JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, E11004, doi:10.1029/2004JE002329, 2004

# Comment on the comment by M. J. Siegert on "A numerical model for an alternative origin of Lake Vostok and its exobiological implications for Mars" by N. S. Duxbury et al.

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Received 23 July 2004; revised 31 August 2004; accepted 20 September 2004; published 19 November 2004.

*INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 9310 Information Related to Geographic Region: Antarctica; 9604 Information Related to Geologic Time: Cenozoic; *KEYWORDS:* Antarctica, Lake Vostok, subglacial

**Citation:** Pattyn, F. (2004), Comment on the comment by M. J. Siegert on ''A numerical model for an alternative origin of Lake Vostok and its exobiological implications for Mars'' by N. S. Duxbury et al., *J. Geophys. Res.*, *109*, E11004, doi:10.1029/2004JE002329.

## 1. Survival of Preglacial Lake Vostok?

[1] There is some debate on the origin of subglacial Lake Vostok and whether the water within the present subglacial lake system contains biota that survived the buildup of the Antarctic ice sheet. One theory suggests that Lake Vostok existed as a preglacial lake before glaciation of the continent at around 15 Ma ago, survived the subsequent period of ice sheet growth, and remained stable beneath the thick ice cover to the present day [*Duxbury et al.*, 2001]. Another hypothesis challenges this view by stating that the early phase of build-up would have resulted in ice grounding throughout the trough which the lake now occupies [*Siegert*, 2004].

[2] According to *Duxbury et al.* [2001], the lake could have survived the growth of the ice sheet as long as the preglacial lake was more than 53 m deep. In their model, subglacial Lake Vostok is considered as an approximate closed system. However, if Lake Vostok existed as a preglacial lake, the closure of the Lake Vostok system must have happened between the initiation of the ice sheet and the establishment of a stable ice cover in East Antarctica [*Siegert*, 2004]. Therefore the dynamic evolution of the ice sheet and its interaction with the preglacial lake should be accounted for in determining whether subglacial Lake Vostok is a direct remnant of a preglacial surficial lake.

[3] *Siegert* [2004] demonstrates that the preglacial lake could not have survived the buildup of the Antarctic ice sheet: water flow beneath an ice mass is controlled by the hydraulic potential gradient, $P_g = \rho_i g \alpha_s + (\rho_w - \rho_i)\, g \alpha_b$, where $\rho_i$ and $\rho_w$ are the density of ice and water, and $\alpha_s$ and $\alpha_b$ are the surface and basal slope, respectively [*Shreve*, 1972]. If the magnitude of surface slope is larger than one tenth the basal slope, water can be driven out of a topographic depression and flow "uphill." Two ice-sheet model studies [*Huybrechts*, 1993; *DeConto and Pollard*, 2003] show that during the inception and growth of the Antarctic ice sheet, the ice sheet margin was situated close to Lake Vostok. The steep margin of the ice sheet across Lake Vostok implies high subglacial hydraulic potential gradients, which led *Siegert* [2004] to conclude that basal water is evacuated as the steep ice sheet margin progresses over the lake. However, none of the above models take into account the interaction of the ice sheet with the underlying lake, whether it be a preglacial or a subglacial lake, and only consider an ice sheet more or less frozen to the underlying bedrock.

[4] Below I present a physical mechanism that allows for subglacial Lake Vostok to survive the buildup of the ice sheet, by taking into account the interaction of the ice sheet with the preglacial/subglacial lake. This hypothesis is supported by the fact that the surface of a preglacial lake as well as the interface between a subglacial lake and the overriding ice sheet can be regarded as a slippery spot.

