

Extensive storage of basal meltwater in the onset region of a major West Antarctic ice stream

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ABSTRACT

A major meltwater body exists beneath a tributary of Bindschadler Ice Stream, West Antarctica, in a region where subglacial lakes have not been mapped but near where rapid vertical motion of the ice sheet surface has suggested shifting of a subglacial water body. The water is trapped by a local reversal in ice-air surface slope arising from ice flow over variable basal topography and from the positive feedback of basal lubrication from the trapped water. Strong variations in the water content of the sediments upglacier of the water body arise from a similar process. These results are revealed by a novel application of the amplitude variation with offset (AVO) seismic technique. The existence of such water bodies and of the strong spatial variation in subglacial sediment properties is not captured in current models of subglacial hydrology, lubrication of ice stream motion, and sediment transport.

Keywords: subglacial meltwater, West Antarctica, ice streams, seismic amplitude.

INTRODUCTION

Large changes in the Earth's ice sheets have been observed, many of which have been attributed to basal processes, including the near-stoppage of Kamb Ice Stream (Retzlaff and Bentley, 1993) and continued deceleration of Whillans Ice Stream (Joughin et al., 2005) in West Antarctica, as well as the acceleration of many other ice streams and outlet glaciers in Antarctica and Greenland (e.g., Payne et al., 2004; Rignot and Kanagaratnam, 2006). Taken together, these changes are contributing to sea-level rise (Alley et al., 2005), and may have implications for the future (e.g., Mercer, 1978). However, our understanding of key basal processes influencing this dynamic behavior is incomplete, and data collection in glaciated regions remains difficult.

Glaciers move by deformation within the ice, often enhanced by sliding between the ice and its bed or deformation within that bed. Sub-freezing sliding is very slow (Cuffey et al., 1999). Thawing allows faster sliding, but the change may be small for glaciers on sufficiently rough bedrock (e.g., Weertman, 1964). Smoothing of the bed by water or soft sediment can greatly increase sliding velocity, with deformation in the sediment contributing in many cases.

Conceptual models of subglacial water systems have typically invoked only limited water storage, either in the lee of bedrock bumps (Walder, 1986; Kamb, 2001) or in subglacial channels or films (reviewed by Rothlisberger and Lang, 1987), with drainage balancing production when averaged over an appropriate subannual interval. Deviations from this behavior were generally considered special cases, e.g., lake formation from heat of subglacial volcanoes (e.g., Nye, 1976), or temporary interruption of meltwater drainage leading to increased water storage, enhanced basal lubrication, and sudden but temporary ice flow acceleration (surge; Kamb et al., 1985).

The steady-state view of sub-ice-sheet hydrology was challenged by Gray et al. (2005) and Wingham et al. (2006); both observed vertical motions of the ice surface in Antarctica that were too rapid to be explained by ordinary ice flow, and both interpreted these as the signature of rapid motion of subglacial waters from one site of enhanced storage to another. Wingham et al. (2006) observed vertical motion over known lakes near

an ice flow divide in East Antarctica, while the observations of Gray et al. (2005) were in the onset region of Bindschadler Ice Stream, West Antarctica, where subglacial lakes were not previously known and where features normally associated with such lakes were absent (Siegert et al., 2005). However, the regions of water storage inferred by Gray et al. (2005) had locally reversed ice-air surface slope, where reduced basal hydrologic gradient would favor water storage (Alley et al., 2006).

The onset of streaming ice flow, and its ability to migrate if perturbed, are important in assessing future behavior of the Earth's ice sheets. Subglacial sediment cover can be a source for till beneath ice streams, which increases basal lubrication and possibly deforms, resulting in rapid motion (Anandakrishnan et al., 1998; Bell et al., 1998; Studinger et al., 2001; Peters et al., 2006). Abundant, high-pressure basal water is also a necessary condition for the initiation of fast ice flow.

Here we apply the amplitude variation with offset (AVO) seismic technique to a tributary of Bindschadler Ice Stream (Fig. 1), just downglacier of the inferred water pocket of Gray et al. (2005), to investigate the presence, characteristics, and distribution of subglacial sediments and water. Our results indicate the presence of a 5–10-m-thick, kilometer long or longer subglacial water pocket, as well as strong spatial variations in nearby basal conditions.

