· Article · **Advances in Polar Science**
doi: 10.13679/j.advps.2019.1.00070 March 2019 Vol. 30 No. 1: 70-75

Characterizing three-dimensional features of Antarctic subglacial lakes from the inversion of hydraulic potential—Lake Vostok as a case study

LI Yan[1,2], LU Yang[1,2], ZHANG Zizhan[1,2*], SHI Hongling[1,2] & XI Hui[1,2]

[1] State Key Laboratory of Geodesy and Earth's Dynamics, Institute of Geodesy and Geophysics, Chinese Academy of Sciences, 430077 Wuhan, China;
[2] University of Chinese Academy of Sciences, 100049 Beijing, China

Received 29 August 2018; accepted 17 December 2018

Abstract To estimate basal water storage beneath the Antarctic ice sheet, it is essential to have data on the three-dimensional characteristics of subglacial lakes. We present a method to estimate the water depth and surface area of Antarctic subglacial lakes from the inversion of hydraulic potential method. Lake Vostok is chosen as a case study because of the diverse and comprehensive measurements that have been obtained over and around the lake. The average depth of Lake Vostok is around 345±4 m. We estimated the surface area of Lake Vostok beneath the ice sheet to be about 13300±594 km^2. The lake consists of two sub-basins separated by a ridge at water depths of about 200–300 m. The surface area of the northern sub-basin is estimated to be about half of that of the southern basin. The maximum depths of the northern and southern sub-basins are estimated to be about 450 and 850 m, respectively. Total water volume is estimated to be about 4658±204 km^3. These estimates are compared with previous estimates obtained from seismic data and inversion of aerogravity data. In general, our estimates are closer to those obtained from the inversion of aerogravity data than those from seismic data, indicating the applicability of our method to the estimation of water depths of other subglacial lakes.

Keywords **three-dimensional features, Lake Vostok, hydraulic potential, subglacial water storage**

Citation: Li Y, Lu Y, Zhang Z Z, et al. Characterizing three-dimensional features of Antarctic subglacial lakes from the inversion of hydraulic potential—Lake Vostok as a case study. Adv Polar Sci, 2019, 30(1): 70-75, doi: 10.13679/j.advps.2019.1.00070

1 Introduction

Subglacial lakes are water bodies mainly found in topographic hollows between the base of an ice sheet and bedrock (Siegert et al., 2000). Basal ice is melted by geothermal heat and heat arising from internal ice deformation and basal sliding. Weight of the ice sheet lowers the melting point of basal ice to about −3℃ (Siegert et al., 2011). Meltwater accumulates in the hollows and forms subglacial lakes. It has been about 50 years since the first subglacial lake was identified from airborne radio-echo sounding data (Robin et al., 1970). The strength of the radio-echo reflected from between the ice-sheet base and bedrock underneath flight lines allow possible areas of water accumulation to be identified (Siegert et al., 1996). Many subglacial lakes have been identified using this method (Oswald et al., 1973; Siegert et al., 1996; Tabacco et al., 1998; Wright et al., 2012, 2014; Rivera et al., 2015). Subglacial lakes can be classified into different categories according to their radio-echo reflections (Carter et al., 2013). On the basis of ice surface elevation change, some underlying lakes have also been detected using satellite altimetry and images (Gray et al., 2005; Bell et al., 2006; Wingham et al., 2006; Smith et al., 2009). Subglacial lakes

* Corresponding author, E-mail: zzhang@asch.whigg.ac.cn

might be habitats for microorganisms; because microorganisms have a critical role in the evolution of life on Earth, the discovery of subglacial lakes has attracted attentions from glaciologists, geophysicists and biochemists (Pavel et al., 2012; Achberger et al., 2016; Bulat et al., 2016). In 2012, the Russian expedition team finally penetrated subglacial Lake Vostok and obtained a frozen water sample (https://www.nature.com/news/russians-celebrate-vostok-victory-1.10021). Sample analysis revealed the presence of two types of bacteria (Bulat et al., 2016), although it is uncertain whether they are inhabitants of the lake or have been introduced by the drilling process.

