

Lake Vostok behaves like a ‘captured lake’ and may be near to creating an Antarctic jökulhlaup

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ABSTRACT. The most well known sub-glacial lake is probably Grímsvötn under Vatnajökul, Iceland, from where jökulhlaups regularly burst forth. It is created by thermal melting under the ice cap. The Antarctic Lake Vostok, on the other hand, is considered to be located over a region with normal geothermal heat transfer, where it can exist because the ice is so thick that its base is at the pressure melting point. This makes it a candidate for testing the Captured Ice Shelf (CIS) hypothesis, which states that the motion of a totally confined ice shelf creates a hydrostatic seal in the form of an ice rim over the threshold. The CIS hypothesis may offer a source of water for the controversial Laurentian jökulhlaups inferred from field data, implicated in dramatic climatic changes. Here I show that Lake Vostok agrees with the hypothesis, and that it may be on the verge of a jökulhlaup, which could create an ice stream and regional drawdown. The result also implies that the lake may well be of pre-glacial origin, and that it may have experienced jökulhlaups also during previous interglacials.

Introduction

The Captured Ice Shelf (CIS) hypothesis was introduced to explain certain enigmas of the Baltic Sea glaciation, such as field data suggesting a partially floating ice in the Bornholm Deep (Erlingsson 1994a, b). It has recently been invoked in the Kattegat (Houmark-Nielsen 2003), and it might offer an explanation to the hitherto controversial jökulhlaups inferred from the Laurentian ice sheet by, e.g., Shaw (1983), Kor *et al.* (1991), Shaw *et al.* (1996), and Beaney and Shaw (2000), by providing a source for the enormous water volumes that are required. Continental-scale jökulhlaups from the North American ice sheet have been implicated in provoking large climatic fluctuations (Blanchon and Shaw 1995). Similar changes have been coupled to fresh water input disturbing the oceanic circulation (Ganapolski and Rahmstorf 2001), which is consistent with the jökulhlaup explanation. The CIS hypothesis may also have significant implications for the behaviour and consequences of large ice sheets in terms of their water and thermal budgets, since it implies less changes in both of those compared to a traditional inland ice.

Until now, the CIS hypothesis has only been evaluated theoretically, and with computer modelling (Erlingsson 1994a, b). This paper presents the first test of the hypothesis using field data from a modern ice sheet, by comparing the predicted

geometry with that of Lake Vostok, the planet's largest existing sub-glacial lake, situated under the East Antarctic ice sheet.

Background

The CIS hypothesis (Erlingsson 1994a, b) was developed in 1990 independently from the sub-glacial mega-lake hypothesis of Shoemaker (1991), using the fluid potential to calculate the **hydrostatic seal**. According to the definition, a CIS is an ice shelf that is grounded on all sides, and the lake under it may be called a **captured lake**. The central postulate is that an ice shelf that crosses a body of water will form a hydrostatic seal on the opposite shore as a result of its motion. This follows logically from the fact that the ice has to be pushed up on the ground to experience significant bed friction, and until it does, it will keep advancing. The advancing ice is predicted to create an **ice rim** at the grounding line, acting as a hydrostatic seal (Fig. 1). This enables the **floating level** to be much higher than the threshold of the lake, until the lake eventually bursts out in a jökulhlaup.

While an initial ice rim appears logically necessary, the question is if the seal can be sustained as the floating level rises significantly above the threshold. This is hereby tested on Lake Vostok. It is a sub-glacial lake under the East Antarctic ice sheet, by the Vostok station (78.467°S, 106.800°E; elevation 3,476 m ref WGS84). The flat, floating ice is a clearly visible topographic feature (Fig. 2). The general ice movement is from West to East, but the ice gets somewhat diverted South along the lake. The surface flow velocity at Vostok station is about 2 m a⁻¹ (Masson *et al.* 2000). The presence of the lake was proved using radio echo sounding (Oswald and Robin 1973). The lake has since been shown to be about 260 km long and 81 km wide, with an area of about 14000 km² (Tabacco *et al.* 2002). It has a volume of 5400 ± 1600 km³, and a maximum depth of almost 800 m (Studinger *et al.* 2004). It is not located over any geothermal hot spot (Souchez *et al.* 2003).

