cycle in the ancient past for example, cannot be quantitatively assessed.

To quantify the second term on the righthand side of Equation (9.3) in a manner such as would yield error bars, or confidence intervals, on the retrodicted surface-temperature history, we suggest that a *family* of coefficient sets $\{e_i\}_{i=1}^{N}$ be estimated. This could be done using information about the accuracy of the measurement devices and the anticipated spatial structures of the convection cells. The family of coefficient sets can then be transcribed into a family of surface-temperature histories using the eigenfunction expansion in Equation (9.3). The envelope which bounds this family of histories would then constitute an error-bar representation of measurement error.

10. Conclusion

We believe that the analysis presented above clarifies our position concerning the quantification of uncertainty and the trade-off between fitting noisy borehole data and satisfying secondary performance constraints, such as simplicity. As to the first position, no absolute measure of uncertainty is possible in the paleothermometry problem due to the inherent memory loss of heat diffusion. What is possible to quantify, however, is the *resolution* of an inverse method such as ours. As to the second position, a tendency to overfit measurement noise in borehole-temperature data can be restrained through the imposition of precisely described secondary constraints on the surface-temperature history. These secondary constraints determine the functional properties of the surface-temperature history, such as the degree to which it oscillates. There are no strict rules which define these secondary constraints; thus, it is perfectly natural to expect two or more widely differing surface-temperature histories to result from the analysis of the *same* borehole-temperature data.

Concerning the question of whether solutions of borehole paleothermometry problems could serve as a check on the interpretation of ice-core isotope stratigraphy, we direct the reader to Firestone (1992). To our understanding, the interpretation of isotopic stratigraphy depends as much on an empirical relationship between present-day surface temperature and present-day isotopic compositions of precipitation as it does on complex theories of the hydrologic cycle. We are aware of no proof that this empirical relationship cannot change with time. We thus re-affirm our interest in developing better methods to solve the paleothermometry problem. Furthermore, we suggest that this development is no less justified than the continued development of ice-core geochemical methods for inferring the paleoclimate.

Department of the Geophysical Sciences, DOUGLAS R. MACAYEAL
The University of Chicago,
5734 South Ellis Avenue,
Chicago, Illinois 60637, U.S.A.

Geophysics Program AK-50, JOHN FIRESTONE
University of Washington, EDWIN WADDINGTON
Seattle, Washington 96195, U.S.A.

29 December 1992 and in revised form 25 January 1993

REFERENCES

Anderssen, R. S. and V. A. Saull. 1973. Surface temperature history determination from borehole measurements. *Math. Geol.*, **5**(3), 269–283.

Bahr, D., W. T. Pfeffer and M. F. Meier. 1992. Stress perturbations from compressional flow: the propagation of calculation errors from the surface to the bed of a glacier. [Abstract.] *Eos*, **73**(43), Fall Meeting Supplement, 159.

Carslaw, H. S. and J. C. Jaeger. 1988. *Conduction of heat in solids.* Oxford, Clarendon Press.

Courant, R. and D. Hilbert. 1953. *Methods of mathematical physics.* New York, Interscience Publishers.

Dahl-Jensen, D. and S. J. Johnsen. 1986. Palaeotemperatures still exist in the Greenland ice sheet. *Nature*, **320**(6059), 250–252.

Dahl-Jensen, D., S. J. Johnsen, W. S. B. Paterson and C. Ritz. 1993. Comments on "Paleothermometry by control methods" by MacAyeal and others. [Letter.] *J. Glaciol.*, **39**(132), 421–423.

Firestone, J. 1992. Resolving the Younger Dryas Event through borehole thermometry. (Ph.D. thesis, University of Washington, Seattle.)

Lachenbruch, A. H. and B. V. Marshall. 1986. Changing climate: geothermal evidence from permafrost in the Alaskan Arctic. *Science*, **234**(4777), 689–696.

MacAyeal, D.R., J. Firestone and E. Waddington. 1991. Paleothermometry by control methods. *J. Glaciol.*, **37** (127), 326–338.

Press, W. H., B. P. Flannery, S. A. Teukolsky and W. T. Vetterling. 1989. *Numerical recipes.* Cambridge, Cambridge University Press.

Wang, K. 1992. Estimation of ground surface temperatures from borehole temperature data. *J. Geophys. Res.*, **97**(B2), 2095–2106.

The accuracy of references in the text and in this list is the responsibility of the authors, to whom queries should be addressed.

