Journal of Glaciology, Vol. 22, No. 87, 1979

IN-SITU MEASUREMENTS OF THE ACTIVATION ENERGY FOR D.C. CONDUCTION IN POLAR ICE*

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ABSTRACT. Electrical resistivity measurements were carried out at station J9 on the Ross Ice Shelf where temperature measurements were available to a depth exceeding three-quarters of the thickness of the shelf. As in a previously published study at a point about 30 km up-stream (Bentley, 1977), the apparent resistivities fit well to a model based upon a steady-state ice shelf with zero bottom balance-rate and an apparent activation energy in the solid ice of 0.15 to 0.25 eV (14–24 kJ mol^{-1}), with preference for the lower end of the range. This model also fits the observed temperature data almost perfectly. Causes of resistivity variation with depth other than the temperature, such as impurity content, metamorphic history, grain size, and crystal orientation, probably do not strongly affect the resistivity depth function. Our conclusion is that the true activation energy in the solid ice is less than 0.25 eV (24 kJ mol^{-1}) and perhaps as small as 0.15 eV (14 kJ mol^{-1}), although a reduction by a factor of two or three in the ionic impurity concentration between 50 and 250 m depth cannot be entirely ruled out as a cause of the low apparent temperature effect. A note added in proof indicates that Herron and Langway (in press) have, in fact, reported a decrease in Na^+ concentration with increasing depth by a factor of two or three.

RÉSUMÉ. *Mesures* in-situ *de l'énergie d'activation pour la conduction d.c. dans la glace polaire.* Des mesures de résistivité électrique ont été conduites à la station J9 de la platforme de glace de Ross où l'on disposait de mesures de températures jusqu'à une profondeur excédant les trois quarts de l'épaisseur de la platforme. Comme dans une étude déjà publiée, portant sur un point d'environ 30 km à l'amont (Bentley, 1977), les résistivités apparentes cadrent bien avec un modèle basé sur un état d'équilibre de la platforme avec un bilan nul au fond et une énergie apparente d'activation dans la glace solide de 0,15 à 0,25 eV (14–24 kJ mol^{-1}), avec plutôt un décalage vers le bas de la gamme. Ce modèle cadre aussi parfaitement avec les données observées de température. Les causes de variation de résistivité autres que la température, telles que la teneur en impuretés, l'historique de la métamorphose, la dimension des grains et l'orientation des cristaux, n'ont probablement pas une forte influence sur la relation température-résistivité. Notre conclusion est que la véritable énergie d'activation dans la glace solide est inférieure à 0,25 eV (24 kJ mol^{-1}) et peut descendre jusqu'à 0,15 eV (14 kJ/mol^{-1}), bien qu'une réduction d'un facteur de deux ou trois dans la concentration en impuretés ioniques entre 50 et 250 m de profondeur ne puisse pas être entièrement admise comme une cause de la faiblesse apparente de l'action de la température. Un paragraphe ajouté lors de la correction des épreuves indique que Herron et Langway (in press), en effet, ont signalés une diminution avec profondeur de la concentration de Na^+ par un facteur de deux on trois.

ZUSAMMENFASSUNG. In-situ-*Messungen der Aktivationsenergie für die Gleichstromleitung in polarem Eis.* In der Station J9 auf dem Ross-Ice Shelf, wo Temperaturangaben bis zu einer Tiefe von über drei Vierteln der Eisdicke vorlagen, wurden Messungen des elektrischen Widerstandes vorgenommen. Wie bei der früher veröffentlichten Studie an einem 30 km stromaufwärts gelegenen Punkt (Bentley, 1977) fügen sich die scheinbaren Widerstände gut in ein Modell, das auf einem stationären Schelfeis mit verschwindender Massenbilanz an der Unterseite und einer scheinbaren Aktivationsenergie im festen Eis von 0,15 bis 0,25 eV (14–24 kJ mol^{-1}) beruht, wobei die untere Bereichsgrenze bevorzugt ist. Dieses Modell erfasst auch die beobachteten Temperaturwerte nahezu fehlerfrei. Andere Ursachen als die Temperatur für die Änderung des Widerstandes mit der Tiefe — wie z.B. Verunreinigungsgrad, Ablauf der Metamorphose, Korngrösse und Kristallorientierung — beeinflussen vermutlich die Tiefenabhängigkeit des Widerstandes nur wenig. Es lässt sich folgern, dass die wahre Aktivationsenergie im festen Eis kleiner als 0,25 eV (24 kJ mol^{-1}) und vielleicht nur 0,15 eV (14 kJ mol^{-1}) ist, obwohl eine Verringerung der Konzentration des Ionengehalts der Verunreinigungen in einer Tiefe zwischen 50 und 250 m um den Faktor zwei oder drei nicht völlig als Ursache für den Effekt wie bei niedriger scheinbarer Temperatur ausgeschlossen werden kann. Eine Fussnote, die während der Drucklegung angebracht wurde, weist darauf hin, dass Herron und Langway (in press) tatsächlich eine Abnahme der Na^+-Konzentration mit der Tiefe um einen Faktor von zwei oder drei festgestellt haben.

