Glaciology

Glaciochemical differentiation of air masses entering Siple Dome, West Antarctica

Paul A. Mayewski *and* Karl J. Kreutz, *Institute for Quaternary Studies, University of Maine*

Siple Dome (81^o 42'S, 148^o 48'W) is currently the site of an intense deep ice coring effort by the United States that is intended to yield a detailed multi-millennial paleoenvironmental record for coastal West Antarctica. High-resolution glaciochemical analysis of this ice core has proven useful in various ways, for example: the identification of annual layers (Kreutz et al. 1999), unique event histories such as volcanic records (Kreutz et al. 1999) and changes in accumulation rate (Kreutz et al. in preparation-a). Glaciochemical measurements also provide a record of the atmospheric circulation systems that can impact a region. In this paper, we use glaciochemical measurements to discriminate among the types of air masses that have affected the Siple Dome region over the past 200 years.

Our rationale for differentiating air masses is based on the following. The chemical composition of an individual air mass can provide a fingerprint revealing the history of the source area over which the transporting air mass passed (Mayewski, Lyons, and Ahmad 1983). Therefore, atmospheric circulation systems can be labeled by identifying the source areas that contribute to their chemistry. In the simplest case, marine versus continental air masses can be differentiated based on the identification of sea salts [such as sodium chloride (NaCl)] versus continental dusts [such as calcium sulfate ($CaSO_4$)], respectively, in the chemistry of these air masses. More complex atmospheric circulation patterns can be differentiated by adding other unique chemical tracers.

The Siple Dome glaciochemical record is a highly resolved (8-10 samples per year). Continuously-sampled time series of the major chemical species found in glacial ice and snow [(sodium (Na), potassium (K), ammonium (NH4), calcium (Ca), magnesium (Mg), sulfate (SO4), nitrate (NO3) and chloride (Cl)] represent over 95 percent of the soluble ionic species comprising the atmosphere. As such, this record affords a variety of chemical combinations that can provide relatively unique tracers for air masses. The sources of the chemical species deposited in polar snow and ice are generally well known, and have been summarized in numerous papers (for example, Whitlow, Mayewski, and Dibb et al. 1992; Legrand and Mayewski 1998).

The statistical methods that we use to develop proxies for atmospheric circulation from our glaciochemical series are similar to standard procedures used to investigate the physical associations within, and between, oceanographical and meteorological records. Briefly described, the empirical orthogonal function (EOF) decomposition provides objective representations of multivariate data by analyzing the covariance structure of its variates (Peixoto and Oort 1992). Results from EOF analysis on Siple Dome ice core data are presented in the table. Components of the EOF, which explain a large proportion of the variance (approximately 10 percent or more), usually have an important physical significance (Piexoto and Oort 1992). On the basis of this assumption, we examine the first four EOFs, which account for approximately 84 percent of the total variance in the ion series.

Empirical orthogonal function (EOF) analysis for the last 200 years of the Siple Dome record.

Variance explained by each EOF mode (%)				
	EOF1	**EOF2**	**EOF3**	**EOF4**
	45.42	17.36	12.97	8.65
Variance decomposition (%)				
Species				
Na	77	4	1	2
NH_4	19	48	0	0
K	70	4	0	3
Mg	68	2	4	0
Ca	29	3	16	51
Cl	80	5	0	4
NO_3	7	1	81	9
SO_4	10	69	0	0

Note: EOF analysis is a type of principal component analysis. It allows one to investigate several variables and identify associations among these variables. The first EOF (EOF1) describes how the variables are associated and how much of the variance is accounted for in this joint description. Therefore, if EOF1 explains 60 percent of variable one and 70 percent of variable two, it describes the majority of the structure of both. EOF1 is, in effect, a new time series that reveals the common association between variables one and two. EOF2 explains other associations that are orthogonal (unrelated in space or time) to EOF1.

This type of analysis is particularly useful in identifying how much of a chemical is associated with a particular wind trajectory or source region. The more chemicals inserted into the analysis potentially the more unique the fingerprint for the air mass.