DATA AND ANALYSIS

We conducted a high-resolution seismic reflection experiment along a 16.7-km-long line following the centerline of a tributary to Bindschadler Ice Stream near its main trunk (Peters et al., 2006) (Fig. 1) during the 2002–2003 Antarctic field season. In addition, we collected global positioning system measurements of surface elevation along that same line. The site was chosen to sample fast-flowing ice while avoiding crevassed areas, and to provide geophysical context for the motion surveys of Price et al. (2002). The seismic data show variations in ice thickness, bed reflectivity, and internal bed structure along the profile (Fig. 2).

The polarity and amplitude of a seismic reflection depend on the contrast in elastic properties across an interface. In AVO analysis, variations in

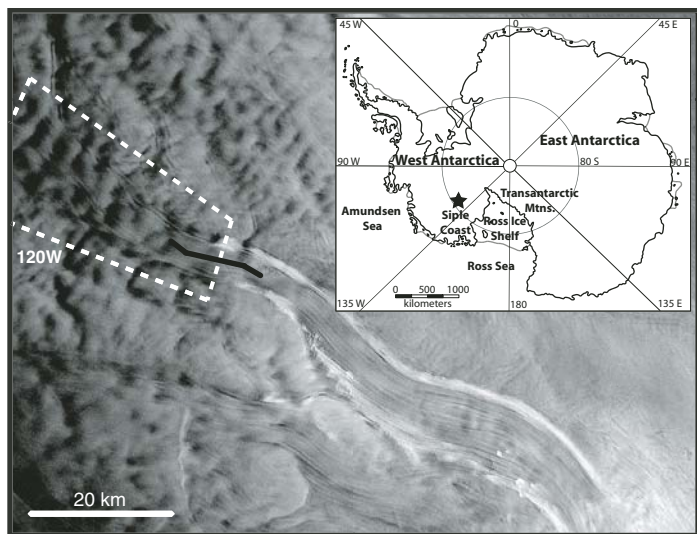


Figure 1: RADARSAT image of the upper reaches of ice stream D (Liu et al., 2001), with black line highlighting location of seismic reflection experiment. Dashed box marks location of the study region of Price et al. (2002) and Gray et al. (2005). Inset is a map of Antarctica with the study area indicated by a star.

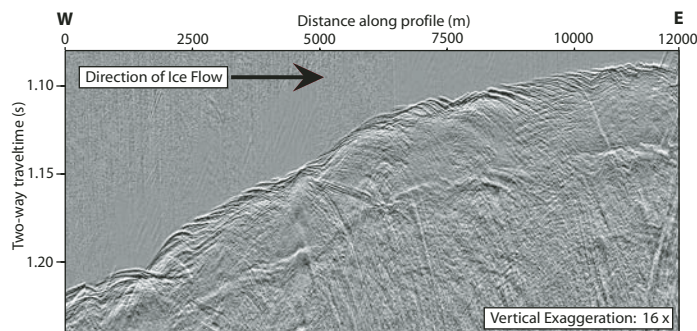


Figure 2: Processed seismic section of the central straight segment from seismic profile in Figure 1. Upper reflection is ice bottom reflection, and reflection ~0.05 s below is a ghost reflection. The main observation to note is the variability in reflectivity of the ice-subglacial bed interface along the profile. No migration was performed on the data, as the average dip of the bed is $<2^\circ$.

