I. ORIGINS
I.1. Formation and geological evolution

ALAIN LAVENU

The Altiplano is a vast intermontane basin in the Central Andes of Peru, Bolivia and Argentina, lying between the Western and Eastern Cordilleras (Fig. 1). It is about 2000 km long and 200 km wide with an altitude varying from 3700 to 4600 metres. It is an endorheic basin. The north and centre of the Altiplano are occupied by large permanently flooded lakes: Lakes Titicaca and Poopo. The southern part is more arid and is the site of "*salares*"*: Coipasa and Uyuni.

Since the early Quaternary, the Altiplano has always been occupied by lakes, but these have not always had the same extent as the present-day lakes. Studies of ancient lake sediments have enabled the history of these lakes to be studied (Orbigny, 1835–1847; Neveu-Lemaire, 1906; Bowman, 1909; Troll, 1927–1928; Moon, 1939; Ahlfeld, 1946; Newell, 1945; Ahlfeld and Branisa, 1960).

Although the Pliocene is characterised by fluviatile and lacustrine deposits corresponding to a relatively warm environment, the transition to the Quaternary is marked by a major climatic change. The climate underwent a sudden cooling and glaciation appeared at about 3 million years BP. Glaciation developed throughout the Quaternary. The climatic change led to profound changes in the type of deposits. The Quaternary sediments of the Altiplano take the form of high altitude facies: glacial and interglacial deposits in the Cordillera and on the piedmont, torrential fluviatile deposits on the piedmont and high plain and lacustrine evaporite deposits in the centre of the basin.

Studies of these ancient lakes and of the main glacial stages in the Eastern Cordillera have allowed the establishment of relationships between the three lake formations and the three most recent stages of glacial recession (Servant, 1977; Servant and Fontes, 1978) (Fig. 2). Recently, the discovery in the north of the Altiplano of two ancient lacustrine episodes has established the

* Vast saltpans with a more or less thick crust of salt covered locally or periodically with shallow water.

C. Dejoux and A. Iltis (eds.), Lake Titicaca, 3–15.

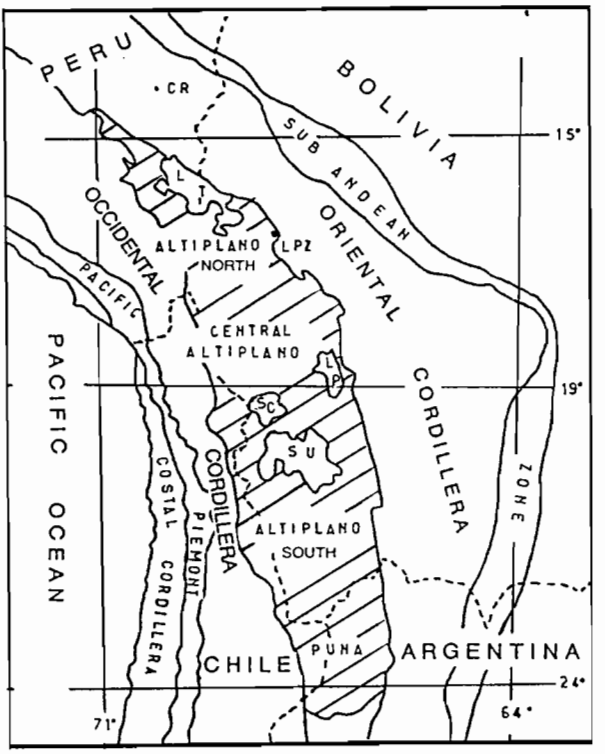

Figure 1. Situation of the Altiplano in the Central Andes chain (from Lavenu *et al.*, 1984). C: Cochabamba; CR: Crucero; LP: Lake Poopo; LPZ: La Paz; LT: Lake Titicaca; SC: Salar de Coipasa; SU: Salar d'Uyuni.

same relationships between lake levels and the two first Quaternary glaciations (Lavenu *et al.*, 1984) (Fig. 3).

Periods of maximum lake extent correspond to the end of glaciations or to the end of glacial stages and are due to the melting of glaciers (Servant and Fontes, 1978). Discontinuities between different stages are marked by ablation surfaces which coincide with the end of the morphological evolution of each interglacial stage.

