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Tectonically controlled subglacial lakes on the flanks of the Gamburtsev Subglacial Mountains, East Antarctica

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[1] The morphology of surface lakes strongly influences their ecology and limnology (Wetzel, 2001). This morphology is a result of both the geologic processes that produce topographic basins and the regional climatic and local hydrologic processes that control water depth and sediment infilling (Carroll and Bohacs, 1999). Although basin forming processes range from glacial scour to meteorite impacts (Cohen, 2003), the deepest, oldest surface lakes are tectonically controlled (Meybeck, 1995) and contain diverse exotic ecosystems (Rossiterm and Kawanabe, 2000). Subglacial lakes are also thought to be ancient systems that may contain exotic biota (Bulat et al., 2004; Karl et al., 1999; Priscu et al., 1999). Here we present evidence for the scale and configuration of 2 large subglacial lakes in East Antarctica that together with Lake Vostok define a province of major lakes on the flanks of the Gamburtsev Subglacial Mountains. Spatially-defined in the new Moderate Resolution Imaging Spectroradiometer (MODIS) imagery of Antarctica (T. Scambos et al., A MODIS-based mosaic of Antarctica: MOA, submitted to *Remote Sensing of Environment,* 2005, hereinafter referred to as Scambos et al., submitted manuscript, 2005), these lakes are aligned parallel to Lake Vostok. Other data shows that they are distinguished by distinct gravity lows, flat ice surface slopes and have estimated water depths of at least 900 m. Surface elevation data indicates that large deep subglacial lakes have a profound influence on the regional ice sheet topography and probably ice sheet flow. These deep subglacial lakes with elongate, rectilinear morphology are tectonically controlled features. Unlike the shallow lakes in West Antarctica and beneath Dome Concordia, these deep subglacial lakes remained stable environments through many glacial cycles since their origin 10–35 Ma enabling the development of novel ecosystems. **Citation:** 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.

1. Subglacial Lakes Distribution

[2] Since the first evidence for subglacial lakes was advanced in 1970 [*Robin et al.*, 1970] over 145 subglacial lakes have been identified in Antarctica ranging in length from 1 to 280 km [*Bogorodsky and Sheremet'yev*, 1981; *Kapitsa et al.*, 1996; *Siegert et al.*, 2005]. While many small and shallow lakes have been found, no lakes similar in area or volume to Lake Vostok (14,000 km^2, volume of 5,400 km^3) [*Kapitsa et al.*, 1996; *Studinger et al.*, 2004] have been identified. Subglacial lakes are concentrated along the ice divides of Dome Concordia and Ridge B where the ice thickness is close to 4000 m [*Siegert et al.*, 2005]. In the Dome Concordia lake province, the subglacial lakes are generally small (<20 km^2) with the exception of the 45 km long Lake Concordia (800 km^2, volume of 160 km^3) [*Tabacco et al.*, 2003; *Tikku et al.*, 2005]. The Ridge B province includes Lake Vostok and smaller lakes to the west (Figures 1 and 2).

2. Description of the 90°E and Sovetskaya Lakes

[3] Here we describe in detail, a large deep subglacial lake aligned along 90°E and a lake beneath Sovetskaya Station. These lakes have been identified in earlier inventories but their size, depth and origin have not been investigated [*Robin et al.*, 1970; *Siegert et al.*, 2005; *Studinger et al.*, 2003b]. Our analysis is based on five data sets including a multiple-image-composite mosaic using MODIS satellite imagery (Scambos et al., submitted manuscript, 2005), aerogeophysical data from the 2000–2001 survey of Lake Vostok [*Studinger et al.*, 2003a], laser-based ice surface altimetry from NASA's Ice, Cloud and Land Elevation Satellite (ICESat), ground traverse data from the 3rd Soviet Antarctic Expedition (SAE, 1958–59) [*Sorokhtin et al.*, 1964], and radar-based satellite ice surface elevation data from ERS-1 [*Liu et al.*, 2001].

[4] The aerogeophysical profile over the 90°E lake extends from Lake Vostok to the foothills of the Gamburtsev Subglacial Mountains, a region thought to be a foreland basin [*Studinger et al.*, 2003b]. Between Lake Vostok and 90°E, the subglacial topography is very rugged, ranging from −300 m to +2400 m asl. The western 7 km of the aerogeophysical ice-penetrating radar data line contains a very bright horizontal basal reflector (Figure 3), characteristic of water contained within subglacial lakes [*Robin et al.*, 1970]. The ice-penetrating radar data over the Sovetskaya lake documents an ice thickness of 4200 m over the lake.

