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GENERAL DISCUSSION

Chairman: W. F. Budd

ANTARCTICA AT 20 ka BP

D E SUGDEN: A few years ago the idea of an expanded late Wisconsin ice sheet in West Antarctica was not readily accepted. During this conference it has been. There is perhaps a danger of accepting the idea uncritically, and it is important to distinguish between evidence and assumption. For example, a radiocarbon date on shells of 31 ka found in till on the floor of the Weddell Sea (as reported by O Orheim) is not, on its own, unambiguous evidence of a late Wisconsin grounded ice sheet. Amino-acid work has shown many such dates to be unreliable.

T J HUGHES: If George Denton were still here he would recommend ice coring along the West Antarctic ice divide between the Ellsworth, Whitmore, and Thiel mountains to see if air-bubble pressures show a higher ice elevation to the limit of glacial erosion in these mountains caused by a uniformly thicker ice sheet. Secondly, could the air-bubble pressures link these higher ice levels to late Wisconsin/Weichselian time?

ICE-CORE STUDIES: DUST AND VOLCANISM

M M HERRON: In Greenland there is abundant evidence that the higher insoluble particle concentrations found in late Wisconsin-age ice are continental dust, a bit more calcareous in nature than today. However, measurements of volcanogenic species such as SO_4^{2-} Cd, and Zn show peaks at about 10, 30, and 60 ka in the Camp Century core. These horizons correlate extremely well with radio echo layers at appropriate depths at sites in Greenland where they are not masked by bottom echoes.

NITRATES

E J ZELLER: Our group has had a lengthy discussion with Mike Herron and we find points of both agreement and disagreement. In brief, both groups get roughly the same mean nitrate value in South Pole firn from cores. Our major disagreement is over the Maunder minimum. Herron analysed the nitrate in a short section of firn core from South Pole, at a depth which he dates as belonging to the Maunder minimum, and he does not find the low nitrate values that we find throughout the Maunder minimum. At this time there is no explanation for this disagreement.

Our laboratory has available a second 60 m Vostok core and we will complete analyses on this within the next six months. This will be of further aid in confirming the results from South Pole and Vostok.

M M HERRON: I have found no evidence of lower nitrate concentrations during the Maunder minimum in solar activity in either the South Pole or in the Dye-3, Greenland, ice core. The latter core has the great advantage of being dated with an accuracy of ±1 a. I have also not found a cycle of 11 a in nitrate concentrations, nor the spurious concentration spikes that were attributed by Rood and others (1979) to supernovae. I believe that analytical problems, including sample handling, may be responsible for the results of Parker, Zeller and Gow which I cannot duplicate.

U RADOK: As a meteorologist I was very intrigued to hear that at long last there was a claim of a surface phenomenon that related unambiguously to the 11 and 22 a cycles. This has been sought for a century but never identified convincingly. The difficulty seems to be that if you have an event that occurs in the upper atmosphere, the time that is needed to bring its effects down to the surface is such that for any event lasting only that long, and possibly longer, the effects are not very likely to survive the trip. I would like to raise the question: how definite is it that you really have found this elusive phenomenon in the nitrates?

EJ ZELLER: We now have high-resolution pit samples from South Pole station which have been collected in three replicate vertical columns spanning 52 a. We see evidence not only of solar activity related to the sunspot cycle, but also of the intense solar flare that occurred in 1972. In addition we have found a correlation of r = 0.54 between nitrate in pit samples and satellite data on charged particle abundance that is available from 1972 to 1979.

WEST ANTARCTIC GROWTH AND DECAY

J WEERTMAN: Will a warming of the oceans actually lead to a reduction of the Antarctic ice sheet even if, as seems likely, it leads to a reduction in size of the ice shelves? For example, we learned at this symposium that Pine Island Glacier is really a "one-dimensional" 100 km long floating ice shelf. Why would chopping off, say, 50 km of this ice shelf lead to any significant change in the size of the West Antarctic ice sheet?

TJ HUGHES: Some people object to my talking of disintegration of the West Antarctic ice sheet. I do this because disintegration means breaking into bits, that is, converting the ice sheet into icebergs. This brings the ice to the heat, which seems to me a more efficient way of removing ice sheets than bringing heat to the ice. Therefore, I would recommend more research on icebergs, both in modelling how icebergs form, as Bill Schmidt and Jim Fastook have done, and in monitoring their size and numbers as Olav Orheim has done. I am impressed with Bob Thomas's model for irreversible grounding-line retreat once a confining ice shelf is removed, and a few giant icebergs can remove an ice shelf in a hurry.

VOLCANIC HEAT AND THE WEST ANTARCTIC ICE SHEET

C S BENSON: An anomalously high regional geothermal heat flux associated with volcanism beneath most of the West Antarctic ice sheet may be a major factor in its instability. It could be far more important than the effect of increasing the CO_2 content of the atmosphere which has attracted attention recently. Heat flux at the bottom surface of the ice sheet goes directly into melting ice, with possible large-scale ponding of water in ways which among other things could produce jökulhlaup-type instability. The interactions between volcanoes and glaciers have been studied for many years by S Thorarinsson and his colleagues in Iceland. The recent explanation of jökulhlaups from Vatnajökull by Björnsson (1974, 1975) represents a fundamental advance in our knowledge of the processes involved. Volcano-glacier interactions on Kamchatka peninsula have been studied vigorously by Vinogradov (1975, 1981) and his colleagues in the Volcanological Institute of Petropavlovsk. Similar studies of ice-covered volcanoes are underway in Alaska (Benson and others 1975, Motyka and others 1980). Most recently, the stunning eruption of Mount St Helens in the state of Washington focused world-wide attention on ice-covered volcanoes.