EOF 1 represents 68-80 percent of the variance in the primary sea salt species (sodium, potassium, magnesium, and chloride) that comprise in the ion suite. This result supports the theory that advection of marine air masses into the region has a dominant role. Stratigraphic investigations (of sea salt input) demonstrate that these sea salt incursions are primarily a winter/spring phenomena.

EOF2 contains close to half of the variance in sulfate and ammonium. The majority of the sulfate arriving at the site is from marine biogenic sources. Ammonium sources arriving at the site are most likely produced in the marine environment, although terrestrial sources of ammonium are also be possible, particularly if air masses pass close to coastal penguin rookeries. Therefore, EOF2 characterizes the input of marine air mass invasions that travel into Siple Dome during late spring/summer.

EOF3 comprises much of the variance in nitrate. Continental scale distributions of nitrate (Kreutz and Mayewski 1999) suggest that this chemical species is most likely carried coastward (from the interior of Antarctica), coastward within nitrate-rich air masses that reside in the lower stratosphere and upper troposphere.

EOF4 contains half of the variance in the calcium series. Since this calcium is separate from the calcium variance associated with sea salts from EOF1, it is associated with non-sea salt sources and, thus, represents the input to the region of terrestrial-source air masses either from ice-free portions of Antarctica or from sites beyond Antarctica. The closest major sources of terrestrial dust to Siple Dome would be air masses that pass over the Transantarctic Mountains before entering the Siple Dome region.

The time series describing EOF1-EOF4 are currently being compared with instrumental series that describe atmospheric circulation over Antarctica. Preliminary results suggest strong associations between, for example, the Amundsen Sea Low series (Kreutz et al. 2000) and the EOF1 series that represents the history of advection of marine air masses to Siple Dome.

In summary, by investigating high-resolution, continuous time series of the major soluble ions in the atmosphere over Antarctica, it will be possible to enhance these descriptions with information on paleoclimate, that rely solely on the stable isotope-temperature relationship, to include descriptions of atmospheric circulation systems.

We wish to acknowledge our colleagues who have contributed extensively to this research, notably Mark S. Twickler, Sallie I. Whitlow, L. David Meeker, E. Meyerson, J. Souney and K. Bridges. We were assisted in the field by ASA and the Polar Ice Coring Office at the University of Nebraska, Lincoln.

References

Kreutz, K.J., and P.A. Mayewski. 1999. Spatial variability of Antarctic surface snow glaciochemistry; implications for palaeoatmospheric circulation reconstructions. *Antarctic Science,* 11 (1).

Kreutz, K.J., P.A. Mayewski, M.S. Twickler, S.I. Whitlow, J.W.C. White, C.A. Shuman, C.R. Raymond, H. Conway and N. Nereson. 1999. Seasonal variations of glaciochemical, isotopic, and stratigraphic properties in Siple Dome, Antarctica. *Sixth international symposium on Antarctic glaciology (ISAG-6), Lanzhou, China, Sept. 5-9, 1998.* Cambridge, United Kingdom: International Glaciological Society.

Kreutz, K.J., P.A. Mayewski, S.I., Whitlow, and M.S. Twickler. In preparation (a). Spatial variability and relationships between glaciochemistry and accumulation rate at Siple Dome and Marie Byrd Land.

Kreutz, K.J., I.I. Pittalwala, P.A. Mayewski, S.I. Whitlow, and M.S. Twickler. 2000. Sea level pressure variability in the Amundsen Sea region inferred from West Antarctic glaciochemical records. *Journal of Geophysical Research, D, Atmospheres*, 105(3).

Legrand, M. and P.A. Mayewski. 1997. Glaciochemistry of polar ice cores: A review. *Reviews of Geophysics* 35, 219-143.

Mayewski, P.A., W.B Lyons, and N. Ahmad. 1983. Chemical composition of a high altitude fresh snowfall in the Ladakh Himalayas. *Geophysical Research Letters* 10(1): 105-108.

Peixoto, J.P. and A.H. Oort. 1992. *Physics of Climate*. New York: American Institute of Physics.

