GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L18501, doi:10.1029/2007GL030769, 2007

Topographic and hydrological controls on Subglacial Lake Ellsworth, West Antarctica

David G. Vaughan,[1] Andrés Rivera,[2,3] John Woodward,[4] Hugh F. J. Corr,[1]
Jens Wendt,[2] and Rodrigo Zamora[2]

Received 1 June 2007; revised 31 July 2007; accepted 20 August 2007; published 19 September 2007.

[1] Subglacial Lake Ellsworth (SLE) was identified using reconnaissance data collected in the 1970s, here we present more detailed surveys. SLE lies beneath 3.2 km of ice in a subglacial valley in West Antarctica. It has an area of only ~18 km^2, is dissimilar to the large tectonically-controlled lakes beneath East Antarctica and is a strong candidate for in situ exploration. Our analysis indicates that the ice above SLE is floating on a fluid whose density is 950–1013 kg m^{-3}. This could indicate freshwater, but certainly precludes seawater, or high salt, acid, or clathrate content. The water in the lake is unlikely to be produced solely by local melt; it is more likely delivered via subglacial drainage. Our surveys show no identifiable hydrological barrier to outflow, meaning SLE is effectively full; new water entering the lake is likely balanced by outflow, which would drain into another lake that we have also identified.

Citation: Vaughan, D. G., A. Rivera, J. Woodward, H. F. J. Corr, J. Wendt, and R. Zamora (2007), Topographic and hydrological controls on Subglacial Lake Ellsworth, West Antarctica, *Geophys. Res. Lett.*, *34*, L18501, doi:10.1029/2007GL030769.

1. Introduction

[2] Subglacial lakes are important because of their effect on subglacial hydrology and ice sheet stability [*Bell et al.*, 2007]; their potential as isolated microbial habitats [*Price et al.*, 2002], and as a possible source of new palaeoclimate proxies. While large tectonically-generated lakes in East Antarctica have been the focus of many studies, evidence is emerging that there are many small subglacial lakes across much of Antarctica [e.g., *Holt et al.*, 2006]. Such lakes have attracted little attention, perhaps because they are numerous, small and unlikely to provide a long-isolated biological environment, but these factors may also imply that these lakes provide a sensible option for the first in situ exploration. Subglacial Lake Ellsworth (SLE) in West Antarctica, has been suggested as a particularly good candidate [*Siegert et al.*, 2004].

[3] Until recently, data from SLE was limited to that collected along a single airborne radar transect in 1977/78 [*Jankowski and Drewry*, 1981]. More than two decades after it was acquired these data were re-analysed. A 10-km segment of lake-like reflections was identified and the ratio between surface and ice-bottom slope in this area taken to indicate that ice was floating [*Siegert et al.*, 2004]. We present recent and more precise data that allow us to improve understanding of SLE and whether it will be a good target for in situ exploration.

2. Data Acquisition

[4] During airborne survey in 2004/05 British Antarctic Survey acquired ice-thickness and surface elevation data over SLE. Techniques used during that campaign are described elsewhere [*Vaughan et al.*, 2006], but include 150-Mhz radar ice-sounding, and surface mapping using a radar altimeter. Centro de Estudios Científicos acquired similar data in 2005/06 during an over-snow campaign (see Figure 1). Surface elevation was measured using a GPS receiver mounted on a vehicle, and ice thickness was measured using a 150-MHz radar system [*Rivera et al.*, 2006]. In both cases, the position of the GPS antenna was determined using kinematic solutions tied to temporary local base stations.

[5] Table 1 shows the results of a crossover analysis performed within and between these datasets. These mean crossover errors closely reflect the techniques employed and allow the precision of the data to be determined with substantial confidence.

[6] For the surface-elevation, the over-snow measurements (2005/06) have a lower RMS error than the airborne ones (2004/05). This reflects the lower precision with which the aircraft position could be determined with GPS (degraded by longer baselines and more rapid accelerations of the aircraft), and the use of a radar altimeter to measure the height of the aircraft above the snow surface. The bias between the surface elevations from each campaign arises from fixing surveys to different base stations.