[5] The MODIS mosaic in this region (Figures 1 and 2) reveals the ice surface topography largely as a function of the slope-controlled patterns of brightness with illumination from solar azimuths between 0–90° East (upper right in Figures 1 and 2). In the mosaic, the 90°E lake resembles Lake Vostok; it is characterized by a 123 km long flat featureless ice surface elongate in the north-south orientation and 20 km wide in the center tapering to 7 km wide at the ends. To the southwest of the 90°E lake, the Sovetskaya

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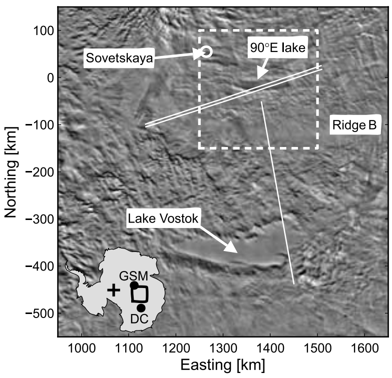

Figure 1. MODIS mosaic of Ridge B region including the 90°E and Sovetskaya lakes as well as Lake Vostok. Geographic north is to the right. The inset map of Antarctica indicates the image location, the Gamburtsev Subglacial Mountains (GSM) and Dome C (DC). Easting and northing are based on a polar stereographic projection with a latitude of true scale at 71°S. The dashed box indicates the location of Figure 2 and the solid white lines locate the profiles in Figure 4.

lake appears as a rectilinear flat featureless region 35 km wide in the east-west orientation that extends for 75 km in a north-south direction.

[6] Over the eastern grounding line of the 90°E lake, the airborne laser altimeter data and the ERS-1 ice surface altimetry (Figure 3a) both indicate a 14-m-deep and 10-km-wide trough in the ice surface coincident with the limit of the bright basal reflector in the ice-penetrating radar and the eastern limit of the flat featureless texture in the MODIS imagery. The ice surface trough at the upstream lake margin (Figure 2) is similar in size and shape to the 5-m-deep and 5-km-wide trough along the upstream margin of Lake Vostok (Figure 4) [*Studinger et al.*, 2003a]. Based on the grounding line trough and the bright horizontal reflector coincident with the flat featureless ice surface, we interpret this structure as a large (∼2000 km^2) subglacial lake, aligned approximately north-south along 90°E. This 90°E lake, similar in area to the state of Rhode Island, is second only Lake Vostok in surface area for a subglacial lake. The closed contour along the eastern edge of the Sovetskaya lake from the ERS-1 data is associated with an 8 m deep grounding line trough resolved by the ICESat altimetry. The estimated surface area of the Sovetskaya lake is ∼1600 km^2.

3. Identification of the Tilted Ceilings: Implications for Circulation

[7] Based on the gradient of the ERS-1 ice surface (Figure 2), the primary ice flow over the 90°E lake is from Ridge B in a generally westerly orientation although a southwesterly component is evident at the southern end of the lake. The ERS-1 ice surface over the 90°E lake [*Liu et al.*, 2001] slopes up 30 m to the north from 3660 m in south to 3690 m in north. In an east-west orientation, the ice surface slopes up 15 m from 3665 m at the eastern shoreline to 3680 m at the western shoreline (Figure 3a). The ice surface gradient indicates the ice flow over the Sovetskaya lake is from southeast to northwest and the ice surface slopes 20 m down to the north from 3670 m in the south to 3650 m in the north. A bedrock ridge bisects the Sovetskaya lake producing a relatively complex lake morphology evidenced in the MODIS imagery and the ice surface elevation.

[8] Using the ice thickness measurements along the ice-penetrating radar profile and the ice surface elevation, we can estimate the ice thickness over the lake assuming the ice sheet is in hydrostatic equilibrium and the lake water is fresh. To test the method, we predicted the ice thickness along the 7 km flight line. The standard deviation between the observed and predicted ice thickness is 9 m, which is below the ∼15 m resolution of the radar data (Figure 3b). Along this profile the observed ice thickness is 3980 m at the eastern ground line and the estimated ice thickness is 4032 m at the western shoreline. The estimated ice thickness along a north-south profile over the lake changes from 3900 m in the south to 4156 m in the north. Over the Sovetskaya lake the 20 m change in surface elevation observed in the ERS-1 ice surface (Figure 2) requires a 200 m thinning of the ice sheet from the observed 4200 m in the south [*Robin et al.*, 1970] to an estimated ice thickness of 4000 m in the north.

