Journal of Glaciology, Vol. 47, *No.* 158, 2001

Reviews

ALLEY, R. B. and R. A. BINDSCHADLER, *eds.* 2001. *The West Antarctic ice sheet: behavior and environment.* Antarctic Research Series 77. Washington, DC, American Geophysical Union. xii + 296 pp. ISBN 0-87590-957-4, ISSN 0066-4634, $65.

The West Antarctic ice sheet: behavior and environment is volume 77 in the Antarctic Research Series published by the American Geophysical Union. It emerged from a Chapman Conference on the West Antarctic ice sheet that was organized by Harold Borns, Jr and Robert Bindschadler and held at the University of Maine in 1998. The volume is ably edited by Richard Alley and Robert Bindschadler, who relate the ice sheet to changing sea level in a preface. The remainder of the volume is divided into five themes.

The first theme is the physical setting of the West Antarctic ice sheet. Mark Fahnestock and Jonathan Bamber present an overview of what has been learned using satellite and aerial remote-sensing technology. The ice surface appears much more rugged in satellite imagery than it does to observers on the surface. This ruggedness is shown to be caused by variations in bed topography and ice–bed coupling due to basal thermal conditions, notably the contrast between heavily crevassed ice streams underlain by a wet bed and the smooth ice ridges or ice domes between ice streams and underlain by a frozen bed. Ian Dalziel and L. A. Lawver investigate the bed beneath the ice sheet in relation to the tectonic evolution of West Antarctica. It consists of several distinct crustal blocks which have shifted in relation to each other over at least 200 Ma. A mantle plume under West Antarctica dating from about 35 Ma has dispersed the continental blocks to their present positions, separated by deep extensional submarine basins produced by the West Antarctic rift system. After the marine ice sheet formed, some rifts and grabens were occupied by ice streams, which today discharge 90% of West Antarctic ice.

The second theme is the history of the West Antarctic ice sheet. John Anderson and Stephanie Shipp examine the history from a marine geological perspective. The West Antarctic ice sheet began as ice caps over highlands on the dispersed crustal blocks, and these ice caps expanded to fill the intervening marine basins, beginning in the Miocene. The ice sheet reached the edge of the continental shelf during the maxima of Pleistocene global glaciation cycles. Ice streams occupied marine troughs (rifts and grabens) across the continental shelf on these occasions. The heads of troughs, where exposed, consist of a dendritic pattern of meltwater channels incised in bedrock where sheet flow of ice was transformed into stream-flow. Harold Borns, Jr examines the ice-sheet history preserved in the terrestrial glacial geological record. That record is most complete in the Ross Sea embayment, where elevated moraines up to 2000 m high have been mapped and partly dated all along the Transantarctic Mountains, and where lobes of marine ice have invaded the Dry Valleys and impounded lakes having datable algae layers. Undated glacial erosional "trimlines" have also been mapped along the Ellsworth Mountains, showing former ice elevations at least 600 m above the present-day ice sheet. Many volcanic nunataks poke through the interior West Antarctic ice sheet. These are sites where "bathtub ring" moraines record former ice elevations. Eric Steig and six co-authors investigate variations and causes of ice-surface lowering driven by climate warming and rising sea level. Former ice elevations at Mount Waesche and at Byrd Station (80° S, 120° W), a site 200 m higher 8000 years ago according to oxygen isotope stratigraphy down the Byrd corehole, were used to control delayed interior lowering generated for grounding-line retreat by ice-sheet models.

The third theme is interactions of the ice sheet with its surroundings. David Bromwich and Aric Rogers link surface precipitation rates from convective storm systems to recent El Niño sea-surface warming events in the tropical Pacific that trigger the Southern Oscillation variations in atmospheric circulation. Moisture-bearing air moves parallel or perpendicular to the West Antarctic coast in phase with Southern Oscillation variations, delivering reduced or enhanced precipitation over the West Antarctic ice sheet. Donald Blankenship and nine co-authors use airborne radar sounding to map the bed, and laser altimetry to map the surface. By correlating surface and bed topography, they argue that the onset of ice streams occurs on a rugged bed where Cretaceous crustal rifts became draped with Cenozoic marine sediments that are mobilized by basal melting.