Since the ice over Lake Vostok is floating moving ice, it is an ice shelf. Since it is landlocked, it is per definition a CIS, so it can be used to test the hypothesis. If the principle works here, in one of the coldest places on Earth and near the ice divide, it implies that a CIS is possible in any zone of any ice sheet, modern or ancient (this is in contrast to subglacial ponding, which is actually more plausible near the ice divide than near the ice margin). However, while jökulhlaups appear inevitable for a CIS in the ablation zone, accumulation zone jökulhlaups are conditional: for there to be a positive mass balance of water under the ice, the ice must be thick enough to reach the pressure melting point, which requires a deep basin.

Lake Vostok's age and origin has been the topic of a recent debate, the issue being whether the lake has existed continuously since before the glaciation, or if it was created by melting under the ice (Duxbury *et al.* 2001, Siegert 2004, Pattyn 2004). If it is of pre-glacial origin, it may contain life forms that have been isolated for tens of millions of years, which makes it even more important to avoid contamination when drilling through the lake ceiling. If life can exist in Lake Vostok, the argument goes, it may also exist in similar environments on other planets, such as Mars, and Jupiter's moon Europa.

The CIS hypothesis offers an alternative model for how a pre-glacial lake can have become trapped under an advancing glacier (Erlingsson 1994a, b). The hypothesis gets

increased support if Lake Vostok is found to conform to it. One of the cases where it can subsequently be applied is on the genesis of Lake Vostok itself, by offering a plausible mechanism for the entrapment of a pre-glacial lake.

Method

For a sub-glacial lake to exist the fluid potential must have a local minimum. The formula for the fluid potential is (Björnsson 1988, 2002; Erlingsson 1994b):

$$\Phi = \rho_i g h - \rho_w g (W-B) \quad (1)$$

where h is ice thickness, W is the floating level, B is the ice base elevation, g is the acceleration due to gravity, and ρ_i and ρ_w is the density of ice and water, respectively. The whole captured lake has the same fluid potential; $\Phi_{CL} = 0$ if W is the floating level of the CIS.

The ice shelf over Lake Vostok is thinner in the south than in the north. This makes it possible to calculate the floating level as follows:

$$W = H_1 - (H_2 - H_1) / (h_2 / h_1 - 1) \quad (2)$$

where H is the ice surface elevation, and the index denotes two different locations on a CIS of varying thickness.

The **equipotential level** is the level where the fluid potential equals that in the captured lake. For convenience, it is assumed that the ground has the same density as ice, following Björnsson (1988). The equipotential level around the captured lake is:

$$E = W - \Delta\rho (H - W) \quad \text{where } \Delta\rho = \rho_i / (\rho_w - \rho_i) \quad (3)$$

Note that W is taken as the lake's floating level. Where the equipotential level is below the (impermeable) ground, water cannot escape from the captured lake.

The fluid potential under the ice (the pressure head) increases away from the lake in a zone surrounding it. This creates a hydrostatic seal. The hydrostatic seal expressed as elevation is:

$$S_H = G - E \quad (4)$$

where G is the ground level. S_H must be greater than zero for the seal to exist.

The calculation of the floating level is sensitive to errors in the determination of the geoid. Elevation values in the North-South profile relative the WGS84 ellipsoid (Tabacco *et al.* 2002) were converted to the OSU91A geoid. The latter is 20 m above the WGS84 ellipsoid in the south and 15 m in the north of the lake. A small error in surface slope becomes a big error in floating level (using the ellipsoid would create a 59 m error). Furthermore, since the equipotential level is 10 times steeper than the surface slope, any error in the floating level is much amplified in the hydrostatic seal level. Add to this the uncertainty in the ground elevation, plus the generalization of it in the map (5 km cells). Based on this, the total uncertainty in the hydrostatic seal height can be estimated to the order of 10^2 m. This is not deemed enough to jeopardize the main conclusion of the study.

Result

In the OSU91A geoid, the southern ice surface is at 3,496 m a s l, and the northern at 3,540 m a s l, a difference of 44 m. The southern ice base is at -295 m and the northern at -735 m, giving ice thicknesses of 3791 m and 4275 m, respectively, a difference of 484 m. This is exactly 11 times the surface elevation difference. Thus, $\Delta\rho = 10$, the ice base slopes exactly 10 times more than the surface, as it should over a fresh water lake. The floating level calculates to 3,151 m a s l (Fig. 3).

