Geomorphic Records along the General Carrera (Chile)–Buenos Aires (Argentina) Glacial Lake (46°–48°S), Climate Inferences, and Glacial Rebound for the Past 7–9 ka : A discusssion

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Comment on "Geomorphic Records along the General Carrera (Chile)–Buenos Aires (Argentina) Glacial Lake (46°–48°S), Climate Inferences, and Glacial Rebound for the Past 7–9 ka" by J. Bourgois et al. (2016)

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The paper by Bourgois et al. (2016) presents new cosmogenic isotope concentrations data that permit them to propose a scenario for the post-glacial evolution of the Lago General Carrera/Buenos Aires (LGCBA). In this comment, we do not discuss the validity of the proposed ages, although ages deduced from cosmogenic isotope concentrations may be affected by complex history, particularly when they are obtained in erratic boulders or dropstones (Putkonen & Swanson, 2003; Delmas et al., 2011). We simply note here basic geomorphological evidence challenging the complex scenario proposed by Bourgois et al. (2016), and showing that the LGCBA has never been endorheic following the retreat of the main glacial tongue. This observation has significant implications on the post-glacial climatic evolution of that area.

As observed by Bourgois et al. (2016) and several previous authors (e.g., Caldenius, 1932; Turner et al., 2005; Hein et al., 2010), shorelines around the lake evidence periods of higher water levels. In the Rio de Las Dunas and Rio Los Maitenes area, Bourgois et al. (2016) note four major terrace levels corresponding to fan deltas whose elevation vary from 500 meters above sea level (m-asl) for the highest T4 terrace, to ~300 m-asl for the lower terrace, the present-day elevation of the lake being 201 m-asl. They propose that the four fan deltas formed in a short time period between 13.7 +/- 0.8 ka and 10.9 +/-1.3 ka, i.e. in less than 1000 years per fan delta. In the "discussion" section of their paper, Bourgois et al. (2016) propose that the three higher terraces (T2-T4) accumulated in ice-walled lake environment, while a major ice-tongue still existed along the lake. They note that the T1 shoreline is largely preserved all around the lake, and they propose that this terrace formed during an endorheic period. The fan delta corresponding to the present-day elevation of the lake (T0 according to the terminology of Bourgois et al. (2016)) would be much more recent, less than 6.7 ka-old. Between the appearance of the T1 and T0 fan deltas, Bourgois et al. (2016) propose that a glacial advance occurred, followed by a tremendous rise of the level of the lake that would have reached elevations larger than 500 m in the Rio de Las Dunas area, i.e. above T4. At that time, according to Bourgois et al. (2016), despite this elevation is now higher than the present-day elevation of the Perito Moreno outlet towards the Atlantic Ocean, the lake would still have been endorheic. Then, Bourgois et al. (2016) conclude that the posterior isostatic rebound uplifted the Rio de Las Dunas area with respect to Perito Moreno from more than 135 m.

In the following, we show that this scenario is not supported by basic geomorphologic observations and generates contradictions. Alternatively, we argue that (1) the T2 fan delta did not accumulate in an ice-walled lake environment; (2) neither T2, nor T1 formed in an endorheic lake, and we identify the outlet corresponding to each of these shoreline systems; (3) velocities of post-glacial rebound following the appearance of shorelines proposed by Bourgois et al. (2016) is overestimated. Finally, we propose a more coherent and simpler post-glacial history of this lake.

1. T2 fan deltas

Figure 1 shows the position and elevation of major shorelines along the lake. The elevation of shorelines was obtained either in the field using differential GPS measurements or altimeters, or using SRTM data to obtain the elevation of shorelines observed in Google Earth images. The two lower shoreline systems correspond to the T1 and T2 terraces observed in the Rio de Las Dunas area. They are largely developed along the LGCBA as previously observed by Turner et al. (2005). They correspond to periods during which the surface of the lake remained stable approximately 100 and 230 m above the present-day level of the lake. Higher terraces, in contrast, are only locally observed, and their elevation does not show any continuity on distances larger than a few kilometers. The simplest explanation for the presence of very high local terraces is that they formed while the glacial valley now corresponding to the LGCBA was still largely occupied by the main glacier, as proposed by Bourgois et al. (2016). Then, when they formed, these terraces may have been higher than the Perito Moreno outlet towards the Atlantic Ocean, and the presence of these very elevated terraces does not imply that the LGCBA area has been severely tilted following their appearance.