Quaternary deposits postdate a polygenic ablation surface S6 of complex history. On the piedmont of the Eastern Cordillera this surface follows a volcanic layer (Chijini tuff) dated at 2.8 million years BP (Lavenu *et al.*, 1989).

The extent and limits of these water bodies are directly related to climatic and tectonic changes (Fig. 3). For this reason the various lacustrine deposits are not superimposed but rather inset one another. The study of the lake levels will be done in chronological order from the most ancient to the most recent.

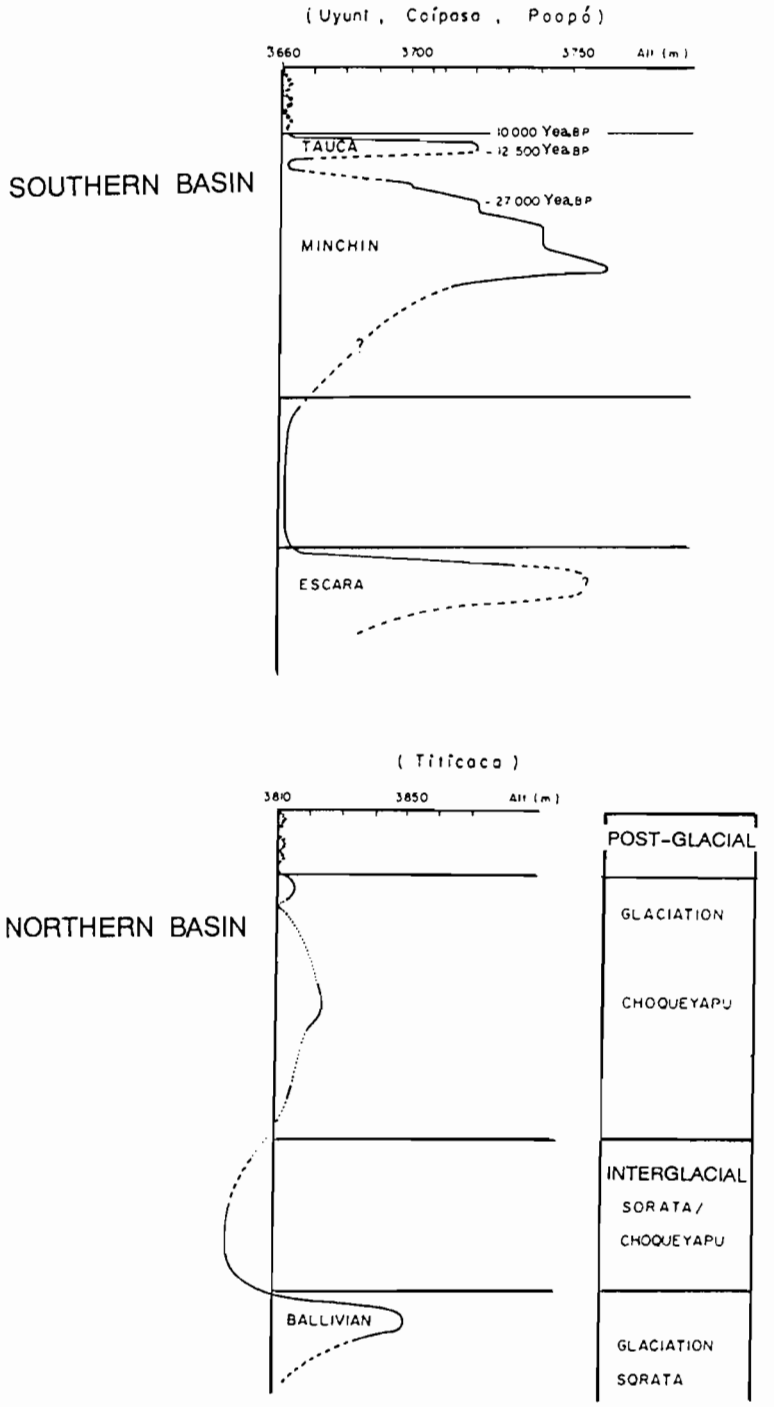

Figure 2. Correlations between Pleistocene glacial and lacustrine formations in the northern Altiplano (from Servant and Fontes, 1978).