INTRODUCTION

Electrical resistivity measurements have been a part of the Ross Ice Shelf Geophysical and Glaciological Survey (RIGGS) since its inception. A complete report on measurements at the RIGGS 1973–74 base camp (B.C.) (Fig. 1) during the first season has already been published (Bentley, 1977, hereinafter referred to as Paper I) and an oral paper has been

* University of Wisconsin, Geophysical and Polar Research Center, Contribution No. 352.

presented on measurements the succeeding season (Bentley, 1976). The measurements in both cases were at stations where the temperature–depth profile was not known. Drilling to a depth of 300 m in the ice shelf was carried out during the 1976–77 field season at station J9 (grid coordinates $7\frac{1}{2}°$ S., $1\frac{1}{2}°$ W.; Fig. 1) about 30 km down-stream from station B.C., as part of the Ross Ice Shelf Project program of drilling through the ice shelf. Although complete penetration of the 420 m-thick ice shelf was not obtained, temperature measurements made in the hole can be extrapolated with little error to the base of the ice. With the temperature known, it is possible to make a more direct determination of the dependence of resistivity on temperature, and thus on the activation energy, than was possible at previous sites.

Fig. 1. Map of the Ross Ice Shelf showing the location and orientation of the resistivity profiles at stations J9 and B.C. The heavy black arrow shows the direction of ice movement.

Field measurements

In November 1976, resistivity soundings were made at J9 along two perpendicular lines, "Profile 1" and "Profile 2", Profile 2 having its center about one kilometer grid south-east of the center of Profile 1. Only Schlumberger measurements were carried out because previously we had experienced difficulties with dipole arrays. These difficulties were presumed to arise from the greater sensitivity of dipole arrays to inhomogeneities near to the surface (Paper I). The lines were extended to a maximum separation (a in Fig. 2) of 600 m along Profile 1 and 700 m along Profile 2.

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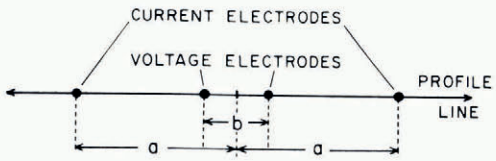

SCHLUMBERGER ARRAY

Fig. 2. Diagram of the Schlumberger array for resistivity measurements. a *and* b *represent inter-electrode distances as indicated.*

The power source was a bank of dry cells of various sizes, producing a maximum of more than 3 kV. Most of the measurements, however, were made using either 1.2 kV or, for short spacings, 90 V. (The large jump in applied voltage was necessary for the current to fall within appropriate ammeter scales.) As before, copper rods were used for all spacings greater than a few meters. Contact resistance was generally reduced to less than one megohm per electrode by using salt water around the current electrodes. (The resistance was judged by measuring the initial current which flowed immediately after the high-voltage circuit had been switched on.) Potential differences were measured with a Keithley 600B electrometer having an input impedance of $10^{14}\ \Omega$. Several leakage measurements were made by disconnecting the wire to one of the current electrodes at the electrode and then switching on the high-voltage source. No test produced a current or potential difference significantly different from zero after the decay of the initial switching transient.