So far more than 400 subglacial lakes have been discovered (Siegert et al., 2016). Most of them are located in the interior of the Antarctic ice sheet (Wright and Siegert, 2012) and can be divided into non-active and active lakes. Most non-active lakes have been discovered using airborne geophysical instruments or field observations. These methods, such as radio-echo sounding, have the advantage of being able to penetrate through thousands of meters of ice to the ice-sheet base (Oswald et al., 1973; Siegert et al., 1996). However, on the scale of the continent, these methods offer little repeatability because of the large numbers of flights that are required; the number of flights required is reduced for specific regions of interest, such as Lake Vostok. Lakes have been usually identified along sparse flight lines. In addition, satellite images can only be used to find lakes with surface depressions that are large enough to be captured by space-borne images (Bell et al., 2006). Surface ice changes overlying active lakes can be detected using satellite altimetry, and hence, temporal changes of the underlying water can be estimated (Fricker et al., 2007). Not all subglacial lakes exist in isolation; some subglacial lakes are connected via subglacial water pathways (Gray et al., 2005; Fricker et al., 2007; Smith et al., 2009). Each of these methods uses a different technique to detect the presence of subglacial water, and each method has its own advantages. Comprehensive datasets of ice surface elevation, ice thickness and bed elevation covering the entire Antarctic continent and the uncertainties of the corresponding data were published in 2013 (Fretwell et al., 2013); Bedmap2 incorporates earlier and latest data collected by a large number of researchers and is critical for the estimation of subglacial water storage.

We estimate depth, surface area, volume and the corresponding uncertainties of these parameters of Lake Vostok from the inversion of hydraulic potential method. Lake Vostok is the largest subglacial lake that has been discovered (Wright and Siegert, 2012); it has been more intensively studied than other lakes; the wide and dense coverage of observations over Lake Vostok provide ample data for the validation of our estimates. Previous estimates from seismic and aerogravity data are used for comparison (Popov et al., 2011a, 2011b, 2012; Siegert et al., 2011).

2 Data and methods

2.1 Data

To calculate the hydraulic potential, both bed elevation and ice thickness data are needed. Bedmap2 provides the latest ice thickness and bed elevation products (Fretwell et al., 2013), both of which were generated by integrating multiple types of observations, such as radio-echo sounding, airborne gravity, airborne altimetry and seismic data collected over past decades. Bedmap2 provides the most detailed bedrock topography data to date; the data are gridded at a resolution of 1 km by 1 km, are derived from multiple data sources and have an extensive temporal coverage. These high-resolution data contribute greatly to the calculation of hydraulic potential in some specific regions, such as Lake Vostok. To correctly assess lake depth, it is necessary to know the uncertainties associated with the original observations and the estimates; this information is presented in Section 2.3. Estimates from seismic and aerogravity data (Siegert et al., 2011) are used to validate water depths derived from the inversion of hydraulic potential.

2.2 Depth, surface area and volume

Water flow and storage beneath an ice sheet is principally governed by the gradient in hydraulic potential. The hydraulic potential is a function of bed elevation and water pressure (Shreve et al., 1972; Livingstone et al., 2013) and can be expressed as

$$\Phi=\rho_w g b+P_w, \quad (1)$$

where Φ is hydraulic potential, ρ_w is water density (1000 kg·m^{-3}), g is gravitational acceleration, b is bed elevation and P_w is water pressure. Water pressure, P_w, is defined as the difference between ice overburden pressure, P_i, ($P_i=\rho_i g h$, where ρ_i is ice density 917 kg·m^{-3}, and h is ice thickness) and effective pressure, N:

$$P_w=P_i-N \quad (2)$$

Model results show that the effective pressure at the ice-sheet base is close to zero (Budd and Jenssen, 1987). Borehole observations confirmed these results by showing that $P_w > 0.95P_i$ (Kamb et al., 2001). On the basis of model results and associated borehole observations, it is reasonable to assume that ice overburden pressure is balanced by basal water pressure, i.e., N can be assumed to be zero (Livingstone et al., 2013; Goeller et al., 2016), which allows Equation (1) to be rewritten as

