Tectonic control of subglacial lakes and ice sheet stability

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Summary The identification of large dynamic subglacial lakes beneath the Antarctic ice sheets and at the onset of a major ice stream indicates that subglacial hydrology and subglacial lakes may play an important role in ice sheet stability. Here we present evidence that the large lakes most likely to influence ice sheet dynamics are coincident with major tectonic boundaries. By providing the basins that capture subglacial water, the continental scale tectonic structure serves as a basic template for the formation of subglacial lakes. The distribution of sedimentary basins and the variability in geothermal heat flux have also been advanced as mechanisms for tectonic processes to influence ice sheet stability through the development of ice streams. Large subglacial lakes whose distribution is controlled to a large extent by the tectonic framework provide a new mechanism for tectonic control on ice sheet dynamics.

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Introduction

Large volume subglacial lakes have the potential to influence ice sheet dynamics either through direct lubrication of the basal regime through the addition of subglacial water or through the modification of the basal thermal regime through active accretion as the ice sheet traverses the lake. Many of the over 150 known subglacial lakes are situated close to the major ice domes in Antarctica where basal melting provides the water. New evidence supports the concept that continental-scale tectonics control large-volume subglacial lakes (Studinger et al, 2003; Bell et al., 2006; Dalziel, 2006). This correlation between large-volume subglacial lakes and major tectonic boundaries is well defined for the largest lakes, Vostok and Recovery. Tectonic control is also evident for 90° E and Sovetskaya Lakes (Bell et al., 2007). While today the onset of ice streaming is only evident at the Recovery Lakes, each of these large-volume lakes has the potential to trigger the onset of ice streaming deep in the interior of the ice sheet as climatic change modifies the form if the ice sheet. The onset of ice streaming will be closely aligned with the major tectonic boundaries forming a tectonic framework for ice sheet dynamics and ultimate collapse.

Tectonic Control of Surface Lakes

The distribution of surface lakes globally is determined by the presence of water and closed basins to capture the water (Meybeck, 1995). For surface lakes, the presence of water is broadly controlled by climatic conditions and the majority of lakes are found north of 40°N. Geomorphic processes that range from glacial to fluvial to volcanic to tectonic control the availability of basins. Together, tectonically and glacially controlled basins represent over 83% of the global lake area. 98% of the surface lake water volume is found in tectonic or glacial basins. Tectonically controlled surface lakes contain over 58% of the water volume locked in surface lakes due to their great depths, even though they represent only 25% of the total surface area. Examples of these large-volume, geodynamically controlled lakes include Malawi, Baikal, Tahoe (USA) and Issyk-kul (Kyrgyzstan). While rift lakes clearly form along active tectonic boundaries, large lakes such as Lake Michigan and the Great Slave Lake are coincident with major tectonic features that have been classified as ancient zones of "structural weakness” (Dalziel, 2006). The distribution of large-volume surface lakes is strongly controlled by the tectonics – either the basin formed by active tectonics or because of the fabric resulting from previous events.

Distribution of Subglacial Lakes

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 (Kapitsa et al., 1996; Siegert et al., 2005). The majority of subglacial lakes are small (<20km in length) and within 100 km of a local ice divide (Siegert et al., 2005). Subglacial lakes are concentrated along the ice divides of Dome Concordia and Ridge B where the ice thickness is close to 4000 m. Large subglacial lakes, associated with deep basins and thick ice, are not always coincident with ice domes. For example, the Astrolabe and Recovery Lakes are examples of large lakes found far from the central domes. While the availability of water for surface lakes is a result of regional climatic conditions, the distribution of subglacial lake water is a function of surface temperature, accumulation, ice thickness, ice velocities and geothermal flux. The second major influence on the distribution of subglacial lakes is the geomorphic control on closed basins. These controls on closed subglacial basins are likely to be similar to those for surface lakes, with subglacial lakes forming in glacially scoured, fluvially formed, volcanically developed or tectonically controlled basins.

Evidence for Tectonic Control of Large Subglacial Lakes

While the coincidence of small subglacial lakes with the ice domes has been known for some time, it is now apparent that the seven largest subglacial lakes have formed in tectonically controlled basins. Containing 72% of the total subglacial water volume (18,000 km^3), these lakes include Vostok, 90E, Sovetskaya and the four Recovery Lakes in Queen Maud Land. The tectonic framework of East Antarctica remains poorly constrained due to the paucity of outcrop and the absence of comprehensive continental-scale data. Thus the major cratonic boundaries documented along the coastline are weakly constrained within the interior as illustrated in Figure 1 in which the locations of the major lakes are superimposed on a reconstruction of East Antarctic with India and Australia (Fitzsimons, 2003). Regional geophysical studies provide additional constraints on the tectonic framework for these lakes.