Data reduction

Data were analyzed by the usual method of plotting the potential difference V versus the current I (see fig. 3 of Paper I). Although the measurements at different separations showed a wide variation in scatter, each graph of V against I could be fitted either by a single straight line, or by two straight lines, one through the points with one direction of current flow, and the other through the points with reversed current. There were no indications of significant deviation from a zero intercept. Consequently, all the data were reduced, using least-square analysis, by fitting lines, forced through the origin, separately to the positive and negative polarizations for each measurement. The average of the two slopes thus obtained, called Ω_+ and Ω_- respectively, was taken as the resistance Ω for that measurement. (Conceptually, it would be preferable to fit the "positive" and "negative" data with lines having equal and opposite intercepts, presumably corresponding to a background telluric potential. However, for the data of this paper, such a procedure does not produce apparent resistivities that are significantly different from those calculated by the simpler method employed here.) Apparent resistivities ρ_a were then calculated from the mean resistances according to the formula

$$\rho_a = \frac{\pi a^2}{b}\left(1-\frac{b^2}{a^2}\right)\Omega,$$

where a and b are the electrode spacings, defined in Figure 2.

The apparent resistivities measured on Profile 1 and Profile 2 are shown in Figures 3 and 4, respectively. Error bars represent $\pm\sigma = \frac{1}{2}\sqrt{(\sigma_+^2+\sigma_-^2)}$, where σ_+ and σ_- are the standard deviations in the determinations of Ω_+ and Ω_-. The error bars indicate, therefore, only the scatter of the points around the "positive" and "negative" regression lines separately, with no contribution from the difference between Ω_+ and Ω_-; this reflects the assumption that any such difference has a physical cause that does not reverse with electrode polarity, and is therefore eliminated by taking the average of Ω_+ and Ω_-.

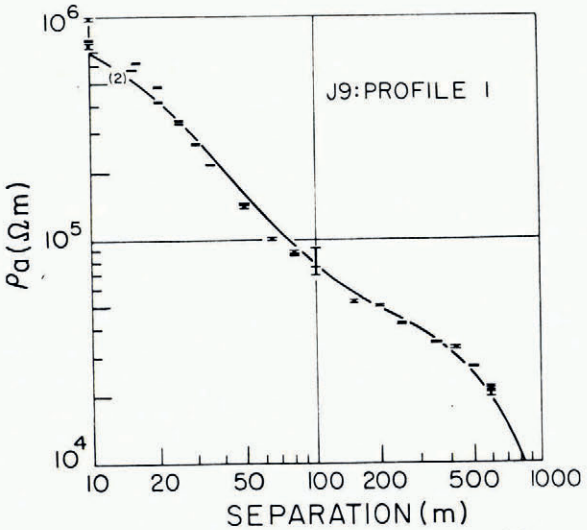

Fig. 3. Observed apparent resistivities at station J9, Profile 1. Pairs of short horizontal lines connected vertically represent error bars determined from the scatter of observed potentials and currents. "(2)" indicates two superimposed observations. The solid line through the points correspond to a resistivity model described in the text.

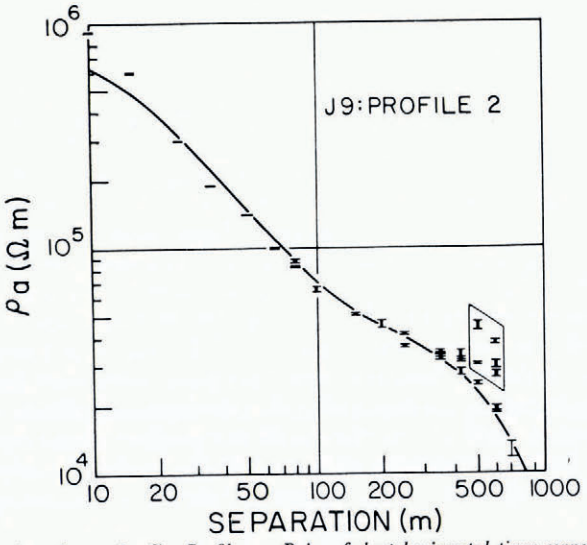

Fig. 4. Apparent resistivity data for station J9, Profile 2. Pairs of short horizontal times connected vertically represent error bars determined from the scatter of observed potential differences and currents. The points enclosed in the parallelogram were considered to be invalid and were not included in further analyses. The solid line shows the same resistivity model as in Figure 3.