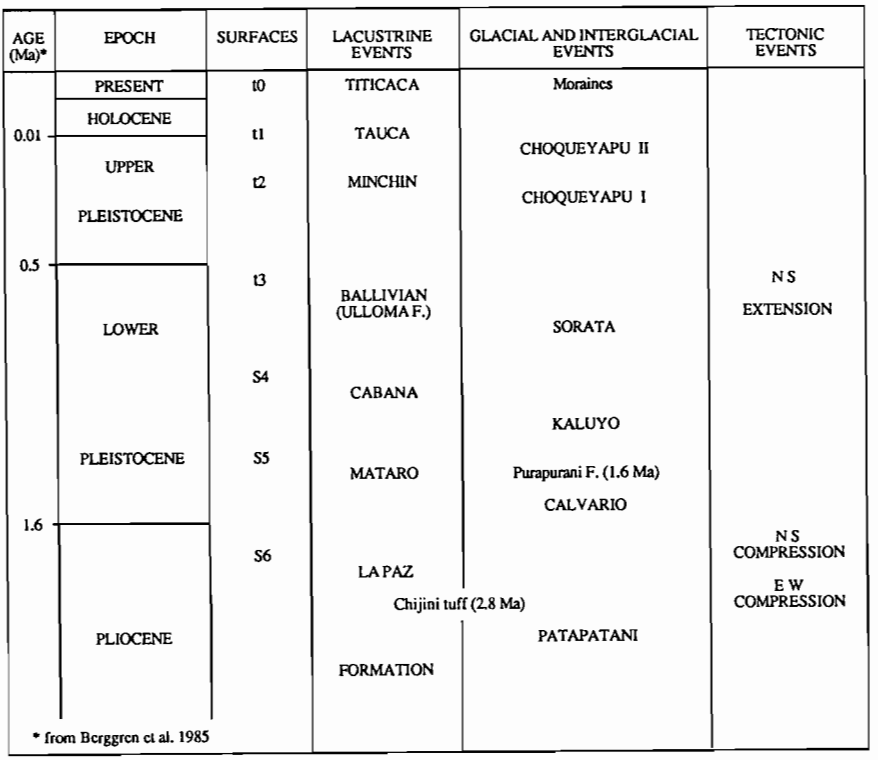

Figure 3. Stratigraphical, morphological and tectonic relationships during the Pleistocene.

The Lower Pleistocene

The existence of the two most ancient lake levels is clearly evident to the north-west of Lake Titicaca in both Peru and Bolivia (Lavenu *et al.*, 1984). The outcrops are marked by coarse torrential and fluviatile sediments at the basin margins and by fine lacustrine deposits towards the centre of the basin (Fig. 4).

The most ancient deposits, called Mataro (Fig. 4), take the form of a series of fluviatile detrital deposits showing alternating beds of ochre-coloured clayey sand and gravelly sand. This incomplete series outcrops over a thickness of about 50 metres. The presence of a fossil deer antler indicates an undifferentiated Quaternary age. The top of the Mataro deposits is an ablation surface developed at a present-day altitude 3950 metres around the paleo-basin (surface S5) (Fig. 5). This lake reached its maximum extension after the Calvario glaciation (Dobrovolny, 1962) after 2.8 My BP (Lavenu *et al.*, 1989). It is the equivalent of the Purapurani Formation of the La Paz basin dated from the lower Pleistocene at 1.6 My BP (Lavenu *et al.*, 1989)

