Origin and Evolution of the Salinas Grandes and Salina De Ambargasta, Argentina

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Abstract. The Salinas Grandes and Salina de Ambargasta, on the eastern side of the Sierras Pampeanas in Argentina, constitute an 18,000 km² tectonic depression. The eastward advance of the tectonic deformation is evident in the topographic elevations that intercept the Llanura Chaqueña. The interpretation of the tectonic processes that create the Salinas Grandes and Salina de Ambargasta are primarily due to the observation of morphotectonic macro indicators and structural field data. These geoforms allow us to interpret the horizontal deformation that has produced the right side displacement of parallel shears within a dextral releasing bend and restraining bend setting. This process occurred within a transtensional-transpressional setting, which produced a depression closure where lakes formed, the formation of Alto de Mancilla, deviation of rivers, the rotation and displacement of ranges and the transformation of lakes into salt flats. These processes are active and are shown by the hydro transference area where the Dulce River discharges into the Salado River, resulting in a considerable decrease of water flow into the Laguna Mar Chiquita.

1. Introduction

Our investigation reveals that the morphotectonic processes that occurred during the Quaternary period closed one large depression, causing lakes to form; then, the superficial water networks that supplied these lakes closed. Eventually the lakes were transformed into enormous salt flats of today and changed other lakes due to further water source closures in lower land areas. These processes occurred on the eastern side of the Sierras Pampeanas, approximately 700 km from the oceanic trench (figure 1), occupying an area of approximately 182,500 km² (figure 2). The relief growth progresses from west to east invading the Llanura Chaqueña [1], where the progradation of arid areas to the east are also produced.

The Sierras Pampeanas constitutes a group of ranges that are separated by a large sedimentary basin and limited by the Puna high plains to the northwest. To the southwest, the Tulum valley separates the Sierras Pampeanas from the Andean chain [2] and to the east, it is bordered by the Llanura Chaqueña (figure 1). The Sierras Pampeanas coincides with an area of low angle subduction between the Nazca and South American Plates; the dip of the slab within the region between 27° S and 33° S is close to 30° [3].
The Salinas Grandes and Salina de Ambargasta (figures 1 and 2) is a tectonic depression of the Sierras Pampeanas. It is a NE strike and it is bordered on the north by the piedmont of the Ancasti and Guasayan ranges and, on the south, by the piedmont of the northern Sierras de Cordoba and Ambargasta Range. On the east and west, the basin stretches to 64° 00' W and 65° 40' W, respectively. The basin includes the provinces of Catamarca, La Rioja, Santiago del Estero and Cordoba, in Argentina (figure 2). Today, the salt flats provide mineral resources as sodium chloride, sodium sulphate and potassium minerals [4]. These minerals form an almost complete crystallized scab over the terrain. They are formed by the sedimentation and later evaporation of concentrated minerals.

Andean sedimentary basins were analysed in different studies by [5, 6, 7, 8, 9, 10, 11]. After the extensive processes in the Cretaceous that gave rise to the dense sequence of Grupo Salta sediments, which reached the southern extreme of the Sierras de Cordoba, these large intermountain depressions and intermountain sedimentary basins in the Sierras Pampeanas seem to have also been formed by compressive, transpressive and transtensive deformation.

**Figure 1.** Study area location. Geographic limits of the Sierras Pampeanas and geomorphologic provinces. Regional structures and main lineaments are shown. CC: Cumbres Calchaquies. SA: Sierra Aconquija. BA: Bloque Ambato. Geomorphological features of the salt, topographic high, the abandoned course (San Bernardo and Saladillo rivers) and current course of the Salí – Dulce rivers are identified. Location of map – Figure 2.

Certain factors, such as the morphology of the Sierras Pampeanas (NS, NW and NE strikes, separated by broad basins) and pre-existing structures and batholites, interacted at the same time to produce deformations that do not strictly work as a compressive mechanism in all cases. Therefore, in the Sierras Pampeanas, in addition to the typical reverse faults, in general, NS strike and double vergent [12, 13], dextral transcurrent, sinistral transcurrent and normal faults are observed [14, 15, 16]. In addition to the landscape modulation, these processes had and still have consequences for natural resources and natural hazards. There is evidence from faulted Quaternary sediments that the west-directed compressional environment is active [17, 18, 19].

