Preliminary analysis of ice cores from Siple Dome, West Antarctica

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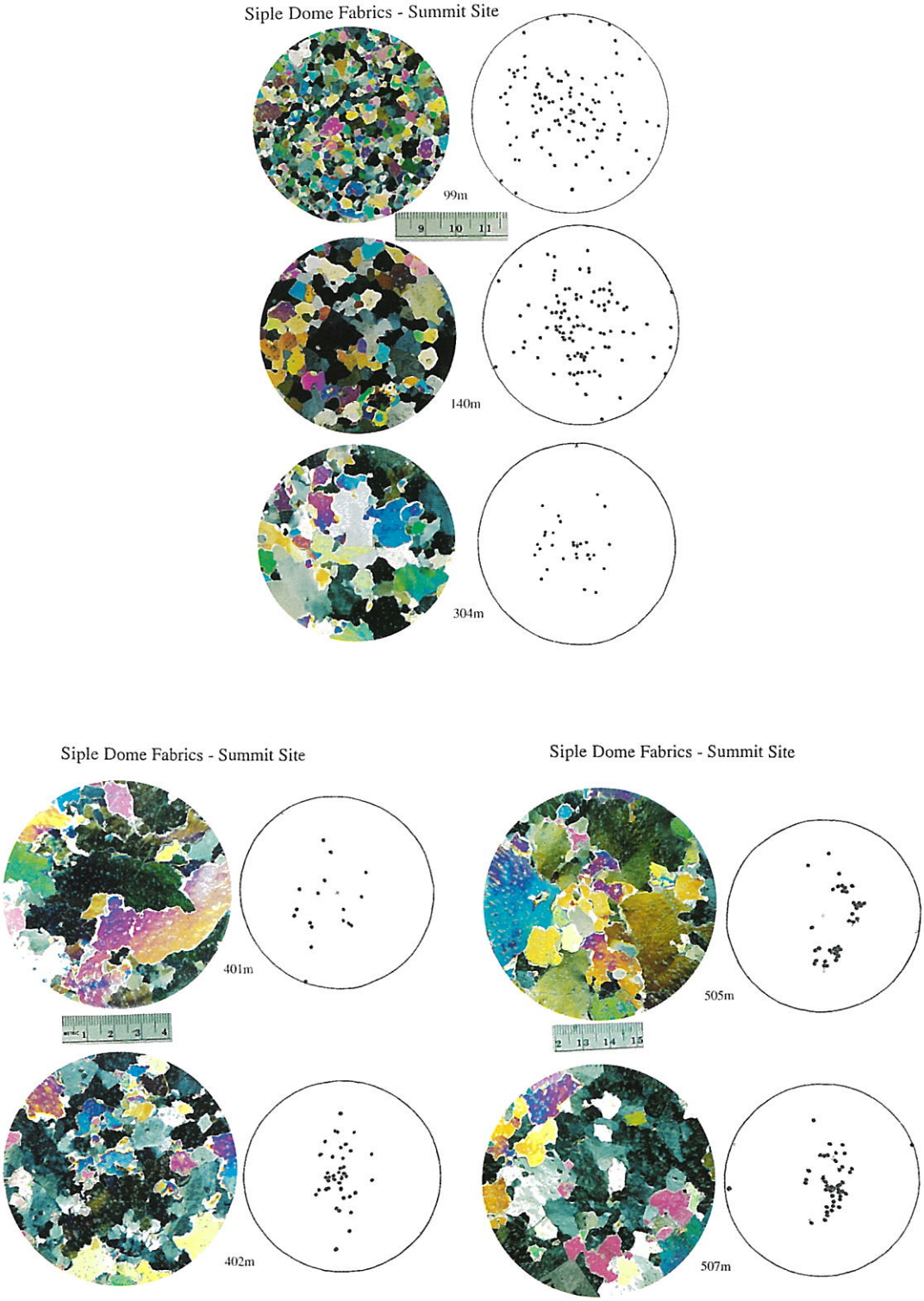

Plate 7a. A. J. Gow and H. Engelhardt, Figure 7.

Siple Dome Fabrics - Summit Site

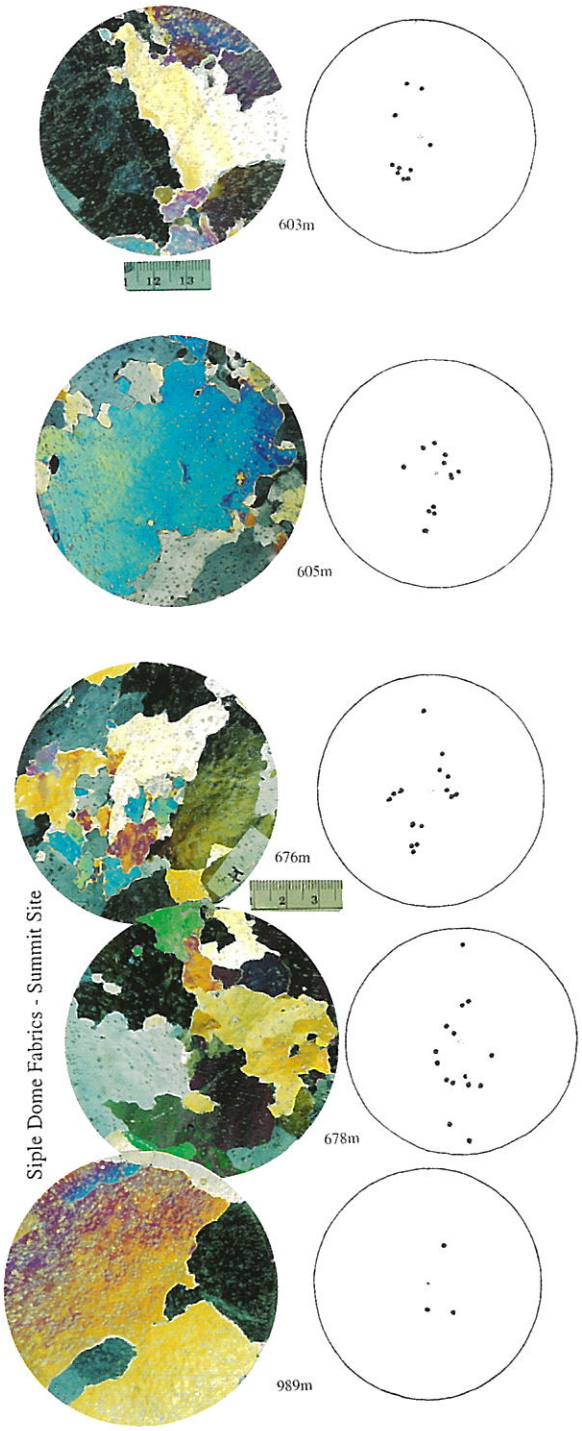

Plate 7b. A. J. Gow and H. Engelhardt, Figure 7.

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Abstract: Results are presented of a preliminary analysis of ice cores obtained by hot water drilling at Siple Dome, Antarctica. Cores were retrieved from pre-selected depths on both the summit and flank of the Dome. These included all cores obtained within 15 m of the bed at the summit site and to within a meter or two of the bed at the flank site. Basal ice at the summit is frozen to the bed at −1.3 °C, approximately 0.5 °C below the pressure melting point. Brittle ice was first encountered at 400 m and continued to the bottom of the ice sheet. Fracturing was most severe around 500–600 m. This fracturing occurred soon after cores were retrieved. However, the mechanical condition of the ice appeared to stabilize within a few days of core recovery. The rapidity of relaxation is attributed mainly to thermal effects associated with the hot water drilling process and partly to the rapidly increasing temperatures and the highly recrystallized nature of the ice below 600 m. Volume expansion of the ice associated with this relaxation process ranged from 0.3 % at around 300 m to nearly 3 % in the deepest ice. Air bubbles were observed at all depths; a decrease in the sizes and concentrations of bubbles in the deepest ice is attributed to gas hydrate formation. An abrupt increase in the size of crystals at around 605 m coincided with an in situ ice temperature of −13 °C. This is about the same temperature at which annealing recrystallization has been observed in cores from Byrd Station, Antarctica and at GISP2 and GRIP in Greenland. A progressive increase in the size of crystals in the upper levels of ice at Siple Dome was accompanied by a reorienting of the crystallographic c-axes, initially favoring a broad clustering of axes about the vertical but changing to vertical, girdlelike fabrics at 400–500 m. This pattern changed to fabrics trending towards either point maxima or ringlike distributions of c-axes in the deeper annealed ice below 600 m. Preliminary measurements of stable isotope (δD) composition of Siple Dome ice indicate a Holocene/Younger Dryas transition at about 650-660 m depth, based on current age dating models. This would put the transition in the zone of annealed ice, marked by extensive grain boundary migration. To what degree the redistribution of chemical constituents by such extensive recrystallization effects the level of resolution of the paleoclimate record preserved in the deeper ice at Siple Dome remains to be seen. It is hoped that cores obtained to bedrock during the austral summer of 1998/1999, will help resolve this and other issues related to the physical and structural properties of Siple Dome ice.

