

drainage by flotation will occur progressively later and, by the time the glacier reaches position "31", flotation will once again be impossible with the amount of ablation shown on the model. Thus, we identify that the likely mechanism of drainage depends on the position of the glacier, and as such may vary through time with fluctuations in the position of the ice. We can postulate that, up to and including 1988, drainage occurred by linkage of the lake with the internal drainage of the glacier as described by Russell (in press) but that in 1990 and 1991 drainage by flotation occurred first, because the lake depth was closer to the critical flotation threshold which was crossed by thinning of the ice due to ablation.

Conclusions

1. The topographically controlled lake depth is variable over time as a function of the changing position of the ice front on the hillside forming the western margin of the lake basin. As the glacier advances, so the maximum possible lake depth increases. This means that, as the glacier advances or retreats, different drainage mechanisms related to different water depths and water pressures may become relevant.

2. Flotation of the ice dam by a depth of water equivalent to 90% of the thickness of the ice-wall margin of the lake is a possibility for the 1991 drainage. If this mechanism does apply, then the timing of the drainage event depends on the rate of seasonal thinning of the ice over the seal rather than on the increasing depth of the lake, which is topographically limited each season.

3. Depending on the position and height of the spillway between the ice and the hillside, which determines the depth which the lake can reach and the relationship between lake depth and ice thickness, different drainage mechanisms might be feasible in different years, with significant implications for the timing, and the geomorphological and glaciological consequences of the drainage.

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SIR,

Aqueous ethanol as an ice-drilling fluid

Since the publication of our paper on the use of butyl acetate as an ice-drilling fluid (Gosink and others, 1991), we have received numerous inquiries about the use of ethylene glycol and aqueous ethanol which have an appreciable history of glaciological application (e.g. Ueda and Garfield, 1969; Zagorodnov, 1989). This letter expresses our reasons for choosing butyl acetate over aqueous ethanol.

The principal factors we considered were: minor yet chemically significant corrosion to the ice sample and to the drill (leading to contamination of the core), solvent penetration of the ice core, density, viscosity, safety and cost.

Aqueous alcohol can rapidly attack ice if either temperature or concentration equilibrium conditions are not met. Non-equilibrium conditions will lead to partial destruction of the all-important core sample or inordinate production of slush which can jam the hole. Since the internal temperature of the borehole varies with depth (generally colder at the top), the ratio of water to alcohol in deep holes must be monitored and changed with depth. Addition of heat will keep the hole open (e.g. Ueda and Garfield, 1969) but it is potentially destructive of the core for sensitive chemical measurements and, unless heat is maintained throughout the operation, severe slush formation or refreezing will occur (Humphrey and

Echelmeyer, 1990). Butyl acetate poses no density or slush-formation problems. Bailing shavings are a mutual problem.

In penetration experiments, aqueous alcohol (50% by volume) was introduced to a c. 150 m (-31°C) depth secondary borehole at Summit, Greenland. The depth of the fluid was about 15–20 m. Short cores were drilled and returned to this laboratory for analysis. About 3 months later, the cold-stored cores were lathed and the melted shavings analyzed. Gas chromatographic analysis revealed that heavy contamination by the alcohol ($\geq 10\,000$ ppm) still remained in the outer 1–2 mm of the core, and that chemically significant penetration occurred to 15–20 mm depth (and by implication, a factor of four or more of foreign water). Alcohol was not detected in any of the samples from the entire center 60 mm diameter parts of all the ice-core samples. The detection limit for the method is c. 0.2 ppm. In experiments with hydrophobic butyl acetate, surface contamination after just a few days was three orders of magnitude lower and penetration was less than 3 mm at the 0.4 ppm level. The presence of 1 ppm of drill fluid with 1 ppm of trace metal would contaminate the ice at the part per trillion level. Polar protic aqueous alcohols will carry much more trace metal and ionic contaminants than hydrophobic butyl acetate.