The standard features of an apparent resistivity curve on an ice shelf, as described in Paper I, again appear clearly. The steep slope for $a < 100$ m reflects densification in the firn, the smaller slope at separations between about 150 m and 400 m is determined principally by the temperature effect in solid ice, and the increase in slope at larger distances results from conduction in the underlying sea-water. For comparison, a calculated apparent resistivity curve for a model that provided a good fit to the data in Paper I is also shown in each Figure.

(This model took the activation energy E to be 1 eV (96 kJ mol^{-1}) down to 40 m depth and 0.25 eV (24 kJ mol^{-1}) at greater depths.)

It can be seen that smooth curves are quite well defined by the observations on both profiles. There is, however, one group of points at 500 to 600 m separation on Profile 2 (indicated by the enclosing parallelogram in Figure 4) that is significantly higher than the curve. The reason for the discrepancy is not known. These measurements were the first ones to be made on this profile, and were all made on the same day. The scatter of the observations is relatively large, but not nearly large enough to explain the high values of apparent resistivity. The leakage potential at $a = 600$ m was found to be 0.0 ± 0.2 mV, compared with closed-circuit potentials of several volts. Even though there is no good *a priori* reason for ignoring these values, they have nevertheless been excluded from further consideration simply because of their disagreement with the remaining results. (A similar situation was found in Paper I, where the reason appeared to be associated with unusually small values of the potential-electrode separation. No such association occurs here.)

The apparent resistivity at $a = 700$ m was measured later on the same day as the discordant group, and yet it appears to fall, if anything, to a value which is too low rather than too high (Fig. 4). If the other values measured on that particular day are to be excluded, the one at 700 m should also be treated with caution, particularly as there is only one measurement at that distance. For that reason, the error bar at $a = 700$ m is indicated by a symbol which is drawn lighter than the others in Figure 4 and succeeding figures.

At each distance on each profile the weighted average apparent resistivity $\bar{\rho}_a$ has been calculated and plotted (Fig. 5). The weighted averages were evaluated using the technique of inverse variances. The standard-error estimates σ_ρ were calculated according to the formula

$$\sigma_\rho{}^2 = \frac{1}{\sum_{i=1}^{n} \frac{1}{\sigma_i{}^2}} + \frac{1}{n}\left(\frac{\sum_{i=1}^{n} \frac{(\rho_a)_i{}^2}{\sigma_i{}^2}}{\sum_{i=1}^{n} \frac{1}{\sigma_i{}^2}} - \bar{\rho}_a{}^2 \right). \qquad (1)$$

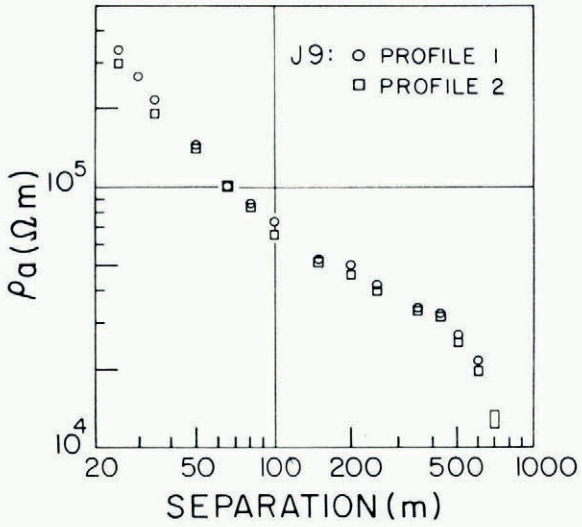

Fig. 5. Apparent resistivity data for station J9, Profiles 1 and 2 shown together. Circles indicate average values from Profile 1, squares denote average values from Profile 2. The error estimate in the apparent resistivity at 700 m is indicated by the height of the rectangle. Other error estimates are no larger than the size of the points.

These standard errors are less than the radius of the points in Figure 5 (except as shown otherwise by the rectangular box at 700 m on Profile 2). Apparent resistivities from the two profiles are nearly in agreement, but those for Profile 2 are slightly less, on the average, than those for Profile 1. In order to remove this difference, so that the slope of the apparent resistivity curve, which is directly related to the activation energy, would be more clearly presented, a factor equal to the average ratio of observed apparent resistivities at the same distances on the two profiles for $a \geqslant 25$ m was applied to Profile 2. Values from the two profiles then were averaged and standard errors calculated by Equation 1 so as to include the remaining differences between the two profiles. In the results (Fig. 6), apparent resistivities for $a < 50$ m have been removed because they are completely dependent upon conditions in the firn zone.