[7] For ice-thickness, a small bias between the campaigns is due to unknown timing errors in the radar systems, different techniques used for the picking of basal echoes, potential for different degrees of off-nadir reflections (the aircraft being much higher above the snow-surface), and differing antenna radiation patterns in the two systems. Internally, however, each dataset is consistent and produces noise which is <1% of the ice thickness.

3. Topographic Context

[8] "Lake-like" echoes have been identified in many radar-sounding surveys [e.g., *Oswald and Robin*, 1973].

---

[1] British Antarctic Survey, Natural Environment Research Council, Cambridge, UK.

[2] Centro de Estudios Científicos, Valdivia, Chile.

[3] Also at Departamento de Geografía, Universidad de Chile, Santiago, Chile.

[4] School of Applied Sciences, Northumbria University, Newcastle upon Tyne, UK.

Copyright 2007 by the American Geophysical Union.
0094-8276/07/2007GL030769$05.00

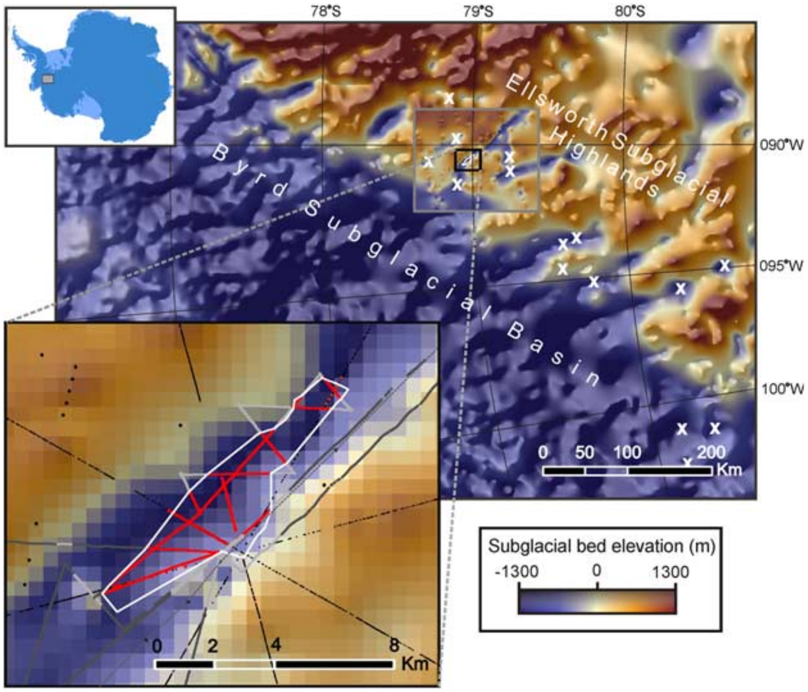

Figure 1. Bed elevation in the vicinity of Subglacial Lake Ellsworth close to 79°S 90°W (perimeter shown in white). The location of other lake-like reflectors identified in the 2004/05 survey are indicated by white crosses. Inset shows the distribution of data from 2004/05 (black lines), 2005/06 (grey lines), and earlier surveys (black dots, the 1977/78 flight is highlighted by dashed line). 2004/05 and 2005/06 data over-printed with red where lake-like reflectors were observed. The grey box shows the extent of Figure 4.

They are characterized as being consistently strong and with low along-track variability indicating a relatively flat reflecting surface. Such echoes appear in radar data from both new surveys (Figure 2) beneath ~3.2 km of ice, over an elongated area roughly parallel to the original 1977/78 flight-track (Figure 1). Profiles across the lake indicate a maximum width of ~2.7 km, and a total area of ~18 km^2, rather less than the 100 km^2 suggested by *Siegert et al.* [2004].