Figure 1 presents density for aqueous ethanol solutions at or very near their freezing points. *CRC handbook* data for the density of aqueous alcohol at 20°C is provided for comparison purposes. At -51°C, the density of 72% alcohol in water appears to be slightly less than that of ice. Adding 5% ethylene glycol to 70% ethanol raises the density to 0.93 Mg m⁻³, but it also increases the viscosity to 65 cp (10% glycol, 60% alcohol = 123 cp). Internal glacier temperatures near -50°C are anticipated for drilling projects in Antarctica. The required less-dense fluid (72% alcohol in water) would be stable on top of the more-dense solutions that would be introduced to the deeper parts of the borehole. However, potential

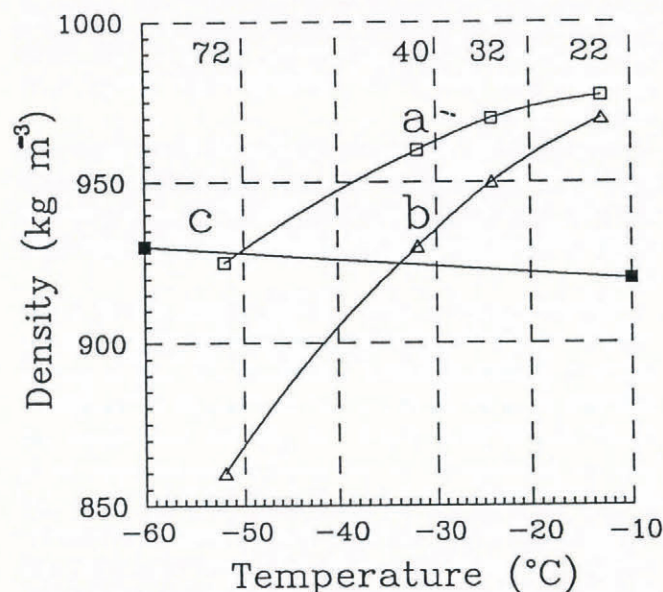


Fig. 1. Density of aqueous ethanol solution at its freezing point (a), and at 20°C (b) and ice (c); concentration of ethanol by weight is shown at the top of the figure.

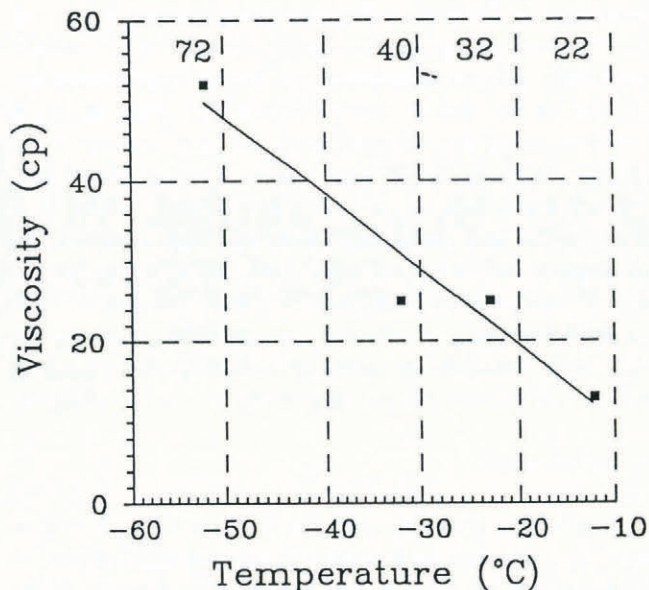


Fig. 2. Viscosity of aqueous ethanol solution at its freezing point; concentration of ethanol by weight is shown at the top of the figure.

problems arise. One problem is that the low alcohol-content, high-density fluid to be pumped to lower levels in the borehole may freeze in the tube passing down through the much colder upper levels. Another problem is that, if heat is added to prevent freezing, then corrosion of the ice wall in the upper part will occur, followed by slush formation when it re-cools. No such mixing problems, density overturn, freezing, etc. exist when butyl acetate is employed.