**2. Methodology**

The main objective of this study is to demonstrate the origin of the Salinas Grandes and Salina de Ambargasta. We use macro indicators like the morphology of the basin, topographic elevations, ranges morphology, network settings drainage, deviation of rivers and morphology to interpret the active tectonic processes which has caused the salt flats. The plain lacks pre-quaternary outcrops of bedrock and evidence collected on the tectonic evolution are exclusively geomorphological [1]. Mesoscopic indicators such as faults geometry and strata attitude are essential complementary data that allow us to
demonstrate the tectonic processes. The landscape evolution and possible consequence to natural resource use and natural risks we also study and analyze. We use Landsat satellite images (NASA), a topographic radar image (NASA), and Geologic Maps at 1:200 000 and 1:250 000 scales [20, 21, 22, 23, 24]. The geology of the study area was prepared from Hojas Geologicas 2963-III [21], 3166-II [22], 3163-I [23] and 2966-IV [24] (figure 2).

First, we made a visual reading and interpretation of the radar image. We analyze and draw landforms, range dispositions, formation of topographic elevations, intermountain depression forms, basin segmentation, and drainage network, diversion of large rivers, drainage decapitation, salt flats and water bodies. We identify faults and major lineaments from published geological mapping and others, product of our interpretation. The resulting morphotectonic map had abundant information but, we draw the most important geological features only. In these maps, we show in greater detail the structural features and the kinematic macro indicators that allow us to interpret the tectonic processes that led to the formation of the salt flats (Figs. 1, 3a, 6a, 6b, 8a, 8b y 8c). With the interpretation of Landsat images, we prepare geological scheme and we enriched it with literature and existing geological mapping (figure 2) that served also to program the fieldwork.

**Figure 2.** Geological study area map. On the north the San Bernardo salt flat is the abandoned channel of the Salí River that flowed to the Salinas Grandes basin an on the northeastern side the Dulce River crosses to flow into the Laguna Mar Chiquita. The old lakes, now the Salinas Grandes and Salina de Ambargasta, are separated by the Alto de Mancilla. To the north, the southern portion of the Ancasti and Guasayán ranges can be observed. On the southern portion, the Ambargasta Range and Sierras de Córdoba can be distinguished. Q: Quaternary; N: Neogene sediments; K: Cretaceous; PC: Carboniferous-Permian; DC: Devonian-Carboniferous; OS: Ordovician-Silurian; C: Cambrian; CP: Precambrian-Cambrian; S: Salt flats; TH: Topographic highs; PB: Province border; L: Lineaments; RF: Reverse fault; TF: Transcurrent fault; 254: Elevation (m); AA’: Profile; 1: Field location.

### 3. Geological setting

The morpho-tectonic evolution of the Andes is commonly attributed to the geometry of the subducted Nazca Plate and, to a lesser extent, the pre-Andean configuration of the crust [25]. Zones of sinistral orogeny-parallel and dextral NE striking are consistent with transpressive deformation kinematically linked to the shortening of the upper crust [26, 27]. The upper crust of the central Andes is segmented into rhomb-shaped domains by the crustal EW shortening [28]. It is related to crustal-strength gradient transverse to the shortening direction and strain localization, controlled by the brittle-ductile strength ratio which determines the geometry and size of basins and associated deformation zones [29].
The crust of the eastern Sierras Pampeanas is characterized by the juxtaposition of terrains along a NS trend, namely Pampia to the west and Cordoba to the east, against Cratón del Río de la Plata [30]. Pampia Terrane and Cratón del Río de La Plata are bordered by the NE strike Transbrasiliano Lineament [31] (figure 1). Most range-delimited faults are Cenozoic, reactivating steep NS trending Paleozoic mylonitic zones [e.g., 32]. [33] suggested that the regional subsidence pattern >500 km from the Sierras Pampeanas area and Llanura Chaco Paranaense could be explained by a thermodynamic flow model when the asthenosphere flow is modified by sub horizontal subduction from the Miocene period and, the subsidence of a short-wave length <300 km is associated with supracrustal loads (accumulation of tectonic scales and lithostatic loads).