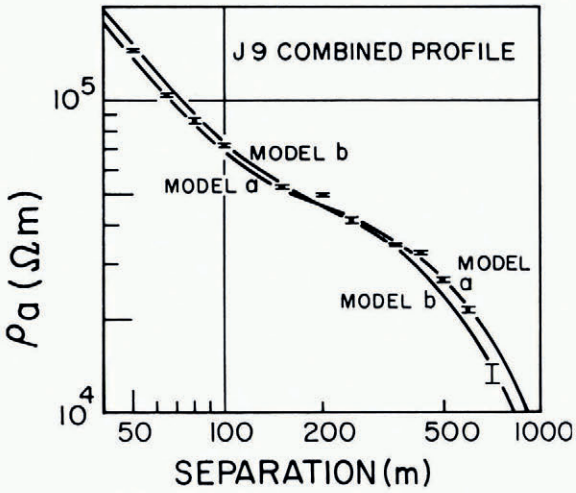

Fig. 6. Apparent resistivity data from both profiles combined, station J9. Both models assume a bottom balance-rate equal to zero; model "a" includes an activation energy of 0.15 eV (14 kJ mol^{-1}) in the solid ice, and model "b" an activation energy of 0.25 eV (24 kJ mol^{-1}) in the ice.

Analysis

Numerical modeling of the apparent resistivity was carried out in the same manner and using the same programs as in Paper I. Temperatures were calculated according to the one-dimensional, steady-state model of Crary (1961). The resulting profile (Fig. 7) shows excellent agreement with the measured temperatures (personal communication from B. L. Hansen and J. Rand) when the bottom balance rate $\dot{b}_H$ is taken to be zero. Although, in reality, it is possible that $\dot{b}_H \neq 0$ because the ice shelf may not be in steady-state, or, because horizontal temperature gradients may be significant, any model that gives the correct temperature is satisfactory for a determination of the resistivity, so we limit further consideration to the case $\dot{b}_H = 0$.

The variation of resistivity with density was assumed to follow the relation

$$\rho_f = \rho_i / v^3,$$

where v is the ratio of firn density to ice density, and ρ_f and ρ_i are the resistivities of firn and ice respectively. This equation follows from Looyenga's (1965) mixing equation, as discussed further in Paper I. Densities were taken from Langway (1975; personal communication, 1977).

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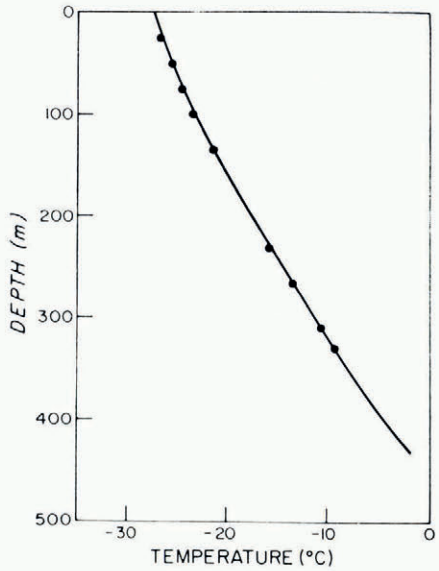

Fig. 7. Temperature against depth as measured in the deep drill hole at station J9. Solid dots indicate measured values, the solid line is calculated from a model assuming steady-state and no bottom melt or freeze.

Two model curves have been calculated, both with $E = 1.0$ eV (96 kJ mol^{-1}) in the upper ice. These two curves, matched at $a = 200$ m, appear to bracket the observations quite well (Fig. 6). The fit appears somewhat better for $E = 0.15$ eV than for $E = 0.25$ eV, particularly if less weight is placed on the rather uncertain value corresponding to 700 m separation.

For direct comparison, the values at station B.C., 30 km up-stream (Paper I), have been re-examined. Apparent resistivities from the two profiles there have been combined, in the same way as before (including the removal of the mean difference), with the results shown in Figure 8. Here again, the two model curves appear to bracket the observations.