The height of the seal around the lake was calculated in a GIS using the Bedmap dataset (ADD Consortium, undated), which includes ice surface and ground elevation for the entire Antarctic with 5 km cell size. It is in Polar Stereographic projection with 71°S as the latitude of true scale and 0°E as the central meridian. The elevation is referenced to OSU91A. The ice elevation was taken from the map “Surface”, while the “Bedelevation” map was used for ground elevation.

The saddle point was calculated to about 200 m (Fig. 4), but since the nearby lake has a value around 50 m, a bias of that amount is assumed, why the threshold seal is estimated to be $S_H = 150 \pm 100$ m.

Discussion

The main objective was to validate the CIS hypothesis. The cross-section in Figure 3 shows that Lake Vostok exhibits features predicted for a CIS: an ice rim, a hydrostatic seal, and an elevated floating level (3,151 m above the geoid). The seal exists all around the lake, and it has a distinct outline under the ice rim (Fig. 4), which is present along most of the grounding line of Lake Vostok. The uncertainty in the calculated hydrostatic seal height does not affect the main conclusion, i.e., that Lake Vostok conforms to the CIS hypothesis, which thus survived the test. It also implies that Lake Vostok may have been a CIS from the outset, and thus of pre-glacial origin, which has implications for the fauna one could expect to find in it.

The main difference between the computer model of a CIS (cf. Erlingsson 1994b), and Lake Vostok, is the thickness of the ice shelf. Factors affecting the CIS thickness include temperature (melting/freezing underneath), inflow velocity, outflow velocity, if the flow over the lake is divergent or convergent in plane, and internal deformation in the CIS. The greater thickness at Vostok mainly reflects the low temperature.

Applying the CIS hypothesis, an inference may be drawn about Lake Vostok's dynamics. Based on radio echo profiles it has been concluded that the lake ceiling is melting in Lake Vostok's northern and western part, while there is accretion (freezing) in the southern and eastern part (Siegert *et al.* 2000, 2003). However, since it takes the ice between 16,000 and 20,000 years to cross the lake (Bell *et al.* 2002), it would appear that the ice with accretion has been over the lake since Pleistocene, while the ice lacking accretion has arrived during Holocene. While those zones have been interpreted as modern-day accretion and melting areas, an origin in long-term dynamics seems an alternative possibility.

The lake ceiling being near the pressure melting point, it follows that a colder climate leads to thicker ice over the lake, and *vice versa*. At the same time, the ice surface in this part of the ice sheet has been calculated to drop by 150 m during Ice Ages due to a decrease in precipitation (Ritz *et al.* 2001). This means that the captured lake ceiling

drops by much more than 150 m during Ice Ages, and conversely, that interglacials cause the volume of the lake to grow by a similar amount. This prediction appears to be confirmed by isotopic studies, which indicate that the lake may have undergone a significant expansion over the last 10^4 to 10^5 years (Tranter *et al.* 2003). The conclusion is that Lake Vostok may undergo cyclical volume changes, by shrinking to a “pond” during Ice Ages, and growing during interglacial periods—quite possibly to the point of bursting out in jökulhlaups.

The lake is practically full at present, since the hydrostatic seal S_H at the threshold was calculated to about 150 ± 100 m relative to the nearby part of the lake. As a comparison, the jökulhlaups in Grímsvötn on Iceland typically start when S_H equals 70 m, but can wait until it is 0 m. They stop when the ice overburden pressure at the threshold exceeds the hydrostatic pressure by 10–15 bars (Björnsson 2002).

A jökulhlaup of a few thousand km^3 from Lake Vostok in the near future can thus not be ruled out. The direction of the jökulhlaup would be through the Byrd Glacier to the Ross Ice Shelf. It could very well trigger the creation of an ice stream, which in turn would lead to a drawdown of the ice surface in that sector of East Antarctica, analogous to what has been inferred to have happened on the other side of the ice divide, in the Lambert Glacier drainage area (Hughes 2003).