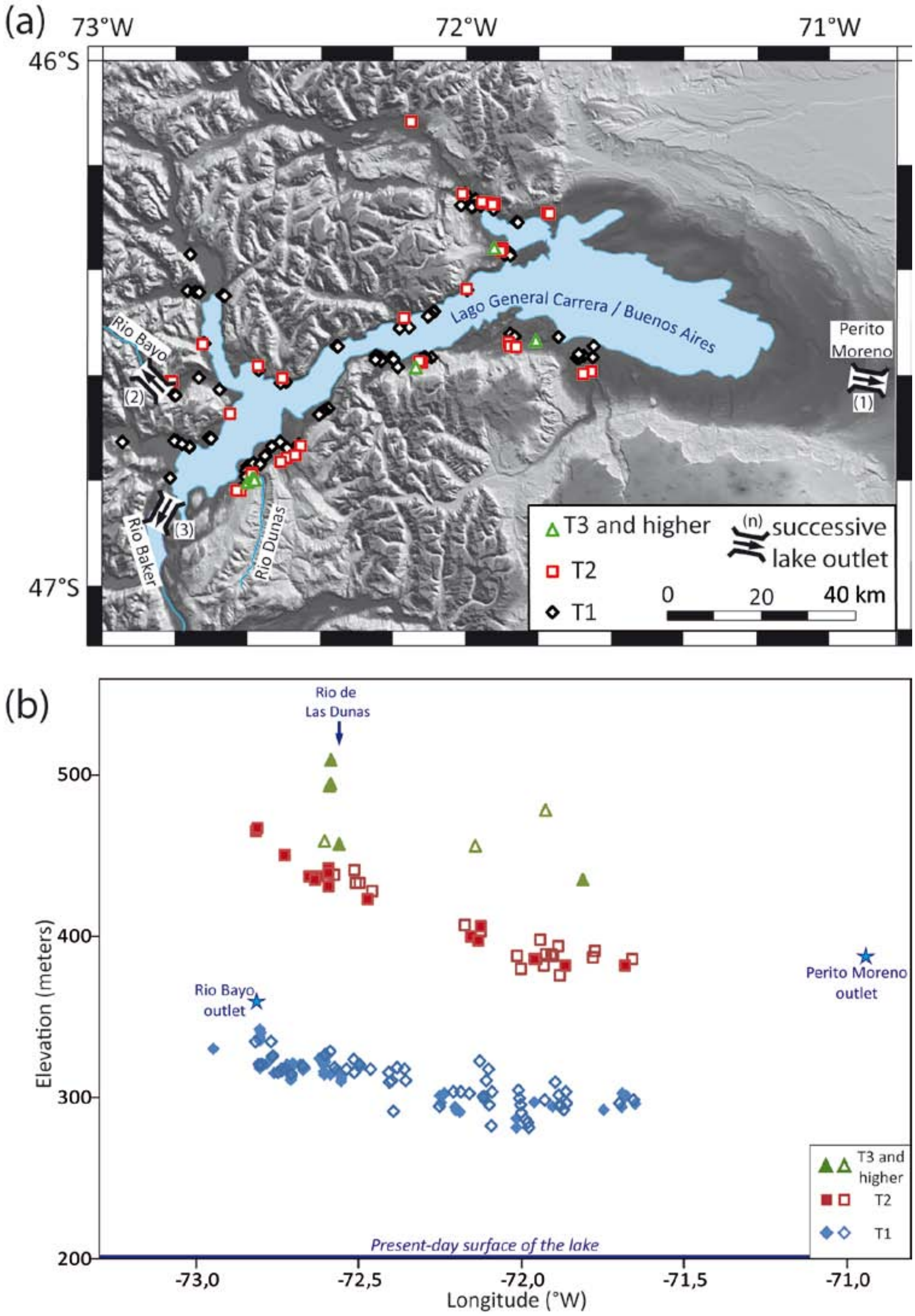

Figure 1: (a) Map and (b) elevation vs. longitude of shorelines located around the LGCBA. In (a), lake outlets are numbered from the oldest to the present-day active one. In (b), filled or empty symbols correspond to shorelines whose elevation has been measured in the field or using SRTM data, respectively.

In contrast, T2 shorelines formed while the main glacier had already abandoned most of the area occupied by the present-day lake. Fan deltas and other shorelines corresponding to this water level, indeed, are largely observed everywhere around the lake (Figure 1). Turner et al. (2005) even show that the LGCBA was merged with the Cochrane Lake at that time, shorelines with comparable elevation being present around this other lake. It is clear then, that T2 terraces in the Rio de Las Dunas area did not form in an ice-walled environment, as proposed by Bourgois et al. (2016).