Whitlow, S., P.A. Mayewski, and J.E. Dibb. 1992. A comparison of major chemical species input timing and accumulation at South Pole and Summit Greenland. *Atmospheric Environment 26A*(11), 2045-2054.

Snow microstructure for snow-air exchange processes at Siple Dome, Antarctica

Mary R. Albert, Geophysical Sciences Division, *U.S. Army Cold Regions Research and Engineering Laboratory*

Chemical records contained within polar ice cores have the potential to provide detailed, long-term information about past climate conditions on Earth. To fully decode the ice core record so that past atmospheric composition may be assessed, we must understand the processes by which atmospheric chemistry signals are recorded in snow and changed in time as the snow is buried and compressed into ice. The purpose of this project is to determine the nature of the physical processes in the near-surface snow and firn that affect transport and exchange among the atmosphere, snow, and firn at the ice-coring site at Siple Dome, Antarctica. The processes depend both upon the forcing from the atmosphere and upon the physical characteristics of the snow and firn. In this paper, we outline the research and provide examples of the microstructure.

Surface processes including diffusion, advection by air flow within the snow, and radiation penetration control heat and mass transfer and chemical transport within the snow. Diffusion occurs in all porous media, and represents a slow mixing process; in general, diffusion in snow is driven by temperature and by concentration gradients. Wind can move air within the near-surface snow, causing more rapid chemical transport and greater exchange than diffusion (Albert 1996). This ventilation of the snow affects chemical composition and exchange within the snow (Waddington et al. 1996; McConnell et al. 1998). Radiation affects energy exchange at the surface, and solar radiation penetration into the snow causes photolytic reactions. We are conducting calculations of energy exchange at the surface using our measurements of solar and longwave radiation together with measurements of air temperature, wind speed, and relative humidity obtained by the University of Wisconsin. We will use these results to model changes in the subsurface snow and firn at Siple Dome. We have also measured the surface pressure forcing by the wind that drives air movement through the snow and have measured inert tracer gases to detect advection and diffusion in the subsurface snow. The physical character of the snow is of prime importance since it controls the extent to which these processes can occur.

Snow is a layered porous medium. The layering is caused by different depositional events (Alley 1988) and can result in snow with very different properties even in adjacent layers. In snow pits and from firn cores at Siple Dome, we have measured stratigraphy, density, permeability, and microstructural characteristics down to a depth of 20 m. We have found that the physical characteristics are strongly layer dependent. Permeability is a property of porous media that controls transport, and it is a measure of the interconnected pore space. At Siple Dome, we have found that the permeability generally *increases* with depth down to 3 m and decreases below that. The lowest permeability that we measured in the top 10 m was measured in the surface windpack.

The microstructure has been characterized by crystal photography and thick-section analysis. Transport within the snow and firn is most strongly dependent upon the characteristics of the pores between the snow crystals; the thick-section images provide insight and statistical information on the nature of the interconnected pore space, which varies dramatically as a function of layer type and depth. Snow density has historically been used as a descriptor of snow, and it is sometimes assumed that lower-density snow will have higher permeability. Our measurements show that this is often not the case. As an example, figure 1 shows a thick section image of two firn samples, each at the same scale. The higher density sample (figure 1a) was taken from approximately 2 m depth in the firn. It has a density of 430 kg/m^3 and a measured permeability of 29 x 10^{-10} m^2. In contrast, the lower-density (212 kg/m^3) wind-packed snow (figure 1b) has a lower permeability, 10 x 10^{-10} m^2. Permeability is closely related to the nature of the interconnected pore space.