Figure 3. 3a) This figure shows the sigmoidal shape of the depression, generated by a releasing bend of the two NS strike-slip faults with dextral kinematics (Clodomira Fault and Pocho Fault), the intermountain basin where the Laguna Grande and Laguna de Ambargasta were formed, later becoming the salt flats. The extension of the limited depression to the north with the Guasayán Range, Ancasti Range, and Ambargasta Range to the south and the extreme north of the Sierras de Córdoba are also highlighted. The San Bernardo River flowed to the south and the Laguna Grande was formed when the western border of the depression was raised by a blind fault (Pocho Fault), vergent to the West. The Alto de Mancilla separated the two salt flats, which were originally one, a restraining step-over of the two NS strike-slip faults with dextral kinematics (Recreo Fault and Dean Funes Fault). Stratification of Pliocene and Pleistocene sequences on either side of the Guasayán Fault show the dextral kinematic of the fault. 3b) Equal area stereo plot (lower hemisphere) of field measure structures in the Recreo area. NNW Strike represent Recreo Fault and conjugate ENE strike structures are consistent with near EW deformation. 1: Salt Flats; 2: Sigmoid geoform; 3: Dextral transcurrence; 4: Stress contraction axis; 5: Reverse fault; 6: Stratification.

Authors of [34] identified an oblique deformation component based on several right-lateral moment tensors calculated by crustal seismicity across Sierras Pampeanas. [35, 14, 15] showed that transgressive tectonic processes occurred during the Pleistocene in the mountains that comprise the Bloque Ambato, Sierra de Aconquija and Cumbres Calchaquíes, NW of the studied area (figure 1). Data from [36] support the hypothesis that high angle reverse faults and a double vergent, in the east margin of the...
Tucumán basin, produced the Guayasan Range and Dorsal Mujer Muerta, transforming the Cretaceous basin into a retro-arc basin (figure 1). Some authors [37] interpreted that to the north of Sierras de Córdoba, pull-apart structure and the seismicity would result from right-lateral oblique motion distributed across the Sierras de Córdoba (figure 1). In the Sierras de Córdoba, south of the studied area, sigmoidal basins are infilled by deformed deposits from Pliocene to Quaternary, enclosing a NS elongated intrusive body. They are consistent with opposite transcurrency along NS strike faults (sineastal shear with a prominent left bend and right lateral strike-slip component showing a dextral bend) [16] (figure 1). The Laguna Mar Chiquita occupies a tectonic depression generated in the middle Pleistocene by the Tostado-Selva reverse fault, which raised the western border of the Alto San Guillermo [38] (figure 1). By 1825, a natural diversion from the Dulce River to Laguna de Ambargasta occurred, and by 1905 another natural diversion from the Saladillo River to Laguna Mar Chiquita occurred [39, 40] (figure 1). The analysis of the seismicity in conjunction with field studies confirms that the tectonic deformation is indeed ongoing [41, 37].

In the study area (figure 2), the oldest geological units are represented by metamorphic rocks composed of schists, amphibolites, gneisses and migmatites from the Precambrian-Cambrian Periods [24]. Plutonic and sub-volcanic rocks composed of granodiorite, monzogranite, rhyolite and dacite porphyries, penetrated and absorbed metamorphic units during the Cambrian Period. These units cover much of the entire Ambargasta Range [23, 24]. Southeast of the study area, some rock outcrops were identified as Famatinian Granites. These rocks, of Ordovician age, consist of tonalite, granodiorite and dacite-rhyolite porphyries [23]. In the Ancasti Range, numerous intrusive bodies of granitic, granodiorite, tonalite, diorite and pegmatite rocks represent the time between the Upper Ordovician-Lower Carboniferous Periods [24]. Terrain sequences assigned to the Carboniferous-Permian in the Ambargasta Range and to the Permian in the Ancasti Range are represented by sandstones and reddish-brown conglomerates and tufficzous red sandstones. The largest intrusive outcropping bodies were found in the northeast sector of the Ambargasta Range. In the Ancasti Range and Alto El Recreo area, reduced outcroppings are present. In the Ambargasta Range, Carboniferous basaltic dikes are also found, resulting from a period of regional extension [23, 21, 24].