$$\Phi=\rho_w g b+\rho_i g h \quad (3)$$

To derive the water depth in subglacial lakes, both sides of Equation (3) is divided by $\rho_w g$:

$$\varphi_0 = b+\rho_i h/\rho_w \quad (4)$$

In Equation (4), hydraulic potential is expressed as a direct function of bed elevation and ice thickness. The value of φ_0 varies, and it is assumed that differences in hydraulic potential are compensated by hydraulic potential produced by meltwater. Therefore, the water depth in subglacial lakes is calculated on the basis of the difference between the hydraulic potential contribution of bed elevation and that of ice thickness. The value of φ_0 is calculated for each 1×1 km^2 grid cell to match the resolution of Bedmap2. Then we use an algorithm from the ArcHydro package to fill all potential sinks ('Fill Sinks' algorithm) (Livingstone et al., 2013). All minima in the φ_0 surface are identified and then the algorithm iteratively fills the value of each minimum to the lowest value within a local 3×3 grid matrix. The fill process is iteratively implemented until no sinks exist. This algorithm is similar to algorithms used to fill sinks in the surface of a digital elevation model to obtain a local equilibrium surface. In Equation (4), the gridded hydraulic potential is expressed in the form of water height. Gridded hydraulic potential, φ_1, is then subtracted from the filled potential surface. In each grid, positive difference between original potential, φ_0, and filled potential, φ_1, is taken as water depth, d:

$$d=\varphi_1-\varphi_0 \tag{5}$$

2.3 Uncertainties

In Equation (4), Φ is a direct function of bed elevation and ice thickness. According to the law of error propagation, the uncertainty in the estimate of Φ, σ_Φ, is given as a function of the uncertainties in the estimates of b, σ_b, and of h, σ_h:

$$\sigma_\varphi = \pm\sqrt{\sigma_b^2+\sigma_h^2} \tag{6}$$

According to Equation (5), uncertainty in the estimate of d, σ_d, can be derived as follows:

$$\sigma_d = \pm\sqrt{2}\sigma_\varphi , \tag{7}$$

which can be expressed as

$$\sigma_d = \pm\sqrt{2\left(\sigma_b^2+\sigma_h^2\right)} \tag{8}$$

Uncertainties of the estimates of bed elevation and ice thickness can be obtained from Bedmap2.

Average water depth, $\bar{d}$ is calculated as follows:

$$\bar{d} = \frac{1}{n}\sum_{i=1}^{n} d , \tag{9}$$

where n is the number of grid cells and d is positive.

Subglacial water volume, v, is estimated from surface area, s, and average water depth, $\bar{d}$:

$$v = s\cdot\bar{d} \tag{10}$$

To estimate the uncertainty in the estimate of the surface area of the lake, σ_s, we use the surface area of the lake obtained from geophysical observations in Bedmap2 as reference. Uncertainty of the estimate of subglacial water volume, σ_v, is thus:

$$\sigma_v = \pm\sqrt{s^2\sigma_{\bar{d}}^2+\bar{d}^2\sigma_s^2} , \tag{11}$$

where $\sigma_{\bar{d}}$ is uncertainty of the estimate of average water depth.

3 Results and comparison

3.1 Comparison of surface area estimates

Among the grid cells where water depth is positive, those that are adjacent to cells where water depth is zero or negative were assumed to mark the boundary of Lake Vostok (Figure 1). We estimated the surface area of Lake Vostok to be about 13300±594 km^2. Our estimate is 14% and 5% lower than the previously published estimates of 15500 and 14000 km^2, respectively (Siegert et al., 2011; Wright and Siegert, 2012). The accuracy of the source data of Bedmap2 might be too low to be able to reflect ice thickness and bed elevation around the lake's margins accurately. Ice thickness and bed elevation data in Bedmap2 had been filtered to provide a relatively smooth topography at regional scales (Fretwell et al., 2013) and could have led to errors in the detection of the lake boundary. Surface depressions detected in satellite images are also used in the estimation of lake boundaries (Scambos et al., 2007; Haran et al., 2014). When such images are available they can be used to provide an initial estimate of the uncertainty of surface area estimates.