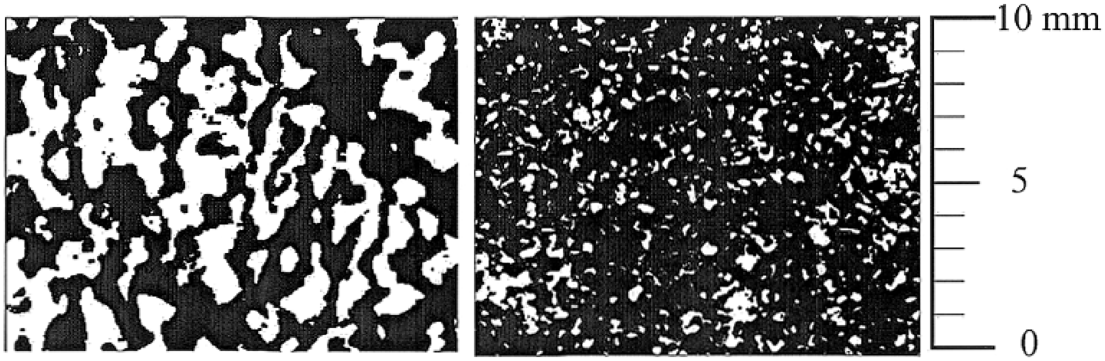


Figure 1. Images from thick sections of snow microstructure: a) density = 430 kg/m^3, equivalent sphere radius = 0.45 mm, mean pore intercept = 0.66 mm b) density = 212 kg/m^3, equivalent sphere radius = 0.13 mm, mean pore intercept = 0.58 mm. Both images are shown on the same scale.

Layering and the nature of the interface between layers also affects transport within the snow (Albert 1996), and many possible types of interfaces exist. Figure 2 depicts an interface between a coarse-grained and fine-grained snow where the layer properties near the interface are not significantly different than the properties away from the interface. This sample was taken from approximately 80 cm below the snow surface. Figure 3 shows an interfacial layer one crystal thick that separates two layers of very similar microstructure; this sample was taken approximately 40 cm below the snow surface. In this case, the layer of single crystal thickness may have been created by solar effects before the layer was buried.

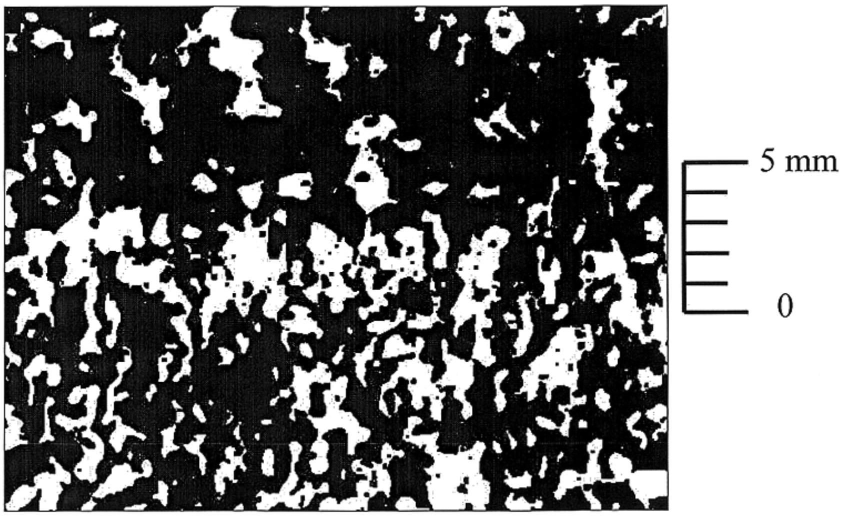


Figure 2. Thick-section image of a snow-layering interface with a smooth transition.

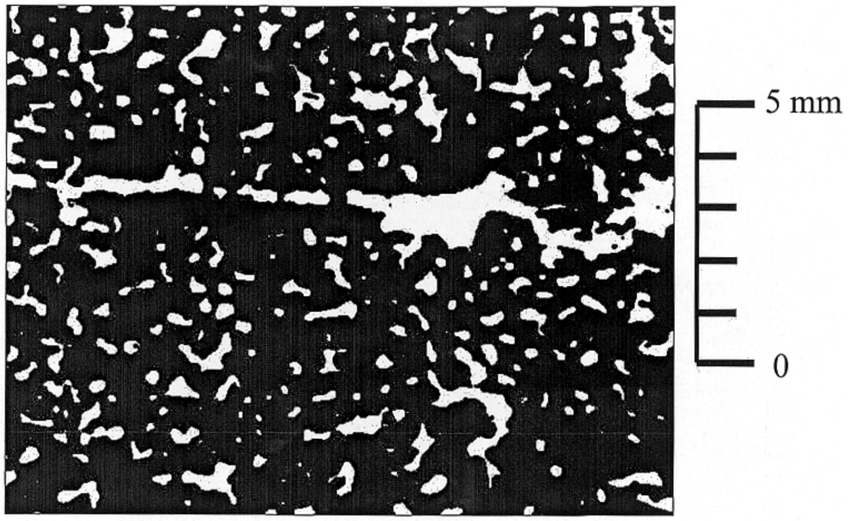


Figure 3. Thick-section image of a buried ice layer of single crystal thickness.