[9] The bed topography around SLE (Figure 1) shows that it lies in a topographic trough, one of several subglacial valleys that terminate on the flanks of the Byrd Subglacial Basin (BSB). Similar lake-like reflectors appear in neighbouring subglacial valleys (Figure 1), including one 15 km down-ice-flow from SLE on the flanks of the BSB. *Vaughan et al.* [2006] suggested that these valleys were formed by small glaciers, that sat at the margin of a smaller ice cap that once existed over Ellsworth Subglacial Highlands, but drained into open water that occupied BSB. If that interpretation is correct, and these subglacial valleys were formed primarily by erosion, and have no tectonic origin, there is no reason per se to assume that they are the site of substantially elevated geothermal heat flux.

4. Floatation Analysis

[10] Analysis of the 1977/78 radar sounding data indicated a ratio in the ice-surface to ice-bottom slopes of ~1/11, sufficient to suggest that the ice was floating but not to determine the nature of the fluid in the lake [*Siegert et al.*, 2004]. The improved accuracy, precision and coverage of the new surveys allow us to improve on this analysis.

[11] If the ice above is wholly supported by the pressure of the fluid in the lake, then the hydrological head, H, across the lake should be constant.

$$H = \frac{\overline{\rho_i}}{\rho_f} h_i + \frac{\left(\rho_f - \overline{\rho_i}\right)}{\rho_f} z_b, \tag{1}$$

where $\overline{\rho_i}$ is the mean density of the ice column, ρ_f is the density of the fluid in the lake; h_i, is the ice-surface elevation and z_b, is the elevation of the lake surface. Here, both elevations were measured with respect to ellipsoid, but

Table 1. Results of Crossover Analysis for 2004/05 and 2005/06 Datasets

	Mean Surface Difference, m	RMS Surface Difference, m	Mean Thickness Difference, m	RMS Thickness Difference, m	Expected ΔH_{RMS}, m
2004/05 Internal crossovers	-	0.82	-	28.1	2.36
2005/06 Internal crossovers	-	2.1	-	21.2	2.56
2004/05–2005/06 crossovers	3.4	1.2	33	20	-

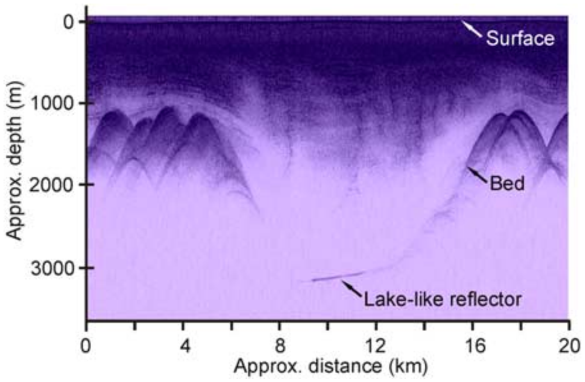

Figure 2. Sample radar section from 2004/05 survey.

given the small dimensions of SLE, it is unlikely that this implies any significant error. Assuming that the near-surface density structure does not vary across the lake we may isolate that effect in constant terms and examine variations in H across the lake using, ρ_i, the full-density of ice at the pressure of the lake. This value is well constrained; a recent assessment of experimental and theoretical data suggests a best estimate of 920 kg m^{-3} but that it can be no higher than 922 kg m^{-3} [*Marion and Jakubowski*, 2004].

[12] Figure 3 shows the RMS-variability of the hydrological head (ΔH_{RMS}) over the lake for both surveys as a function of ρ_f, with ρ_i = 920 kg m^{-3}. For both datasets ΔH_{RMS} is a minimum for a range of ρ_f. Our crossover analysis indicated that the uncertainty in the measurements should contribute ±2.56 m and ±2.36 m to ΔH_{RMS} in 2004/05 and 2005/06 surveys respectively, so where the value of ΔH_{RMS} falls below these values the data satisfy the model described above; outside this range the model has failed to explain the data. Thus the 2004/05 data are explained if ρ_f is 950–1013 kg m^{-3}, and the 2005/06 data if ρ_f is 960–991 kg m^{-3}.