The fourth theme is the distinction between slow sheet flow and fast stream-flow. Robert Bindschadler, Jonathan Bamber and Sridhar Anandakrishnan evaluate criteria for locating where fast stream-flow emerges from slow sheet flow. The appearance of long transverse crevasses flanked by bands of shear crevasses, flow stripes consisting of parallel ridges and troughs aligned in the downslope direction, flowline profiles that are generally convex for sheet flow and concave for stream-flow, bed topography, especially dendritic bedrock channels that converge on broad bedrock troughs, and peaks in the gravitational driving stress are all discussed. Charles Raymond, Keith Echelmeyer, Ian Whillans and Chris Doake analyze the stability of shear margins alongside ice streams. When the bed is soft mud, ice coupling across shear margins to hard beds between ice streams provides the major resistance to the downslope gravitational force that drives fast motion in ice streams. The competing narrowing and widening tendencies of ice streams make lateral shear margins unstable. Barclay Kamb describes various borehole measurements in West Antarctic Ice Streams B and C, including changes in hydrostatic head over time. From these data and mechanical creep tests on wet till at the bed, he shows how till deformation controls ice-stream stability even if side shear supports the ice stream during fast flow. Christine Hulbe and Anthony Payne review contributions of ice-sheet models to understanding the dynamic behavior of the West Antarctic ice sheet. A major goal of these models is to couple ice dynamics to bed conditions, notably subglacial hydrology, bedrock roughness and till deformation, in ways that interact with the partitioning of ice flow into internal creep, basal motion and side shear components.

The fifth theme investigates individual ice streams as case-studies that illustrate the complexity of stream-flow. Chris Doake and seven co-authors show that Rutford Ice Stream has dynamic behavior that is not fundamentally different from the behavior of Siple Coast ice streams, even though it is much thicker, has a low bedrock headwall, one rock side-boundary (the Ellsworth Mountains) and one ice side-boundary (Fletcher Promontory). David Vaughan and nine co-authors investigate Pine Island Glacier. It and its neighbor, Thwaites Glacier, are the two fastest Antarctic ice streams, they drain one-third of the grounded West Antarctic ice sheet, their drainage basins are lowering $>0.1\,\mathrm{m\,a^{-1}}$, and their floating ice tongues do not provide the buttressing that the huge Ross and Filchner–Ronne Ice Shelves provide to other West Antarctic ice streams. For Pine Island Glacier, up to $12\,\mathrm{m\,a^{-1}}$ of ice melts from the underside of the floating tongue, and its grounding line is now retreating $>1\,\mathrm{km\,a^{-1}}$. The sheet-flow to stream-flow transition occurs in a fan of converging flow 150 km long in which subglacial meltwater channels underlie a dendritic stream-flow network that branches from the main trunk of the ice stream through the whole ice-drainage basin. Glacially eroded bedrock and abiotic glacial marine sediments in Pine Island Bay indicate that Pine Island Glacier has undergone substantial retreat in historical time. Ian Whillans, Charles Bentley and Cornelis van der Veen compare Ice Streams B and C, which are typical Siple Coast ice streams except that Ice Stream B is the fastest (up to $850\,\mathrm{m\,a^{-1}}$) and Ice Stream C is the slowest (slowing to a stop near its grounding line). They present a detailed examination of the onset of stream-flow, crevasse patterns, flow traces, lateral shear zones, velocity changes in space and time, bed conditions and ice-shelf buttressing. Sridhar Anandakrishnan, Richard Alley, Robert Jacobel and Howard Conway examine why Ice Stream C is not "off" along its whole length; the onset region is still "on" and the terminal region has been "off" for only 150 years. They favor piracy of basal water by Ice Stream B, so that sticky spots beneath Ice Stream C lose water lubrication and become stickier. Microearthquakes ("icequakes") induced by tidal flexure and propagating from the Ross Ice Shelf up the stagnating part of Ice Stream C were linked to cyclic lubrication of sticky spots.