Thick-section imaging of microstructure allows quantitative statistical information about the nature of the snow grains and pore space that would be very difficult or impossible to determine otherwise. We are currently relating information from thick sections to measurements of permeability, in order to develop a predictive model of firnificatin. We are also using the snow property measurements in our model calculations of heat, mass, and chemical transport within the snow and firn.

I thank my field partner, NSF-REU student Edward "Ted" Shultz, for his enthusiasm and hard work, both at Siple Dome and at CRREL. Bert Davis provided good advice on thick-section processing and imaging. Gina Luciano, a Dartmouth

student participating through the Women in Science Program, is providing conscientious and capable image processing and cold-room assistance. I thank the Polar Ice Coring Office, the WAISCORES Science Coordination Office, and Antarctic Support Associates for field support. This research was supported by National Science Foundation grant OPP 95-26601.

References

Albert, M.R. 1996. Modeling heat, mass, and species transport in polar firn. *Annals of Glaciology*, 23, 138-143.

Alley, R.B. 1988. Concerning the deposition and diagenesis of strata in polar firn. *Journal of Glaciology*, 34 (108), 283-290.

McConnell, J.R., R.C. Bales, R.W. Stewart, A.M. Thompson, M.R. Albert, R. Ramos, 1998. Physical based modeling of atmosphere-to-snow-to-firn transfer of H_2O_2 at South Pole. *Journal of Geophysical Research*, 103(D9), p.10, 561-10,570.

Waddington, E.D., J. Cunningham, S. Harder 1996. The effects of snow ventilation on chemical concentration. In *Chemical Exchange Between the Atmosphere and Polar Snow*, NATO Advanced Science Institutes Series ASI Series, vol. 43, E.W. Wolff and R.C. Bales, eds., Springer-Verlag, New York, p. 403-452

Changes in the Filchner-Ronne Ice Shelf Since 1957

John C. Behrendt, *Institute of Arctic and Alpine Research, University of Colorado, Boulder and U.S. Geological Survey, Denver*

Ted. A. Scambos, *National Snow and Ice Data Center, CIRES, University of Colorado, Boulder*,