To predict the timing of a possible jökulhlaup requires better data of the glacier bed, and a holistic hydro-glacial model formulation. The floating level and hydrostatic seal location are subject to change as the water level of the sub-glacial lake rises, so a simple mass balance calculation will not suffice. The modelling challenges include handling the fact that the velocity in a point is influenced by conditions also at other locations (which requires a holistic model), and dealing with the passage from a grounded ice to a floating ice and back again to a grounded ice. While Erlingsson (1994b) used a traditional ice model with *ad hoc* modifications to solve these problems, the geometrical force balance presented by Hughes (2003) seems to offer the necessary theoretical framework, if coupled with calculations of fluid potential.

Although Hughes developed the theory with an ice stream in mind, he addressed all the relevant factors for the modelling of ice flow in a CIS as well. In fact, one may view a traditional ice dome, an ice shelf, and a CIS as three extremes (Fig. 5). Ice streams and ice surges will fit somewhere in between, presumably with floating levels that fluctuate rapidly in time and space. An implication is that a model of ice streams may be tested on the three extremes in Figure 5, and that Lake Vostok can serve as an example of a CIS.

Validating the CIS hypothesis may also turn out to have implications for climate change research, since the CIS hypothesis allows for large sub-glacial lakes. During the Ice Ages, favourable conditions existed both in North America and Europe. When the expanding ice sheets reached the Hudson Bay and the Baltic Sea, respectively, ice shelves could spread over them. If these ice shelves were captured, lifted, and thus made to advance, very large sub-glacial lakes may have formed, especially in North America. A jökulhlaup from such a sub-glacial lake would have been many orders of magnitude larger than one from Lake Vostok, quite possibly as large as the outburst floods inferred by Shaw (1983), Kor *et al.* (1991), and others.

One may also wonder if this sub-glacial water is related to the “implicit ice” in Hudson Bay and the Baltic Sea, in the analysis of sea-level change in Peltier (2002). At any rate, sub-glacial water in a CIS may accumulate over continents without freezing,

and may be returned to the ocean in a geological instant without the need of energy to melt it. A Laurentian CIS could be large enough to be significant for palaeoclimatic and palaeoceanographic reconstructions, apart from the obvious geological implications. Making a computer model of the Laurentian glaciation based on Hughes' (2003) formula with fluid potential (and thus CIS prediction) added, therefore seems a worthwhile undertaking.

Conclusion

It is concluded that Lake Vostok conforms to the Captured Ice Shelf theory as regards the crucial ice rim and hydrostatic seal formed at the grounding line, where the ice shelf leaves the sub-glacial lake. The lake's volume appears to vary with the climate, with a low volume during Ice Ages, and a large volume during interglacial periods—possibly to the point of a jökulhlaup many thousands of years into each interglacial. Such a jökulhlaup could conceivably lead to Byrd Glacier forming an ice stream, and to a drawdown of East Antarctica through the Ross Ice Shelf. The lake might therefore be at the heart of an inner dynamic in the ice sheet. Lake Vostok is now almost full, and a jökulhlaup of several thousand cubic kilometres appears possible at any time.

The most profound implications of the CIS hypothesis are, however, predicted to come in our understanding of ice sheet dynamics during the ice ages. The possibility of a giant Laurentian CIS appears worth examining, as it might explain observed rapid climatic fluctuations, sudden transgressions, and inferred mega-scale sub-glacial outburst floods.

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Illustrations

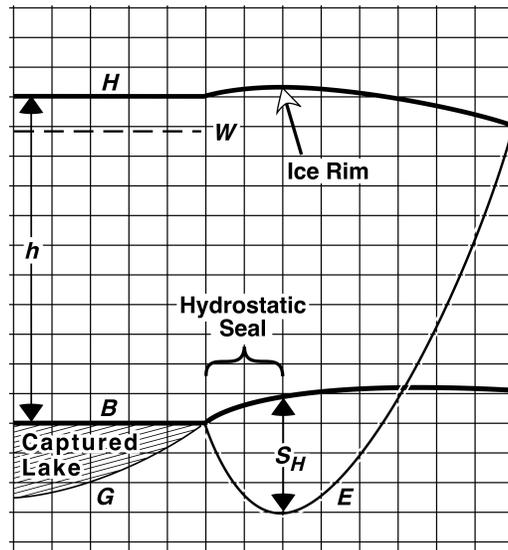


Figure 1. Hypothetical profile along a flow line across the grounding line of a CIS. The hydrostatic seal is a zone of increasing fluid potential away from the lake. S_H = height of hydrostatic seal, H = ice surface, W = floating level, B = ice base, G = ground level, h = ice thickness, E = equipotential level. The latter is a vertically exaggerated mirror image of the ice surface around W .