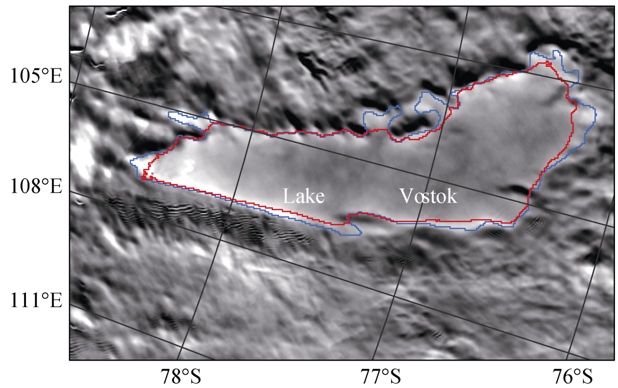

Figure 1 Comparison of estimated boundaries of Lake Vostok. Red line indicates results from this study; blue line indicates lake's boundary as given by Bedmap2. Background image is from Mosaic of Antarctica (MOA) 2009 (Haran et al., 2014).

3.2 Comparison of depth estimates

Water depths for each 1×1 km^2 grid cell were calculated using Equation (5) and are shown in Figure 2a. There is a good agreement between water depths estimated from BedMap2 and those derived from seismic data (Figure 2b) in terms of the basic distribution of depths. Both sets of depth estimates clearly show the two sub-basins of Lake Vostok. The southern sub-basin is clearly deeper than the northern one, and the two sub-basins are separated by a shallow ridge. We estimated average depth of Lake Vostok to be 345±4 m.

To quantify the difference between depth estimates, we compared estimates obtained from seismic data and inversions of hydraulic potential and aerogravity data (Figure 3). For the north basin, our estimate is closer to that obtained from the inversion of aerogravity data; both estimates indicate that the north basin extends to a depth of about 450–500 m. In contrast, estimates from seismic data only indicate a depth of about 200 m, which is half of that estimated by the two inversion methods. For the south basin, both estimates from inversion indicate that this sub-basin extends to a depth of around 850 m. Estimates from seismic data indicate a depth of about 1150 m, which is about 130% that indicated from inversion. Surface area estimates from inversion are larger than those from seismic data.