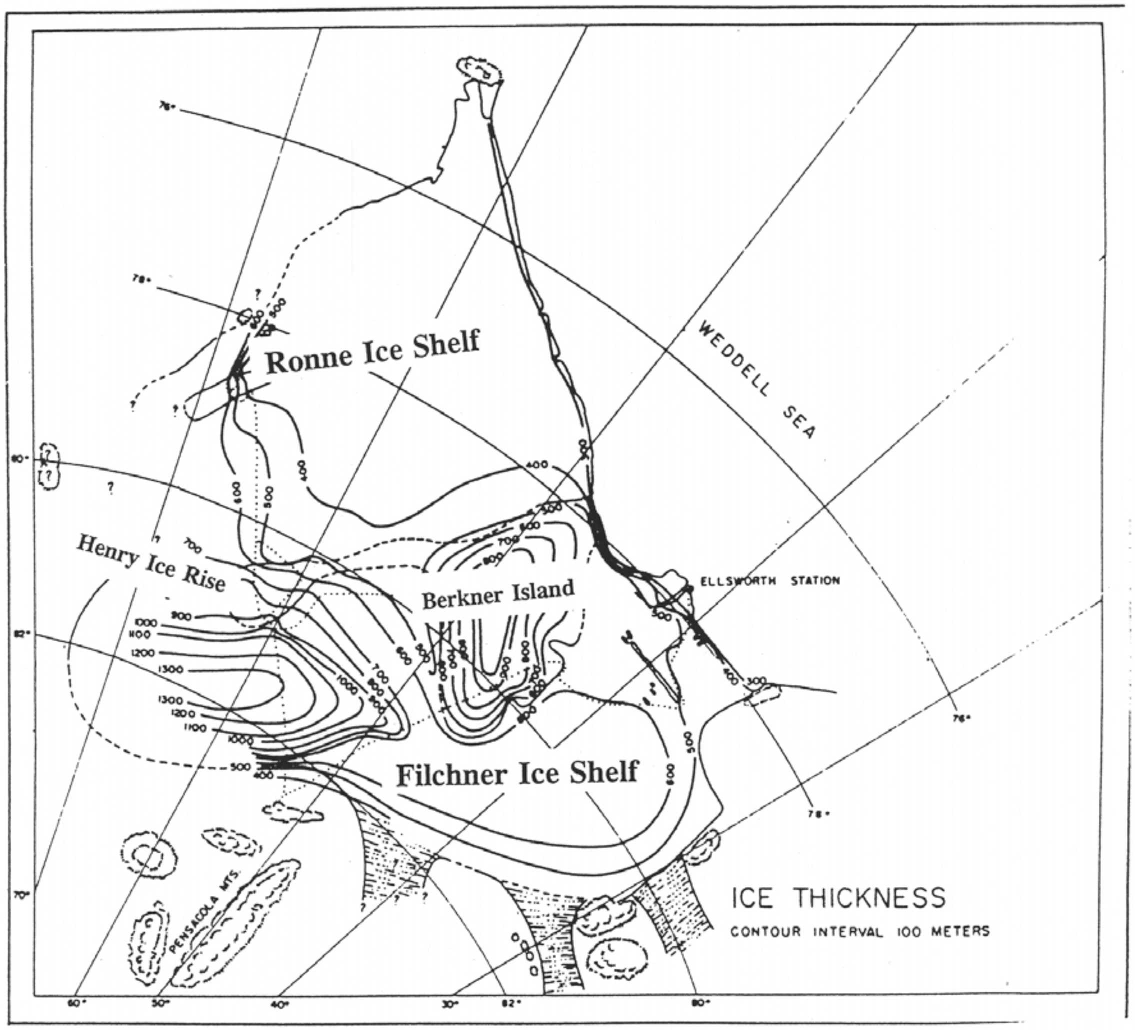
Nolan B. Aughenbaugh, *Department of Geology, University of Mississippi*

The Filchner Ice Shelf Traverse of 1957-1958 (International Geophysical Year) made the initial glaciological and geophysical observations of the Filchner-Ronne Ice Shelf (FRIS) on an oversnow traverse that acquired (among various data) surface elevation and seismic reflection determinations of ice-shelf thickness and depth to bedrock. In 1965-1966, the U.S. Geological Survey made seismic reflection measurements of ice-shelf thickness and depth to bedrock southwest of the Filchner Ice Shelf Traverse in the area south of Berkner Island-Henry Ice Rise (Behrendt et al. 1974). However, these sparse surveys remained the only coverage until the 1994-1995 seismic traverse of Johnson and Smith (1997). We compare this recent data set with the earlier data and infer measurable thinning of the ice shelf (greater than or equal to 50 m) since the 1957-1958. Figure (modified only by addition of later accepted names of features) shows the ice thickness as known from 1957-1958 measurements collected by the Filchner Ice Shelf Traverse (Behrendt 1962a and b) in this only partially explored area at the time.

Ideally, we would compare seismic reflection soundings at the same locations, but the seismic data are not located in the same positions in the 1957-1958 and 1994-1995 surveys. The 1957-1958 seismic measurements (Behrendt 1962b) of ice-shelf thickness were used to control calculations of ice-shelf thickness (Behrendt 1962b) from barometric elevations assuming hydrostatic equilibrium for floating ice over a broad area of the Filchner-Ronne Ice Shelf.