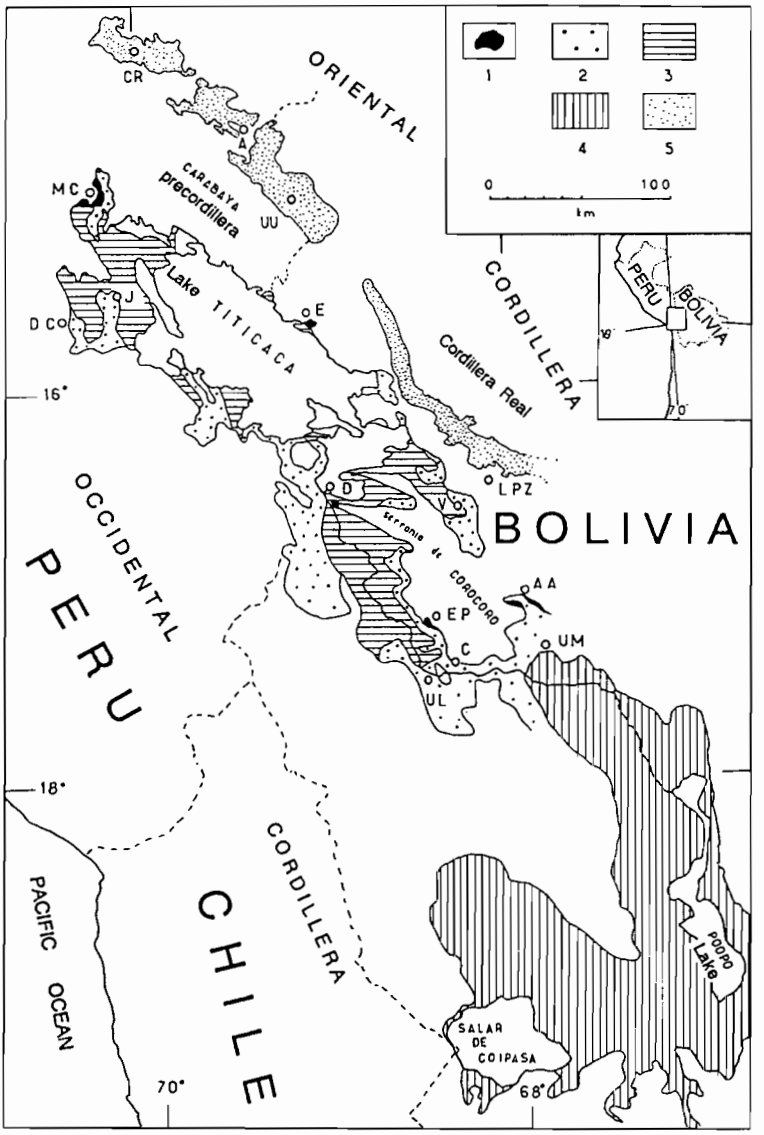

Figure 4. The extent of lakes in the north and centre of the Altiplano (from Lavenu *et al.*, 1984). 1: Lake Mataro; 2: Lake Cabana; 3: Lake Ballivian (Ulloma and Azangaro formations); 4: Lake Minchin; 5: Glacial and fluvio-glacial formations in the piedmont and Eastern Cordillera. A: Ananea; AA: Ayo Ayo; C: Callapa; CR: Crucero; D: Desaguadero; DC:Deustua-Cabana; E: Escoma; EP: Estacion Pando; J: Juliaca; LPZ: La Paz; MC: Mataro Chico; UL: Ulloma; UM: Umala; UU: Ulla Ulla; V: Viacha. Lakes Escara and Tauca are not represented. In the area of Lake Poopo and Salar de Coipasa, the limits of Lake Tauca are included within the boundaries of Lake Minchin. In the north, the limits of Lakes Minchin and Tauca are almost the same as those of the present-day Lake Titicaca.

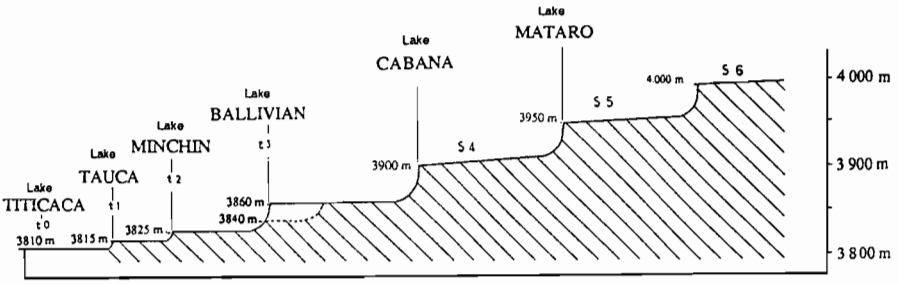

Figure 5. Spatial relationships of various lake levels in the north of the Altiplano (from Lavenu *et al.*, 1984).

and the equivalent of the Ayo Ayo lower Pleistocene deposits further south (Hoffstetter *et al.*, 1971).

The Cabana Formation, which formed after the Kaluyo glaciation (Servant, 1977), insets the previous series. This spatial relationship shows that the Cabana water body had a smaller area and volume than the previous one. The lacustrine deposits, which again include fluviatile beds, outcrop over a thickness of about 50 metres. This formation has been eroded to form the surface S4 at an altitude of 3900 metres.