Sandstones and fine reddish conglomerated outcroppings during the Cretacic are primarily presented in the Ambargasta Range, at the southeast end of the study area, tilted smoothly to the east. A reduced outcropping was identified in the southern area of Ancasti Range [23, 21, 24]. The Neogene sediment cover is expansively distributed in a NW trend, composed of a marine lower member and upper continental one, including the Ancasti Range, Alto El Recreo, the southern area of the Guasayan Range, Alto de Mancilla and the southern area of the Ambargasta Range. Outcroppings are represented by brown sandstones, brown reddish clay and sandy white limestone, discordantly arranged above basement and Cretaceous sediments. Quaternary deposits are represented by sandstones, conglomerates, mud, loess and salt deposits [22, 23, 21, 24].

4. Results

The intermountain depression was once covered by a lake of approximately 18,000 km2 (figure 2), generating resources completely different from those the salt flats exhibit today [4]. Consequently, like the landscape, the environment has also changed from humid to semi-arid conditions [42, 18].

4.1. Data obtained from the interpretation of satellite images

4.1.1. Sigmoidal or rhomb-shaped morphology. The outstanding morphotectonic regional feature is the sigmoid or rhomb-shaped morphology of the depression, with NE strike, that accommodated the Salinas Grandes and Salina de Ambargasta (figure 1). In The radar image, we see a raised area of NNW strike, which divides the basin in the central area (figures 1, 6a). This is the Alto de Mancilla, a hill that rises only 100 m above the salt flats and dividing the intermountain depression (figures 2 and 3a). The Salina
de Ambargasta have a very conductive fill of a 2500 m depth [31]. The sigmoidal shape of the basin and pop-up structure of the Alto de Mansilla are a typical geomorphological feature of releasing and restraining bends [43, 44, 45].

The Guasayan Range and the Dorsal Mujer Muerta is a pop-up uplifted by a double verging high angle thrust fault system, similar to the Sierra de Aconquija and Cumbres Calchaquies, and probably began to uplift in the Pleistocene Period, producing the compartmentalization of an earlier foreland basin [36, 13, 46, 47]. We interpret that this positive relief (Guasayan Range and Dorsal Mujer Muerta) is limited to the east by the blind thrust Clodomira Fault (figures 1 and 3a). South of the salt flats, to the western edge of the Sierras de Córdoba, crops out a mayor reverse fault (Pocho Fault) with westward displacement [48].

These two major structures, Clodomira Fault to the NE and Pocho Fault to the SW, enclose the depressed area occupied by the Salinas Grandes and Salina de Ambargasta. We interpret that ENE-striking deformation reactivated with dextral horizontal displacement the Clodomira and Pocho structures and givin rise to a subsiding pull-apart basin with sigmoid or rhomb-shaped morphology (figures 1, 2, 3a). This transtensive system acts on a depressed area between the Ancasti Range - Guasayán Range to the north and Sierras de Córdoba - Ambargasta Range to the south. The depression was closed through a blind fault, vergent to the west, related to the Pocho Fault, that created the Laguna Grande and Laguna de Ambargasta.

4.1.2. Pop-up structure. The Alto de Mancilla is a hill with NNW strike, which rises 254 masl, a barely imperceptible elevation that divides the depression in Salinas Grandes and Salina de Ambargasta (figures 1, 2, 4). This hill is the southern continuation of the Guasayán range – Dorsal Mujer Muerta pop-up uplift and its southern end, it is attached in small pieces to the southwest side of the Ambargasta range (figure 2). We interpret that its morphotectonic history is closely linked to the mountains and structures that limit, north and south. Its core granitic rock of Carbonic age is primarily covered by Quaternary fluvial aeolian deposits [21, 24], which obstruct the observation of neogene units and geological structure (figure 2).

![Figure 4](image_url)

**Figure 4.** The profile outlines blinded NS strike-slip faults with dextral kinematics that raise the Alto de Mancilla pop-up structure, separating the Salinas Grandes from the Salina de Ambargasta. 1: Quaternary aeolian sediments. 2: Quaternary sediments of the salt flats. Profile location in Figure 2.

