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TEXTURE OF POLAR FIRN FOR REMOTE SENSING

by

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ABSTRACT

Knowledge of the texture of polar firn is necessary for interpretation of remotely sensed data. We find that dry polar firn is an irregularly stratified, anisotropic medium. Grains in firn may be approximated as prolate spheroids with average axial ratios as high as 1.2 or greater and with a preferred orientation of long axes clustered around the vertical. Such elongate grains are preferentially bonded near their ends into vertical columns, so that grain bonds show a preferred horizontal orientation. The grain-size distribution is similar in most firn and the normalized distribution is stationary in time, but the distribution is somewhat different in depth hoar. Fluctuations of firn properties are large near any depth, but decrease with increasing depth. With increasing depth, anisotropy of surfaces decreases, bond size relative to grain size decreases slightly, and number of bonds per grain and fraction of total grain surface in bonds increase. Grain size increases linearly with age below 2 to 5 m, but increases more rapidly in shallower firn.

1. INTRODUCTION

Most remote-sensing techniques applied to polar ice sheets sample the firn to some depth. Interpretation of data collected then requires knowledge of firn properties (density, texture, and their variations) and how the radiation being sensed interacts with those properties. For example, Zwally (1977) has shown that microwave brightness temperatures depend on grain size in firn in a strong, nonlinear manner, suggesting that knowledge of grain size, its distribution, and its depth variation (and perhaps grain shape and other factors) is necessary to interpret microwave data. Here we present some data on the texture of firn that may be of interest in formulating models for remote sensing.

2. METHODS

We measure textural quantities on thin sections of firn using standard metallographic techniques. These techniques are detailed elsewhere (e.g. Gow 1969; Underwood 1970; Kry 1975; Gubler 1978; Narita and others 1978; Alley 1986; all of these sources except Underwood [1970] also include applications of the techniques to firn and snow, and present results similar to some of those reached here). We make all measurements on photographs of thin sections viewed in reflected light, and thus on truly two-dimensional surfaces, but use transmitted, cross-polarized light to aid in identification of grain boundaries.

Many quantities can be calculated without *a priori* assumptions about firn geometry (Table I). These are based on the counting measures ρ_c and N_i^j. The fraction of randomly placed points that falls within grains on a section plane is denoted ρ_c, and is an unbiased estimator of the volume fraction of ice (relative density) in the bulk sample. N_i^j is the number of intersections per unit length between randomly placed test lines (which may be directed) and traces of surfaces on a section plane. N_g and N_f refer to intersections with traces of grain bonds and free (ice–air) surfaces, respectively, and N^h and N^v refer to horizontally directed and vertically directed test lines on a vertical section plane, respectively. Quantities that can be calculated from these measurements include mean free paths in individual grains (L_g), pores (L_p) and solid regions of ice (L_s), and mean spacings along test lines between centers of grains (l_g), pores (l_p), and ice regions (l_s); on vertical sections these quantities can be determined in both vertical (L^v, l^v) and horizontal (L^h, l^h) directions. We can also calculate the total area per unit volume of ice–ice contact (S_g) and ice–air contact (S_f), the fraction of surface on the average grain involved in bonds (β), and the non-random fractions of total ice–ice surface oriented horizontally (ω_g) and ice–air surface oriented vertically (ω_f; the anisotropy parameters, ω, are the differences between the surfaces encountered by vertical and horizontal traverses on a section normalized by the total surface present, and $\omega_g=\omega_f=0$ if all surfaces are oriented randomly). Equations are given in Table I, and are derived in Underwood (1970).

Other textural quantities can be calculated only if certain reasonable but unsubstantiated geometric assumptions are made. Some such quantities are the grain size (*A*,

TABLE I. STEREOLOGIC QUANTITIES CALCULATED FROM SIMPLE COUNTING MEASUREMENTS FOR SAMPLE FROM SITE 4530, ICE STREAM A, WEST ANTARCTICA. (All quantities are defined in methods section of text.)