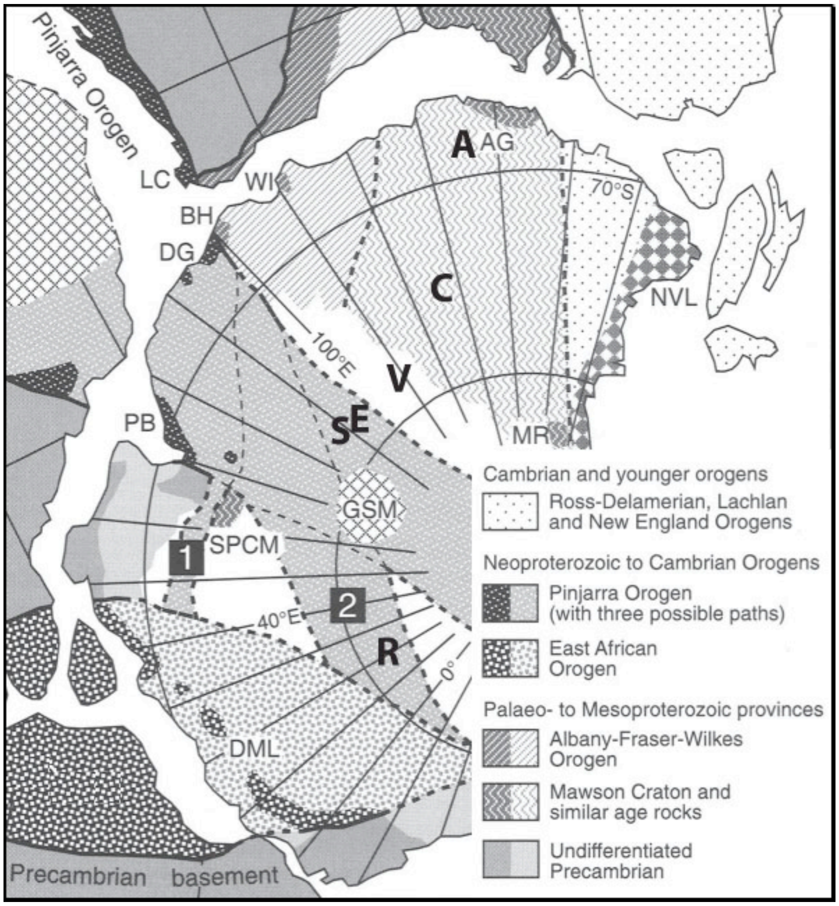

Figure 1. Tectonic Framework of East Antarctica, reconstructed with India and Australia (after Fitzsimons, 2003), with location of large subglacial lakes – Recovery (R), Sovetskaya (S), 90E (E), Vostok (V) and Astrolabe (A) – as well as Dome C lake district and Lake Concordia (C). GSM – Gamburtsev Subglacial Mountains; DML – Dronning Maud Land.

While Lake Vostok (Figure 1, 'V') is located over 1000 km from the closest outcrop, the Fitzsimons (2003) interpretation suggests that it may be coincident either with the inland extension of the Pinjarra Orogen, which outcrops at the Bunger Hills, or with a boundary between the Mawson Craton and Wilkes Orogen Rocks. Recent aerogeophysical surveying over Lake Vostok (Studinger et al., 2003) clarified the lake's tectonic setting. Lake Vostok (15,690 km^2) is located along a major tectonic boundary with rugged non-magnetic crust to the west and highly magnetic crust with subdued topography to the east (Studinger et al., 2003). Situated within the interior of the East Antarctic craton, the Vostok Collision Zone is a well-defined boundary between two major crustal blocks, most likely the consequence of the overthrusting of a pre-existing passive continental margin by thick thrust sheets (Studinger et al., 2003) (Figure 2). The Lake Vostok Basin appears to have formed by the reactivation of this collision zone, possibly during the breakup of Gondwana.

