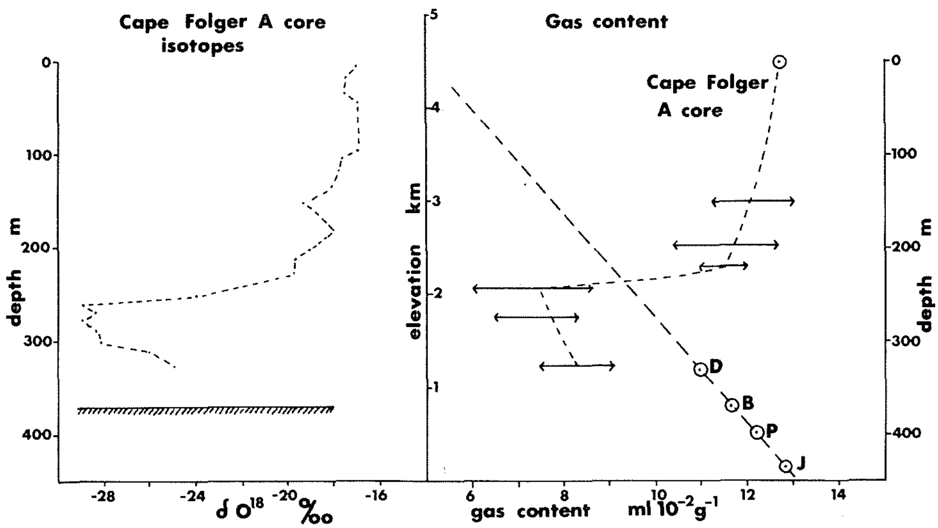


FIGURE 6. The variations in mean gas content for the cores from *J*, *P*, *B* and *D* are shown against elevation together with the variation with depth in the Cape Folger core in comparison with the isotope variations.

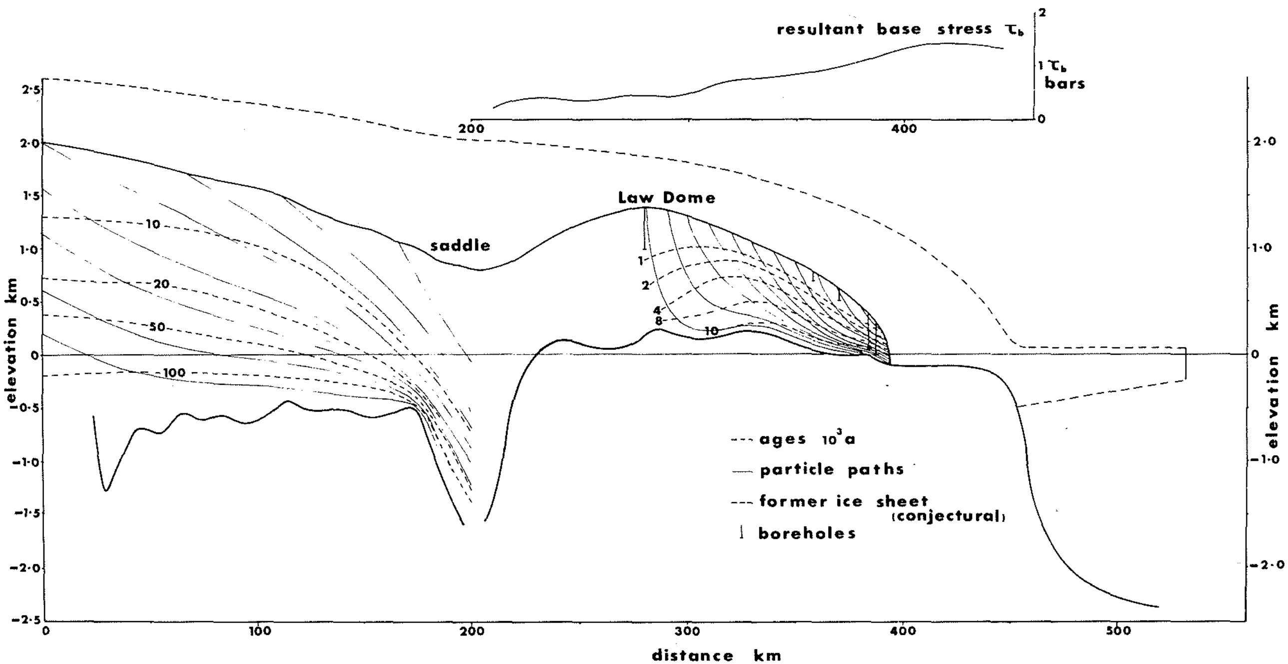


FIGURE 7. The surface and bedrock profile for the present ice sheet over Law Dome and to the south is shown together with calculated particle paths and ages. An estimated profile for a former extent is shown on the assumption that it was grounded to the edge of the continental shelf with a slightly increased base stress than at present.

magnitude to those at present in Law Dome allows construction of a possible ice sheet shape and size which fits the above criteria. For an ice sheet thickness which just reaches zero slope over the saddle point but does not turn negative the resultant profile is shown in Fig. 7. The flux from the interior still diverges in the valley and flows out the Vanderford and Tottern Glaciers. If the ice sheet were any thicker than this the present dome area could be overridden from further inland. One further explanation of the cold origin isotopes could be the eventual cut off, from thinning, of the ice flow from the interior.

With the ice thickness of Fig. 7 the surface of the coldest region flowing to Cape Folger could be perhaps just 6°C colder than the Dome summit. This would still leave $\sim$4–5‰ $\delta(^{18}O)$ remaining for possible climate effects. However, there is still the question of the speed of the change shown in Fig. 6. This suggests that if there is a rapid lowering of the ice sheet it could be by a surge. Recent analyses using an extension of the model of Budd and McInnes (1974) to Antarctica suggests that surging is likely to be the rule rather than the exception, and in which case elevation changes comparable to those indicated in Fig. 7 could result.

These considerations are still somewhat speculative at this stage but nevertheless should be kept in mind, at least until further analysis has been carried out.

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## DISCUSSION

**Swithinbank:**

Do you plan to drill on the summit of Law Dome for long-term palaeoclimatic studies?

**Budd:**

We have obtained a core to the depth of 380 m from the Dome summit and have carried out a preliminary coarse survey of the isotopes as given by Budd and

Morgan (1973). We have also found that clear annual variations of $\delta(^{18}O)$ occur in the core as shown by our Fig. 2. However, we no longer have a continuous core from the surface because parts were used for $^{210}Pb$-dating in 1970. Hence we plan to obtain another continuous core there for detailed isotope studies of the upper layers.

**Dansgaard:**
You mentioned $^{210}Pb$-dating. Do you intend to date the core by stratigraphic methods (stable isotopes or dust)?

**Budd:**
Yes, the core from the Dome summit has large, clear annual layers (about 0.6 m of ice per year) with a range of $\delta(^{18}O)$ of about $8^0/_{00}$ persisting below 100 m. So we believe it will be possible to follow the annual layers there to the bottom of our core at 380 m depth.

REFERENCE TO DISCUSSION

Budd, W. F. and Morgan, V. I. (1973) See above.