The figure shows a maximum ice-shelf thickness of 1,300 m south of Henry Ice Rise, the result of ice entering the Filchner-Ronne Ice Shelf System from the East Antarctic Ice Sheet via the Foundation Ice Stream (not shown). Direct comparison of the 1957-1958 (Behrendt 1962a and b) and 1994-1995 (Johnson and Smith 1997) contour maps of ice-shelf thickness show the greatest thickness of 1,100 m in the same area in the 1994-1995 data. The apparent thinning indicated is 200 m in the intervening 37 years.

We assume that the errors are solely in the 1957-1958 contour map because of the errors in barometric elevation used to calculate the floating ice thickness (figure). However, the apparent 200-m thinning must be greater than any possible error we can identify. We conservatively estimate a minimum thinning of 50 m from 1957-1958 to 1994-1995.



Ice thickness map of Filchner-Ronne Ice Shelf Area as mapped by Filchner Ice Shelf Traverse in 1957-58 (International Geophysical Year) modified from Behrendt, (1962a). Tabulated data are in Behrendt (1962b). The area was only partially explored at that time.

As can be seen from the figure, the profile along a flow line in the Filchner Ice Shelf from the 1,300 m contour to about 200 m at the ice front in the Weddell Sea shows a dramatic thinning almost certainly due to bottom melting. Using these data and strain measurements made in 1957-1962 (Lisignoli 1964), Behrendt (1968) estimated several meters of bottom melting per year in from the ice front to about 100 km.

Surface and aircraft observations made on the Filchner Ice Shelf Traverse showed a low snow-ice topographic ridge connecting Berkner Island to Henry Ice Rise. This ridge was called Malville Peninsula in early papers (Neuburg et al 1959; Behrendt 1962b). Malville Peninsula (more properly called "ice rumples" in present terminology) was separated from the approximately 1,300-m thick ice shelf to the south by a 50- to 100-km long zone of linear subparallel crevasses that prevented access. By the time the first nonclassified satellite data were available about 1970, Malville Peninsula was not apparent. It was assumed that the 1957 interpretation was in error. However, we now believe this feature has vanished due to ice-shelf thinning. A U.S. Government mission in 1957-1958 put in topographic ground control and trimetrigon areal photography in the area for a classified satellite mission (Behrendt 1998). In 1995, 1963-declassified intelligence satellite photography (DISP) was made available. These photographs show no evidence of the Malville Peninsula indicating that if ice rumples had been in this area had been in existence in 1957-1958 they had disappeared by 1963.

This work was supported by the U.S. Geological Survey and various grants from the National Science Foundation over the past 40 years.

References

Behrendt, J.C. 1962a. Geophysical and glaciological studies in the Filchner Ice Shelf area of Antarctica, *Journal of Geophysical Research,* 67, 221-234.

Behrendt, J.C. 1962b. Summary and Discussion of the Geophysical and Glaciological work in the Filchner Ice Shelf Area of Antarctica, *Geophysical and Polar Research Center Research Report No. 62-3*. University of Wisconsin, 66p.

Behrendt, J.C. 1968. The structure of the Filchner Ice Shelf and its relation to bottom melting, *ISAGE Symposium*, Hanover, 488-496.

Behrendt, J.C. 1998. *Innocents on the Ice; A Memoir of Antarctic Exploration, 1957*. Boulder, Colorado: University Press of Colorado, 428p.

Behrendt, J.C., J.R. Henderson, L. Meister, and W.L. Rambo. 1974. *Geophysical and glaciological investigations of the Pensacola Mountains and adjacent glacierized ares of Antarctica*, United States Geological Survey Professional Paper, No. 844, 28p.

Johnson, M.R. and A.M. Smith. 1997. Seabed topography under the southern and western Ronne Ice Shelf derived from seismic surveys, *Antarctic Science*, 9(2), 201-208.

Lisignoli, C.A. 1964. Movement of the Filchner Ice Shelf, Antarctica, *Transactions American Geophysical Union,* 45, (International Geophysical Bulletin), 391-397.

Neuberg, H.A.C., E.Thiel, P.Walker, J. Behrendt, and N. Aughenbaugh. 1959. The Filchner Ice Shelf, *Annals Association of American Geographers,* 49 (2) 110-119.