		Vert. Sect.		Horz. Sect.
Lengths (mm)		Horz.	Vert.	
L_g	$\dfrac{2\rho_c}{N_f+2N_g}$	0.57±.02	0.71±.04	0.58±.02
L_p	$\dfrac{2(1-\rho_c)}{N_f}$	0.75±.03	1.18±.06	0.85±.03
L_s	$\dfrac{2\rho_c}{N_f}$	0.78±.03	1.22±.06	0.75±.03
l_g	$\dfrac{2}{N_f+2N_g}$	1.13±.03	1.40±.06	1.23±.02
l_p	$\dfrac{2}{N_f}$	1.53±.04	2.40±.10	1.60±.03
l_s	$\dfrac{2}{N_f}$	1.53±.04	2.40±.10	1.60±.03
Densities (relative)				
ρ_c		0.51±.01		0.47±.02
Areas (S_g, S_f in mm²/mm³)				
β	$\dfrac{2S_g}{2S_g+S_f}$	0.31±.01		0.23±.01
Isotropic firn				
S_g	$2N_g$			0.38±.02
S_f	$2N_f$			2.49±.04
Anisotropic firn				
S_g	$N_g^h+N_g^v$	0.53±.03		
S_f	$\dfrac{\pi}{2}N_f^h+\left(2-\dfrac{\pi}{2}\right)N_f^v$	2.41±.05		
ω_g	$\dfrac{N_g^v-N_g^h}{N_g^v+N_g^h}$	0.12±.06		
ω_f	$\dfrac{N_f^h-N_f^v}{N_f^h+\left(\dfrac{4}{\pi}-1\right)N_f^v}$	0.31±.03		

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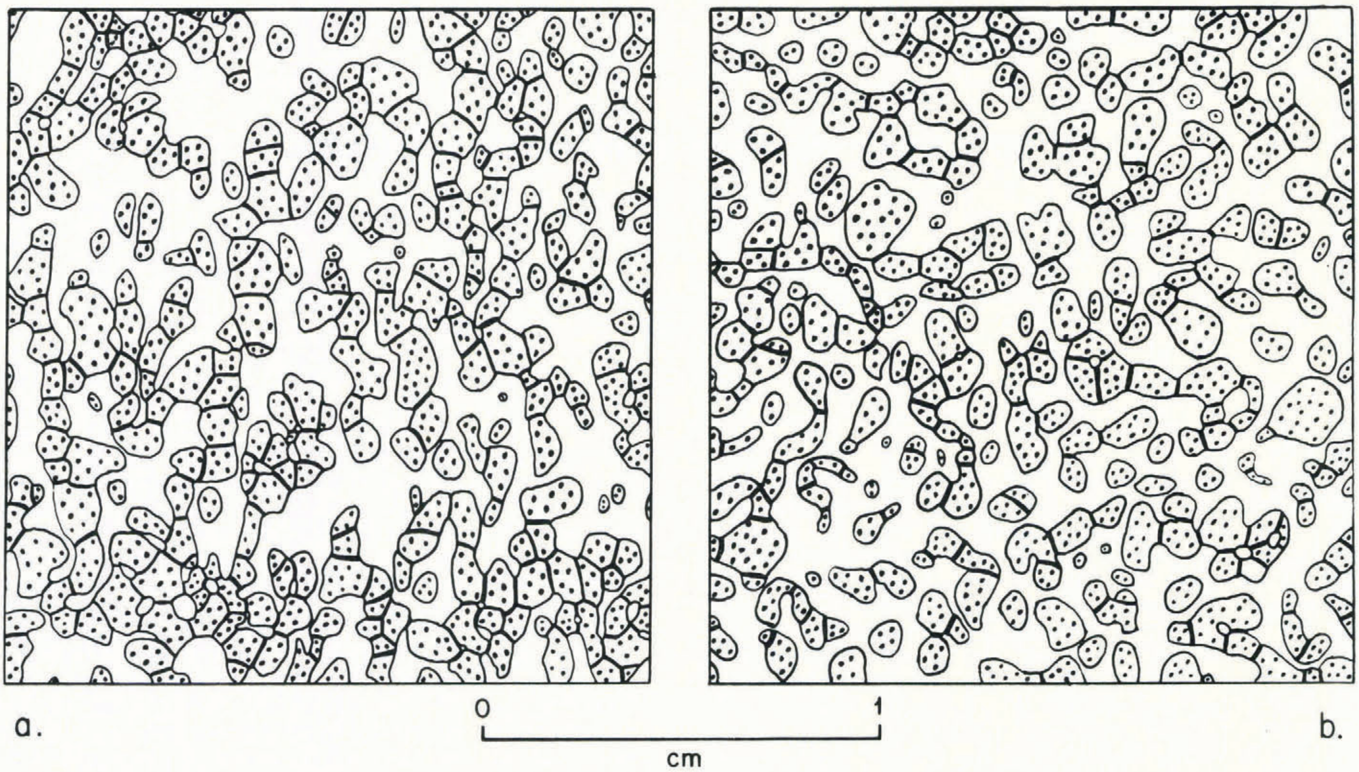