Physics of Ice Core Records
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1. Introduction

A major purpose of the Siple Dome drilling is to obtain a high resolution core to bedrock in ice approximately 1000 m thick. The dome, situated at 81.65°S–148.81°W between ice streams C and D in West Antarctica (Fig. 1), reaches a maximum elevation of about 620 m above sea level. Bedrock is located approximately 380 m below sea level directly beneath the dome summit. A major consideration in selecting this particular site was to choose a west Antarctic coastal location with ice thick enough to yield a core containing a > 100 kyr paleoclimate record. Results of an airborne ice penetrating radar survey by Blankenship in 1994/1995 show a clear pattern of internal reflecting horizons down to a depth of 600–650 m. Surface profiling by Jacobel in 1994/1995 [see Raymond et al. 1995] also show these internal reflectors

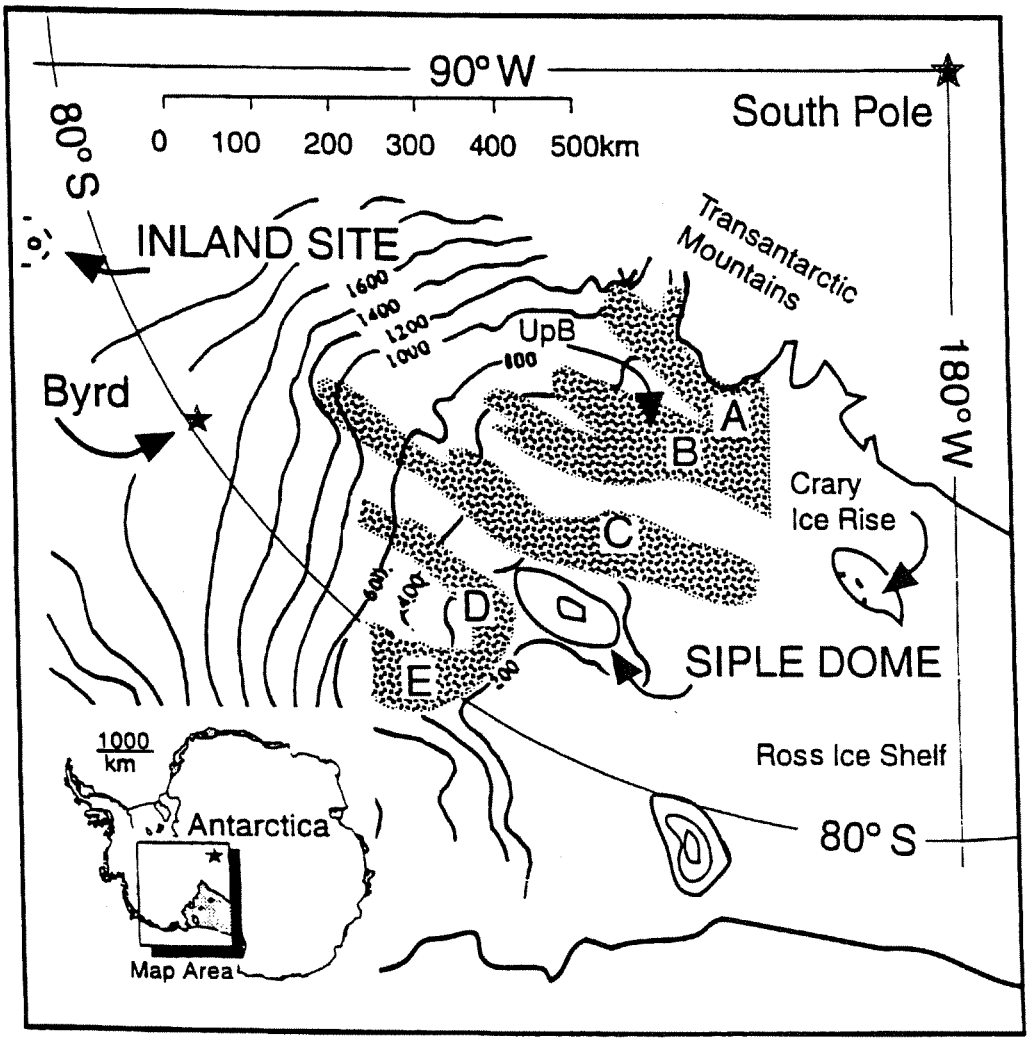


Figure 1: Location map [modified from Alley and Whillans 1991].

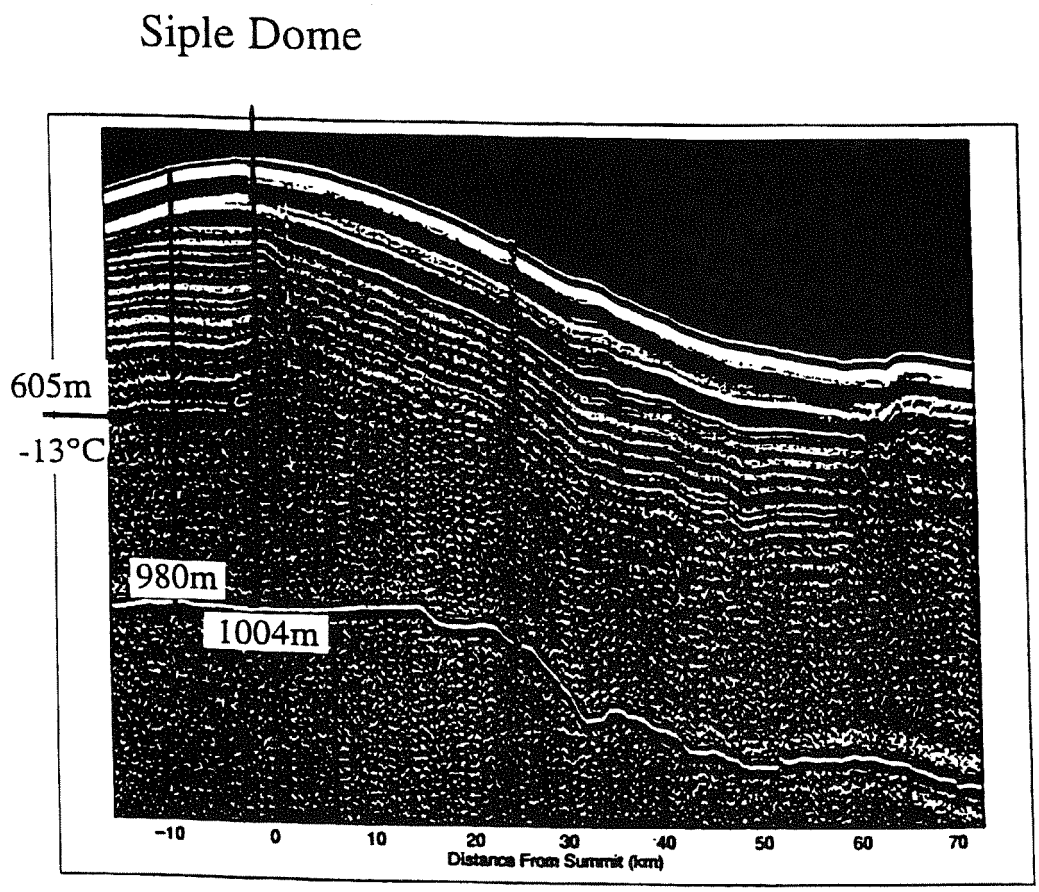


Figure 2: Radar profile across Siple Dome showing surface and bed characteristics and internal reflecting horizons. South is to the right and north is to the left [modified after Raymond et al. 1995]. The 1997/98 hot water drilling and coring sites, and the depth and temperature at which strong internal layering begins to fade are also indicated.