The Alto de Mancilla is bordered by blind thrust faults with opposite inclinations, with continuity from the Sierra de Guasayán and Sierra de Ambargasta, Recreo Fault to the west and Dean Funes Fault to the east, respectively (figures 2, 4). Recreo Fault is the southern extension of the observed blind fault in the southern Tucumán Basin through seismic lines [36] and Dean Funes fault separates the Ambargasta range of the Sierras de Córdoba (figures 2, 3a).
The morphology of the Alto de Mancilla hill allows us to interpret that Recreo and Dean Funes faults experienced dextral lateral displacement, related to ENE-striking deformation, generating a pop-up structure with a restraining bend (figures 2, 3a). Tracing the NE profile, we can observe that the Salinas Grandes are elevated with respect to the Salina de Ambargasta, showing that they are separated by a blind thrust fault, deepening to the east, which raises the western edge of Alto de Mancilla (figure 4). The Alto de Mancilla is a pop-up structure which divides the basin in Salinas Grandes and Salina de Ambargasta.

4.1.3. Salt flats. A concrete fact we see today is the existence of two major salt flats (Salinas Grandes and Salina de Ambargasta) occupying each an approximate area of 8,800 km² and 6,300 km², respectively (figures 1, 2). These salt flats initially formed large lagoons (Laguna Grande and Laguna de Ambargasta) and should have been connected with a drainage system that filled it. There are still small lagoons (lagunas San Francisco and La Amarga) as vestiges of those great lagoons (figure 2). The Sali river born in the northern Cumbres Calchaquíes and discharges into the Laguna Mar Chiquita; its southeast drain is interrupted abruptly to cross the Guasayán range - Dorsal Mujer Muerta (figure 1); this responds to progressive uprising and the lateral faulted growth belts or anticlines propagated along blind faults [49]. We interpret that the Sali river initially drained into the Laguna Grande and then was deflected by the uprising ranges, draining eastward through the Guasayán range - Dorsal Mujer Muerta with the name of Dulce river; evidence of this surface drainage is the Salina San Bernardo (figures 1, 2, 5). Later, topographic tectonic obstacles experienced changes in the southward strike of the Dulce river; such is the case of Saladillo river which filled the Laguna de Ambargasta basin [1, 38].

4.1.4. Ambargasta Range and domino structures. Other morphotectonic macro indicators that show a horizontal transcurrence and produce domino structures are represented by the Ambargasta Range and by a group of lower ranges to the southwest of Dean Funes town, respectively: Alto El Corito and Alto La Higuerita (figure 6).

Figure 5. The profile outlines the Salina San Bernardo, originated by the Sali River. To the east is bordered by the pop-up structure Guasayán range and to the west by Alto El Recreo. 1: Quaternary aeolian sediments. 2: Metamorphic basement. Profile location in Figure 2.

The EW compressive deformation of the Andean tectonics has acted on a morphostructural landscape with dominant NS strike, generating structures of submeridional strike. But, the current morphostructural landscape in the Sierras Pampeanas is represented by ranges and mountainous blocks dismembered into smaller ranges with NE, N and NW strike [14]. The main ranges that are part of the Sierras de Cordoba block are: Guasapampa range with NNW strike and, Grande and Chicas range with NNE strike. The Ambargasta range with NE strike is separated from the Sierras de Cordoba by the Dean Funes Fault. According to Grande and Chicas range strikes, as defined by the reference NNE strike line, the Ambargasta range would have turned 5º clockwise and displaced approximately 20 km to the SE through the Dean Funes Fault, through of the near EW compression that provoked a right lateral displacement, imparting a NE orientation (figure 6a).
The hills located to the southwest of the Dean Funes town, Alto El Corito and Alto La Higuerita, are composed of Cambrian granitic rocks and are covered by Neogene sediments (figures 2, 6a, 6b). This group of hills form domino structures with NNE strike and are cut by a sinestral shears along a NW strike (figure 6b). The Alto El Corito is segmented into three sectors, and the Alto La Higuerita is segmented into two. This process is active; a recent analysis of the seismicity of the eastern Sierras Pampeanas by [41] shows focal mechanism solutions of events located in the area of Dean Funes that are consistent with a sinestral shear along a WNW strike nodal plane and a dextral shear along a NNE strike nodal plane (events 2698 and 1964).