## 2. Subglacial-Lake Effect

[5] Lake Vostok is associated with a prominent morphological surface feature within the Antarctic ice sheet, i.e., the ice-sheet surface is relatively flat and featureless, consistent with the surface of an ice shelf. Ice flow over a large subglacial lake should be analogous to the flow of an ice shelf, as ice flowing over water experiences very low traction [*Pattyn*, 2003; *Pattyn et al.*, 2004]. To demonstrate this effect in detail, a dynamic experiment is carried out with the higher-order ice-sheet model of *Pattyn* [2003]. This model solves the field equations that describe the conservation of mass for incompressible materials and the conservation of angular and linear momentum. The Stokes system is solved by applying hydrostatic approximation to the vertical force balance. The model is capable of simulating three-dimensional grounded ice sheet flow as well as the flow of an ice shelf and an ice stream in a transient way [*Pattyn*, 2003].

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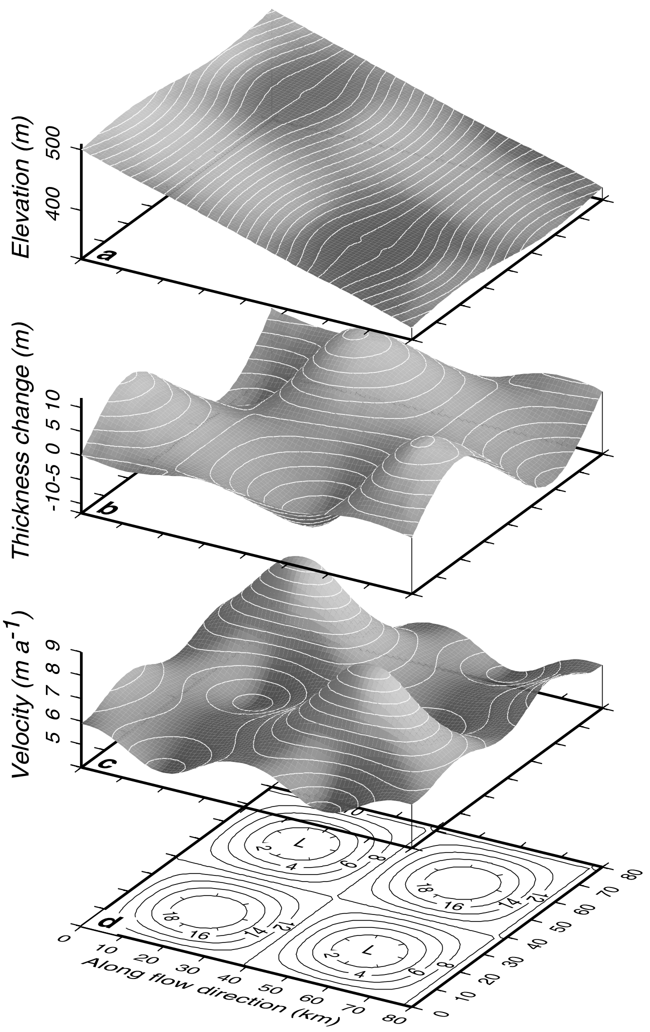

**Figure 1.** Effect of a slippery spot (subglacial lake) on ice sheet geometry and velocity field: (a) predicted steady-state surface topography; (b) predicted change in ice thickness compared to initial uniform slab of 1600 m; (c) predicted horizontal surface velocity magnitude; (d) basal friction field $\beta^2$ varying between 0 (subglacial lake marked by L) and 20 kPa a m$^{-1}$. Ice flow is from left to right.