to be continuous and uniform, across the dome and for some distance, beyond it (Fig. 2). The ice dome is also seen to be underlain by a relatively flat bed extending outwards several kilometers. The pattern of internal reflections, as indicated by the radar, indicates that the flow divide has most likely, not migrated over a time scale corresponding to the age of the ice at half thickness, estimated at around 10,000 years [Raymond et al. 1995]. Best estimates, based on analysis of shallow cores obtained within the past 4 years at Siple Dome indicate a current accumulation rate of 9–11 cm of ice/yr; 10 m temperature measurements indicate a mean annual air temperature of –25 °C.

2. Core drilling procedure

Cores on which the present results are based were obtained by hot water drilling at three separate sites in the immediate vicinity of Siple Dome. These cores were retrieved during the austral summer of 1997/1998 in

lieu of cores that were to have been drilled by the Polar Ice Coring Office (PICO) as part of the West Antarctic Ice Sheet Cores (WAISCORES) program. Unfortunately, because of equipment problems with the PICO electro-mechanical drill, coring at the main drill site was terminated for the season at a depth of 155 m. Fortunately, a hot water drill modified for coring [Engelhardt et al.; paper in preparation] was made available to the project by one of the authors (HE). This drill, used primarily for drilling access holes in glaciers was adapted for coring by attaching the hot water drill hose to a 4 m-long Lexan tube fitted on the bottom with a hollow brass ring perforated with a number of high pressure water jets. This brass ring constitutes the cutting head of the drill and hot water is delivered to it from the hose through four thermally-insulated stainless steel tubes located along the outside of the Lexan core barrel. The water in the hole is cooled to about 5 °C prior to drilling a core. Built into the cutting head is a core catching device consisting of two sharpened spring-loaded wedges. Raising the core barrel at the end of a drilling run activates the wedges which grip the ice, break the core free and prevent it from slipping out of the barrel. To avoid melting of the core during transit to the surface the water in the drill hole is kept at the pressure melting temperature at all depths. Thermal shock of the ice during drilling with hot water is largely eliminated because the cutting of the core is done at the overburden pressure in the liquid filled hole. Fracturing of cores of the deeper ice can occur if the core is raised too quickly. For example, about one hour is needed to raise a core from 1000 m to the surface if significant fracturing of the ice is to be prevented.

Cores obtained by hot water drilling measured 3–4 m long and 0.09–0.10 m in diameter. On reaching the surface they were removed from the core barrel and then transferred to a small tent shelter to relax (Fig. 3). This was a necessary prerequisite since most of the core was retrieved from within the so-called brittle zone which at Siple Dome extended from 300–400 m depth to the bottom of the ice sheet. After several days of relaxation, involving cracking and microfracturing of previously unfractured, freshly drilled ice, cores were moved to the core storage trench located alongside the PICO drill. All subsequent examination and measurements on cores were conducted in a small undersnow laboratory situated near one end of the storage trench.

Drilling for cores was carried out at three separate sites, two of which were located on the dome summit in close proximity to the PICO drilling site. The hole nearest the PICO drill was bored primarily to determine the temperature at the bed. Of the three cores taken in conjunction with this drilling the deepest was retrieved from within 15 m of the ice/rock interface, located 1004 m beneath the surface of the dome. A few sparsely distributed, millimeter-sized rock particles were observed in this core. Additional cores were taken at approximately 100 m intervals to a depth of 600 m at a second hole located about 400 m from the first drill site. A third drilling was conducted on the flank of the dome, 8.5 km from the summit (See Fig. 2). Eleven cores were taken at this site, including a final core retrieved from within a meter or two of the bed, located 980 m below the surface. Unlike the situation at the summit site the core taken close to the bed at the flank site did not appear to contain any entrained debris.

Figure 3: Core being removed from Lexan core barrel used with hot water drill. The barrel is 4 m long and takes a 0.90 – 0.10 m diameter core.

3. Analytical techniques

3.1 Core studies

Initial investigations of cores were conducted on a light table to evaluate annual layer structure and other stratigraphic features, wherever present, and to document salient features of the relaxation process such as crack patterns and other visible signs of ice modification. These examinations were then followed by precision density measurements on selected samples. These measurements were made by hydrostatic weighing in reagent grade isooctane (2-2-4 trimethylpentane). This measurement technique yields densities to an accuracy of 0.0003 Mg/m^3; it has been used extensively in previous studies of polar ice cores by Langway[1958a, 1962] and Gow [1968a, b], not only to evaluate a major index property of ice but also to estimate in situ bubble pressures.

Crystal structure studies were conducted on thin sections prepared from 5 –10 mm thick slices of ice cut either parallel or perpendicular to the long (vertical) axis of the core. The preparation and subsequent examination of thin sections were carried out, following techniques described in Langway [1958b], Rigsby [1960] and Gow [1970].

Thin sections measuring 1 mm or less, depending on the average size of crystals in the section, were photographed in plain transmitted light and between crossed polarizers to document both crystal and entrapped bubble characteristics in the ice. Crystal size was determined on the basis of the number of crystals in a given area of a thin section photograph. The mean crystal cross-section was simply obtained by dividing the area of crystals counted by the total number of crystals. Crystal fabric studies were performed on a Rigsby

universal stage. Due to the limited availability of core, and cognizant of the needs of other WAISCORES researchers, c-axis measurements were generally confined to one, or occasionally, two thin sections taken from each of the 3–4 m long cores.

3.2 Borehole temperature measurements

Temperature measurements were confined to the 1004 m deep hole drilled nearest the PICO drill site. A string of 21 thermistors was lowered in to the water-filled hole and allowed to freeze in with the deepest thermistor located in virtual contact with the bed. Measurements of the entire profile were made at regular intervals during the next 6 weeks, by which time the temperature readings were estimated to have stabilized to within 0.1 °C of their true in situ values.

4. Results and discussion

4.1 Borehole temperatures

Results of temperature measurements in the 1004 m deep hole at the summit of Siple Dome are presented in Figure 4, superimposed on the temperature profile measured at Byrd Station [Ueda and Garfield, 1969]. The major purpose for drilling a hole to bedrock at this location was to determine if the ice in contact with the bed was at the pressure melting point. This knowledge is critical to core drilling since any water associated with pressure melting could seriously impact on any attempt to penetrate the ice/rock interface. If the temperatures measured at Siple Dome have in fact stabilized then it would appear that the temperature of the ice in contact with the bed (−1.3 °C) is about 0.5 °C colder than the pressure melting point, estimated on the basis of the 1004 m thick ice at the Summit core drilling site. This finding is in agreement with the bore hole drillers' observation that no change occurred in the water level in the hole when the drill reached the bed. This is interpreted as indicating the absence of any hydraulic connection between the borehole and any source of basal water. Such a change could have been expected if the ice sheet at Siple Dome was not frozen to its bed. With this information the core drillers at the PICO drilling site should be able to undertake drilling into the bedrock at Siple Dome without fear of freezing in the drill. This was precisely the problem that drillers encountered at Byrd Station when the accumulation of substantial melt water for some distance above the bed led ultimately to loss of the drill [Garfield and Ueda, 1976].

The near-perfect superimposition of the temperature profile over the bottom 800 m at Siple Dome and Byrd Station implies a near identical geothermal flux at both these locations. Based on the near-linear rate of change of temperature with depth of 0.03 °C/m we estimate a basal heat flow of about 0.075 w/m^2. This compares closely with a basal heat flux of 0.080 w/m^2 obtained by Alley and Bentley [1988] from bore hole temperature measurements at ridge BC, on the Siple Coast of West Antarctica.