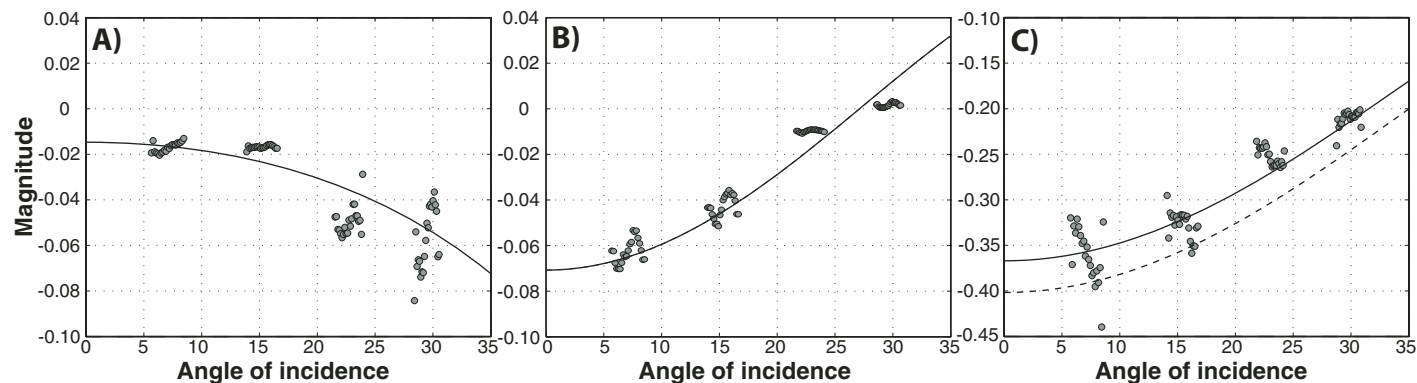


Figure 3: Bed reflectivities for different angles of incidence measured at three locations along the seismic profile. Gray dots are our corrected amplitude measurements, and solid curves represent the best-fit reflectivity models to these data. Physical properties of the ice and the subglacial materials that were used to calculate these curves are in Table 1. Note the difference in vertical scale between Figures 3A and 3B and Figure 3C. A: Measurements from region between 9900 m and 10,000 m in Figure 2. Best-fit curve is typical of low-porosity (30% or lower) till, which we refer to as stiff till. B: Measurements from region between 7600 m and 7700 m in Figure 2. Best-fit curve is typical of high-porosity (40+%) till, which we refer to as soft till. C: Measurements from region between 11,400 m and 11,500 m in Figure 2. Solid curve is the best-fit curve, and dashed curve is representative of pure water beneath the ice. We interpret this response to be that of a subglacial water pocket.

the reflectivity of a seismic reflector over a range of incidence angles can be used to determine the change in elastic properties (seismic velocity and density) across that interface via the Zoeppritz equations (e.g., Aki and Richards, 1980). Because the elastic properties of ice are well known and nearly constant (Table 1), AVO measurements can be used to determine the elastic properties of the bed. The compressional wave (P-wave) velocity of the subglacial layer is most sensitive to its density, whereas shear wave (S-wave) velocities are sensitive to frame rigidity. S-wave velocities are high in well-consolidated materials, low in soft, deformable sediments, and zero in water (Blankenship et al., 1986).

Much previous work in glaciated regions has used normal incidence and near-normal incidence experiments to study bed character (e.g., Bentley, 1971; Atre and Bentley, 1993, 1994; Smith, 1997; Anandkrishnan, 2003; King et al., 2004). Other studies have used larger incidence angles to study temporal variations related to subglacial water discharge (Richards, 1988; Nolan and Echelmeyer, 1999a, 1999b). Despite prior successes, determination of absolute reflectivity through normal incidence work remains difficult and limited because of uncertainties in source strength, receiver coupling, and attenuation in the ice, unless good-quality data are acquired. In addition, near-normal incidence reflectivity is relatively insensitive to S-wave velocity, and therefore cannot be used to determine fluid content accurately. However, the reflection coefficient becomes sensitive to S-wave velocity as the incidence angle at the bed increases, allowing AVO to more accurately characterize the subglacial bed.

We measured reflection amplitudes from common midpoint (CMP, a series of reflections from the same point along the bed) gathers of the ice bottom reflection for incidence angles ranging from normal incidence to $\sim 35^\circ$ in order to calculate the seismic properties of the basal layer (Fig. 3). In each case, we combined several CMP gathers, averaging properties across 100 m sections of the bed. For accurate characterization using AVO analysis, the basal layer must be thicker than $1/4$ wavelength, which is ~ 5 m for soft till. Analysis of traveltimes in the normal incidence data (Fig. 2) showed that ~ 5 – 20 m of unconsolidated material separates ice from bedrock, sufficient for AVO analysis.

The difference in S-wave velocity between stiff tills ($<30\%$ porosity, $V_s \sim 1000$ m/s), soft tills ($\sim 40\%$ porosity, $V_s < 200$ m/s), and water ($V_s = 0$ m/s) allows sensitive discrimination of subglacial properties using AVO analysis (Fig. 3). A lower porosity, stiff till has a negative reflection coefficient at small angles of incidence that becomes increasingly negative at larger angles of incidence (Fig. 3A). For a higher porosity, soft till, the reflectivity is negative at small incidence angles and becomes positive

with increasing angle of incidence (Fig. 3B). The reflectivity of water is strongly negative (an order of magnitude larger amplitude than either till case) at small angles of incidence and becomes progressively less negative at greater angles of incidence (Fig. 3C).