[6] A uniform slab of ice of 80 by 80 km in size and $H$ = 1 600 m thick, lying on gently sloping bed ($\alpha$ = 0.115°) is considered. The basal boundary condition is written as $\vec{\boldsymbol{\tau}}_b = \vec{\mathbf{v}}_b\beta^2$, where $\vec{\boldsymbol{\tau}}_b$ is the basal drag, $\vec{\mathbf{v}}_b$ is the basal velocity vector and $\beta^2$ is a friction coefficient. For large $\beta^2$, $\vec{\mathbf{v}}_b$ is small or zero (ice is frozen to the bedrock); for $\beta^2 = 0$, ice experiences no friction at the base (slippery spot) as is the case for an ice shelf. In the experiment below, the basal friction coefficient $\beta^2$ is defined by a sine function ranging between 0 and 20 kPa a m$^{-1}$ (Figure 1d). Periodic lateral boundary conditions were applied and the model was run to steady state. The effect of a slippery spot on the ice slab is shown by a local increase in ice velocity where friction is low (Figure 1c) as well as a flattening of the ice surface above this spot (Figure 1a). This flattening is due to a thinning of the ice upstream from the slippery spot and thickening of the ice downstream (Figure 1b) and is a direct result of the lack of basal shear across the slippery spot. *Gudmundsson* [2003] found a similar behaviour for a linear viscous medium.

## 3. Advance of an Ice Cap Over a Slippery Spot

[7] A flattened ice surface across a slippery spot, such as a subglacial lake, implies lower subglacial hydraulic potential gradients, due to their dependence on surface slope. This would prevent water to be driven out the subglacial trench. To verify this hypothesis the following dynamic experiment was carried out. On a rectangular domain of 1 500 by 1 500 km, a small steady-state ice cap was established by defining the surface mass balance distribution in such a way that the margin of the ice cap lies near the preglacial lake (Figure 2):

$$\dot{b}(t) = 0.02(200 + 0.125\,t - d),$$

where $\dot{b}$ is the surface mass balance (m a$^{-1}$), $d$ is the distance to the center of the ice cap (km) and $t$ time (a). Running the model for $t = 0 \rightarrow 10^4$ a, gradually increases the size of the accumulation area in time so that the model ice cap overrides the preglacial lake (defined as a slippery spot with $\beta^2 = 0$). Once overridden, it becomes a subglacial lake (Figure 2). The same experiment was repeated without the presence of a lake.

[8] The "dynamic lake" experiment shows that when the ice sheet margin crosses the lake, the air/ice surface interface remains relatively flat as compared to the situation in which a lake is not considered (Figure 3). The surface of the ice sheet across the lake never exceeds slopes higher than 0.4°, while without ice/lake interaction, surface slopes exceed 1.5° (Figure 4). It is therefore likely that subglacial water is not driven out of the system, as hydraulic potential gradients remain too low. Surface slopes across the lake would even become lower if a subglacial depression

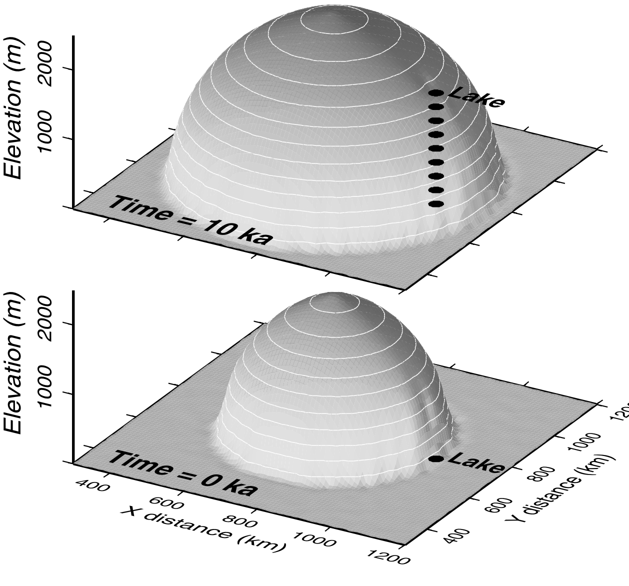

**Figure 2.** Ice sheet geometry (bottom) before ($t$ = 0) and (top) after ($t$ = 10 ka) the preglacial lake is overridden by the ice sheet margin.