On the piedmont and in the Cordillera, the surfaces S5 and S4 usually stand above the valleys of the present-day streams by several tens of metres. The existence of these two surfaces in the north and centre of the Altiplano suggests that the Ulloma-Callapa sill, now crossed by the river Desaguadero in a gorge, did not exist in the lower Pleistocene and that the two lakes, Mataro and then Cabana, thus each formed a single water body on the Altiplano (Fig. 6).

The Upper Pleistocene

The sediments of Lake Ballivian, which formed after the Sorata glaciation (Ulloma Formation in Bolivia and Azangaro Formation in Peru), insets the Cabana deposits (Bowman, 1909).

These deposits are very fossiliferous and recent works have enabled them to be attributed to the lower Pleistocene age: Ensenadian or lower Lujanian in the South American chronology (Hoffstetter, 1986; Marshall *et al.*, 1991; Marshall and Salinas, 1991). A comparable fauna exists in the Tarija basin in southern Bolivia, where a volcanic stratum has been given an Ensenadian age of 0.7 My BP (McFadden *et al.*, 1983). The sediments of Lake Ballivian correspond to a water body situated at a present-day altitude of 3860 metres. At the foot of hills and in the Cordillera, the ablation surfaces corresponding

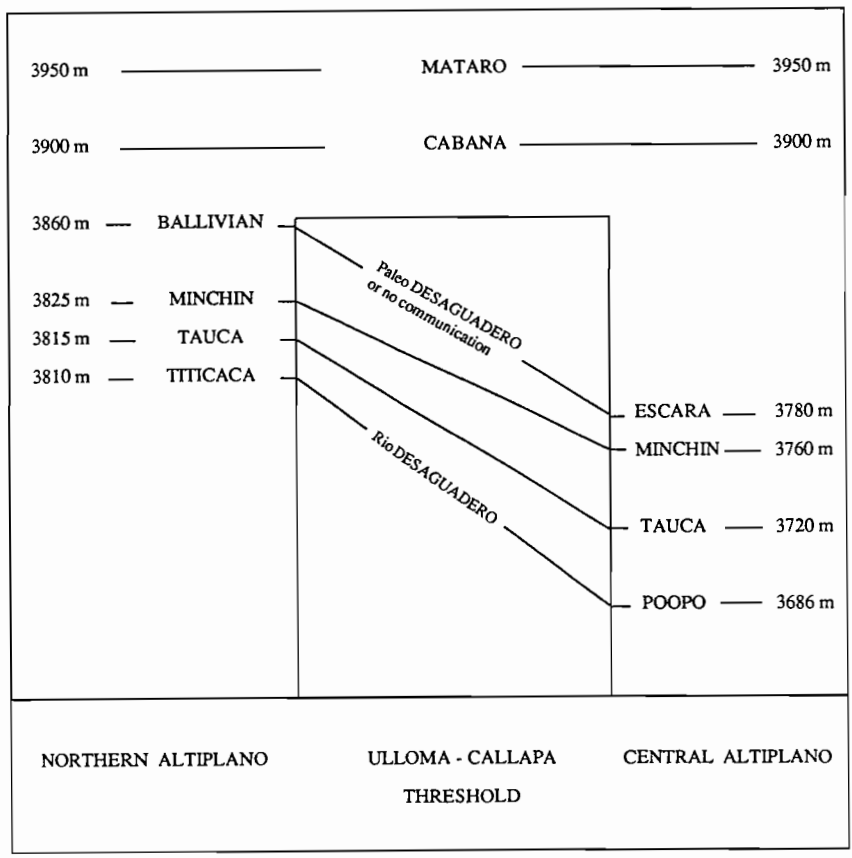

Figure 6. Communications between the Northern and Central Altiplano (from Lavenu *et al.*, 1984).

to these sediments form alluvial terraces (t3) covering considerable areas. These terraces usually lie 5 to 6 metres above the level of present-day streams.

A few signs of lacustrine terraces around Lake Titicaca at an altitude of 3840 metres could correspond to a postglacial episode of the first Choqueyapu stage.

In the southern Altiplano, the lacustrine layers of the Escara formation could correspond to those of Lake Ballivian (Servant, 1977). These layers are at a lower present-day altitude (3780 metres) and demonstrate the existence of the Ulloma-Callapa sill.

