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Comment on "A numerical model for an alternative origin of Lake Vostok and its exobiological implications for Mars" by N. S. Duxbury, I. A. Zotikov, K. H. Nealson, V. E. Romanovsky, and F. D. Carsey

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[1] The origin of Lake Vostok, the huge East Antarctic subglacial lake, is critical to understanding the biota expected in this extreme environment. *Duxbury et al.* [2001] investigate whether a preglacial Lake Vostok could have survived the mid-Miocene glaciation of Antarctica, at around 15 million years ago, by using a two-dimensional (2-D) thermodynamic model. The model accounts for heat exchange between the Earth, the lake, the ice sheet, and the atmosphere. Accumulation of ice on the glacier surface is accounted for, as is melting and freezing of ice at the ice-water interface. The model assumes that the lake is a closed system and that it is 500 m deep. During the first 3300 years as the glacial cover builds up subglacial freezing is predicted and the lake level lowers by 53 m. After this time subglacial melting is predicted as the lake level rises. *Duxbury et al.* [2001] conclude that so long as the preglacial lake was more than 53 m deep it would have survived the period of ice sheet initiation and growth. This, they contend, has significant implications for exobiological studies on Mars as, by analogy to their model of Lake Vostok, ancient preglacial microorganisms could be present beneath the Martian glaciated surface. Whether the lake is a closed system or not is critical to *Duxbury et al.*'s [2001] model. At present, as *Duxbury et al.* [2001] point out, the lake could be considered to be in an approximate closed state (although this is not certain). However, this would definitely not be the case in preglacial times, nor could it have been the case at the onset of glaciation, as the known basal environments of temperate and semitemperate glaciers testify. Consequently, the closure of the Lake Vostok system must have happened, if at all, some time between ice sheet initiation and the establishment of a large, stable ice cover in East Antarctica. The process of ice sheet growth in Antarctica, which involves the three-dimensional flow of ice and its interaction with climate and topography, is not accounted for within the model used by *Duxbury et al.* [2001]. This process is, however, fundamental to the production of subglacial water and the development of water pressure gradients that define the subglacial hydrology in an open system. *Duxbury et al.*'s [2001] conclusion that a preglacial Lake Vostok survived the glaciation of Antarctica should therefore be revised with this process in mind.

[2] In order to assess whether Lake Vostok could have survived the onset of glaciation, consideration needs to be given to (1) the glaciological conditions that permit the lake to exist today and those which do not allow other similarly sized subglacial troughs to be occupied by large lakes, (2) models that describe the onset of glaciation in Antarctica, and (3) subglacial hydrology and water pressure gradients, particularly in subglacial troughs at the margin of the present ice sheet (as an analogy to Lake Vostok during ice sheet buildup).

[3] Lake Vostok is over 250 km long and 50 km wide and is situated beneath between ~3750 m (over the south of the lake) and ~4150 m (over the north) of ice in central East Antarctica. Flow of ice across Lake Vostok has been shown by Interferometric Synthetic Aperture Radar data to be predominantly from west to east [*Kwok et al.*, 2000]. Ice surface elevation varies over the lake by only ~50 m from the northern end downward to the south, and there is virtually no surface gradient from west to east across the lake. The gradient of the ice-water interface is ~10 times that of the ice sheet surface, sloping steadily downward from south to north. Seismic data reveal that the southern end of Lake Vostok is 510 m deep [*Kapitsa et al.*, 1996]. On the basis of these limited data, and the subglacial morphology on the sides of the lake, Lake Vostok appears to occupy a large subglacial trough that is relatively deep in the south [*Siegert et al.*, 2001] and possibly in the north also (M. Studinger, personal communication, 2003). The morphology of the trough has been likened to a "rift valley" as it is crescentic in shape and several hundred meters deep [*Studinger et al.*, 2003].

[4] There are several overdeepened troughs in Antarctica that are over 100 km in length and tens of kilometers wide [*Drewry*, 1983]. The origin of these troughs is open to debate. Some may have formed through tectonic processes such as rifting and faulting prior to glaciation at around 15 million years ago. Many troughs display the hallmarks of

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glacial erosion, as they are U-shaped and overdeepened. Although several troughs are likely to be "actively" eroding, as they are occupied by fast flowing ice (such as in the Astrolabe Subglacial Trench), many must be relic topographic features formed by an earlier, smaller phase of Antarctic glaciation (such as the Adventure Subglacial Trench in Dome C) [*Drewry*, 1975].

[5] Examination of the morphology of the seven largest troughs in Antarctica reveals that Lake Vostok's is not unique in terms of size. The longest is the Lambert trough; the Astrolabe Subglacial Basin is the widest and the deepest, has the steepest sides, and houses the greatest thickness of ice; and the largest by area is the Byrd Subglacial Basin in West Antarctica. Despite there being several large, deep trenches in East Antarctica (where the ice is at melting point), only Lake Vostok's is occupied by a large lake. Understanding the reason for this is critical to assessing Lake Vostok's history.