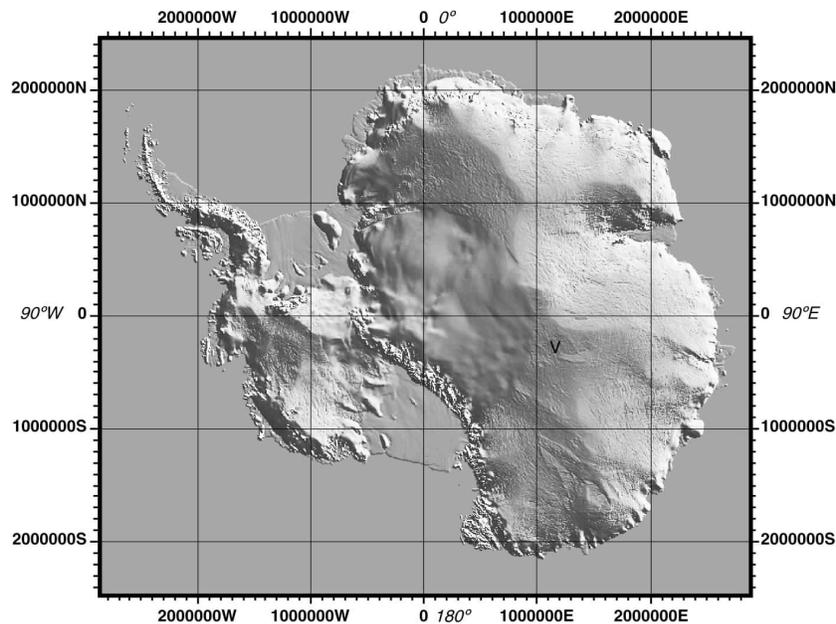


Figure 2. Contrast-stretched hill shaded elevation map of the Antarctic centred on the South Pole, with the light from the upper right. The **V** indicates the location of the Vostok station, at the southern end of Lake Vostok, which is visible as an even grey zone outlined by a thin light-and-dark line above and below it. Polar Stereographic coordinates in metres. Based on a DTM from Liu *et al.* (2001).

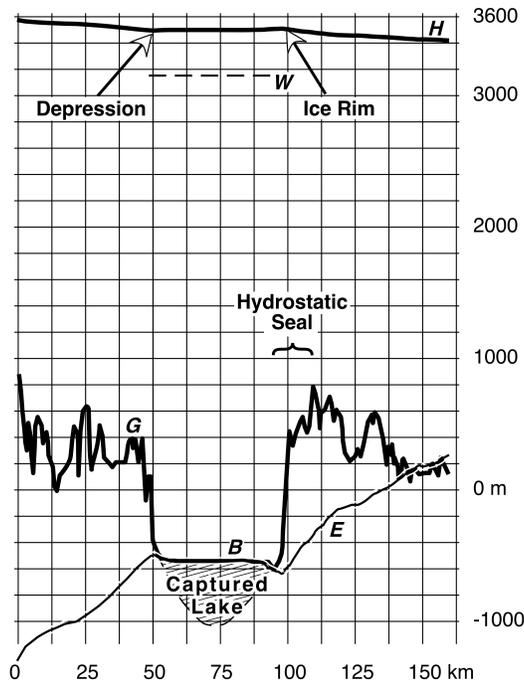


Figure 3. West-East section over Lake Vostok along a flow line. Ice movement is to the right. The ice rim is 7 m high, and is best seen as its mirror in line *E*. The ice rim starts to form by compressing flow shortly before the grounding line, after which the flow goes over to extending flow. Also note the depression at the floating line where the ice enters the lake under compressing flow. Profile from section “ew2” in Tabacco *et al.* (2002). The bottom under the captured lake is hypothetical. Abbreviations as in Fig. 1.