The end of the Pleistocene is marked by the Lake Minchin deposits which inset those of Lake Ballivian. This water body is characterised by an ablation

surface and terraces (t2) situated at 3825 metres altitude, between 10 and 15 metres above the present level of Lake Titicaca. Upstream on the Altiplano these terraces form alluvial terraces situated 3 to 4 metres above the present-day streams.

This lake, divided into two water bodies by the Ulloma-Callapa sill, was very reduced in extent in the north of the Altiplano, but greater in area in the south. Incomplete fossils have enabled it to be assigned to the undifferentiated Lujanian age (Lavenu, 1984; Marshall and Sempéré, 1991; Marshall *et al.*, 1991). In the south, an intermediate lacustrine terrace has been dated to 27,000 years BP (Servant and Fontes, 1978).

The Holocene

The Holocene of the Altiplano is characterised by Lake Tauca (Servant, 1977), also divided into two water bodies by the Ulloma-Callapa sill. Its area was reduced compared to Lake Minchin. Low alluvial peaty terraces are found all around this paleolake throughout the Altiplano and in the Cordillera. This is the t1 system, situated 1 metre above the level of the thalwegs. In the centre of the Altiplano, Servant and Fontes (1978) have assigned it an age of between 12,500 and 10,000 years BP.

Lakes Minchin and Tauca are related to the melting of the glaciers of the Choqueyapu glaciation which included two main stages, (Troll, 1930; Troll and Finsterwalder, 1935) Choqueyapu I before Minchin and Choqueyapu II before Tauca.

Lake Tauca stabilised at 5 metres above the present level of Lake Titicaca. In the north of the Altiplano, it was at a level of 3815 metres, and in the south at 3720 metres. The area of the lake can be estimated at a minimum of about 52,000 km^2. Servant and Fontes (1978) gave it an area of 43,000 km^2 in the south of the Altiplano. In the north the Tauca water body must have covered about 9000 km^2. These water bodies progressively reduced in size, so that all that remains is Lake Titicaca (8560 km^2) at 3810 metres altitude in the north of the Altiplano, Lake Poopo (3686 m) in the centre and the salares (3650 m) in the south. Over the same period the glaciers have also decreased in volume and area.

Neotectonics

The Andean Cordillera had practically acquired its present-day altitude in the Pliocene. Between 2 and 3 My BP the upper Pliocene deposits were subjected to tectonic compression. This shortening, trending NE-SW to E-W, was responsible for reverse faulting and folding (Lavenu, 1988; Lavenu and Mercier, 1992). In the early Quaternary a second minor compressional deformation affected deposits aged from the upper Pliocene to the early