[13] We conclude that the density of the fluid in the lake must be substantially less than that of seawater (1041 at 28 MPa), and shows no indication of containing substantial concentrations of acid, salts or heavy clathrates which would also raise the density above that for freshwater. The fluid density that gives the best fit to one of our datasets is slightly lower than that of freshwater (1013 kg m^{-3} at 28 MPa). Although it is unlikely that the assumptions in this analysis are sufficiently precise to make definitive conclusions in this regard, the only explanation for such a low density we find plausible is the presence of unconsolidated frazil ice below the ice-bottom reflector. However, it is very unclear how such a layer would accumulate or remain unconsolidated for long enough to accumulate enough thickness to influence the fluid density substantially. Our interpretation is thus that the lake contains freshwater, a conclusion that is supported by the observation of a sub-ice bottom reflector in one radar transect across the lake, which confirms low conductivity of fluid in the lake [c.f. *Gorman and Siegert*, 1999].

5. Hydrological Analysis

[14] Several authors [e.g., *Flowers and Clarke*, 1999] have used the distribution of hydrological head to predict the paths of subglacial water transport beneath glaciers and ice-sheets. We have calculated hydrologic head according to equation (1) for the region around SLE (Figure 4). This indicates that subglacial water is likely to flow away from the ice-divide and be channeled down the several subglacial valleys towards Byrd Subglacial Basin, including the subglacial valley in which SLE lies. The good coverage of data close to the downstream end of SLE allows us to show that, to the resolution of our survey (±2.5 m) there is no hydrologic sill blocking water-flow out of the lake, on its route towards the lower lake (Figure 4). It appears that SLE is, in a hydrological sense, full, and any input of water from ice-melt or transport from the interior basin, is likely to displace water into the lower lake.

6. Source of Lake Water

[15] Using the internal layers imaged in the 1977/78 radar *Siegert et al.* [2004] predicted high rates of ice-melt of ~17 cm yr^{-1} above SLE. However, the accuracy of this melt-rate is uncertain because the 1977/78 flight was not completely aligned with the ice-flow. Such a value would require around 1.6 Wm^{-2} of heat to melt the ice, ~27 times the geothermal heat flux expected in this area [*Parizek et al.*, 2003; *Winberry and Anandakrishnan*, 2004]. Actually, our interpretation that SLE occupies an erosional feature suggests that we should not, per se, expect unusually high geothermal flux beneath SLE, and without a plausible source of extra heat we must consider that the source of the water in the lake is not local. Since there is no evidence for an upstream lake that could supply SLE, we suggest that subglacial melt produced at low rates across the hydrological catchment area (~200 km^2) of SLE is delivered by an active subglacial water supply.

[16] The melt-rate calculated for SLE was also used to calculate a turnover-time (5000 years) for the water [*Siegert et al.*, 2004], which must now also now be in doubt. Although some of the geothermal and frictional energy across the subglacial catchment for SLE must be lost through thermal conduction; a good starting point might be to assume that all the geothermal heat across the

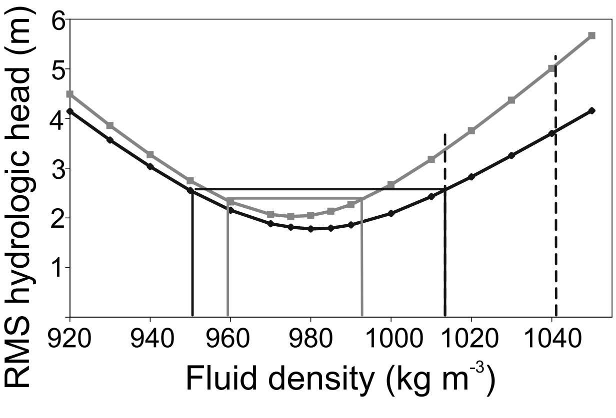

Figure 3. RMS-variance in hydrological head for 2004/05 (black diamonds) and 2005/06 (grey squares), assuming an ice-density of 920 kg m^{-3}. RMS-variance implied by the density of seawater (1041 kg m^{-3} at 28 MPa) is higher than expected from the uncertainties implied by the crossover analysis, 2.36 m and 2.56 m respectively.