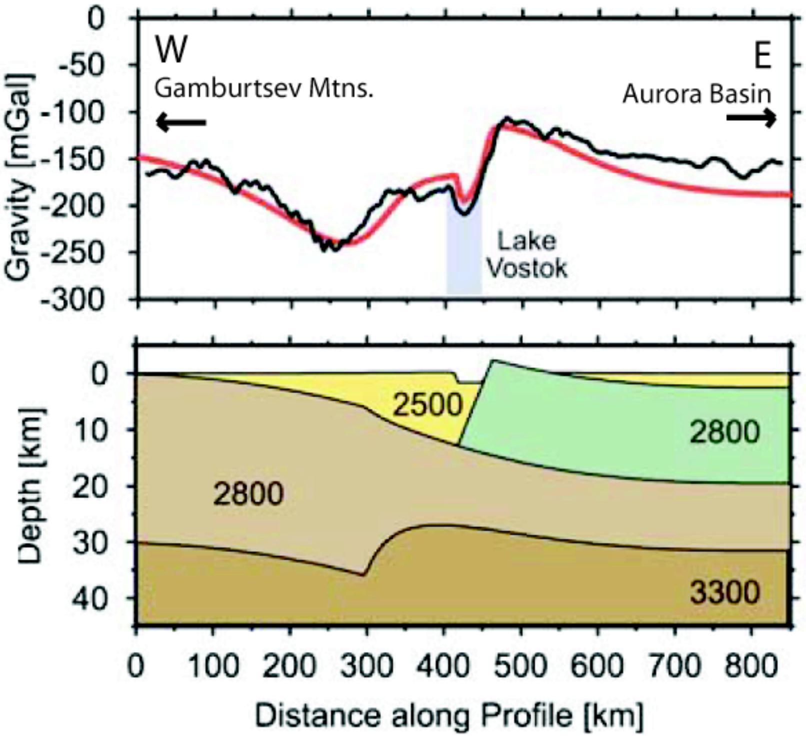

Figure 2. Gravity profile across Lake Vostok (Studinger et al., 2003). Upper panel shows observed gravity (black) and flexural model gravity (red). The flexural model of the Vostok Collision Zone is shown in the bottom panel with overthrust block (green), the former continental margin (tan) and mantle (brown) and the infilling sediments (yellow). The densities of the units in gm/cm^3 are indicated in the blocks.

The 90° E (2,420 km^2), and Sovetskaya (1,745 km^2) Lakes located on the flanks of the Gamburtsev Subglacial Mountains are aligned parallel to Lake Vostok (Figure 1, 'S', 'E'). In the Fitzsimons (2003) interpretation, these lakes may be associated with the Pinjarra Orogen. These lakes are distinguished by distinct coincident gravity lows, and have estimated water depths of at least 900 m. For a subglaical lake water depth refers to the thickness of the water layer between the base of the ice sheet and the water-rock interface. These deep subglacial lakes with elongate, rectilinear morphology are tectonically controlled features. The sub-rectangular morphology of the Sovetskaya and 90°E lakes and their position along the western edge of this foreland basin (the Vostok Collision Zone) indicates that these features may be similarly fault controlled. The tectonic fabric of this foreland basin provides the template for the elongate fault-bounded topographic depressions necessary to form this province of large, deep subglacial lakes.

In East Antarctica, on the western flanks of the Gamburtsev Mountains, the Recovery Lakes (Figure 1, 'R') are a series of four lakes, each of which is among the largest identified subglacial lakes (A – 3,915 km^2; B – 4,385 km^2; C – 1,490 km^2; D – 3,540 km^2). Together, the area of the Recovery Lakes (13,330 km^2) is similar to that of Lake Vostok. The Fitzsimons (2003) interpretation is poorly constrained in this region. Flexural modeling of surface gravity data indicates that the Recovery Lakes are coincident with a tectonic boundary, characterized by >2 km thinning of the crust and a regional elevation shift from an average 500 m above sea level to the east to 500 m below sea level to the west. Teleseismic studies indicate thinning of the crust in this region (Shapiro et al., 2003) but the absence of regional geophysical data precludes the further definition of the tectonic setting of this region.

The two other known large subglacial lakes are Lake Concordia (800 km^2), ~100 km north of Concordia Station, and Astrolabe (~1600 km^2), ~140 km inland from the French Station, Dumont d'Urville. Lake Concordia is located in an elongate valley, but no clear tectonic control is evident. While Astrolabe Lake is close to the western boundary of the Mawson Craton, a Paleo and Mesoproterozoic igneous province, (Finn et al., 2006), no detailed data currently exists to constrain the tectonic setting of this lake.

Linking subglacial lakes and ice sheet dynamics

The largest known subglacial lakes are all closely associated with tectonic boundaries. Subglacial lakes capture water from large areas and effectively concentrate the energy from basal melting. This energy stored as water within subglacial lakes is released either through basal accretion or through catastrophic drainage where it can have a significant impact on ice flow. Presently, only the Recovery subglacial lakes appear to play an active role in the onset of rapid flow and the dynamic evolution of ice sheets. Other large subglacial lakes have the potential to become active components of the ice streaming systems. Large lakes far from the center of the ice sheet, proximal to the ice margin such as the Recovery Lakes, and possibly Astrolabe Lake, are likely to be the first lakes to be associated with rapid flow. By providing the basins where large subglacial lakes can form, the tectonic framework of Antarctica serves a fundamental role in the evolution of the ice sheet.

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