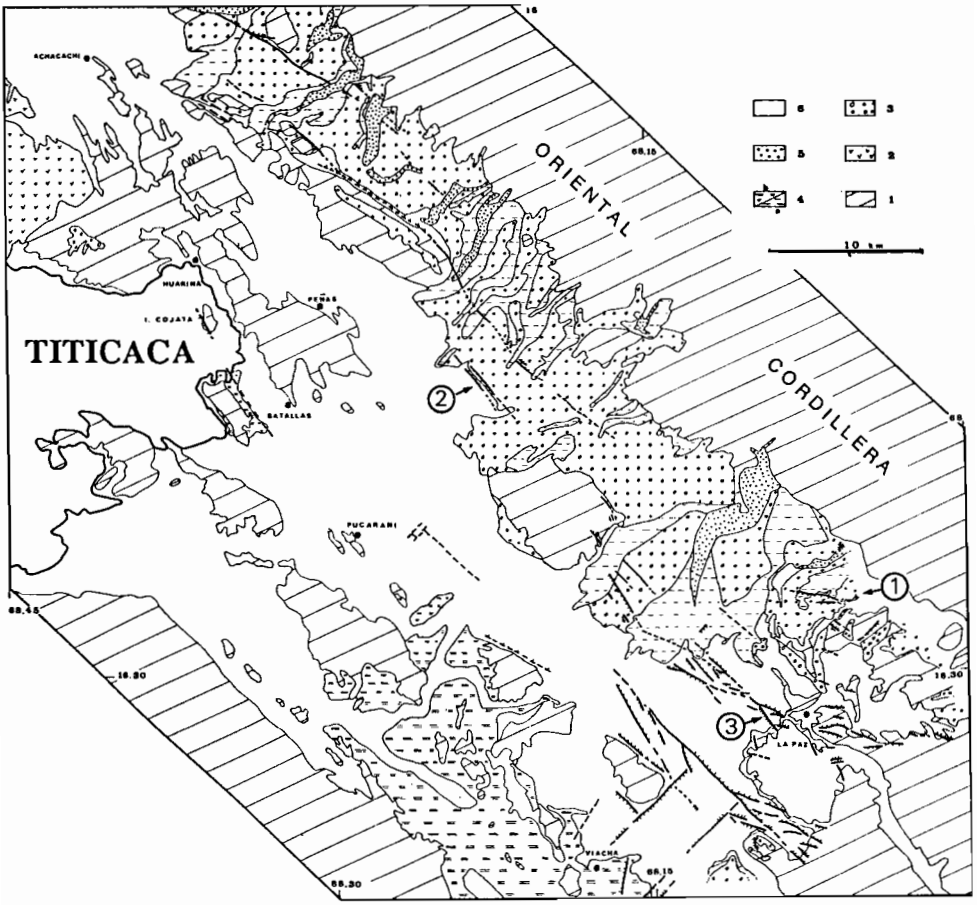

Figure 7. Structural diagram of the Eastern Cordillera piedmont between La Paz and Lake Titicaca (from Lavenu, 1981). 1: undifferentiated pre-Pleistocene formations; 2: Quaternary volcanic formations; 3: pre-Sorata glacial formations; 4: (a) Sorata moraines, (b) Ulloma Formation; 5: Choqueyapu moraines; 6: Recent Quaternary.

Quaternary. This deformation led to the formation of reverse faults resulting from a N-S shortening.

Following these compressional events, the Altiplano and particularly the piedmonts of the Western and Eastern Cordilleras were affected by tectonic extension in a N-S to NNE-SSW direction. This deformation, which has affected all Quaternary deposits up to the present, is due to a high topography effect. This special state of stress is described for the Central Andes of Peru by Sébrier *et al.* (1985).

These deformations caused major fracturing in the Plio-Quaternary deposits between Lake Titicaca and La Paz. The normal faults have a WNW-ESE to NW-SE trend (Fig. 7).

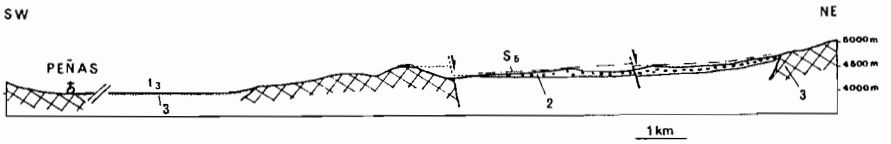

Figure 8. Cross-section of the Eastern Cordillera north-west of Peñas. Quaternary faults with throws of hundreds of metres (from Lavenu, 1981). 1: undifferentiated pre-Pleistocene formations; 2: lower Pleistocene formations; 3: recent Quaternary.

After the formation of surfaces S6 and S5 and the accumulation of Purapurani interglacial deposits dated at 1.6 My BP (Lavenu *et al.*, 1989), the extensional deformation trending N-S affected lower Pleistocene deposits (Fig. 8). Steep scarps in the La Paz region demonstrate the existence of a first period of extension in the Pleistocene (before S6 and S5). Near La Paz the vertical throw of some normal faults trending 120°E attains 400 metres (Fig. 9; points 1 and 2 on Fig. 7). The same is true on the shores of the lake to the west of Huarina, at the foot of the Eastern Cordillera, where deposits of Pliocene age are uplifted to abnormally high altitudes. On the north-east shores of the lake at Escoma the S4 surface is situated at altitudes of between 3900 and 3960 metres (Fig. 10). The differences in altitude between S5 and S4 of 200 metres and between S5 and S6 of 100 metres are also abnormally high compared to those in the centre of the Altiplano where they are only 50 metres.