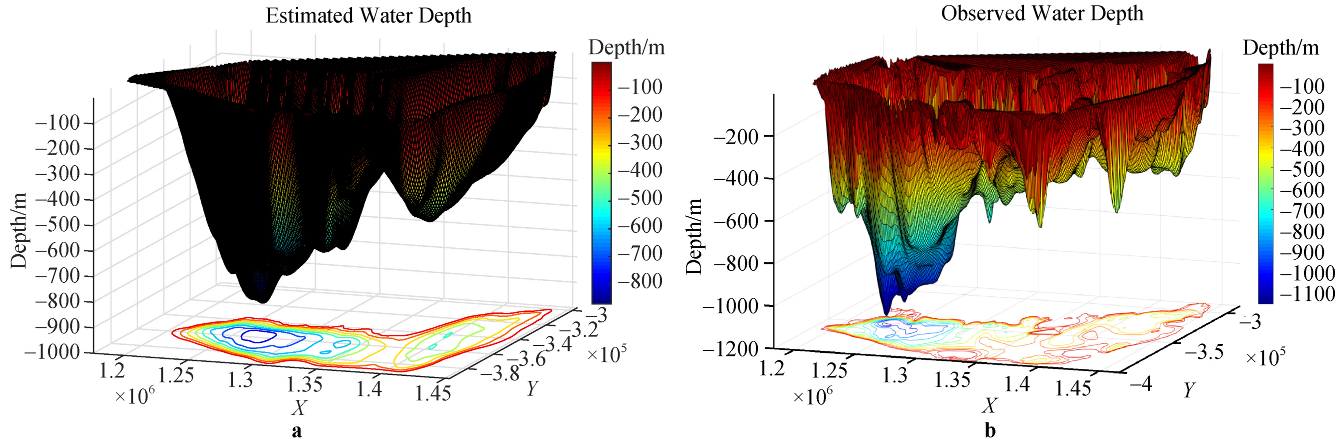

Figure 2 Comparison of estimated depths of Lake Vostok shown in three dimensions. **a**, Estimates derived from the inversion of hydraulic potential. **b**, Estimates derived from seismic data (Siegert et al., 2011). Horizontal coordinates in **a** and **b** are expressed in the South Pole Stereographic projection.

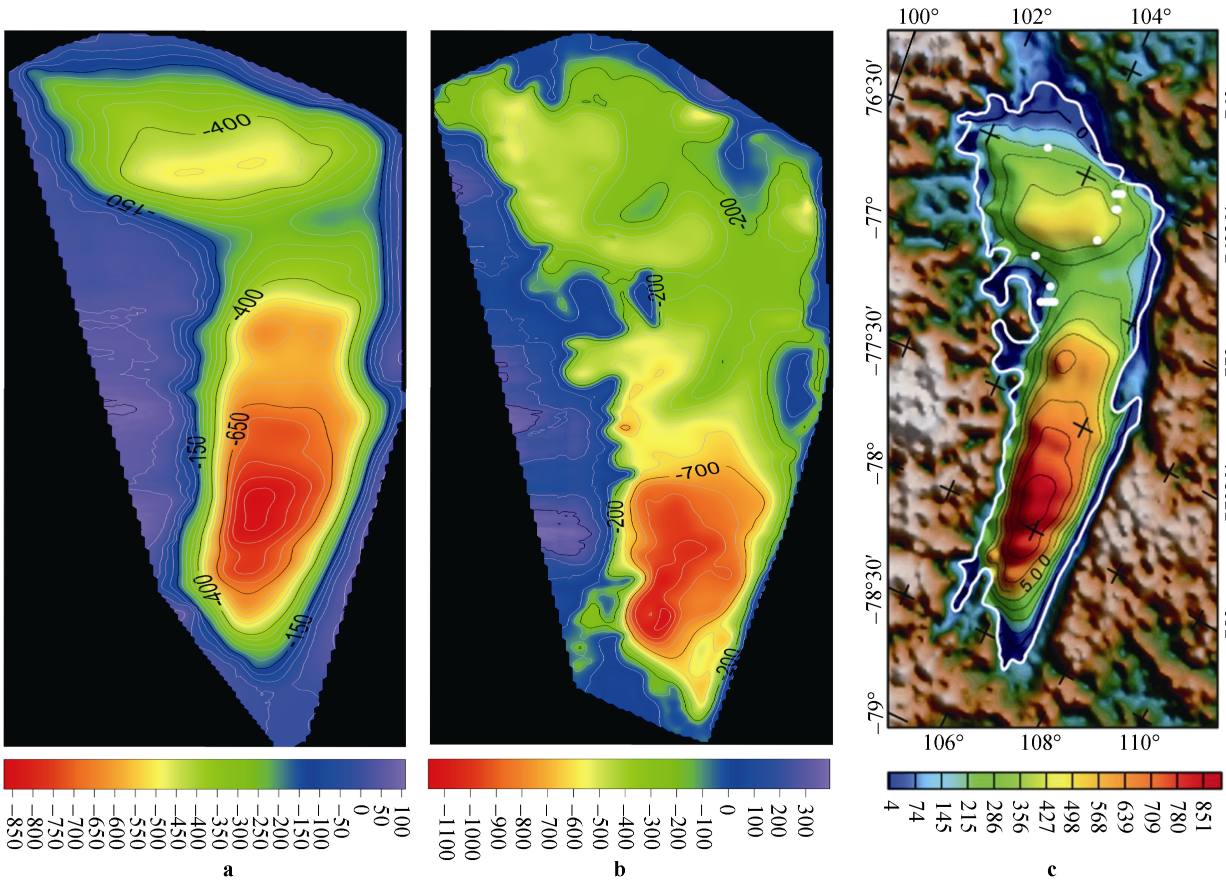

Figure 3 Comparison of estimated depths of Lake Vostok's shown in planar view. **a**, Estimates derived from the inversion of hydraulic potential. **b**, Estimates derived from seismic data. **c**, Estimates derived from inversion of aerogravity data (Plate 3c in Siegert et al., 2011).