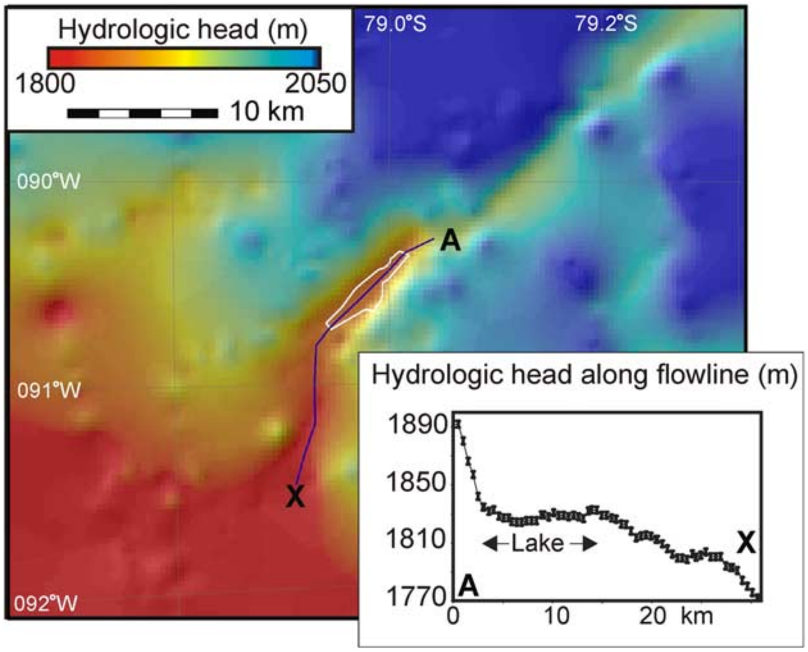

Figure 4. Hydrological head around SLE. Lake perimeter is shown by white line, and inset shows hydrological head along the profile from SLE to the lower lake at X. Note: the profile shows no significant barrier to flow from SLE to the lower lake.

catchment is available to melt ice to recharge SLE. With a water depth of 100 m, a turnover-time for water in the lake of 10 000 years is possible. However, until geothermal heat flux, water volume, and temperature gradients are known, it is impossible to constrain this calculation within an order of magnitude either way.

7. Discussion

[17] Two independent field campaigns over SLE have now been completed. Its spatial extent has been mapped, its area estimated (18 km^2), and the subglacial topography around it investigated. SLE is clearly very different from tectonically-controlled lakes reported in East Antarctica [*Studinger et al.*, 2003; *Bell et al.*, 2006]. SLE is one of several lakes occupying subglacial valleys that are likely erosional features formed during less extensive glacial conditions. A date when such conditions existed in this area would put an upper limit on the age of the lake, but no such date is available, although evidence from a site near the current margin of WAIS suggests it was less extensive in at least one recent interglacial [*Scherer et al.*, 1998].

[18] The observation that subglacial lakes can form in such erosional features suggests that they do not to require elevated geothermal heat flux to form. This, together with the observations that they can form in areas of slow ice-flow even close to the present hydrological divide, suggests that small subglacial lakes may be much more widespread than previously thought. These lakes are probably not formed by direct melting above the lake cavity, but are more likely fed by the accumulation of melt water from the surrounding ice sheet.