Fig.1. Tracings of portions of (a) vertical and (b) horizontal thin sections from 2.7 m deep at site 4530, ice stream A, West Antarctica.

defined here as 3/2 the average grain cross-sectional area on a plane of section; Alley 1986), the sphericity (ϕ, which measures how closely a given grain cross-section approaches a circle and is defined here as the ratio of the radii of the largest inscribed circle in a grain to the smallest circumscribed circle about that grain; Alley and others 1982), the relative bond size (α, defined here as the ratio of the radii of the average bond to the average grain; Alley 1986) and the coordination number or number of bonds per grain (n_3; Alley 1986). The assumptions involved in these calculations are discussed by Underwood (1970), Kry (1975), and Alley (1986), among others.

3. RESULTS

Consider Fig.1, which shows portions of vertical and horizontal thin sections from about 2.7 m depth at site 4530 on the downstream part of ice stream A, West Antarctica. This is a warm (≈–25 to –30°C), low accumulation (≈0.1 m/a water; Bull 1971) site. The samples were cut from a fine-grained layer of bulk density 472 kg m^{-3}; however, the layer did not appear perfectly homogeneous. The horizontal section was cut from just above the vertical.

It is immediately evident from inspection that the firn is isotropic in a horizontal plane but is anisotropic and inhomogeneous vertically; compared to other samples, the anisotropy here is strong but not atypical. The thin layer near the bottom of the vertical section was visible on the firn core as a resistant crust.

Data collected from these sections are shown in Tables I and II. All data from the vertical section were taken above the thin crust. If the vertical and horizontal sections sampled the same homogeneous firn, then the point-count densities, total specific surfaces, and intercept lengths in the horizontal direction would be the same for the two sections. However, both stratigraphic inspection of the firn core and careful examination of Fig.1 show that vertical inhomogeneity exists within the layer studied; thus, differences between the horizontal and vertical sections are expected. Errors arising from counting are given in the tables; errors arising from violation of assumptions cannot be evaluated accurately.

Orientation data for these sections are shown in Fig.2. It should be evident that the grains have no preferred orientation in the horizontal plane but a strong vertical orientation, and that grains tend to be joined at their ends by horizontal bonds to form vertical columns. One possible model of a grain in firn is a prolate spheroid with axial ratio b. If we assume that all grains have the same value of b and have their long axes oriented vertically, then $b=L_g^v/L_g^h=1.2$ (see Table I). Because orientations of long axes of grains show a distribution, $b>1.2$ ($b\approx1.4$ may be a good estimate, but we cannot demonstrate this rigorously).

The normalized grain-size distribution for the horizontal sample, calculated using the Saltykov area method (Underwood 1970: 123-126) is shown in Fig.3. The Saltykov method, which assumes that grains are spherical, may be reasonably accurate for large grains but can become erratic or nonphysical for the smallest grain sizes; the smoothed curve in Fig.3 was drawn up so as to be physically realistic. This distribution is quite similar to the steady distribution expected by Hillert (1965) for normal grain growth, with the maximum grain radius equal to about twice the average grain radius, and also is similar to distributions we see in other firn samples. Although further work is required, our data indicate that the grain-size distribution is similar to Fig.3 for most firn in the upper 10 m, with the exceptions that depth hoar tends to show a stronger peak at smaller grain sizes and that distributions in the top 0.5 m tend to be somewhat variable. (Results for depth hoar also may be less reliable than for other firn

TABLE II. STEREOLOGIC QUANTITIES REQUIRING GEOMETRIC ASSUMPTIONS, FOR SAMPLE FROM SITE 4530, ICE STREAM A, WEST ANTARCTICA. (Variables are defined in methods section of text. All assumptions may be violated slightly, so error limits cannot be constructed exactly. We expect that all values are within ±20% and may be within ±10 or less.)