4.2 Ice core relaxation characteristics

Cores recovered from even moderate depths in an ice sheet are subject to changes in a number of physical properties because of release of the confining pressure. The overall process is generally referred to as relaxation, first documented in detail by Gow [1971] in regard to deeply drilled cores retrieved at Byrd Station. This process of

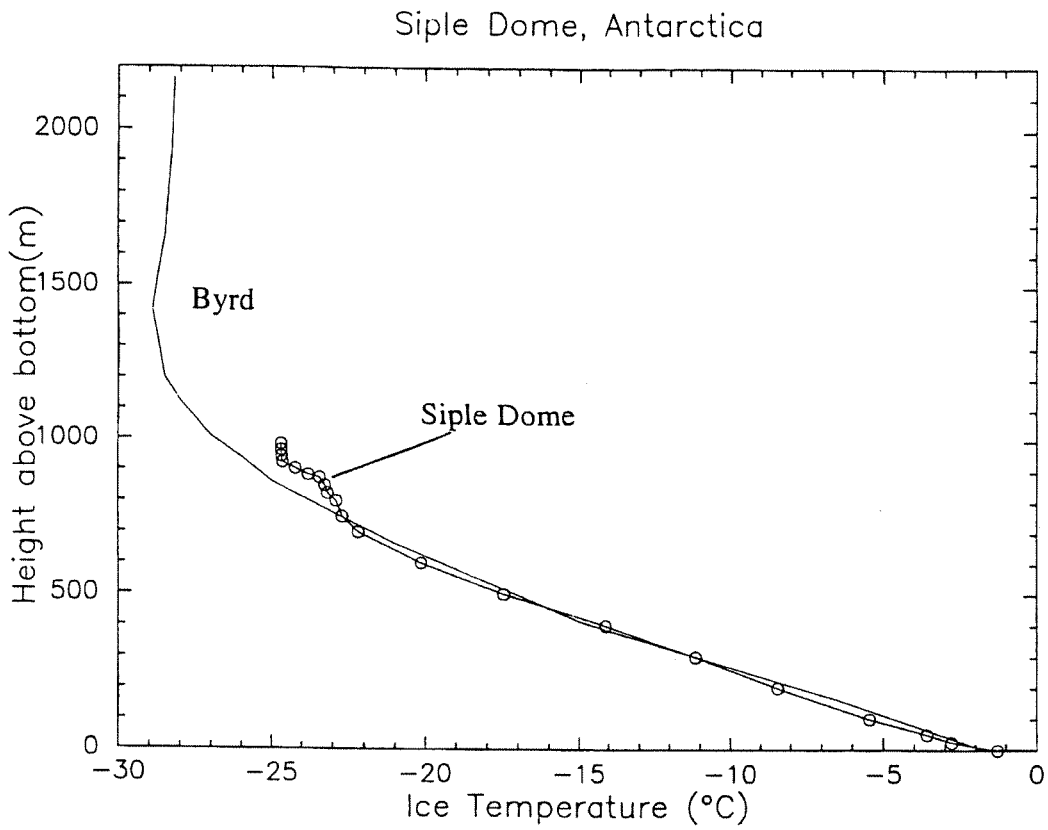


Figure 4: Siple Dome temperature profile superimposed on the Byrd Station profile. Temperature at the bed at Siple Dome measured −1.3 °C, ~0.5 °C below the calculated pressure melting point.

relaxation manifests itself in a number of changes, including microcracking, fracturing, decompression and frequent splitting of pressurized air bubbles trapped in the ice, and exsolving of atmospheric gas previously converted in deeper parts of an ice sheet to gas hydrates which then dissociate as cores relax. Relaxation is most readily monitored through a combination of repeated precision density measurements and thin section examinations. The region in which relaxation changes are most marked has been referred to as the brittle zone [Gow, 1971]. It was anticipated that at least the bottom 50–60 % of the ice at Siple Dome would be in the brittle zone, but that the intensity of the brittleness would depend largely on the temperatures in the ice. Also, we could expect pressurized air bubbles to persist to the ice/rock interface, to be accompanied by appreciable diffusion of the air into the ice to form gas hydrates.

Initial examination of relaxation characteristics of cores at the three hot water drill sites indicate the following. Observations of the mechanical condition of the thermally drilled cores, prior to their removal from the transparent core barrel, indicated minimal fracturing of the ice, though breaking of the 3–4 m long cores into a number of smaller sections was a general characteristic. Following removal of

the cores from the Lexan core barrel a rapid relaxation of the ice was observed that persisted for several days while the cores were retained at elevated surface air temperatures at the three drill sites, before they were transferred to the WAISCORES storage trench in readiness for more detailed examination of their relaxation characteristics.

Cores from the top 300 m were retrieved and retained in excellent mechanical condition, essentially devoid of cracks and fractures as shown in Figure 5. Faint layering was observed in a number of cores. Spacing between the layers varied from 6–8 cm in cores from the summit of Siple Dome to as much as 17 cm in a flank core. This layering, possibly annual in nature, was not observed in deeper ice below 400 m.

Cores from around 400 m were now broken into several pieces, but individual pieces either lacked or possessed very few cracks. However, bubble splitting with cracks propagated parallel to the basal glide planes of host crystals and intracrystalline cleavage cracking was widespread in these cores. A double melt layer, several millimeters thick at 402.20 m, was observed in the summit core. It would appear that the onset of brittle fracture occurs between 300 and 400 m; it continued to the bottom of the ice at both the summit and flank drill sites.

Fracturing of brittle ice was most severe around 500–600 m. For example, in cores from 504–508 m, subhorizontal fractures are predominant but inclined fractures were also present. Cores from 603–607 m were similarly fractured but "healing" of cracks was also becoming apparent. In cores form 676–680 m there was also widespread "healing" of cracks; additionally the pattern of vapor figure/cleavage crack features in this ice indicated, for the first time, the presence of large crystals. The inclined nature of crystals in this ice could easily be mistaken for inclined layering. Inspections of thin sections readily revealed the true nature of this macrocrystalline ice. The same was true of deeper ice; in the case of cores from 988–991 m some crystals extended across the entire 10 cm length of a vertical thin section. A further feature of the macrocrystalline ice in the deepest cores was that a significant part of the relaxation appears to be facilitated by the formation of closely spaced cracks paralleling the basal glide planes of crystals (see for example, the section of ice from 989 m in Fig. 5).

A significant feature of brittle ice relaxation at Siple Dome was the rapidity with which it stabilized at elevated surface air temperatures, generally a few days to a week after cores had been drilled. This allowed brittle ice to be sawed or sectioned with ease within a few days after drilling. Such rapid stabilization of the relaxation process was not previously observed in other cores from Antarctica and Greenland [Gow 1971, Gow et al. 1997]. The nature of the coring itself –by continuous circulation of hot water in the drill hole– has likely contributed significantly to the rapidity of relaxation. In deeper ice this rapid stabilization of the relaxation process can likely be attributed, in part at least, to the attainment of annealing temperatures (warmer than ~–13 °C) at around 600 m and the accompanying growth of very large crystals. This situation applied at both the summit and flank drilling sites.