[19] Hydrostatic analysis has confirmed that SLE is a fluid-filled lake and that the ice above it is floating. The residual hydrostatic anomalies suggest that any bridging stresses must be very low (probably only a few Pa), which may provide further support for the lake being filled. The density of the fluid in the lake is too low to be seawater, excluding the possibility that SLE is simply a captured relict of open-marine conditions, which has been suggested as a possible origin for other subglacial lakes [*Duxbury et al.*, 2001; *Pattyn*, 2004; *Erlingsson*, 2006]. Similarly, it is unlikely that the fluid contains substantial concentrations of acid, salts or clathrate mixtures of more than a few percent. The fluid in SLE is likely to be relatively fresh water.

[20] The analysis of hydrological head indicates that the lake cavity is either full, or very close to full. It is thus likely that as new subglacial water enters the lake it will be balanced by over-flow. This over-flow is likely to flow down the hydrologic gradients into a lower lake identified on the flank of the Byrd Subglacial Basin. Contrary to earlier expectations [*Siegert et al.*, 2004], we conclude that SLE is well-connected to an upstream drainage system and to a downstream drainage system and other lakes. It is, however, not possible to determine whether outflow is continuous, or episodic as has been observed elsewhere [*Gray et al.*, 2005; *Wingham et al.*, 2006; *Fricker et al.*, 2007].

[21] The possibility of a constant or frequent flux of water through SLE implies a lower likelihood that it contains long-isolated microbial communities. It does however imply that contamination of SLE during in situ exploration would have consequences for downstream lakes, but since the floatation condition appears to be satisfied so precisely it should be possible to ensure pressure-equalization in a drill hole before the lake was penetrated, so as to minimize contamination. Neither of these concerns suggest that SLE is any less suitable than other subglacial lake for early in

situ exploration and it should remain a "prime candidate" [*Siegert et al.*, 2004].

[22] **Acknowledgments.** We appreciate the contribution made by field personnel of the British Antarctic Survey, Centro de Estudios Científicos, Antarctic Logistics and Expeditions LLC, University of Kansas and the Chilean Ministry of Defence and Army, without whose professionalism this work would not have been possible. We thank Martin Siegert, Adrian Jenkins, Michael Studinger and an anonymous reviewer for constructive comments. JW supported by NERC grant NE/D008751/1. CECS is funded by the Millennium Science Initiative and Empresas CMPC.

References

Bell, R. E., M. Studinger, M. A. Fahnestock, and C. A. Shuman (2006), Tectonically controlled subglacial lakes on the flanks of the Gamburtsev Subglacial Mountains, East Antarctica, *Geophys. Res. Lett.*, *33*, L02504, doi:10.1029/2005GL025207.

Bell, R. E., et al. (2007), Large subglacial lakes in East Antarctica at the onset of fast-flowing ice streams, *Nature*, *445*, 904–907.

Duxbury, N. S., I. A. Zotikov, K. H. Nealson, V. E. Romanovsky, and F. D. Carsey (2001), A numerical model for an alternative origin of Lake Vostok and its exobiological implications for Mars, *J. Geophys. Res.*, *106*(E1), 1453–1462.

Erlingsson, U. (2006), Lake Vostok behaves like a 'Captured lake' and may be near to creating an Antarctic Jokulhlaup, *Geogr. Ann., Ser. A*, *88*(1), 1–7.

Flowers, G. E., and G. K. C. Clarke (1999), Surface and bed topography of Trapridge Glacier, Yukon Territory, Canada: Digital elevation models and derived hydraulic geometry, *J. Glaciol.*, *45*(149), 165–174.

Fricker, H. A., et al. (2007), An active subglacial water system in West Antarctica mapped from space, *Science*, *315*(5818), 1544–1548, doi:10.1126/science.1136897.

Gorman, M. R., and M. J. Siegert (1999), Penetration of Antarctic subglacial lakes by VHF electromagnetic pulses: Information on the depth and electrical conductivity of basal water bodies, *J. Geophys. Res.*, *104*(B12), 29,311–29,320.