Figure 1 shows that the T2 elevation regularly decreases from ~440 m in the western part of the lake, to less than 400 m in the Chile Chico area (71.7°W). This latter elevation approximately corresponds to that of the Perito Moreno outlet (388 m) towards the Atlantic Ocean, suggesting that T2 shorelines elevation has been controlled by this outlet. Thus, T2 shorelines did not appear around an endorheic lake as argued by Bourgois et al. (2016), but they formed while the lake was flowing towards the Atlantic Ocean, when valleys towards the West where still filled by glaciers, as proposed by Turner et al. (2005).

2. T1 shorelines

Beneath T2, another shoreline system (T1) approximately situated 300 m-asl is also present everywhere around the lake (Figure 1). T1 being significantly lower than Perito Moreno, it is clear that the lake did not flow towards the Atlantic Ocean at that time. Bourgois et al. (2016) note that T1 formed while the SW outlet of the lake via the Rio Baker was still occupied by a glacier. They note, indeed, that the Rio Baker was flowing eastward towards the lake at that time, and they propose that the lake had no outlet when T1 formed. T1, however, corresponds to a unique prominent shoreline identified by abundant deposits that can be followed almost continuously on tens of kilometers. Although some other shorelines can be observed at elevations below T2, they are poorly preserved with few clear shoreline features (Turner et al., 2005), and there is no fan delta associated to these shorelines. Endhoreic lakes are known to be largely and rapidly affected by climatic changes, and their water level generally varies continuously (e.g., Harrison and Digerfeldt, 1993). Then, the water level during the endorheic period of the lake's history should not have remained almost permanently at the same position, resulting in the appearance of a unique prominent shoreline below T2.

Figure 1b shows that the elevation of T1 is close to that of the water divide between the Rio Bayo and Rio Tranquillo valleys. Rio Tranquillo is located NW of the LGCBA and flows towards the LGCBA, while Rio Bayo flows towards the Pacific Ocean (Figure 2). It suggests that this valley may have constituted an outlet of the lake towards the Pacific Ocean during the formation of T1 shorelines. Following the opening of the Rio Baker outlet SW of the lake, the level of the lake dropped again and the Rio Bayo outlet was abandoned.

According to the 1 arc-second SRTM data, the elevation of the water divide separating the Rio Bayo and Rio Tranquilo valleys is 361 m-asl. This is ~20 meters higher than T1 shorelines at the longitude of the western LGCBA. Geomorphologic data, however, suggest that the Rio Bayo valley constituted the outlet of the lake during the appearance of these shorelines. Indeed, the basement close to the water divide is carved by deep and narrow canyons whose elevation measured in the field is ~340 m-asl, i.e. close to the elevation of T1 shorelines (Figure 2). We propose that these deep canyons have been carved when the Rio Bayo constituted the outlet of the LGCBA. Later on, they have been partly filled by sediment coming from present-day lateral tributaries of the valley. The present-day Rio Bayo – Rio Tranquillo water divide along the road going from the LGCBA to Bahia Exploradores corresponds to an active alluvial fan. The growth of this fan is increasing the elevation of the water divide, which may explain the difference between the present-day elevation of the divide and that of T1 shorelines.

These topographic arguments suggest that the Rio Bayo valley constituted the first outlet of the LGCBA towards the Pacific Ocean, before another outlet through the present-day Rio Baker opened.

This interpretation contradicts any endorheic episode in the lake history to explain shorelines elevation.

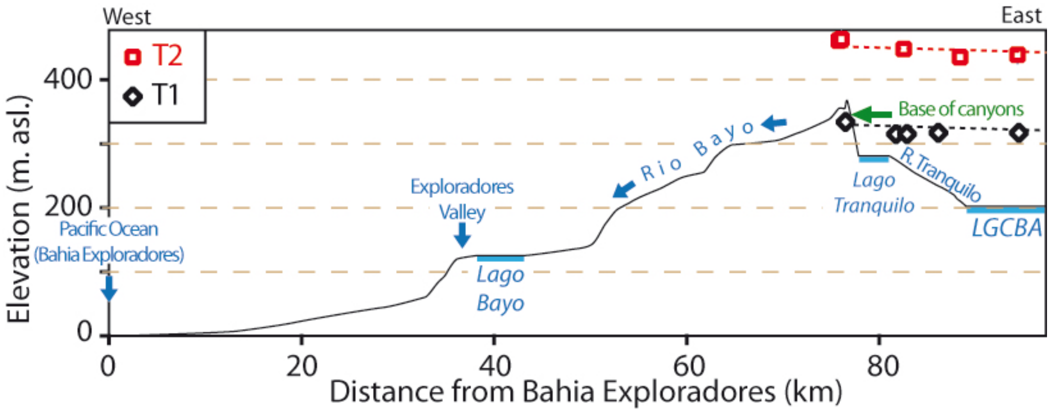

Figure 2: Topographic profile along the Rio Bayo and Rio Tranquilo Valleys, from the LGCBA to the Pacific Ocean. Red squares and black diamonds report the measured elevation of T2 and T1, respectively. The elevation of the water-divide and the presence of deep canyons carved in the basement suggest that the lake was flowing into the Rio Bayo valley when T1 shorelines formed.