Before the development of S4, an extensional tectonic movement occurred at the foot of the Eastern Cordillera, which caused the Cordillera to be uplifted relative to the Altiplano. This extensional deformation, by causing sinking of the land surface, favoured the establishment of Lakes Mataro and Cabana. It was certainly at this epoch that the lowest part of the Altiplano, the trough in which Lake Titicaca is now situated, was really created. The deepest part of the present lake reaches nearly 284 metres near to Soto Island in Peru (Boulangé and Aquize, 1981).

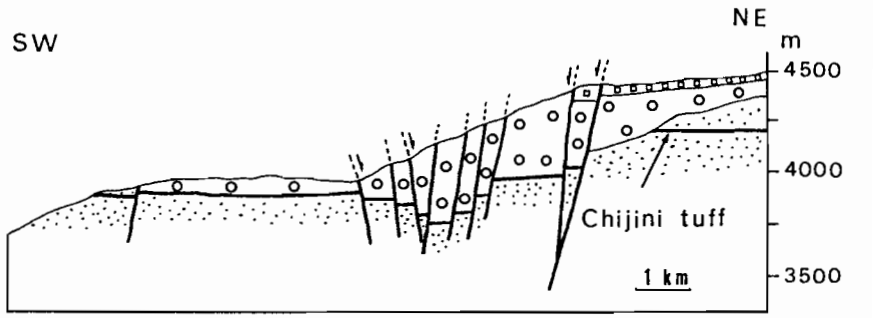

Figure 9. Section of the Quebrada Minasa (point 1 *Figure* 7) (from Lavenu, 1988). squares: Sorata moraines; circles: pre-Sorata glacial formations; dots: La Paz Pliocene formation.

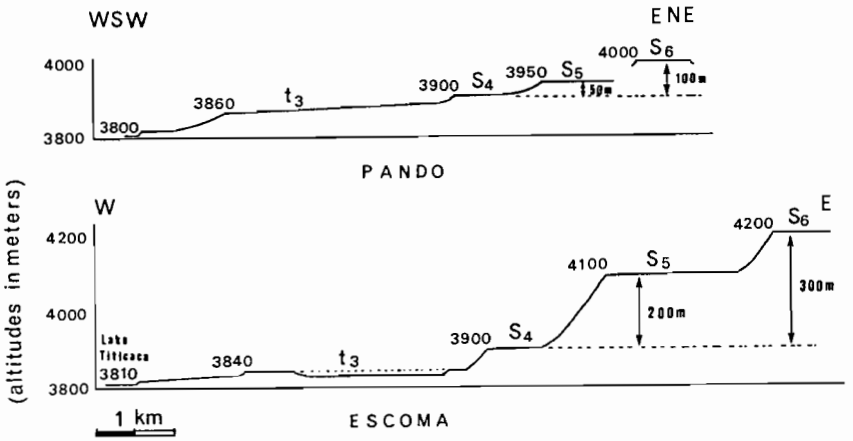

Figure 10. Spatial relationships of ablation surfaces in the central Altiplano (Pando) and on the Eastern shore of Lake Titicaca (Escoma) (from Lavenu *et al.*, 1984).

A later extensional tectonic deformation affected the S4 surface. In the Eastern Cordillera the moraines of the Sorata glaciation intrude deeply into the valleys, another sign of the relative uplifting by comparison with the Altiplano.

The extensional deformations of the upper Pleistocene and the Holocene are weaker and the morphological displacements less important. Numerous indicators show that this N-S extension is continuing: at Llojeta (point 3 on Fig. 7), the S3 surface which represents the topographic surface of the Altiplano has a vertical throw of nearly one metre; to the east of Peñas the Choqueyapu moraines are cut by normal faults; on Cojata island, the level of Lake Minchin deposits is raised by faulting to more than 17 metres above the present lake level.

Conclusion

The present lake system on the Altiplano is the result of the evolution of a more ancient system which began from the lower Pleistocene, with the transition at the end of the Pliocene from a relatively warm climate to a cool damp climate.

The presence and size of the lakes are directly related to the recession of glaciers at the start of the interglacial periods. As in the case of the glaciers, the areas of successive lacustrine water bodies decreased considerably over the course of the Quaternary.

Plio-Quaternary tectonic deformations fractured the piedmont of the Eastern Cordillera. Neotectonic extensional activity trending N-S has typified all the Quaternary. The tectonic trough which was to be occupied by the present-

day Lake Titicaca was created in the lower Pleistocene, following Lake Cabana and before Lake Ballivian.

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