	Vert. Sect.	Horz. Sect.
A (mm^2)	0.85	0.70
ϕ	0.57	0.65
α	0.57	0.58
n_3	4.6	3.4

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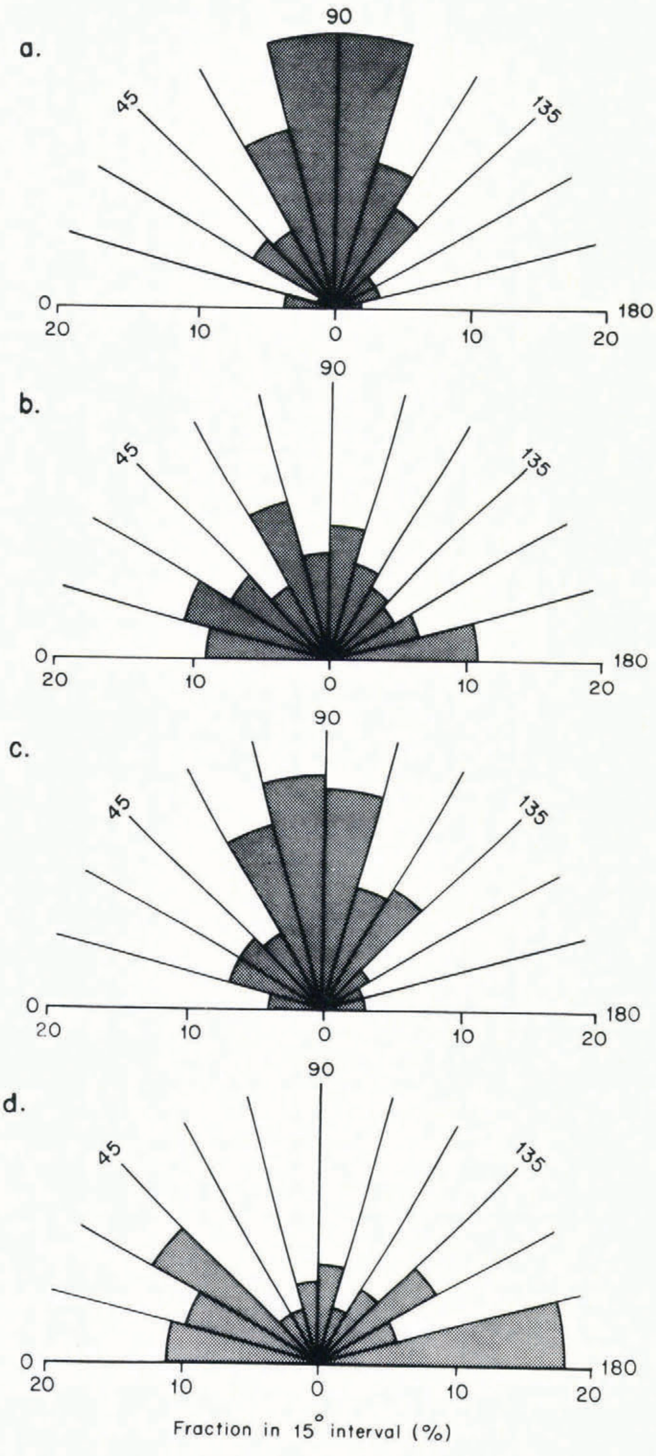

Fig.2. Orientation data for sections shown in Fig.1; 90° is vertical on vertical sections, 0° and 180° are horizontal, and full scale is 20% of grains on a section in a 15° interval. a) Long axes of grains, vertical section. b) Long axes of grains, horizontal section. c) Angles between centers of grains in contact, vertical section. d) Orientations of grain bonds, vertical section.

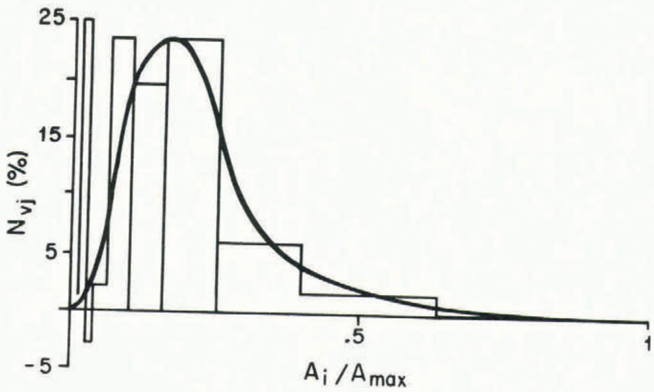

Fig.3. Normalized grain-size distribution for horizontal section shown in Fig.1, treating grains as spheres. N_{vj} is the fraction of grains per unit volume having the maximum cross-sectional area, A_i, divided by the maximum cross-sectional area of the largest grain in the sample, A_{max}.

because of the irregular shapes of depth-hoar grains.) To accord with other workers (Gow 1969; Duval and Lorius 1980) we also report grain size as an average cross-sectional area in Table II and Fig.4 (see Methods section, above).