Repeated density measurements over time have proven a convenient means of monitoring the time dependent nature of relaxation in ice cores [Gow 1971]. Because density measurements on brittle ice at Siple

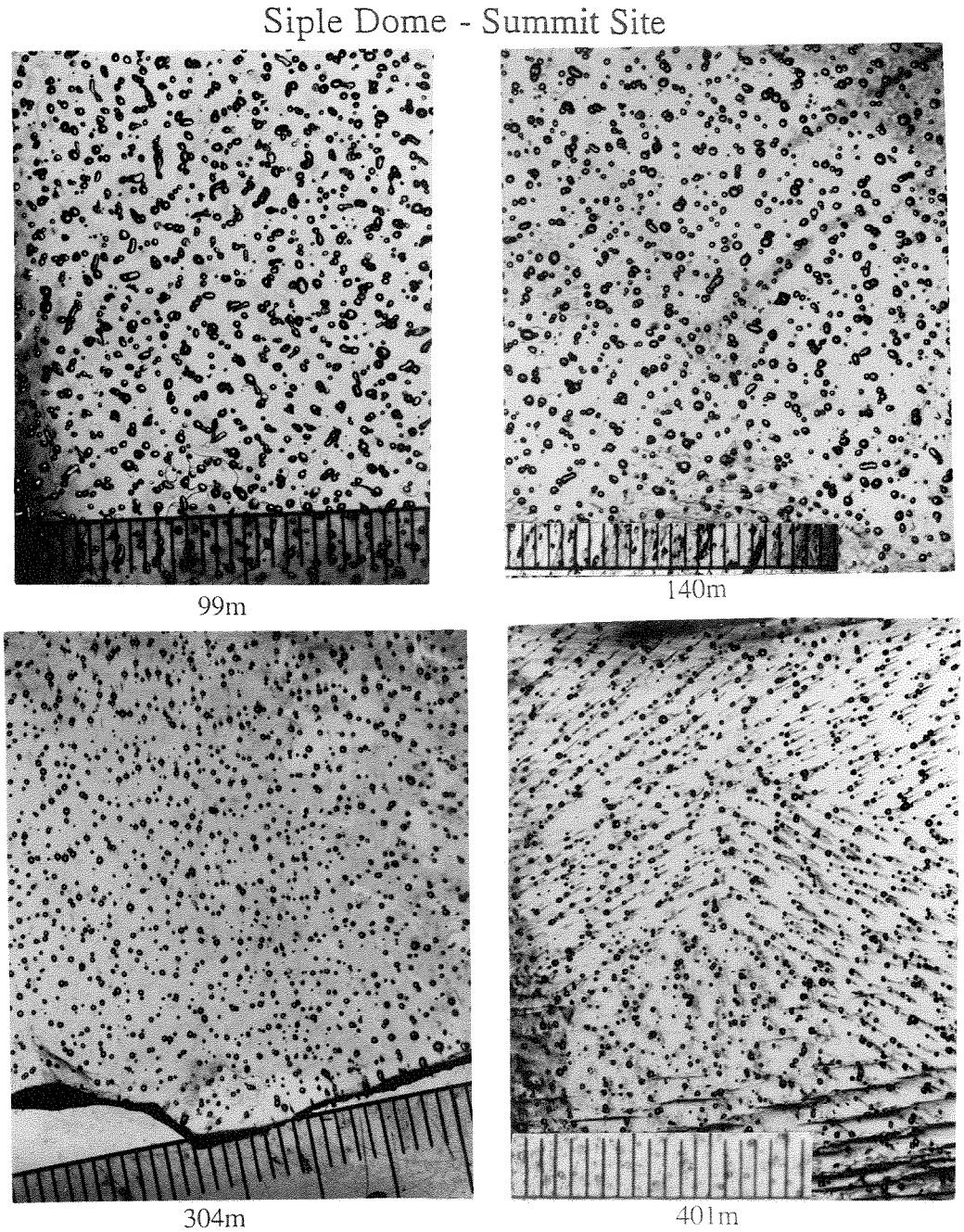
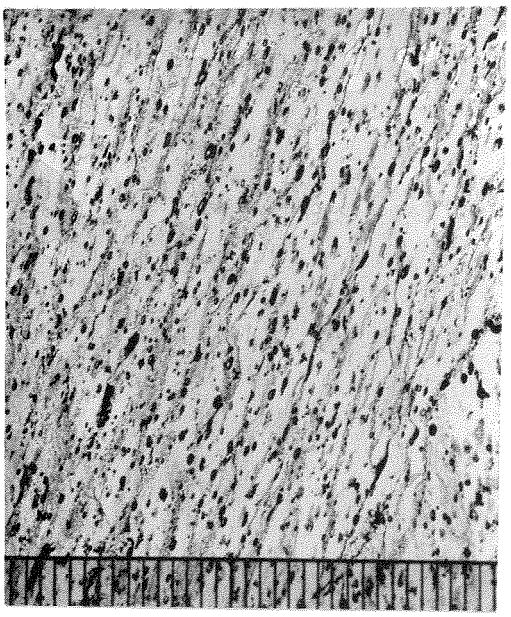


Figure 5: Air bubble characteristics and fracture patterns in ice cores from Siple Dome. Note bubbles intersected by cracks at 401 m, widespread fracturing at 605 m and cracking parallel to basal glide planes in a single crystal of very coarse-grained ice from 989 m. Scale in millimeters.

Siple Dome - Summit Site

605m

678m



989m

Figure 5 (continue): Air bubble characteristics and fracture patterns in ice cores from Siple Dome. Note bubbles intersected by cracks at 401 m, widespread fracturing at 605 m and cracking parallel to basal glide planes in a single crystal of very coarse-grained ice from 989 m. Scale in millimeters.

Dome could not be undertaken until cores had relaxed sufficiently to allow samples to be cut on a bandsaw, it was necessary to calculate in situ densities below 300 m in order to determine the magnitude of the relaxation. This was done by assuming a bubble close-off porosity of 0.098 at the firn-ice transition depth (~50 m) and equalization of the entrapped air bubble and ice overburden pressures at 300 m (~25 bars). A comparison of these calculated in situ densities with densities measured one to two weeks after cores were drilled (Table 1) clearly shows the magnitude of the relaxation. Volume increases, calculated from the measured density changes, are seen to range from 0.3 % at around 300 m to nearly 3 % in the deepest ice. This kind of volume expansion is much greater than that observed in other deep cores from Antarctica or Greenland. As noted earlier, it seems likely that the very nature of hot water coring itself has accelerated the relaxation process, leading to the very substantial volume changes observed over such a short time interval.

4.3 Air bubbles

Air bubbles were observed at all levels in the Siple Dome ice cores, as clearly revealed in Figure 5. Some modification of the original bubble structure by the circulation of hot water is apparent in most cores. This effect appears to be confined to

Table 1: Relaxation characteristics of Siple Dome ice cores. In situ density values were calculated on the basis of a bubble close-off porosity of 0.098 at 50 m depth and equalization of the entrapped air bubble and the absolute overburden pressures at 300 m.

Relaxation of Summit Core, Siple Dome			
Depth (m)	Calculated In Situ Density (Mg/m3)	Measured Density (Mg/m3)	Relaxation (Vol. %)
303	0.9158	0.9135	0.25
402	0.9166	0.9095	0.76
505	0.9168	0.9009	1.73
605	0.9167	0.9009	1.72
676	0.9166	0.8940	2.47
989	0.9158	0.8893	2.89

Relaxation of Flank Core, Siple Dome			
Depth (m)	Calculated In Situ Density (mg/m3)	Measured Density (Mg/m3)	Relaxation (Vol. %)
302	0.9158	0.9132	0.28
404	0.9166	0.9134	0.35
503	0.9168	0.8996	1.88
603	0.9167	0.8982	2.02
703	0.9166	0.8960	2.25
809	0.9164	0.9014	1.64
901	0.9162	0.8978	2.01
972	0.9160	0.8928	2.53
977	0.9159	0.8947	2.32

the outer parts of cores, leading to elongation of bubbles in radiate fashion for a distance of a few millimeters in from the sides of cores. A zone of increased bubble size was observed in cores from ~600 m at the summit sites, but not in deeper cores. The extent of such a change must remain undetermined until cores obtained at the main PICO drilling site in 1998/1999 are examined in detail. However, there is some evidence from thin section observations of a decrease in the size and concentration of bubbles in the deepest ice, an indication possibly of gas hydrate formation.