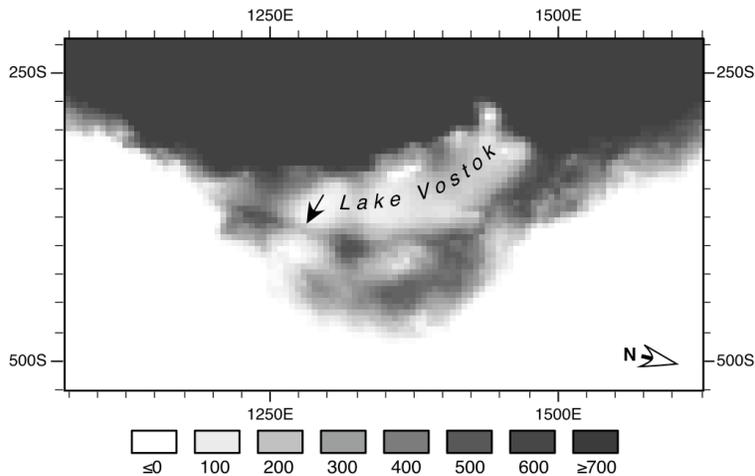


Figure 4. The hydrostatic seal at Lake Vostok. The ice flow from West to East creates an ice rim on the eastern (lower) side of the lake. The arrow shows the ice movement direction, while also pointing to the saddle in the ice rim where the hydrostatic seal height S_H ca 200 m. The average value of S_H in the lake is ca 140 m, with a minimum of -33 m. The deviation from the true value of 0 m reflects the uncertainty in the data, notably in the elevation of the ice base. Polar stereographic coordinates in km. The grey-scale is continuous with 1 m resolution between the indicated levels.

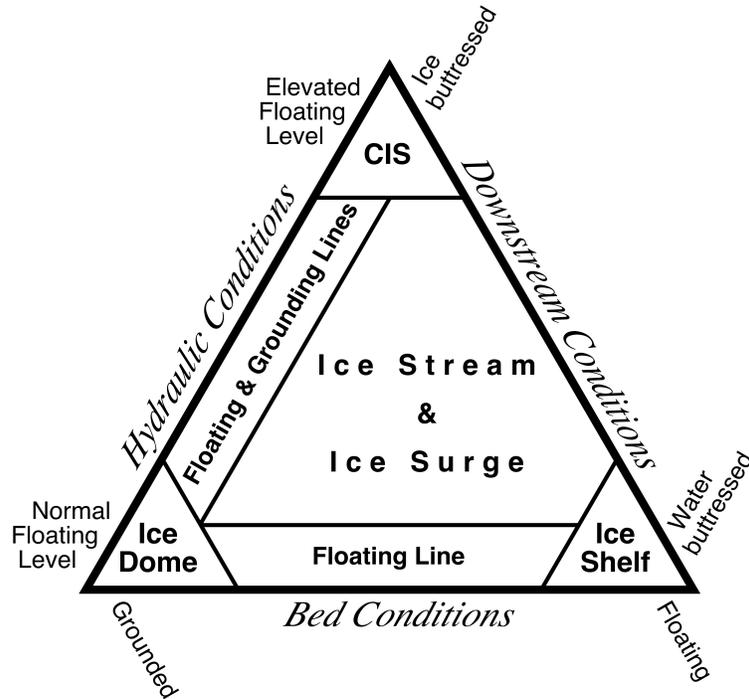


Figure 5. Conceptual classification of glacial phenomena domains in a triangle diagram. Ice domes and other grounded glaciers can be described by the equation of Nye (1952), and ice shelves can be described by the equation of Van der Veen (1983), but the geometrical force balance by Hughes (2003) addresses the entire bottom edge. If the fluid potential (Björnsson, 1988; Erlingsson, 1994b) is added, Hughes' equation holds promise to be applicable also to captured ice shelves (CIS), as well as to the intermediate phenomena. The position of ice streams and ice surges in the diagram is tentative, and other factors, such as bed friction, may in reality play the decisive role.