We have been studying the variability and diagenesis of firn in some detail on the ridge between ice streams B and C on the Siple Coast of West Antarctica, and some of our data are shown in Fig.4. Ridge BC is similar in accumulation rate (≈0.08 m/a water) and temperature (≈−26.5°C) to site 4530. Data in Fig.4 from the upper 2 m are from a detailed pit study, and deeper data were collected from a core. Points to notice especially include: 1) grain size increases linearly with age below about 2.5 m (the regression line for data from 5–40 m is shown in the figure; see also Gow 1969; Alley and others 1986[a], [b]); but increase is more rapid in shallow firn where vapor transport down temperature gradients dominates grain growth (Colbeck 1983); 2) vertical anisotropy forms at shallow depth and then decreases steadily below about 2–3 m to essential isotropy below about 15 m; 3) density variations and other variations typically (but not always) decrease with increasing depth. Also, coordination number increases with depth whereas the relative size of grain bonds is large near the surface and decreases slightly with depth.

4. CONCLUSIONS

Polar firn is an irregularly stratified, inhomogeneous, anisotropic material. Measurements of density, specific surfaces and their anisotropy, and mean free paths in ice, individual grains, and air in specified directions can be made from thin sections with high accuracy and with no or few untestable assumptions. Grain size, grain-size distribution, relative bond size, coordination number, grain shape, and other parameters also can be calculated from measurements on thin sections, but all require assumptions regarding geometry that cannot be checked rigorously.

Grains in firn typically are elongated vertically and align vertically in columns. Grains may be modeled as prolate spheroids in which the axial ratio can vary from nearly 1 (for deeper firn or for firn in high-accumulation areas where little time is allowed for development of anisotropy in near-surface regions) to perhaps 1.4 or more in strongly anisotropic firn. Long axes of grains cluster about the vertical but show some distribution.

Grain size increases linearly with age (and almost linearly with depth) below about 2-5 m, but increases more rapidly in shallower firn. Anisotropy of free surfaces decreases with increasing depth to about zero below about 15 m. The fraction of grain surface involved in bonds and the coordination number increase rapidly with depth, but the bond size relative to grain size decreases slightly with increasing depth. Variations in these parameters near any depth are quite large in shallow firn, but tend to decrease slightly with increasing depth.

Collection of data such as these is a slow process, and other sorts of data could be collected. Optimization of data collection will require identification of those parameters that are most important for understanding remotely sensed data.

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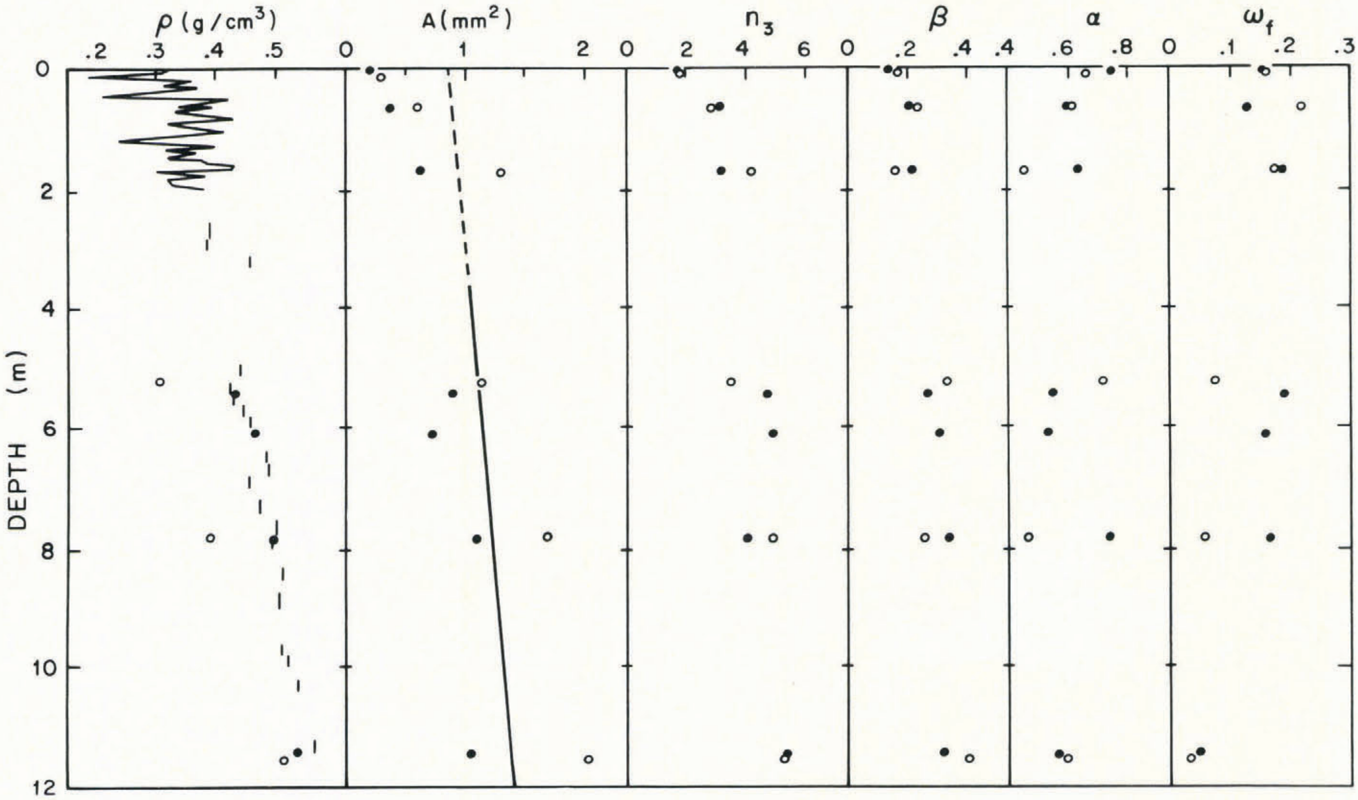