3.3 Comparison of water volume estimates

By integrating water depths over every grid cell, we estimated the total water volume of Lake Vostok to about 4658±204 km^3. This is closer to the estimate of 5400 km^3 derived from the inversion of aerogravity data (Studinger et al., 2004), but is much lower than the value of 6350 km^3 estimated from seismic data (Siegert et al., 2011). According to Equation (8), the maximum uncertainty of our estimate can reach 200 m which might explain the difference between the estimates.

4 Summary

In this paper, we estimated the water depth and surface area of Antarctic subglacial lakes from the inversion of hydraulic potential method. The method was applied to Lake Vostok as a case study. Estimates from the inversion of hydraulic potential are closer to those from the inversion of aerogravity data than those from seismic data. Quantitative differences between the estimates were discussed. This case study shows that this method can be used to characterize three-dimensional features of other subglacial lakes when detailed ice thickness and bed elevation data are available.

Acknowledgments This work was jointly funded by the Natural Science Foundation of China (Grant nos. 41674085 and 41621091) and the National Key Basic Research Program of China (973 program, Grant nos. 2012CB957703 and 2013CB733301). We thank Martin Siegert for providing suggestions on the comparison of results. We also thank Sergey Popov for providing Lake Vostok bathymetry data obtained from seismic sounding. Finally we thank two anonymous reviewers who provided comments that improved the manuscript.

References

Achberger A M, Christner B C, Michaud A B, et al. 2016. Microbial community structure of Subglacial Lake Whillans, West Antarctica. Front Microbiol, 7: 1457, doi: 10.3389/fmicb.2016.01457.

Bell R E, Studinger M, Fahnestock M A, et al. 2006. Tectonically controlled subglacial lakes on the flanks of the Gamburtsev Subglacial Mountains, East Antarctica. Geophys Res Lett, 33(2): L02504, doi: 10.1029/2005gl025207.

Bulat S A. 2016. Microbiology of the subglacial Lake Vostok: first results of borehole-frozen lake water analysis and prospects for searching for lake inhabitants. hilos Trans A Math Phys Eng Sci, 374(2059): 20140292, doi: 10.1098/rsta.2014.0292.

Carter S P, Blankenship D D, Peters M E, et al. 2007. Radar-based subglacial lake classification in Antarctica. Geochem Geophy Geosy, 8(3), doi: 10.1029/2006gc001408.

Fretwell P, Pritchard H D, Vaughan D G, et al. 2013. Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. Cryosphere, 7: 375-393.

Fricker Ha, Scambos T, Bindschadler R, et al. 2007. An active subglacial water system in West Antarctica mapped from space. Science, 315(5818): 1544-1548, doi: 10.1126/science.1136897.

Goeller S, Steinhage D, Thoma M, et al. 2016. Assessing the subglacial lake coverage of Antarctica. Ann Glaciol, 57(72): 109-117, doi: 10.1017/aog.2016.23.

Gray L, Joughin I, Tulaczyk S, et al. 2005. Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite radar interferometry. Geophys Res Lett, 32(3): 259-280.

Kamb B. 2001. Basal zone of the West Antarctic ice streams and its role in lubrication of their rapid motion. The West Antarctic ice sheet: behavior and environment, 77: 157-199.

Livingstone S, Clark C, Woodward J, et al. 2013. Potential subglacial lake locations and meltwater drainage pathways beneath the Antarctic and Greenland ice sheets. Cryosphere, 7(6): 1721-1740.