The viscosity data presented in Figure 2 are for aqueous ethanol solutions at or very near their freezing points. The per cent alcohol content is indicated by the numbers at the top of the figure. It is desirable from the point of view of the transit time of the drill string that the viscosity of ice-core drilling fluids be closer to the 10 cp end of the curve. A discussion of this time and energy point has been presented in Gosink and others (1991). Fluids with a viscosity of 20–25 cp are easily workable in moderate-depth boreholes (≤ 1000 m). While the prospect of 50 cp fluid in Antarctic operations is not desirable, it can be overcome and is substantially better than the extremely adverse viscosity problems associated with ethylene-glycol solution. For example, Hansen (1976) used terms such as “pasty” or “difficult to work” for 20–50% ethylene glycol–water mixtures. Low viscosity (< 10 cp) is a serious problem for ball-bearing lubrication but not for roller or needle bearings.

From an environmental and personal safety consideration, ethanol is the best of all fluids, even over our recommended butyl acetate. In work-place air, 1000 ppm of the alcohol vapors are permitted. (10 000 ppm for several hours will induce intoxication in some people and is near the fire limit.) As far as the environment is concerned, ethanol is a natural, widely occurring product and would be rapidly consumed by the microbiota in any water body into which it might be spilled. Its infinite solubility would assure its rapid dispersion and the volatility of ethanol is good in terms of a land spill.

However, there is a serious concern with respect to fire

hazard. The flash point of aqueous ethanol is lower than that of butyl acetate, which is considered safe only in view of the low temperatures at which it will be used. Table 1 shows the flash point of ethanol and aqueous ethanol. The data were determined in a commercial testing laboratory

Table 1. Flash point of ethyl alcohol and aqueous solutions (in comparison with other fluids)

Per cent alcohol	Flash point °C
100	10
50	22
30	28
(Butyl acetate)	29
(Fuel oil)	~66

or taken from the literature. Butyl-acetate and fuel-oil data are added for comparison. One mitigating factor is that only 20–70% solutions of ethanol will be employed, but the flame point for 50% or greater concentrations is below the temperature of the heater element in the warm-up hut.

The manufacture cost of ethanol is about half that of butyl acetate but the major advantage comes in the transportation cost to the remote drill sites (about \$3–4 kg⁻¹), amounting to tens of thousands of dollars per borehole. Nominally, 50% solutions would be required and the snow will not require any (or very little) added heat because of the corrosive nature of ethanol towards snow to be used to dilute the alcohol.

In summary, aqueous ethanol is decidedly cheaper and easier to employ than either butyl acetate or fuel oil, and may be a useful ice-core drilling fluid in warm ($\geq -25^{\circ}\text{C}$) boreholes and where density overturn is not a problem, i.e. in holes of moderate depth with temperature gradients of $\leq 2^{\circ}\text{C}$ per 100 m. The viscosity properties of aqueous ethanol are vastly superior to those of ethylene-glycol solutions, even at -55°C , and workable for shallow-to moderate-depth (<1000 m) boreholes. It is, unquestionably, an environmentally sound choice. The drawback is its flammability when enriched above 30% but its paramount weakness is the potential for contamination in parts per trillion analyses.

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Ablation thresholds and ash thickness

In their paper on the mode of formation of ablation hollows, Rhodes and others (1987) presented some useful ideas on a small scale, but nevertheless an interesting problem. Ablation hollows, often called ablation polygons or sun cups (Matthes, 1934; Jahn and Klapa, 1968) are common features which form more or less regular networks of hollows and interconnecting ridges, on the surface of compacted “spring” snow. In resolving some of the conflicting observations in the literature, Rhodes and others explained how these hollows can form under conditions in which ablation is forced either by direct solar radiation or by turbulent heat transfer. To achieve this, the role of dirt is considered, in terms of the opposing