Fig.4. Textural data for firn from ridge BC, West Antarctica. Shown are density (ρ), grain size (A), coordination number (n_3), fraction of grain surface in bonds (β), relative bond size (α), and anistropy of ice–air surfaces (ω_f). Errors are similar to, or slightly larger than, those in Tables I and II. Open circles are depth hoar; solid circles are typical and fine-grained firn. Density data include a pit profile in the upper two meters (continuous line), measurements made on long core sections (vertical bars), and measurements made by point counting thin sections (open and solid circles). The regression line for A is fitted to data from 5–40 m deep, and is included to emphasize the rapid rate of increase of grain size in near-surface firn.

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REFERENCES

Alley R B 1986 Three-dimensional coordination number from two-dimensional measurements: a new method. *Journal of Glaciology* 32(112): 391–396

Alley R B, Bolzan J F, Whillans I M 1982 Polar firn densification and grain growth. *Annals of Glaciology* 3: 7-11

Alley R B, Perepezko J H, Bentley C R 1986[a] Grain growth in polar ice: I. Theory. *Journal of Glaciology* 32(112): 415–424

Alley R B, Perepezko J H, Bentley C R 1986[b] Grain growth in polar ice: II. Application. *Journal of Glaciology* 32(112): 425–433

Bull C 1971 Snow accumulation in Antarctica. *In* Quam L O (*ed*) *Research in the Antarctic. A symposium presented at the Dallas meeting of the American Association for the Advancement of Science – December 1968*. Washington, DC, American Association for the Advancement of Science: 367-421 (Publication 93)

Colbeck S C 1983 Theory of metamorphism of dry snow. *Journal of Geophysical Research* 88(C9): 5475-5482

Duval P, Lorius C 1980 Crystal size and climatic record down to the last ice age from Antarctic ice. *Earth and Planetary Science Letters* 48(1): 59-64

Gow A J 1969 On the rates of growth of grains and crystals in South Polar firn. *Journal of Glaciology* 8(53): 241-252

Gubler H 1978 Determination of the mean number of bonds per snow grain and of the dependence of the tensile strength of snow on stereological parameters. *Journal of Glaciology* 20(83): 329-341

Hillert M 1965 On the theory of normal and abnormal grain growth. *Acta Metallurgica* 13(3): 227-238

Kry P R 1975 Quantitative stereological analysis of grain bonds in snow. *Journal of Glaciology* 14(72): 467-477

Narita H, Maeno N, Nakawo M 1978 Structural characteristics of firn and ice cores drilled at Mizuho Station, East Antarctica. *Memoirs of National Institute of Polar Research*. Special Issue 10: 48-61

Underwood E E 1970 *Quantitative stereology*. Reading, MA, Addison-Wesley Publishing

Zwally H J 1977 Microwave emissivity and accumulation rate of polar firn. *Journal of Glaciology* 18(79): 195-215