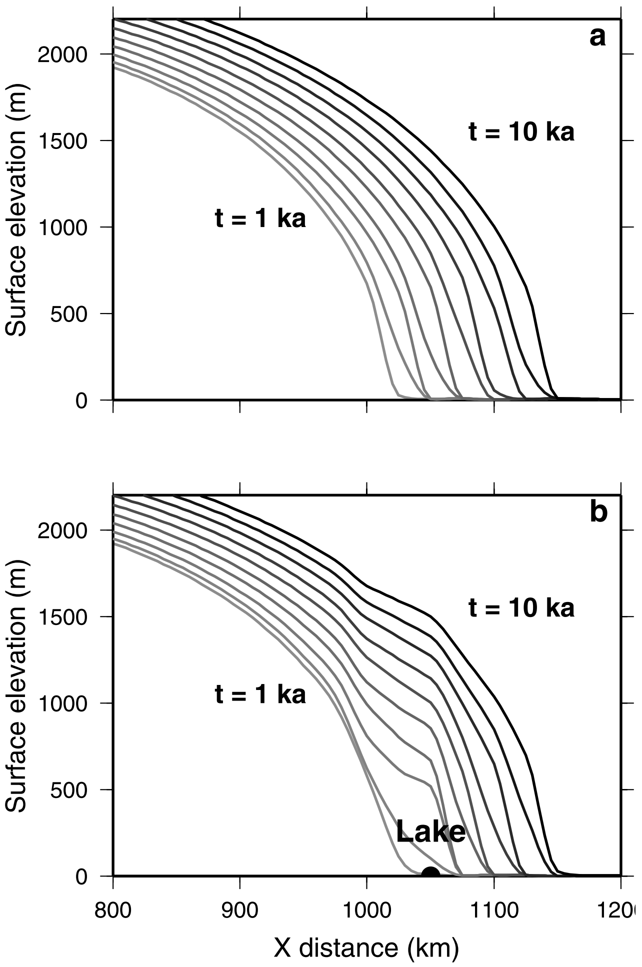

**Figure 3.** Cross section through the ice cap every 1000 a between 1 and 10 ka (a) without and (b) with the presence of a slippery spot (lake).

(trough) was considered in the model. Furthermore, increasing the lake size (at present the model lake size is 25 by 25 km) would have a similar effect [*Pattyn*, 2003].

## 4. Discussion

[9] The major deficiencies of the model are that complex marginal ice features, such as grounding line dynamics, subglacial topography of the trough or buoyancy effects are not explicitly taken into account. The criterion of hydraulic gradients is relevant as long as the lake is completely covered and sealed by the over-riding ice. However, during the period when the ice margin crosses the lake, the glacier terminus might be calving in the lake, thereby forming a floating ice tongue. With the exception of the two largest ice shelves of the Antarctic ice sheet (Ross and Ronne Ice Shelves), ice-shelf thickness along the East-Antarctic continent is of the order of 300–400 m. Ice shelves are much thinner than grounded ice because they deform by horizontal spreading and this spreading rate is balanced by the hydrostatic equilibrium at the calving front. Therefore grounding-line advance in a deep trough requires very high upstream ice flux and velocity gradients at the grounding line in order to guarantee a significant thickening of the ice shelf. Several deep subglacial troughs exist all over East Antarctica and those situated near the coast are occupied by large outlet glaciers and ice streams. Shirase Glacier in Dronning Maud Land, for instance, discharges into a deep submarine trough and even though ice thickness across the grounding line is 900m, the thickness of the floating ice tongue is half as much [*Pattyn and Derauw*, 2002]. With the exception of the calving front, the floating tongue is surrounded by the grounded ice sheet, so that the grounding line borders the narrow embayment. Flowline model experiments have shown that significant grounding line advance within the trough is difficult, unless a large increase in upstream discharge is accounted for [*Pattyn and Decleir*, 1995]. In the case of preglacial Lake Vostok, where, contrary to Shirase Glacier, the water surface is limited to the trough, it is likely that the floating tongue reached the downstream side of the trough and sealed off the lake to form a subglacial cavity before extensive grounding of the ice sheet within the lake was possible. At the time the lake was sealed by the over-riding ice, the water inclusion would act as a slippery spot and the mechanism described above would apply.