Oswald G K A, Robin G de Q. 1973. Lakes Beneath the Antarctic Ice Sheet. Nature, 245(5423): 251-254.

Pavel T. 2012. Russian researchers reach subglacial Lake Vostok in Antarctica. Adv Polar Sci, 23(3): 176-180.

Popov S V C Y B. 2011a. Vostok Lake, East Antarctica: shore line and surrounding subglacial water cavities. Ice and Snow, 1: 13-24.

Popov S V M V N, Lukin V V, Popkov A M. 2011b. Vostok Lake, East Antarctica: ice thickness, lake depth, ice base and bedrock topography. Ice and Snow, 1: 25-35.

Popov S V M V N, Lukin V V, Popkov A M. 2012. Russian seismic, radio-echo and seismological investigations of Vostok Lake. Ice and Snow, 2: 31-38.

Rivera A, Uribe J, Zamora R, et al. 2015. Subglacial Lake CECs: Discovery and in situ survey of a privileged research site in West Antarctica. Geophys Res Lett, 42(10): 1279-87.

Scambos T A, Haran T M, Fahnestock M A, et al. 2007. MODIS-based Mosaic of Antarctica (MOA) data sets: Continent-wide surface morphology and snow grain size. Remote Sens Environ, 111(2): 242-257, doi: 10.1016/j.rse.2006.12.020.

Shreve R L. 1972. Movement of water in glaciers. J Glaciol, 1972, 11(62): 205-214, doi: 10.3189/s002214300002219x.

Siegert M J, Dowdeswell J A, Gorman M R, et al. 1996. An inventory of Antarctic sub-glacial lakes. Antarc Sci, 8(3): 281-286, doi: 10.1017/s0954102096000405.

Siegert M J, Popov S, Studinger M. 2011. Vostok subglacial lake: A review of geophysical data regarding its discovery and topographic setting. Geophy Monograph Series, 192: 45-60, doi: 10.1029/2010gm000934.

Siegert M J, Ross N, Le Brocq A M. 2016. Recent advances in understanding Antarctic subglacial lakes and hydrology. Philos Trans A Math Phys Eng Sci, 374(2059): 20140306, doi: 10.1098/rsta.2014.0306.

Siegert M J. 2000. Antarctic subglacial lakes. Earth-Sci Rev, 50(1): 29-50, doi: 10.1016/s0012-8252(99)00068-9.

Smith B E, Fricker H A, Joughin I R, et al. 2009. An inventory of active subglacial lakes in Antarctica detected by ICESat (2003–2008). J Glaciol, 55(192): 573-595, doi: 10.3189/002214309789470879.

Studinger M, Bell R E, Buck W R, et al. 2004. Sub-ice geology inland of the Transantarctic Mountains in light of new aerogeophysical data. Earth Planet Sc Lett, 2004, 220(3): 391-408, doi: 10.1016/s0012-821x(04)00066-4.

Tabacco I E, Passerini A, Corbelli F, et al. 1998. Determination of the surface and bed topography at Dome C, East Antarctica. J Glaciol, 44(146): 185-191, doi: 10.3189/s0022143000002501.

Wingham D J, Siegert M J, Shepherd A, et al. 2006. Rapid discharge connects Antarctic subglacial lakes. Nature, 440(7087): 1033-1036, doi:10.1038/nature04660.

Wright A P, Young D A, Bamber J L, et al. 2014. Subglacial hydrological connectivity within the Byrd Glacier catchment, East Antarctica. J Glaciol, 60(220): 345-352, doi: 10.3189/2014jog13j014.

Wright A P, Young D A, Roberts J L, et al. 2012. Evidence of a hydrological connection between the ice divide and ice sheet margin in the Aurora Subglacial Basin, East Antarctica. J Geophys Res-Earth, 117(F1), doi: 10.1029/2011jf002066.

Wright A, Siegert M. 2012. A fourth inventory of Antarctic subglacial lakes. Antarct Sci, 24: 659-664.