Table 1 and Figure 4 display the results along our seismic profile. Bed conditions vary strongly, with soft till and stiff till regions alternating along most of the profile, and a large (at least 1 km long; it may extend farther downstream) and deep (5–10 m) water pocket at the downstream end. Figure 4 also shows surface elevation and hydrologic potential at the bed, calculated assuming constant offset between ice overburden pressure and water pressure.

DISCUSSION

The gradient in basal hydrologic potential is controlled primarily by the ice-air surface slope; bed slope is ~ 10 times less important. Along our survey line, surface slopes exert the primary control on hydrologic potential, but bed slopes cannot be ignored. For steady water drainage between ice and till (Kamb, 2001), a distributed water system (colloquially, a film) will be thinner and less extensive in regions of steeper potential gradient, and water will tend to flow around local potential highs (a local flow component transverse to our survey line, which regionally follows subglacial water flow). Because lubrication of ice flow increases with water-film thickness or extent, which would increase with water supply, regions of locally high potential or steep potential gradient along our line are expected to reduce lubrication and increase local basal shear

stress. In turn, higher basal shear stress may strengthen and dewater till by slightly lowering basal water pressure relative to the ice overburden pressure (Robin and Weertman, 1973). At the clast scale, higher basal shear stress gives larger fluctuations in ice-bed contact pressure, and water flows in the lowest pressure regions available while avoiding the higher pressure ones. By the same logic, regions of low hydrologic potential or potential gradient will tend to have soft, lubricating till, or water pockets providing efficient lubrication.

Consistent with these considerations, Figure 4 shows low-water-content till (“stiff” till) occurring where the hydrologic potential is high or has a steep gradient. Higher-water-content till (wet, “soft” till) occurs in regions of lower hydrologic potential or small to reversed potential gradient, as does the water pocket. Although this correspondence is very good, it is not always exact. The shortest wet till region on our line begins at ~ 7500 m, where the potential gradient reverses, but extends slightly downglacier into a region where the hydrologic gradient has returned to normal and is steepening. We currently attribute this minor difference to our lack of transverse data, and to the fact that our tripartite stiff till–soft till–water classification cannot capture the full complexity of the system.

Our results suggest interesting feedbacks in the subglacial regime, in agreement with Price et al. (2002), who inferred transverse bands of low and high basal shear stress along the same tributary of Bindschadler Ice Stream. Ice flow causes the surface slope to reflect basal topography and lubrication (e.g., Whillans and Johnsen, 1983), with the surface steepening to drive ice flow across bedrock highs or less lubricated regions. The resulting surface slopes largely control the hydrologic potential and thus the basal lubrication. Notably, the nature of the flowing ice causes some wavelengths of basal topographic or lubrication variations to be transmitted to the surface more efficiently than others. Along our 12 km survey, for example, the surface slope exhibits three broad bands over a horizontal distance equivalent to about six times the ice thickness (~ 2 km), similar to the expectations from the theory of Whillans and Johnsen (1983). If subglacial erosion increases with increasing basal shear stress (e.g., Alley et al., 1997), then these couplings may provide a mechanism by which glacier erosion amplifies certain topographic wavelengths (Whillans and Johnsen, 1983).

The stored subglacial water along our profile is of special interest. Gray et al. (2005) observed a dipole of vertical motion (sinking ~ 30 cm over a region a few kilometers wide at an upglacier site, and rise of a similar-sized “bull’s-eye” by as much as 50 cm ~ 10 km downglacier during a 24 day interval, with an estimated volume transfer of $\sim 10^7$ m³). Gray et al. (2005) suggested that rapid water transfer from one storage site to another had occurred, although they lacked direct observations of water. Our discovery of a large water body in the region, along with our observed stiff till–soft till conditions and the banding of basal shear stress inferred by Price et al. (2002), may relate to the movement of water at the bed, as suggested by Gray et al. (2005).