3. Isostatic post-glacial rebound and chronology of post glacial features around the lake

Both the T2 and T1 shorelines are tilted towards the East (Figure 1), evidencing the isostatic rebound that resulted from the decreasing weight of the North Patagonian Icefield (Turner et al., 2005). The eastward tilting of T1 shorelines is much smaller than that of T2, showing that only a small fraction of the total post-glacial rebound occurred following it. In the western part of the lake, the average slope of T1 and T2 are ~0.42 and 0.95 m/km, respectively. The relative uplift of the Rio de Las Dunas area with respect to Perito Moreno has been ~40 meters since the appearance of T2 shorelines. We acknowledge that the total relative uplift since the Last Glacial Maximum has been larger than 40 meters, but it is not possible to estimate it looking at higher kame terraces because their elevation have been controlled by the surface of the glacier and not by distant outlets.

Bourgois et al. (2016) propose that the T2 fan delta grew while the lake was still occupied by a glacial tongue, whereas posterior and higher shorelines would have formed around an ice-free lake. The Patagonian ice-field load during the formation of the T2 fan deltas resulted in a 40 meters relative subsidence of the Rio de Las Dunas area with respect to Perito Moreno. On the other hand, Bourgois et al. (2016) propose that, following the appearance of fan deltas, the level of the lake rose again above 500 m-asl in the Rio de Las Dunas area. This scenario implies that the Las Dunas area had subsided again more than 135 meters with respect to Perito Moreno. This seems contradictory, because longer glaciers should result from a more voluminous and heavier Patagonian ice-field and then, they should correspond to a larger isostatic deflection. Moreover, a larger part of the isostatic deflection inherited from the Last Glacial Maximum ice load may still have been present when the older fan deltas appeared. Then, the isostatic rebound scenario proposed by Bourgois et al. (2016) generates contradiction. Bourgois et al. (2016) propose that the relative uplift of the Rio de Las Dunas with respect to Perito Moreno has been larger than 135 m since 7.9 ka, i.e. that the average relative uplift velocity has been larger than 17 mm yr^{-1}. In fact, considering the age of ~12 ka obtained by Bourgois et al. (2016) for T2 fan delta, the relative uplift velocity has only been 40 meters/12 kyr, i.e. 3.3 mm yr^{-1} for 12 ka.

If the isostatic rebound following the appearance of T2 and T1 shorelines accommodates a relative uplift of the Rio de Las Dunas area with respect to Perito Moreno smaller than 40 meters, it is not possible to follow Bourgois et al. (2016) when they argue that T4 fan deltas have been submerged after T2 and T1. Indeed, T4 was much higher than the Perito Moreno outlet when T2 appeared. Then, we think that the chronology proposed by Bourgois et al. (2016) for the appearance of shorelines in the Rio de Las Dunas area must be revised.

Conclusions

We raise major issues concerning the geomorphic interpretation proposed by Bourgois et al. (2016) of the post-glacial evolution of the LGCBA. In particular, we propose that the two major shoreline levels widely present around the lake mark two different successive outlets of the lake, the first one towards the Atlantic Ocean via Perito Moreno, and the second one via the Pacific Ocean (Bahia Exploradores) through the Rio Bayo Valley. Then, we argue that the LGCBA has never been endorheic following the Late Glacial Maximum. This has significant implications on the climatic evolution of the area. The LGCBA has been collecting water from the North Patagonian Icefield, which now receives several meters precipitations per year. We argue that water fluxes from Patagonian mountains to the lake always remained large enough to maintain the LGCBA open. We also show that the postglacial isostatic rebound has probably been slower than that proposed by Bourgois et al. (2016) and that a rise in the level of the lake at elevations higher than 500 meters in the Rio de Las Dunas area following the appearance of T1 fans would not have been possible because it would have been much higher than the Perito Moreno outlet toward the Atlantic Ocean. Thus, the timing of shorelines appearance around the LGCBA must be revised taking into account the new geochronological data provided by Bourgois et al. (2016) but also considering a postglacial evolution of the lake fitting with first-order geomorphological observations.

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