In present-day Antarctica the only observed and reported subglacial eruption was at Deception Island (Baker and others 1969, Brecher and others 1974). Indeed, from a volcanological point of view, polar regions are perhaps best known for the unique record of volcanic events, even from distant sources, which is preserved in snow strata. An excellent example of this was presented by Hammer (1980). However, as we consider the direct melting of glacier ice by volcanic activity in polar regions the spectacular eruptive events may not be the most important, even if they tend to dominate people's thoughts about volcanism; a sustained high geothermal flux under the entire West Antarctic ice sheet may be overwhelmingly more important.

If the ice-rock interface at the base of the ice sheet is at the melting point, nearly all the geothermal heat flux becomes available for melting ice. So far, we have direct evidence of sub-ice water bodies beneath parts of the Antarctic ice sheet but not beneath the Greenland ice sheet. Two holes have now been drilled to bedrock in the Greenland ice sheet. No basal melting was observed in these holes since their basal temperatures were below -10°C. In contrast, we have direct evidence of basal melting of the Antarctic ice sheet beneath Byrd station (80°S, 120°W). Not only was the bottom temperature at the melting point (-1.6°C at 197 bar) but ample melt water was present; it "flooded the hole to a height of about 50 m" (Gow and others 1968).

In addition to the direct evidence of basal melting 2 km beneath Byrd station, radio echo-sounding is yielding increasing evidence of sub-ice water bodies beneath parts of the Antarctic ice sheet (Oswald 1975, Drewry and others 1981). These observations should be considered in the light of studies by LeMasurier and Wade (1968). They cite evidence of recent volcanic activity ".... within a large belt of late Cenozoic volcanism that extends down the Antarctic Peninsula, across Marie Byrd Land, and northward along the Hallett Coast to Cape Adare and the Balleny Islands. Granite plutons of late Mesozoic age underlie the eastern part of this volcanic terrain, in the Antarctic Peninsula and in Ellsworth Land". The closest thing to direct observation of current volcanic activity within the West Antarctic ice sheet is LeMasurier and Wade's (1968) report of fumarolic activity on Mount Berlin (76°03'S, 135°50'W) and Mount Hampton (76°29'S, 125°54'W). They interpret these observations to indicate "recent volcanic activity in Marie Byrd Land, and that the circum-Pacific orogenic belt may extend without interruption from Ellsworth Land across Marie Byrd Land". Evidence that volcanic rocks extend farther south in Marie Byrd Land than the exposures mentioned above is provided by recent geophysical studies by Jankowski and Drewry (1981). By using magnetics, radio echo-sounding, and other geophysical data they suggest that volcanic rocks extend across the Byrd Subglacial Basin to 81°S.

The normal geothermal heat flux is adequate to melt 5 mm a^{-1} of ice. The heat flux calculated by Gow and others (1968) for the base of the ice sheet at Byrd station exceeds this and is adequate to melt 7 mm a^{-1} of ice. It is not unusual for regional heat flux values to be several times higher than this in volcanic areas and an order of magnitude higher in proximity to fumarolic zones. The heat flux required to maintain the fumarolic activity observed by LeMasurier and Wade (1968) on top of volcanoes which protrude through the West Antarctic ice sheet to elevations exceeding 3 000 m, can be expected to produce significant subglacial melting at the base of the ice sheet. The rates of production of basal melt water and the potential for accumulating it in lake-like reservoirs with subsequent discharge are obviously important to the stability of the ice sheet. Some effects of subglacial water have been considered at this meeting (Bindschadler 1982, Weertman and Birchfield 1982). One of the most important steps required now is an assessment of the geothermal heat flux beneath the West Antarctic ice sheet. A good way to start would be to focus on confirmation of the tentative conclusions by LeMasurier and Wade. Among other things they suggested infrared scanning of rock exposures in West Antarctica and determination of the ages of granitic plutons in Marie Byrd Land mountain ranges. These, combined with detailed examination of fumarolic areas including the measurement of geothermal heat flux wherever possible would be very useful at this stage in our knowledge.

ICE FLOW AND SLIDING

R H THOMAS: I suggest that we also consider what is happening at the sides of ice streams and glaciers; these may provide more resistance to movement than the beds. In this context we should include the effects of anomalously high temperatures at the sides, due either to internal heat generation by the very high shear strain-rates, or to the warming effects described by Pfeffer at this meeting.

TJ HUGHES: Tad Pfeffer studied ice fabrics from shallow cores he obtained across Byrd Glacier and adjacent Darwin Glacier in Antarctica. Both ice streams have strong lateral shear zones determined from their transverse velocity profiles. The Byrd Glacier shear zone was too heavily crevassed to permit sampling of sound ice where the shear would be concentrated. However, Darwin Glacier moves only one-eighth as fast so the shear zone was unfractured and, working under the guidance of Tony Gow at CRREL, Pfeffer found very strong single-maximum ice fabrics with nearly horizontal optic axes.

RH THOMAS: I strongly support the measurement of more ice temperatures, particularly near the bed. And here I should like to make a plea for the development of an effective thermal probe. Important problems (additional to the obvious ones) that could be addressed include basal melting/freezing rates beneath ice shelves and detection of bands of warm ice that might exist at the sides of fast ice streams.

A HIGASHI: With regard to the mechanical properties of Antarctic ice, we need in situ experiments on deep core ice as Shoji did with Greenland cores, because of the effects of air bubbles, cracks, and also of fabrics. I would highly recommend anyone who is planning to drill deep cores in Antarctica to try such experiments.

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