SIR,

Supraglacial lake drainage near Søndre Strømfjord, Greenland

An unseasonal release of meltwater from the western margin of the Greenland ice sheet near Søndre Strømfjord was noted by residents of Søndre Strømfjord during January and February 1990 (Russell, 1990). Russell (1990) proposed a possible release of subglacial meltwater to account for the unusual flows into the Ørkendalen and Sandflugtdalen rivers. Since this event, further observations pertinent to the observed release of meltwater have come to light. Two circular depressions, located at a distance of 20–30 km from the ice-sheet margin, were observed on the ice surface from aircraft flying into Søndre Strømfjord (Fig. 1). The nature, origin and significance of these unusual features are briefly considered.

Photographs of these features were taken late in the winter of 1990 with a hand-held video camera from an aircraft cockpit by Captain U. Larsen. Frames were

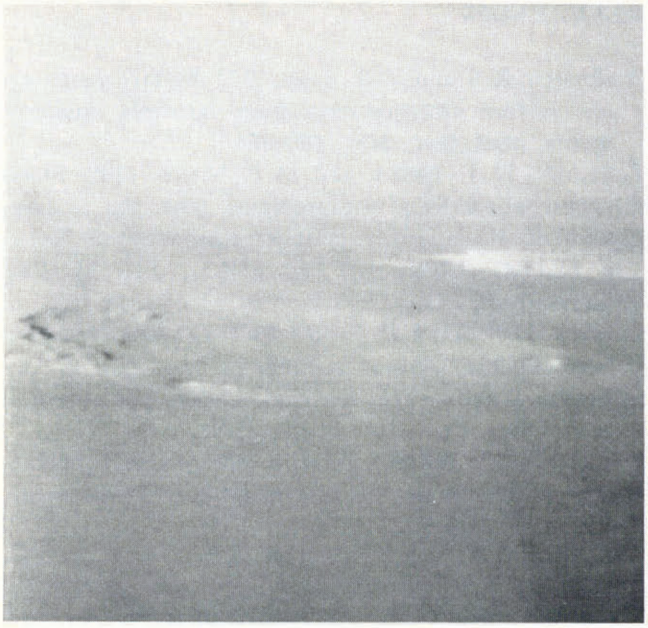

Fig. 1. Two circular crater-like depressions on the ice-sheet surface c. 30 km from the ice-sheet margin. Depressions are 1.5–2 km in diameter and are characterized by a series of concentric circular fractures. (Photograph by courtesy of U. Larsen.)

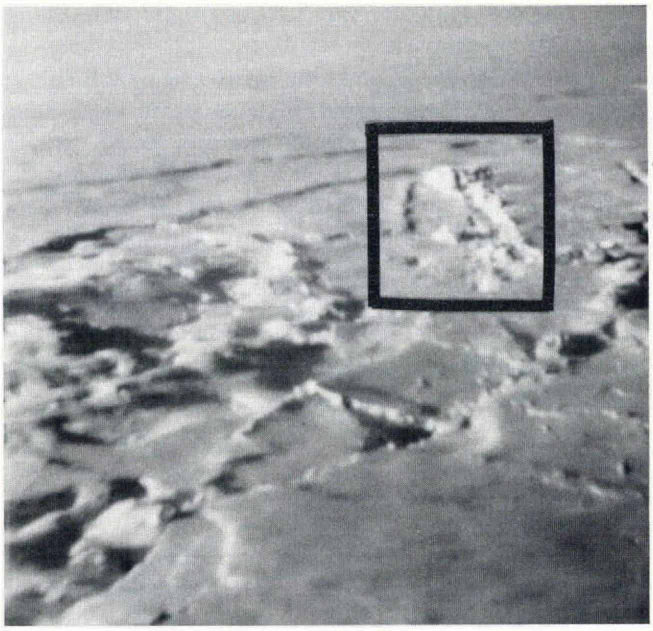

Fig. 2. A close-up view of the far depression in Figure 1. Note hummocky topography accentuated by shadows. The box represents the area enlarged in Figure 3. (Photograph by courtesy of U. Larsen.)