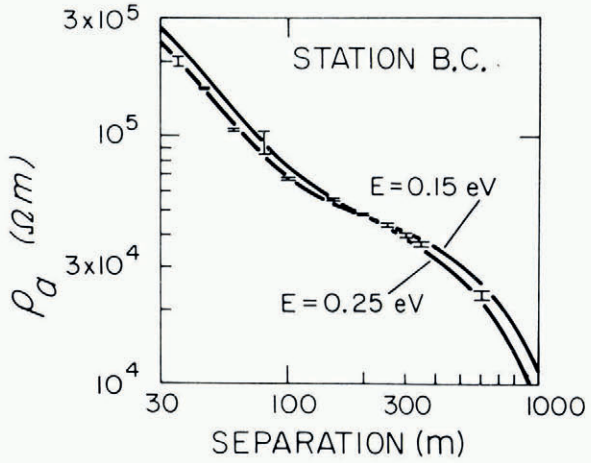

Fig. 8. Combined apparent resistivities for station B.C. Solid lines indicate the same two models as in Figure 7.

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Discussion

In considering the results of these measurements, it should be borne in mind that we are concerned primarily with ice-shelf depths between roughly 50 and 250 m, and thus with temperatures colder than −15°C. Conductivities at greater depths have little observable effect on the apparent resistivity measured at the surface, because the domination of current flowing in the very conductive sea-water (0.3 Ω m) beneath the ice shelf leads to low signal-to-noise ratios for V. At depths less than 50 m, density effects dominate all others.

Taken at face value, the results presented suggest that the activation energy for d.c. conduction in the Ross Ice Shelf at temperatures between −15 and −25°C lies between 0.15 and 0.25 eV (14–24 kJ mol^{-1}), perhaps rather closer to the smaller figure than the larger. The larger figure is in good agreement with measurements made elsewhere on polar ice, particularly some recent measurements (Glen and Paren, 1975; Fitzgerald and Paren, 1975; Fitzgerald and others, 1977). However, our analysis does not take into account possible resistivity changes with depth in the solid ice due to factors other than temperature (e.g. impurity content, crystalline structure, grain size, or metamorphic history). Although the specific effect of these various factors on the resistivity is not known, resistivities certainly do vary from place to place in polar ice, as shown, for example, by the factor-of-two difference between the temperature-corrected resistivities at J9 and B.C. and those near Roosevelt Island and at Byrd Station (Paper I). From the plots of resistivity against depth corresponding to each model (Fig. 9) we can see that if the activation energy is actually 0.25 eV, then an apparent value of 0.15 eV would be produced by an increase in resistivity with increasing depth of about 50% from other sources.

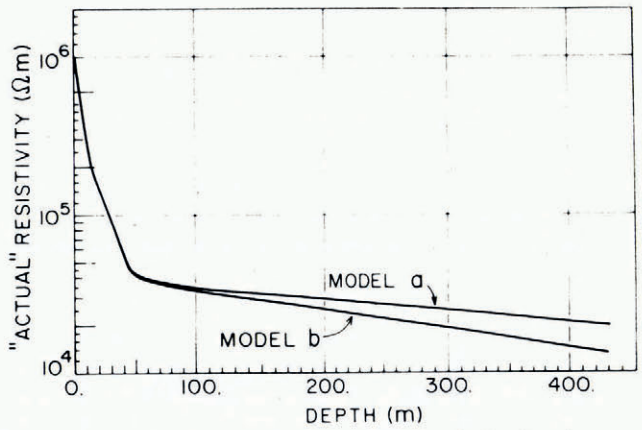

Fig. 9. "Actual" resistivities as a function of depth in the ice shelf at station J9 based on the two models of Figure 7, relative to an assumed resistivity of 10^6 Ω m at the surface. Since the surface value is not well determined, the true resistivity at a particular depth may be in error by a factor of two or more. "Actual" resistivities at depths greater than 250 m are not well controlled by the observed data.

The age of the ice at a depth of 250 m is on the order of 3 000 years (Thomas, 1976). The length of time for the ice to move from the grounding line to the drill site is on the order of 1 000 years, corresponding to a depth of about 100 m (Thomas, 1976). Most of the ice within the depth range of primary concern has, therefore, probably accumulated on the grounded West Antarctic ice sheet, whereas the upper part, of course, originated on the ice shelf itself.