4.4 Crystal size measurements

The crystal size profile measured on cores from the summit of Siple Dome is presented in Figure 6. Also included, for comparative purposes, is the crystal size profile measured by Gow and Williamson [1976] on cores from Byrd Station, Antarctica. Beginning at 60 m, where a mean crystal cross-sectional area of 0.1 cm^2 was measured, we observed a progressive increase in crystal size to a depth of ~300 m at Siple Dome. The mean crystal cross-section measured 2 cm^2 at this depth and remained constant to 500 m. By ~600 m the crystal size had increased abruptly to ~5 cm^2 followed by further substantial increases in the mean crystal cross-sectional area at 678 m and at 989 m where crystal sizes of the order 80 cm^2 were observed. This included a vertical thin section in which the entire area of the section consisted of a single crystal, indicating the likelihood of crystals larger than 80 cm^2 being present in the deeper ice at Siple Dome. This dramatic increase in the size of crystals observed in cores from ~600 m and deeper coincided with an in situ temperature of –13 °C. This temperature is in the range of temperatures (–15 to –10 °C) at which dynamic annealing recrystallization (migration recrystallization), leading to abrupt increases in crystal size, has been observed at Byrd Station [Gow and Williamson 1976] and at the GISP2 [Gow et al. 1997] and GRIP [Thorsteinsson et al. 1997] coring sites in Greenland. This is demonstrated for Byrd Station in Figure 6 where trends in crystal size changes are similar to those observed at Siple Dome, but with the notable exception that the zone of decreased crystal size preceding the onset of annealing recrystallization at Byrd Station appears to be absent from the profile at Siple Dome. An additional characteristic of annealed ice at Siple Dome was the interlocked nature of the crystals, yielding a texture akin to a three-dimensional jigsaw puzzle. This texture appears typical of polar glacier ice subject to annealing recrystallization at temperatures warmer than –15 °C. At both Siple Dome and Byrd Station this abrupt change to coarse-grained ice occurs at –13 °C.

Hot water coring could have induced some recrystallization in the upper levels of annealed ice at Siple Dome but this is unlikely to have happened below 700 m where in situ temperatures conducive to natural annealing recrystallization must have existed for thousands, if not tens of thousands of years, based on current models of age dating of ice at Siple Dome [Nereson et al. 1996].

4.5 C-axis fabrics

Thin section photographs and associated c-axis fabrics of ice cores from the summit of Siple Dome are shown in Figure 7. All fabric diagrams are based on equal area projections of c-axes measured in horizontal thin sections. Accordingly, a

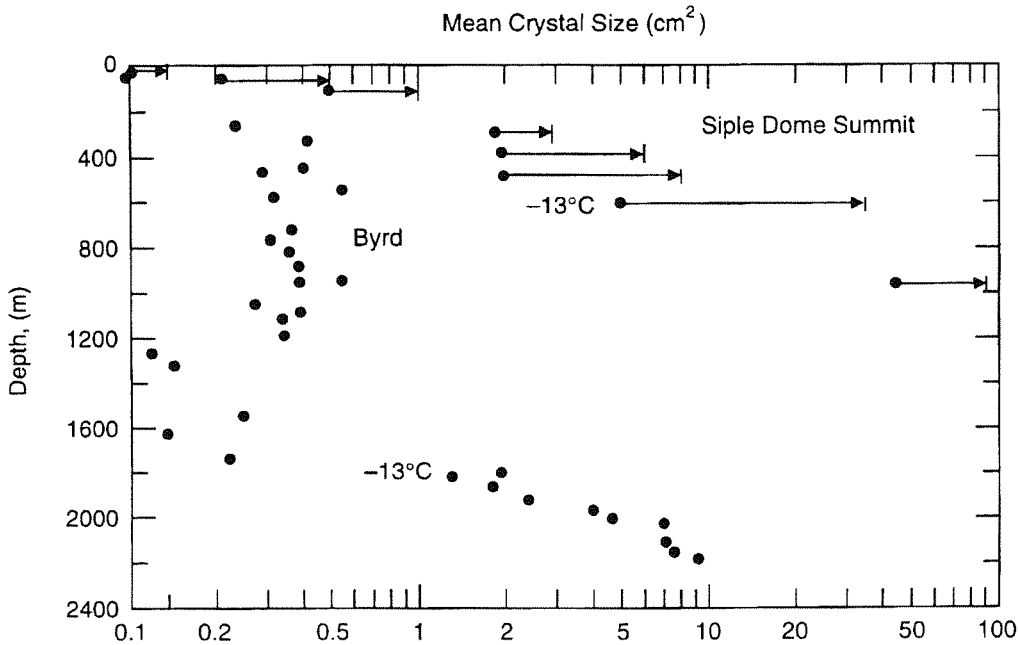
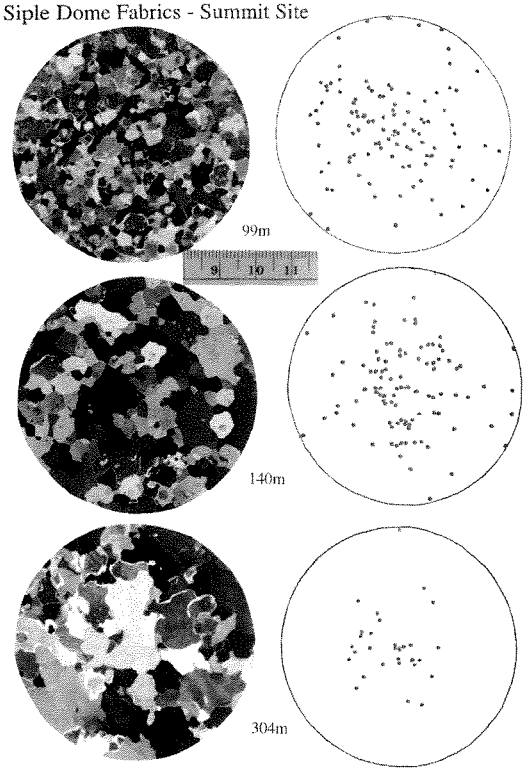


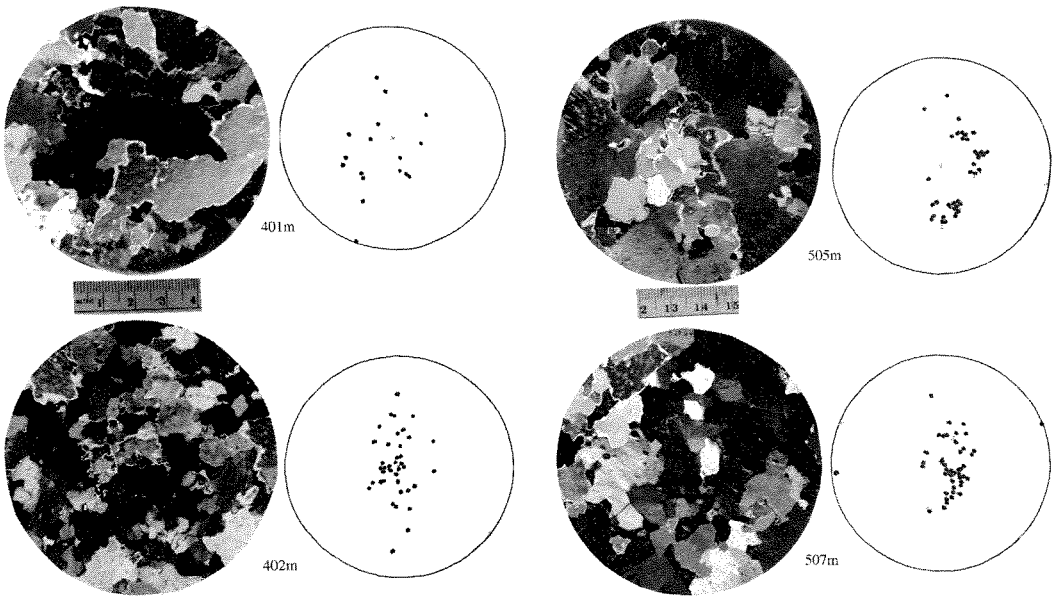
Figure 6: Comparative plots of crystal size versus depth in cores from Siple Dome Summit site and Byrd Station. Note abrupt increase in size of crystals, beginning at ~−13 °C at both locations. Size of largest crystal observed at each depth indicated by arrowhead.

vertical c-axis would project as a point at the center of the diagram; a horizontal c-axis would be represented by a point located at the edge of the stereographic projection.