[6] The ice above the Lake Vostok trough is distinct in that it has a low surface gradient (0.0002 from north to south), which is due to the ice shelf type flow that occurs over the lake [e.g., *Pattyn*, 2003]. This situation is controlled by the flow of grounded ice upstream of the lake (i.e., the lake does not dictate the flow of grounded ice upstream). Currently, there is only 50 m worth of north-south slope in the grounded ice that flows across the trough's western margin, and this translates into the elevation change over the lake itself. If the slope of the grounded ice across the lake's western margin were changed, so too must the ice surface slope over the lake. For example, if there were 200 m of grounded ice elevation change across the western margin of the lake, the ice surface change over the lake itself must match this value and the elevation of the ice-water interface would change by ~2000 m. Thus the reason that a lake exists within the Vostok trough, and that ice shelf flow is subsequently permitted, is due primarily to the flow direction of grounded ice, and the minimal surface elevation change that occurs across the lake's upstream margin. This is a fundamental concept about the sustainability of Lake Vostok in its present form. For all other troughs, ice flows across large subglacial troughs at an angle greater than 30° to their long axes, causing relatively large ice surface gradients across their flanks and interiors, the establishment of high water pressure gradients, and the evacuation of water. (The flow of water beneath an ice mass is controlled by the water pressure gradient, P_g, which can be calculated by

$$P_g = \rho_i g \alpha_{surface} + (\rho_w - \rho_i) g \alpha_{bed}, \quad (1)$$

where ρ_i is the density of ice (~910 kg m^{-3}), ρ_w is the density of water (~1000 km m^{-3}), g is the acceleration due to gravity (9.81 m s^{-2}), $\alpha_{surface}$ is the ice surface slope, and α_{bed} is the slope of the ice base [*Shreve*, 1972]. Thus, if the magnitude of surface slope is over ~1/10 of the basal slope, water can be driven "uphill" and out of a topographic depression.)

[7] Ice growth in Antarctica has been modeled numerically by *DeConto and Pollard* [2003] using an ice sheet model coupled with an atmospheric general circulation model. They show that the buildup of ice would not be uniform across the continent, as is implied by *Duxbury et al.* [2001]. Rather, ice forms first across the highest topography and flows down to lower elevations over time. According to *DeConto and Pollard*'s [2003] model, the ice margin would at some stage in the past have been much closer to Lake Vostok than it is currently. We can assess whether such a situation would permit a large lake to be retained in a deep subglacial trough by comparing the situation with conditions in the Astrolabe Subglacial Basin today.

[8] The Astrolabe Subglacial Basin, located 200 km from the margin of the East Antarctic Ice Sheet, has often been referred to as a rift valley similar to Lake Vostok's [*Cudlip and McIntyre*, 1987; *Siegert and Glasser*, 1997] and at its deepest is over 2 km below the sea level. If the ice in East Antarctic were taken away, the trench would retain water and a large, deep lake would exist. According to the model used by *Duxbury et al.* [2001], such a lake would survive the onset of glaciation and be present today. Subglacial melting is known to occur in the Astrolabe Subglacial Basin, as a subglacial lake has been identified at its mouth [*Siegert et al.*, 1996]. There is, however, no large lake in the trough itself. Instead, water generated at the base of the ice sheet is evacuated through the trough in response to the water pressure gradient. The Astrolabe Subglacial Basin is thus an open system. The assumption made by *Duxbury et al.* [2001] that Lake Vostok was a closed system during the period of ice sheet growth is therefore not supported by contemporary glaciological analogy. Furthermore, the absence of a large lake within the deepest regions of the Astrolabe Subglacial Basin today supports the contention that water within the Vostok trough was driven out during the early phase of ice sheet growth in Antarctica.

[9] On the basis of the requirement that Lake Vostok has on the glaciological conditions surrounding it, the inferred subglacial hydrology of the modern ice sheet, and glaciological theory regarding the initiation of ice sheets, it appears unlikely that Lake Vostok, or any other lake, could have survived the onset of glaciation in Antarctica in the way described by *Duxbury et al.* [2001]. It should be noted, however, that a glacial origin for Lake Vostok does not rule out the possibility of ancient lake floor sediments being present within the lake.

[10] Finally, although a 2-D thermodynamic model may be inappropriate for investigating the history of subglacial Antarctica, it may be applicable to the Martian subsurface (if the ice sheet processes detailed in this commentary are absent). Hence the exobiological implications presented by *Duxbury et al.* [2001] may still be valid for Mars.

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