The water depth we observed is much greater than the vertical displacement observed by Gray et al. (2005) (our observations and theirs are not exactly at the same location, nor at the same time; achieving such surface- and space-based observation of a still-unpredictable event is highly unlikely in the near future). This suggests the possibility that only partial drainage of the subglacial pocket occurred, consistent with outburst flood behavior elsewhere (e.g., Nye, 1976). Drainage events would cause much basal lubrication if water drainage were widely distributed, but little lubrication if the flow occurred in narrow channels. As yet, we have only the limiting value of 24 days on the rate of drainage, with no information on the pattern. Steady-state drainage of subglacially derived waters is nearly incapable of moving sediment (e.g., Alley et al., 1997). Release of stored subglacial water allows orders of magnitude more sediment transport and generation of water-washed sediments, but the very broad constraints on flow velocities still leave great uncertainties.

TABLE 1. SEISMIC PROPERTIES OF THE ICE AND SUBGLACIAL BED OBSERVED ALONG THE SEISMIC PROFILE

Bed lithology	P-wave velocity (m/s)	S-wave velocity (m/s)	Density (kg/m ³)
Ice-known	$3800 \pm 10^*$	$1840 \pm 10^*$	$917^†$
Stiff till (Fig. 3A)	1800 ± 150	1000 ± 100	1900 ± 150
Soft till (Fig. 3B)	1650 ± 150	200 ± 50	1750 ± 150
Water-observed (Fig. 3C)	1550 ± 100	50 ± 50	1100 ± 100
Water-known (Fig. 3C)	$1498^†$	0	$1000^†$

*Peters et al. (2006)

†CRC Handbook of Chemistry and Physics (Lide, 1995)

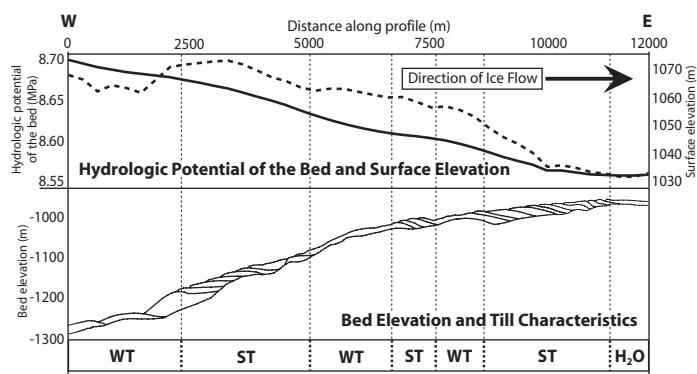


Figure 4: Interpretation of basal conditions of ice stream D along the seismic profile. Upper plot gives surface elevation (solid curve) and bed hydrologic potential (dashed curve) along the profile. Lower image is interpreted seismic section. Thickness of till ranges from ~ 5 m to 20 m in this region. A cycle of soft till (or wet till, labeled WT) to stiff till (labeled ST) sections of the bed is observed, with a water pocket present in the far downstream reaches of the profile (labeled H₂O). Wetter regions of bed are in regions of low surface elevation gradient and decreased hydrologic potential, with water pocket located in a region with negligible surface elevation gradient and an absolute low in hydrologic potential along the seismic profile. Divisions from stiff till to soft till to water were chosen from changes observed in the amplitude variation with offset (AVO) responses along the profile.

Our data show storage of a large volume of water in the onset region of a tributary of Bindschadler Ice Stream, in an area where subglacial lakes have not been previously mapped and where the hydrologic potential gradient is substantial when averaged over horizontal distances of ~10 ice thicknesses. Well-lubricated regions of water or soft till alternate with stiff till regions along flow. The soft till and water regions seem to share a common origin, with basal and topographic lows reducing the overlying slope and thus the subglacial hydrologic potential gradient, ponding water to increase basal lubrication and amplify the spatial contrast. Persistence of poorly lubricated regions helps restrain ice flow, but the existence of stored water opens the possibility that water release could increase lubrication transiently. Our results, together with those of Gray et al. (2005), show that storage and release of basal water occur beneath the West Antarctic ice streams, and have important implications for basal lubrication, sediment fluxes, erosion, and ice-flow behavior.