I conclude my review with an historical perspective. That the West Antarctic ice sheet was largely grounded below sea level on the Antarctic continental shelf was first recognized by Harry Wexler and by Charles Bentley and Ned Ostenso (Bentley and Ostenso, 1961; Wexler, 1961). They speculated on how such an ice sheet could have formed. In 1962, John Hollin suggested that the Antarctic ice sheet advanced and retreated across the Antarctic continental shelf in response to lowering and rising sea level caused by advance and retreat of Northern Hemisphere ice sheets (Hollin, 1962). By 1968, George Denton and Richard Armstrong found evidence that an ice sheet had formerly grounded in the Ross Sea and had invaded the Dry Valleys, a possibility first suggested by Robert Falcon Scott (Denton and Armstrong, 1968). Also in 1968, John Mercer found evidence from outlet glaciers through the Transantarctic Mountains that the West Antarctic ice sheet had not only been much larger than at present, but it also may have largely collapsed, possibly in the Sangamon, with former advances and retreats occurring in the Ross Sea (Mercer, 1968a, b). He subsequently defined ice sheets grounded below sea level as "marine ice sheets" and he identified the West Antarctic ice sheet as the only remaining Quaternary marine ice sheet (Mercer, 1970). In 1970, Gordon Robin and colleagues, using the new radar sounding technology, identified five ice streams that drained the West Antarctic ice sheet and supplied the Ross Ice Shelf. They named these Ice Streams A through E (Robin and others, 1970b). Ice Stream C was described as a "pseudo ice shelf" on a watery bed (Robin and others, 1970a), a view that retains credibility today. In 1972, Henry Brecher and Gilbert Dewart measured snow accumulation rates and ice thicknesses along the 157 km length of the Byrd Station Strain Network (BSSN), which was constructed almost parallel to an ice flowline from Byrd Station (80° S, 120° W) to the West Antarctic ice divide by the United States Geological Survey. Ian Whillans remeasured the strain network and, using these data, showed that the ice surface was lowering at an increasing rate downslope along the whole length of the BSSN (Whillans, 1973). This was the first direct evidence that gravitational collapse of the West Antarctic ice sheet, which had begun as sea level rose during termination of the last global Quaternary glaciation, was continuing to the present day, some 6000 years after all Quaternary ice sheets except the ones in Antarctica and Greenland had collapsed completely. Ian's discovery became the primary justification for studying the stability of the West Antarctic ice sheet, which Johannes Weertman called "glaciology's grand unsolved problem" (Weertman, 1976). Ian went on to become a primary organizer and participant in efforts to address this problem, until his untimely death at age 57 on 16 May 2001. Volume 77 in the Antarctic Research Series serves as both a progress report and as a testament to Ian, my friend and colleague throughout my glaciological career.

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REFERENCES

Bentley, C. R. and N. A. Ostenso. 1961. Glacial and subglacial topography of West Antarctica. *J. Glaciol.*, **3**(29), 882–911.

Denton, G. H. and R. L. Armstrong. 1968. Glacial geology of the McMurdo Sound region. *Antarct. J. U.S.*, **3**(4), 99–101.

Hollin, J. R. 1962. On the glacial history of Antarctica. *J. Glaciol.*, **4**(32), 172–195.

Mercer, J. H. 1968a. Antarctic ice and Sangamon sea level. *International Association of Scientific Hydrology Publication* 79 (*General Assembly of Bern 1967 — Snow and Ice*), 217–225.

Mercer, J. H. 1968b. Glacial geology of the Reedy Glacier area, Antarctica. *Geol. Soc. Am. Bull.*, **79**(4), 471–486.

Mercer, J. H. 1970. A former ice sheet in the Arctic Ocean? *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **8**(1), 19–27.

Robin, G. de Q., C. W. M. Swithinbank and B. M. E. Smith. 1970a. Radio echo exploration of the Antarctic ice sheet. *International Association of Scientific Hydrology Publication* 86 (Symposium at Hanover 1968 — *Antarctic Glaciological Exploration (ISAGE)*), 97–115.

Robin, G. de Q., S. Evans, D. J. Drewry, C. H. Harrison and D. L. Petrie. 1970b. Radio-echo sounding of the Antarctic ice sheet. *Antarct. J. U.S.*, **5**(6), 229–232.

Weertman, J. 1976. Glaciology's grand unsolved problem. *Nature*, **260**(5549), 284–286.

Wexler, H. 1961. Growth and thermal structure of the deep ice in Byrd Land, Antarctica. *J. Glaciol.*, **3**(30), 1075–1087.

Whillans, I. M. 1973. State of equilibrium of the West Antarctic inland ice sheet. *Science*, **182**(4111), 476–479.