The fabric diagram of the section from 60 m, located about 10 m below the firn-ice transition, shows a random distribution of c-axes; however in the remaining sections between 60 and 400 m a progressive clustering of the crystallographic c-axes about the vertical is observed. Such a pattern, coupled to significant changes in the sizes and shapes of crystals, is consistent with a deformational process dominated by rotation of the c-axes of the crystals towards the axis of vertical compression [Alley 1988]. However, this trend towards a broad clustering of c-axes about the vertical was replaced quite suddenly in sections of ice from 400 and 500 m by a vertical girdle-like distribution of the c-axes. This orientation pattern is more compatible with ice flow dominated by longitudinal extension [Alley 1988]. Beginning at 605 m, coincidental with the onset of annealing recrystallization, this pattern changed to point maxima or ringlike distributions of c-axes about the vertical. In this deeper ice it would appear that rapidly increasing temperatures reaching to within 0.5 °C of the pressure melting point at the bed are exerting as much control on the c-axis fabric as the deformation. However, the very limited number of crystals present in the single thin sections of ice we examined below 600 m precludes a more definitive evaluation of their fabric patterns at this time. This situation will be resolved only when cores obtained at the PICO drilling site in 1998–1999, allowing for multiple sectioning of

Siple Dome Fabrics - Summit Site





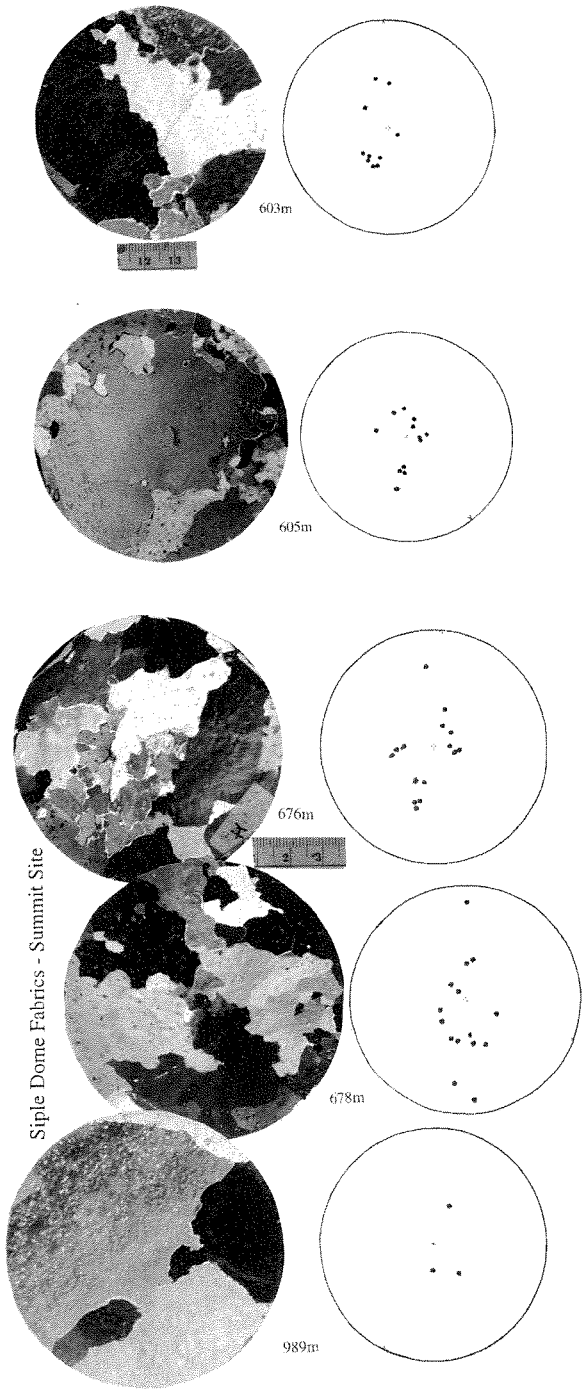


Figure 7: Crystal structure (photographed between crossed polarizers) and c-axis fabrics of horizontally sectioned cores from Siple Dome Summit. Smallest scale subdivisions measure 1 mm. (See color plates 7a and b.)

oriented samples, are examined in detail. The fabrics of the flank cores have yet to be fully analyzed, but a cursory examination of several representative thin sections shows crystal characteristics generally similar to those observed at the summit site.

As indicated earlier, a large number of additional holes were drilled for installing strain rate meters on both the summit and flank of Siple Dome. Data from meters emplaced at various depths in the ice sheet should prove invaluable in assessing ice flow characteristics at Siple Dome and in interpreting c-axis fabrics observed in ice cores.

An interesting feature of the radar profile in Figure 2 is the virtual disappearance of strong internal reflections at around 600 m at Siple Dome. This is the same depth at which we observe the onset of annealing recrystallization at −13 °C. In this particular instance it would be tempting to speculate on a possible connection between the loss of strong internal reflectors in the radar profile and the growth of very large crystals associated with annealing recrystallization. While the exact nature of such reflectors is still being debated the current prevailing view would seem to favor some orderly process of chemical constituent deposition at the surface of an ice sheet as the most likely cause in addition to density variations and crystal orientation changes. The role of recrystallization would be to cause migration of any chemical constituents to the gain boundaries which, in the case of rapidly enlarging crystals, would lead to a randomizing redistribution of the constituents within the ice. In the particular case of the very large crystals observed in annealed ice at Siple Dome this redistribution of chemical constituents could have occurred on a scale that effectively degrades or even obliterates internal radar reflections. Further consideration of this topic is beyond the scope of this paper, but a search of other radar records to determine if such a correlation exists at other deep drilling sites where annealed ice has been penetrated would seem warranted.

4.6 Debris entrainment

As noted earlier only a few millimeter-sized rock particles were observed in the bottom core from the summit of Siple Dome. The mechanism by which these particles became entrained in the basal ice is yet to be determined. No entrained debris was observed in any cores from the flank site. An attempt to obtain a piston core of the basal material at the summit was unsuccessful.

Expectations of finding volcanic ash in the Siple Dome cores did not materialize. These expectations were based on the documented evidence of the widespread occurrence of tephra in cores of middle and late Wisconsin age from Byrd Station [Gow and Williamson 1971]. These deposits can, in the main, be traced to volcanic centers in West Antarctica. Given its close proximity to Byrd Station it was anticipated that similar infalls of volcanic ash and dust would be found in ice of comparable age at Siple Dome. According to the age-depth scales predicted for Siple Dome by Nereson et al. [1996] tephra coeval with that observed in the Byrd core should be concentrated in the depth range 700–800m. None was observed in any of the 4m-long cores taken from below 700 m at either the summit or flank of Siple Dome. However, a layer of fine-grained ice of the kind associated with tephra layers in the Byrd core was observed in a vertical thin section of ice from 672 m at Siple Dome. Absence of tephra in the Siple Dome ice may simply

be due to the limited amount of core recovered by hot water drilling. Determining the true nature of preservation of tephra must now await inspection of cores obtained by PICO in 1998–1999.

4.7 Stable isotope measurements

Preliminary measurements of stable isotope (δD) composition of ice from the summit and flank of Siple Dome are plotted in Figure 8. Each data point corresponds to the average value over the length of a 3-4m long core. The significantly negative δD value of 306.22 ‰ for the summit site sample from 989 m is puzzling. This sample was located about 15 m above the bed and contained rock particles which may indicate some unusual origin for this ice. No such δD depression is seen in the near-bottom sample from 977 m at the flank site. Since this ice contained no visible trace of entrained debris it would appear that significant differences in basal ice properties may exist between the summit and flank sites located just 8–9 km apart.