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REFERENCES CITED

- Aki, K., and Richards, P.G., 1980, *Quantitative seismology: Theory and methods*: New York, W.H. Freeman and Co., 573 p.
- Alley, R.B., Cuffey, C.M., Evenson, E.B., Strasser, J.C., Lawson, D.E., and Larson, G.J., 1997, How glaciers entrain and transport basal sediment: Physical constraints: *Quaternary Science Reviews*, v. 16, p. 1017–1038, doi: 10.1016/S0277-3791(97)00034-6.
- Alley, R.B., Clark, P.U., Huybrechts, P., and Joughin, I., 2005, Ice-sheet and sea-level changes: *Science*, v. 310, p. 456–460, doi: 10.1126/science.1114613.
- Alley, R.B., Dupont, T.K., Parizek, B.R., Anandakrishnan, S., Lawson, D.E., Larson, G.J., and Evenson, E.B., 2006, Outburst flooding and the initiation of ice-stream surges in responses to climatic cooling: A hypothesis: *Geomorphology*, v. 75, p. 76–89.
- Anandakrishnan, S., 2003, Dilatant till layer near the onset of streaming ice flow of ice stream C, West Antarctica, detected by AVO (amplitude vs offset) analysis: *Annals of Glaciology*, v. 36, p. 283–286.
- Anandakrishnan, S., Blankenship, D.D., Alley, R.B., and Stoffa, P.L., 1998, Influence of subglacial geology on the position of a West Antarctic ice stream from seismic observations: *Nature*, v. 394, p. 62–65, doi: 10.1038/27889.
- Atre, S.R., and Bentley, C.R., 1993, Laterally varying basal conditions beneath ice streams B and C: West Antarctica: *Journal of Glaciology*, v. 39, p. 507–514.
- Atre, S.R., and Bentley, C.R., 1994, Indication of a dilatant bed near Downstream B camp, ice stream B, Antarctica: *Annals of Glaciology*, v. 20, p. 177–182.
- Bell, R.E., Blankenship, D.D., Finn, C.A., Morse, D.L., Scambos, T.A., Brozena, J.M., and Hodge, S.M., 1998, Influence of subglacial geology on the onset of a West Antarctic ice stream from aerogeophysical observations: *Nature*, v. 394, p. 58–62, doi: 10.1038/27883.
- Bentley, C.R., 1971, Seismic evidence for moraine within the basal West Antarctic ice sheet, in Crary, A.P., ed., *Antarctic snow and ice studies II*: American Geophysical Union Antarctic Research Series, v. 16, p. 89–129.
- Blankenship, D.D., Bentley, C.R., Rooney, S.T., and Alley, R.B., 1986, Seismic measurements reveal a saturated porous layer beneath an active Antarctic ice stream: *Nature*, v. 322, p. 54–57.
- Cuffey, K.M., Conway, H., Hallet, B., Gades, A.M., and Raymond, C.F., 1999, Interfacial water in polar glaciers and glacier sliding at -17°C : *Geophysical Research Letters*, v. 26, p. 751–754, doi: 10.1029/1999GL000096.
- Gray, L., Joughin, I., Tulaczyk, S., Spikes, V.B., Bindschadler, R., and Jezek, K., 2005, Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite interferometry: *Geophysical Research Letters*, v. 32, article L03501, doi: 10.1029/2004GL021387.
- Joughin, I., Bindschadler, R.A., King, M., Voigt, D., Alley, R.B., Anandakrishnan, S., Horgan, H., Peters, L., Winberry, P., Das, S.B., and Catania, G., 2005, Continued deceleration of Whillans Ice Stream, West Antarctica: *Geophysical Research Letters*, v. 32, L22501, doi: 10.1029/2005GL024319.
- Kamb, B., 2001, The lubricating basal zone of the West Antarctic ice streams, in Alley, R.B., and Bindschadler, R.A., eds., *The West Antarctic Ice Sheet: Behavior and environment*: American Geophysical Union Antarctic Research Series, v. 77, p. 157–199.
- Kamb, B., Raymond, C.F., Harrison, W.D., Engelhardt, H., Echelmeyer, K.A., Humphrey, N., Brugman, M.M., and Pfeffer, T., 1985, Glacier surge mechanism—1982–1983 surge of Variegated Glacier, Alaska: *Science*, v. 227, p. 469–479, doi: 10.1126/science.227.4686.469.
- King, E.C., Woodward, J., and Smith, A.M., 2004, Seismic evidence for a water-filled canal in deforming till beneath Rutford Ice Stream, West Antarctica: *Geophysical Research Letters*, v. 31, L20401, doi: 10.1029/2004GL020379.