[10] Another possible scenario is put forward by *Doran et al.* [2003], based on an analysis of Lake Vida, an ice-sealed lake in the Dry Valleys, Antarctica, covered by 19 m of lake ice. They conclude that if a large subglacial lake such as Lake Vostok had existed without overlying glacial ice before glaciation, it would have shifted to an ice-sealed mode just before being over-ridden by glaciers. Even lakes in more temperate settings than today may have followed the path of Lake Vida during a transition into a severe glacial period. For such a scenario, the presence of water (or brine) underneath the surface ice cover would act as a slippery spot for the ice sheet during its advance, so that the above described mechanism still holds.

[11] If preglacial Lake Vostok survived the expanse of the Antarctic ice sheet, one may argue why subglacial troughs near the edge of the Antarctic continent are devoid of water, such as Astrolabe subglacial basin. According to the model results of *DeConto and Pollard* [2003], advance of the

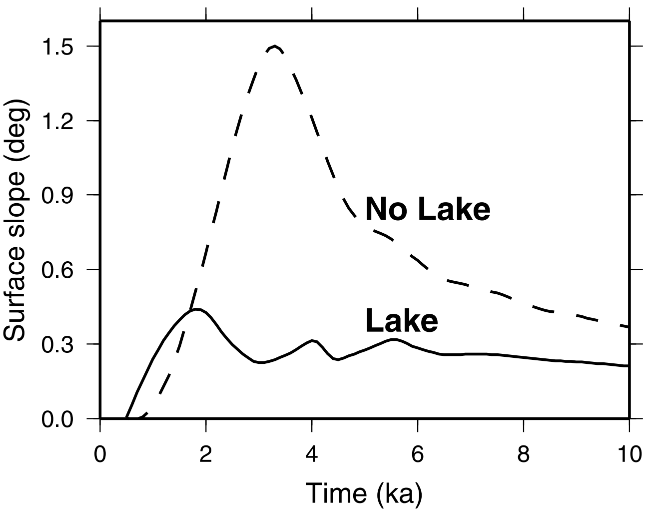

**Figure 4.** Magnitude of surface slope in time with and without the presence of a slippery spot.

Antarctic ice sheet across Astrolabe subglacial basin occurred much later than the advance over preglacial Lake Vostok. At that time, the Antarctic ice sheet was much bigger and climate significantly cooler, which would not permit the existence of a preglacial lake. Alternatively, an "ice-block" lake, as they exist in the Dry Valleys [*Doran et al.*, 2003], could have occupied the trough. Nevertheless, even under the hypothesis of the existence of a preglacial lake in Astrolabe basin, its survival is hampered by the subsequent waxing and waning of the ice sheet and associated sea-level changes in more recent geologic times (e.g., Pliocene). Lake Vostok, on the contrary, is due to its central position much more protected beneath the stable cover of the central part of the East-Antarctic ice sheet.

## 5. Conclusions

[12] If Lake Vostok existed as a preglacial lake prior to 15 Ma ago, it could have survived subsequent mid-Miocene glaciation, and remained stable beneath the thick ice cover to the present day, as stipulated by *Duxbury et al.* [2001]. Model simulations demonstrate that due to the interaction of the ice sheet with the lake surface (treated as a slippery spot), ice-sheet surface slopes near the edge of the ice sheet remain low, so that subglacial water is not driven out of the subglacial trough due to enhanced hydraulic potential gradients. Survival of the lake after initiation of the Antarctic ice sheet implies that possible microorganisms and their remnants within the water can be older than 5–30 Ma [*Duxbury et al.*, 2001].

[13] **Acknowledgments.** This comment forms a contribution to the Belgian Research Programme on the Antarctic (Federal Office for Scientific, Technical and Cultural Affairs), contract EV/03/08A. The author is indebted to Heinz Blatter and Martin Siegert for their helpful reviews.

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