[9] Melting and freezing have been documented in both Lake Vostok and Lake Concordia based on accretion ice reflectors [*Bell et al.*, 2002], basal ice chemistry [*Jouzel et al.*, 1999] and ice thicknesses [*Tikku et al.*, 2004, 2005]. Above both the 90°E and Sovetskaya lakes, the overlying ice sheet forms a tilted ceiling similar to the ice sheet above Vostok. The tilted ceilings will introduce lake circulation as

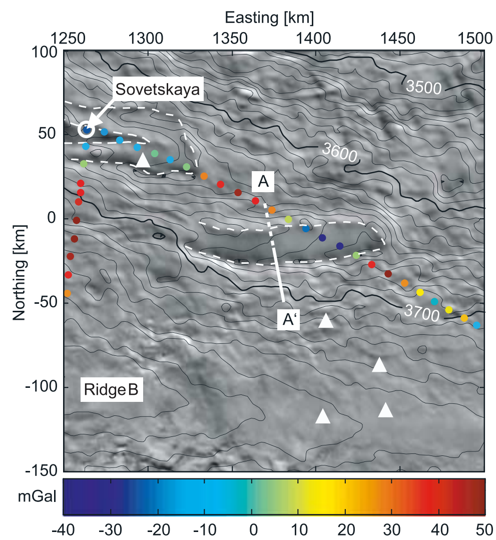

Figure 2. Subglacial lakes near 90°E. The base map is the MODIS mosaic (Scambos et al., submitted manuscript, 2005). 90°E is the zero line along the y axis (km northing). The 10 m ice surface elevation contours are from the ERS-1 data [*Liu et al.*, 2001]. The triangles are the lake locations [*Siegert et al.*, 2005]. The white line shows the location of Figure 3 with the solid line indicating the extent of the radar data shown and the dashed line indicating the profile where the ice thickness was estimated. The colored points indicate free-air gravity measurements from the 1958 SAE in mGal [*Sorokhtin et al.*, 1964].

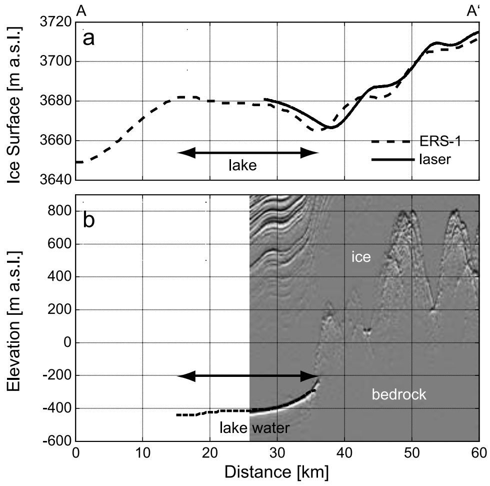

Figure 3. Stacked profiles along profile over 90°E Lake. Location is shown in Figure 2. Subglacial lake is from 15–35 km across as indicated by double-ended arrows. (a) Airborne laser altimetry [*Studinger et al.*, 2003b] and ERS-1 ice surface [*Liu et al.*, 2001] measurements along profile. (b) Ice-penetrating radar and predicted ice thickness (dashed line) along profile. Accreted ice basal reflector is located at 32 km along profile.

well as melting and freezing of the ice sheet [*Mayer et al.*, 2003; *Wüest and Carmack*, 2000]. Over the 90°E lake, the ice thickness increases rapidly adjacent to the eastern shoreline and a weak basal reflector (Figure 3b, 32 km) indicates that accretion of lake water as ice may occur along the grounding line as the lake dynamically interacts with the overlying ice sheet.