- Lide, D.R., ed., 1995, *Handbook of chemistry and physics* (76th edition): Boca Raton, Florida, CRC Press, 2624 p.
- Liu, H., Jezek, K., Li, B., and Zhao, Z., 2001, *Radarsat Antarctic Mapping Project digital elevation model, version 2*: Boulder, Colorado, National Snow and Ice Data Center.
- Mercer, J.H., 1978, West Antarctic Ice Sheet and CO_2 greenhouse effect: A threat of disaster: *Nature*, v. 271, p. 321–325, doi: 10.1038/271321a0.
- Nolan, M., and Echelmeyer, K., 1999a, Seismic detection of transient changes beneath Black Rapids Glacier, Alaska, USA: I. Techniques and observations: *Journal of Glaciology*, v. 45, p. 119–131.
- Nolan, M., and Echelmeyer, K., 1999b, Seismic detection of transient changes beneath Black Rapids Glacier, Alaska, USA: II. Basal morphology and processes: *Journal of Glaciology*, v. 45, p. 132–146.
- Nye, J.F., 1976, Water flow in glaciers: Jokulhlaups, tunnels, and veins: *Journal of Glaciology*, v. 17, p. 181–207.
- Payne, A.J., Veli, A., Shepherd, A.P., Wingham, D.J., and Rignot, E., 2004, Recent dramatic thinning of largest West Antarctic ice stream triggered by oceans: *Geophysical Research Letters*, v. 31, L23401, doi: 10.1029/2004GL021284.
- Peters, L.E., Anandakrishnan, S., Alley, R.B., Winberry, J.P., Voigt, D.E., Smith, A.M., and Morse, D.L., 2006, Subglacial sediments as a control on the onset and location of two Siple Coast ice streams, West Antarctica: *Journal of Geophysical Research*, v. 111, B01302, doi: 10.1029/2005JB003766.
- Price, S.F., Bindschadler, R.A., Hulbe, C.L., and Blankenship, D.D., 2002, Force balance along an inland tributary and onset to Ice Stream D: West Antarctica: *Journal of Glaciology*, v. 48, p. 20–30.
- Retzlaff, R., and Bentley, C.R., 1993, Timing of stagnation of Ice Stream C, West Antarctica, from short-pulse radar studies of buried crevasses: *Journal of Glaciology*, v. 39, p. 553–561.
- Richards, M.A., 1988, Seismic evidence for a weak basal layer during the 1982 surge of Variegated Glacier, Alaska, USA: *Journal of Glaciology*, v. 34, p. 111–120.
- Rignot, E., and Kanagaratnam, P., 2006, Changes in velocity structure of the Greenland Ice Sheet: *Science*, v. 311, p. 986–990, doi: 10.1126/science.1121381.
- Robin, G.D., and Weertman, J., 1973, Cyclic surging of glaciers: *Journal of Glaciology*, v. 12, p. 3–18.
- Rothlisberger, H., and Lang, H., 1987, *Glacial hydrology*, in Gurnell, A.M., and Clark, M.J., eds., *Glacio-fluvial sediment transfer: An alpine perspective*: Chichester, UK, John Wiley and Sons, p. 207–284.
- Siegert, M.J., Carter, S., Tabacco, I., Popov, S., and Blankenship, D.D., 2005, A revised inventory of Antarctic subglacial lakes: *Antarctic Science*, v. 17, p. 453–460, doi: 10.1017/S0954102005002889.
- Smith, A.M., 1997, Basal conditions of Rutford ice stream, West Antarctica, from seismic observations: *Journal of Geophysical Research*, v. 102, p. 543–552, doi: 10.1029/96JB02933.
- Studinger, M., Bell, R.E., Blankenship, D.D., Finn, C.A., Arko, R.A., Morse, D.L., and Joughin, I., 2001, Subglacial sediments: A regional template for ice flow in West Antarctica: *Geophysical Research Letters*, v. 28, p. 3493–3496, doi: 10.1029/2000GL011788.
- Walder, J.S., 1986, Hydraulics of subglacial cavities: *Journal of Glaciology*, v. 32, p. 439–445.
- Weertman, J., 1964, Glacier sliding: *Journal of Glaciology*, v. 5, p. 287–303.
- Whillans, I.M., and Johnsen, S.J., 1983, Longitudinal variations in glacial flow: Theory and test using data from the Byrd Station Strain Network, Antarctica: *Journal of Glaciology*, v. 29, p. 78–97.
- Wingham, D.J., Siegert, M.J., Shepherd, A., and Muir, A.S., 2006, Rapid discharge connects Antarctic lakes: *Nature*, v. 440, p. 1033–1036, doi: 10.1038/nature04660.

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