"grabbed" using an ERDAS image-processing system, enabling photographs to be taken. Each circular depression is in excess of 1.5–2 km diameter, the boundary of which is marked by a series of concentric fractures (Fig. 1). The interior of both structures is characterized by a more chaotic, hummocky appearance, with secondary fracture lines (Figs 2 and 3). Relief within the circular depressions is irregular as indicated by shadows behind fracture edges and hummocky zones of ice blocks (Figs 2 and 3). In at least one location, the ice surface is littered with individual blocks (Fig. 3). Although detailed topographic information is not available, total relief amplitude produced by these depressions was estimated at 10 m. The location of these depressions corresponds with that of large supraglacial lakes familiar for many years to pilots as "permanent" features on the ice sheet. Observations of similar-sized supraglacial lakes made during the summer months indicates that they form to considerable depth and contain rafts of seasonal lake ice.

Supraglacial depressions of similar morphology to those described here have been noted on Antarctic ice shelves (Mellor, 1960; Mellor and McKinnon, 1960; Swithinbank, 1988). The features described from the Antarctic ice shelves are oval in shape, reaching dimensions of 1.5 km × 3 km with depths as great as 80 m (Mellor and McKinnon, 1960). The Antarctic depressions also have an irregular bottom topography, indicative of ice collapse. Mechanisms for ice-surface collapse include the emptying of an englacial water reservoir or an ice-covered supraglacial lake (Mellor and McKinnon, 1960). The latter explanation appears to be most acceptable for the collapse structures observed in the Antarctic (Mellor and McKinnon, 1960; Swithinbank, 1988). Mellor and McKinnon (1960) suggested that meltwater contained in these lakes periodically drained through crevasses into the sea below the ice shelves. The term "ice doline" has been suggested for such depressions showing signs of cavity collapse (Mellor, 1960). The term "ice doline" seems appropriate to describe the Greenland depressions because of their similarity to those described from the Antarctic.

Fig. 3. Close-up of fracture patterns and hummocky topography. Note large numbers of ice blocks scattered across the snow surface, indicating considerable disruption and possible water upwelling during lake drainage. (Photograph by courtesy of U. Larsen.)

https://doi.org/10.3189/S0022143000016105 Published online by Cambridge University Press

The fact that these unusual depressions were observed simultaneously with extraordinary water flow from the ice margin near Søndre Strømfjord would suggest that these phenomena are linked. Two water-filled ice dolines 1.5 km in diameter with an average depth of 10 m would contain about $35 \times 10^6 \text{m}^3$ of water. This is the same order of magnitude as the volume of water released from the ice margin, as estimated by Russell (1990). If the ice dolines are deeper, their water-storage capacity would be closer to the suggested $90 \times 10^6 \text{m}^3$ of water released during the drainage event (Russell, 1990). As there was no sign of water flow over the ice surface and as water was observed emanating from the ice-sheet margin it is suggested that these lakes drained either sub- or englacially.

The drainage of supraglacial lake water into two major outwash systems supports the existence of well-established drainage routeways which are likely to survive from year to year. Supraglacial lake drainage, although rarely observed during the winter months, may take place more regularly in the summer months. Supraglacial storage of meltwater is likely to delay the run-off of a significant proportion of the annual melt. The release of supraglacially stored water is also likely to be important for downstream river-channel morphology and sedimentology. Supraglacial lake drainage may be as important as the drainage of ice-marginal lakes when large ice sheets are considered. The drainage of supraglacial lakes should also be recognized in relation to the meltwater-flow regimes of proglacial rivers emerging from former ice sheets in Europe and North America.

I should like to thank K. Swanson and A. Reenberg for keeping me up to date with the above events. Thanks also go to R. Gard, Department of Geography, University of Aberdeen, for operating the ERDAS system and obtaining the photographs.

School of Geography,
Kingston University,
Kingston-upon-Thames,
Surrey KT1 2EE, England

ANDREW J. RUSSELL

24 May 1992

REFERENCES

Mellor, M. 1960. Correspondence. Antarctic ice terminology: ice dolines. *Polar Rec.*, **10**(64), 92.

Mellor, M. and G. McKinnon. 1960. The Amery Ice Shelf and its hinterland. *Polar Rec.*, **10**(64), 30–34.

Russell, A.J. 1990. Correspondence. Extraordinary meltwater run-off near Søndre Strømfjord, West Greenland. *J. Glaciol.*, **36**(124), 353.

Swithinbank, C. 1988. Satellite image atlas of glaciers of the world. Antarctica. *U.S. Geol. Surv. Prof. Pap.* 1386-B.

ERRATUM

Vol. 39, No. 131, p.114, Fig. 3.

The photographs for Figure 3c and 3d were inadvertently switched. We apologise for this error.