Gray, L., I. Joughin, S. Tulaczyk, V. B. Spikes, R. Bindschadler, and K. Jezek (2005), Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite radar interferometry, *Geophys. Res. Lett.*, *32*, L03501, doi:10.1029/2004GL021387.

Holt, J. W., D. D. Blankenship, D. L. Morse, D. A. Young, M. E. Peters, S. D. Kempf, T. G. Richter, D. G. Vaughan, and H. F. J. Corr (2006), New boundary conditions for the West Antarctic Ice Sheet: Subglacial topography beneath Thwaites and Smith glaciers, *Geophys. Res. Lett.*, *33*, L09502, doi:10.1029/2005GL025561.

Jankowski, E. J., and D. J. Drewry (1981), The structure of West Antarctica from geophysical studies, *Nature*, *291*, 17–21.

Marion, G. M., and S. D. Jakubowski (2004), The compressibility of ice to 2.0 kbar, *Cold Reg. Sci. Technol.*, *38*(2–3), 211–218.

Oswald, G. K. A., and G. D. Q. Robin (1973), Lakes beneath Antarctic Ice Sheet, *Nature*, *245*, 251–254.

Parizek, B. R., et al. (2003), Subglacial thermal balance permits ongoing grounding-line retreat along the Siple Coast of West Antarctica, *Ann. Glaciol.*, *36*, 251–256.

Pattyn, F. (2004), Comment on the comment by M. J. Siegert on "A numerical model for an alternative origin of Lake Vostok and its exobiological implications for Mars" by N. S. Duxbury et al., *J. Geophys. Res.*, *109*, E11004, doi:10.1029/2004JE002329.

Price, P. B., et al. (2002), Temperature profile for glacial ice at the South Pole: Implications for life in a nearby subglacial lake, *Proc. Natl. Acad. Sci. U. S. A.*, *99*, 7784–7844, doi:10.1073/pnas.082238999.

Rivera, A., et al. (2006), Expedicion al lago subglacial Ellsworth, *Bol. Antartico Chil.*, *25*(1), 7–10.

Scherer, R. P., et al. (1998), Pleistocene collapse of the West Antarctic Ice Sheet, *Science*, *281*(5373), 82–85.

Siegert, M. J., R. Hindmarsh, H. Corr, A. Smith, J. Woodward, E. C. King, A. J. Payne, and I. Joughin (2004), Subglacial Lake Ellsworth: A candidate for *in situ* exploration in West Antarctica, *Geophys. Res. Lett.*, *31*, L23403, doi:10.1029/2004GL021477.

Studinger, M., et al. (2003), Ice cover, landscape setting, and geological framework of Lake Vostok, East Antarctica, *Earth Planet. Sci. Lett.*, *205*(3–4), 195–210.

Vaughan, D. G., H. F. J. Corr, F. Ferraccioli, N. Frearson, A. O'Hare, D. Mach, J. W. Holt, D. D. Blankenship, D. L. Morse, and D. A. Young (2006), New boundary conditions for the West Antarctic ice sheet: Subglacial topography beneath Pine Island Glacier, *Geophys. Res. Lett.*, *33*, L09501, doi:10.1029/2005GL025588.

Winberry, J. P., and S. Anandakrishnan (2004), Crustal structure of the West Antarctic rift system and Marie Byrd Land hotspot, *Geology*, *32*(11), 977–980.

Wingham, D. J., et al. (2006), Rapid discharge connects Antarctic subglacial lakes, *Nature*, *440*, 1033–1036.

H. F. J. Corr and D. G. Vaughan, British Antarctic Survey, Natural Environment Research Council, Madingley Road, Cambridge CB3 0ET, UK. (d.vaughan@bas.ac.uk)

A. Rivera, J. Wendt, and R. Zamora, Centro de Estudios Científicos, Arturo Prat 514, Valdivia, Chile.

J. Woodward, School of Applied Sciences, Northumbria University, Ellison Place, Newcastle upon Tyne NE1 8ST, UK.