Isotope compositions from both the summit and flank sites indicate a Holocene/Younger Dryas transition occurring between 600 and 700 m. Lack of intervening core prevents a more precise determination of the transition depth, but estimates based on current models of the

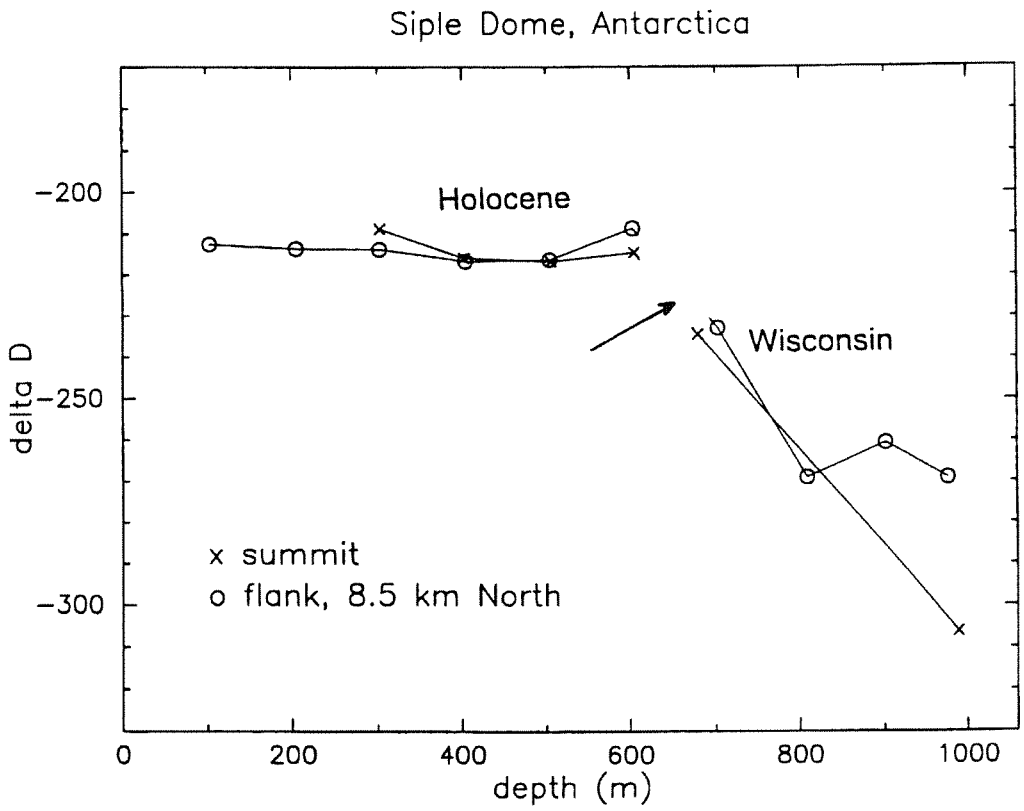


Figure 8: Plot of stable isotope measurements made on cores from the summit and flank of Siple Dome. Analyses were performed by Dr. Jean Jouzel on samples prepared at Siple Dome by Dr. Jean Robert Petit.

age-depth relationships at Siple Dome [Nereson et al. 1996] yield a transition depth of around 650–660 m (curve 2 in Fig. 9). If so, this could mean that δD values at 678 m (summit site) and 702 m (flank site) correspond with the Bolling-Allerod or middle deglaciation interval (13000–14000 BP) immediately preceding the Younger Dryas. Even a warming at 603 m at the flank site, indicated by the slightly elevated δD value, would be consistent with the early climatic optimum of the Southern hemi-

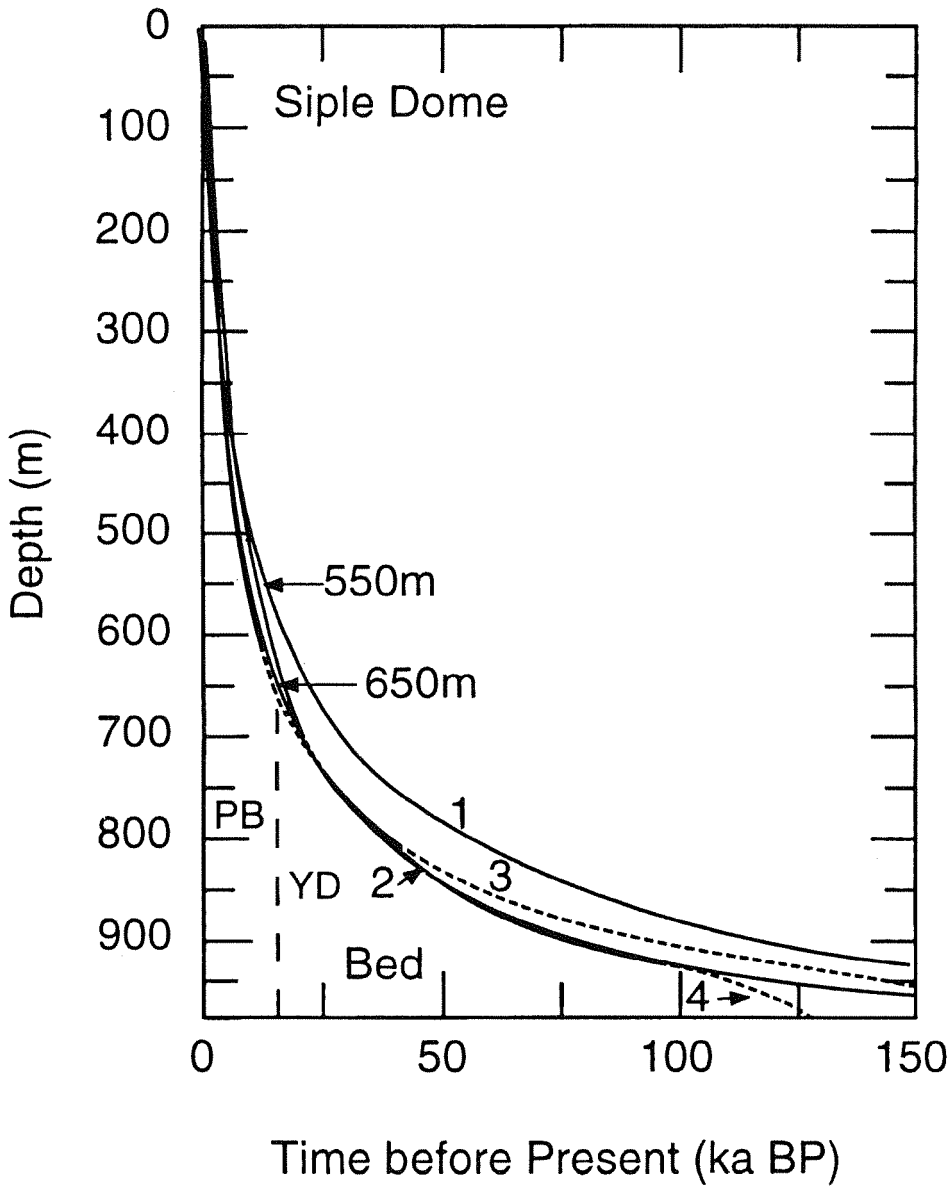


Figure 9: Age estimate modeling of the Siple Dome ice sheet after Nereson et al. [1996]. Depths to the Holocene/Younger Dryas transition (~11,600 yrs) for age-depth variants 1 and 2, derived from finite element modeling, are also indicated.

sphere around 9000 BP. The 50–60 per mil change in δD at Siple Dome is also consistent with other Antarctic records.

A Holocene/Younger Dryas transition depth of 650 m would place it in the upper levels of highly recrystallized ice, marked by the growth of very large crystals and accompanying widespread grain boundary migration. To what degree the resultant redistribution of chemical constituents in the ice, by annealing recrystallization, has compromised original deposition records and hence, the level of resolution of the paleoclimate record preserved in early Holocene and in Wisconsin-age and older ice at Siple Dome, remains to be determined. Resolution of this and other issues related to the physical and structural properties of Siple Dome ice will hopefully be accomplished through detailed analysis of cores recently obtained is to the bottom of Siple Dome by PICO. This drilling, completed during 1998–1999, will also allow for direct comparison of the properties of these cores with those obtained with the hot water drill.

Notwithstanding, the results presented in this paper clearly demonstrate the great potential value of the hot water drill, with its coring capability, as a reconnaissance tool for expedient evaluation of future deep core drilling sites in Antarctica.

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