4. Depth Estimate: Support for Tectonic Origin of Lakes

[10] Gravity data can be used to estimate water depth of subglacial lakes [*Studinger et al.*, 2004]. The 3rd SAE traverse conducted geophysical studies across this region. While no seismic measurements were acquired over the lake [*Sorokhtin et al.*, 1964], gravity data was collected every 11 km (Figure 2). A distinct 80 mGal free-air gravity low is centered over the 90°E lake and a 70 mGal free-air gravity low exists over the Sovetskaya lake. Simple models of the gravity field can be used to constrain the water depths in the 90°E lake using the calculated ice thickness tied to the radar estimates. For models with a bedrock density of 2670 kg/m^3, a minimum water depth of 900 m is estimated based on the topography observed along the airborne radar profile. The estimated volume of the 90°E lake is ~1800 km^3. The estimated water depths are similar to the maximum water depths resolved with both seismic and gravity inversions over Lake Vostok [*Masolov et al.*, 1999, 2001; *Studinger et al.*, 2004] and are also similar to other tectonically controlled lakes such as fault-bounded lakes including Tahoe, USA (501 m) and Issyk-kul, Kyrgyzstan (668 m) as well as rift lakes including Tanganyika, Africa (1479 m), Malawi, Africa (706 m) and Baikal, Siberia (1637 m) [*Herdendorf*, 1982]. With the exception of the Great Slave Lake, Canada (624 m) glacially scoured lakes tend to have maximum water depths of less than 420 m [*Herdendorf*, 1982]. While the majority of surface lakes are glacial in origin (75%) [*Meybeck*, 1995], the majority (85%) of the deep lakes (>500 m) are tectonic in origin [*Herdendorf*, 1982; *Cohen*, 2003]. We interpret the steep, rectilinear morphology of these subglacial lakes to indicate a tectonic origin. While tectonic control of these basins is not indicative of active tectonics or elevated geothermal heat flow, the basin bounding faults should provide conduits of active fluid flow rich in dissolved minerals into the lakes. These deep elongate basins probably pre-date the onset of Antarctic glaciation and likely contained surface lakes prior to becoming encased in ice.

5. Influence of Large Subglacial Lakes on Ice Sheet Geometry

[11] Subglacial lakes are often assumed to have little influence on ice sheet dynamics. Ice sheet elevation profiles across the 90°E lake and Lake Vostok demonstrate that large subglacial lakes have a profound effect on the surface topography of the ice sheet, and by inference, on ice flow. The ice sheet elevation profiles (Figure 4) show the parabolic ice sheet profile with 5–10 m undulations characteristic of grounded ice flow in the interior, until the lakes are reached. At the upflow grounding line, the ice surface slope steepens, producing a marginal trough 5 to 20 meters deep. The profiles show a characteristic gentle downward slope over both lakes, and a ridge at the downstream grounding line. This pattern in the topographic profiles reflects the strong transitions in basal boundary conditions that control the rate that ice enters and leaves the lakes.

6. Summary and Implications

[12] It is striking that these newly defined lakes and the eastern shoreline of Lake Vostok are all aligned parallel to 90°E and that Lake Vostok and the 90°E lake have a significant impact on the ice sheet geometry. *Studinger et al.* [2003b] demonstrated that Lake Vostok formed along the

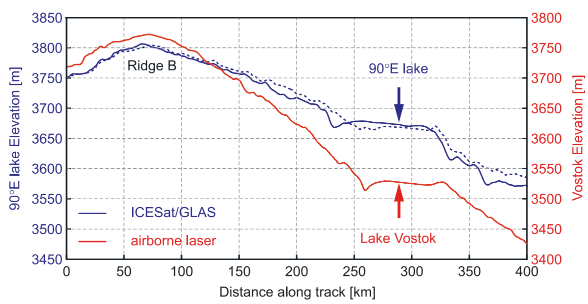

Figure 4. Ice surface elevation over 90°E lake (blue) and Lake Vostok (red). The profiles over the 90°E lake are from ICESat's Laser 2a operations period and are somewhat oblique to ice flow. These GLAS12 Release 21 elevations have a spacing along track of ~172 m and vertical accuracy of a few decimeters based on analysis of crossover residuals (C. A. Shuman et al., ICESat Antarctic elevation data: Preliminary precision and accuracy assessment, submitted to *Geophysical Research Letters*, 2005). Profile locations are shown in Figure 1.

eastern edge of a foreland basin that extends to the west beneath Ridge B toward the Gamburtsev Subglacial Mountains and that the linear eastern shoreline of Lake Vostok is a fault controlled tectonic boundary. The subrectangular morphology of the Sovetskaya and 90°E lakes and their position along the western edge of this foreland basin indicate these features may be similarly fault controlled. The tectonic fabric of this foreland basin or preexisting structures [*Studinger et al.*, 2003b] provides the template for the elongate fault-bounded topographic depressions necessary to form this province of large, deep subglacial lakes [*Wetzel*, 2001; *Meybeck*, 1995]. The tectonically controlled depth of these lakes should provide consistent water depths through changing climatic conditions over the past 10–35 My [*Carrol and Bohacs*, 1999]. These deep subglacial lakes are likely to have been stable environments through many glacial cycles and may have developed novel ecosystems [*Rossiterm and Kawanabe*, 2000; *Bulat et al.*, 2004; *Karl et al.*, 1999; *Priscu et al.*, 1999], in contrast to many of the shallow lakes in West Antarctica [*Siegert et al.*, 2004] and beneath Dome Concordia [*Tabacco et al.*, 2003; *Tikku et al.*, 2005].

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