Impurities, even if very dilute, could have a large effect on the resistivity. According to Gross and others (1978), resistivity is proportional to [NaCl concentration]$^{-q}$, where q is about 0.4 or 0.5. This means that the 50% increase in resistivity with depth mentioned above could be brought about by reducing the impurity content by a factor of 2 to 3.

The evidence relating to impurity variation with depth at J9 is scanty, indirect, and partly contradictory. In a study of impurities in ice cores at Little America V, near the front of the Ross Ice Shelf, Langway and others (1974) found a cationic concentration decreasing with depth down to about 150 m; the variation between 50 and 150 m is almost an order of magnitude. On the other hand, Gow (1968) found a variation of only about a factor of two in the electrolytic conductivity of melted ice between 50 m and 150 m depth from the same core hole. Both Gow (1968) and Langway and others (1974) suggest that the ice below about 150 m at Little America originated on the grounded ice sheet of West Antarctica, and that the West Antarctic ice is purer than the ice accumulating on the ice shelf. If so, the same might be true at J9 resulting in a low apparent activation energy. On the other hand, it is difficult to extrapolate from Little America to J9 and the region up-stream, which is everywhere at least 500 km from the ocean. Certainly there is no firm reason to expect a two- or three-fold up-stream decrease in impurity concentration, even though the snow mostly falls from cyclonic storms that have moved across the ice shelf into West Antarctica (personal communication from W. Schwerdtfeger, 1978). This point may be decided when chemical analyses on J9 ice cores are available.*

Differences in the metamorphic histories between ice samples can almost certainly produce large variations in conductivity. For example, it appears likely that the very low resistivity of cold polar ice results from its formation through a purely metamorphic process, that is, without melting (Fitzgerald and others, 1977). Furthermore, it also appears likely that the basal ice coming from the West Antarctic ice streams, which presumably has had a very different metamorphic history from the ice nearer the surface, has an exceptionally high resistivity (Bentley, 1976; Shabtaie and Bentley, in press). However, since there is no reason to suspect any significant difference in the metamorphic history (other than different ages) along the ice-particle paths that correspond to depths of 50 and 250 m at J9, this factor can probably be discounted.

In contrast, significant variations in the grain-size and the crystalline fabric with depth in the ice shelf can be expected (e.g. Gow, 1968), but there is no reason to expect any marked change in the resistivity as a function of either of these variables. Fitzgerald and Paren (1975) found no difference in the electrical behavior of ice samples from depths of 155 m and 1 454 m at Byrd Station, corresponding to a much larger age difference and much larger differences in grain-size and crystal fabric than would be expected between 50 and 250 m at J9. However, their measurements were made at frequencies of 10 kHz to 100 kHz and do not necessarily imply that there are no differences in d.c. conductivities.

These considerations, together with the very close agreement between the results at B.C. and J9, encourage us to believe that the activation energy, as determined by the resistivity method, does represent the true temperature effect on the ice in the ice shelf.

Conclusion

The new measurements at station J9 where the temperature has been measured, together with a re-examination of the values at station B.C. reported earlier (Paper I), suggest that the activation energy in the solid ice is rather less than 0.25 eV and perhaps as small as 0.15 eV. However, an alternative interpretation, that there is a reduction by a factor of two or three in the ionic impurity concentration between 50 and 250 m depth, cannot be entirely ruled out.

* *Note added in proof:* Herron and Langway (in press; personal communication from C. C. Langway) report a decrease in Na^+ concentration in the J9 ice core from about 75 p.p.b. (parts per billion) at 50 m depth to about 30 p.p.b. at 150 m, with the expectation that the concentration would remain approximately constant at greater depths. This is just the factor of two or three needed to produce an apparent activation energy of 0.15 eV from an actual value of 0.25 eV, as explained above.

ACKNOWLEDGEMENTS

The author is especially grateful to L. L. Greischar and S. Shabtaie for their aid with field work at J9. D. G. Albert, J. W. Clough, J. F. Kirchner, H. Kohnen, and H. L. Pollak also provided helpful assistance. This research was supported by National Science Foundation grant DPP72-05802.

MS. received 17 May 1978 and in revised form 19 July 1978

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