**Figure 6.** 6a) Diagram that shows macro indicators of the Quaternary dextral transcurrency. In the Quaternary, the Ambargasta Range must have veered 5° to the east and 20 km to the SE, disengaging from the Sierras de Córdoba by the Dean Funes NNW strike-slip faults with dextral kinematics. The reactivation of Recreo and Dean Funes faults with dextral horizontal displacement generated topographic elevation Alto de Mancilla that divided the lagoons drained by the Sali River. The sinestral Holocene reactivation of the Sierra Baja de San Marcos Fault along a NW step is also shown (Massabie et al. 2003). 1: Reverse fault; 2: Quaternary transcurrent fault; 3: Quaternary transpressive strike; 4: Ambargasta Range edge. 6b) This figure shows that the Alto El Corito and Alto La Higuerita were cut by sinestral transversal faults along a NW strike. These faults are consistent with the near EW compression. 6c) Equal area stereo plot (lower hemisphere) of field measure structures in the Dean Funes Faults area. NNW Strike represent Dean Funes Fault and conjugate NE strike structures are consistent with near EW deformation.

In a context of shear strain [50], the Dean Funes Fault is a “P structure” and faults of the Alto El Corito and Alto La Higuerita could be “R' structures” or block rotation by dextral strike-slip faulting [51] (figure 6a, 6b).

4.2. Field data
We collect some structural data (faults and strata attitude) from field studies, principally in basement rocks and Neogene sediments and we found deformations in Quaternary sediments on the Dean Funes area. The structural data that were achieved in the field relating to the origin of the salt flats can be found in the Guasayan Range, Alto El Recreo and the Dean Funes area (figures 1 and 2).

At the east hillock of Recreo village (Alto El Recreo), on the north side of Alto de Mancilla, metamorphic rock outcrops are covered in parts by Neogene and Quaternary sediments. The foliation of the metamorphic basement (070°/80°) is deepening to the east with high angles, which is a product of a reverse fault that deepens to the east. A group of conjugate structures with NE and NW strike are consistent with a near EW compressive strain system (figures 2, 3b, 5).
The reverse Guasayán Fault, presents evidence of reactivation with right lateral displacement [52]. We measure sedimentary structures, east and west of the Guasayán Fault. To the east of the fault, the stratification of the Las Cañas (Pliocene) and Concepción (Pleistocene) formations, deepens to the southeast (100°/70° and 110°/20°, respectively); whereas on the western edge of the range, the strata of the Sali River Formation (Middle Miocene) gently tilts to the WNW (280°/10°), highlighting the right lateral displacement of the fault (figure 3a).

In the Dean Funes Fault area, at the boundary between Sierras de Córdoba and Ambargasta Range, a conjugate structures pattern can be measured affecting Quaternary sediments. Two Quaternary sedimentary sequences were deposited over previously fractured Cambrian granitic rocks; the first sequences over basement, are fractured with the same structural pattern of the granitic basement. Faults affecting Quaternary sediments are normal faults, with small displacements, formed over a pre-existing structural system. This conjugate structures are consistent with a near EW compressive strain system (figures 6c, 7a).

Approximately 10 km to the southeast of the Copacabana Range outcrops a sequence of brown muddy sandstones of the upper Cretaceous Río Copacabana Formation (figure 2). These rocks are fractured by low angle normal faults deepening NNW, with similar orientation to the Dean Funes Fault area structures [15] (figures 7a, 7b).

4.3. Morphotectonic evolution
Quaternary evolution can be outlined as follows. The Sali River was the main collector of the east slope of the Cumbres Calchaquies, Sierra de Aconquija and Bloque Ambato and flowed from north to south, reaching the plain as the San Bernardo River (figures 1, 8a). Tectonic deformation (ENE-striking transtension) began to undulate the plain, reactivating de Pocho Fault and generating Laguna Grande, the first reservoir of water from the Sali – San Bernardo River (figure 8a). Quaternary EW shortening [41, 37] reactivated the western directed Pocho thrust fault [15] uplifting the western edge of the plain where Laguna Grande was located (figure 8a).

Constant relief generation led to the formation of the Guasayan Range, Dorsal Mujer Muerta, and Alto El Recreo. These ranges constitute the eastern boundary of the Tucuman Basin. The Sali River was diverted to the east through a fault that divides the Dorsal Mujer Muerta and Guasayan Range, then veered south along the Saladillo River to the Laguna de Ambargasta [38] (figures 2, 8b). Diversion of the Sali River transformed the San Bernardo River valley into a salt flat, which occupies a small valley of approximately 55 km north to south in length and 7 km wide, located between the Guasayan Range on the east and Alto El Recreo on the west (figures 2, 5).

The Alto de Mancilla pop-up formed with transpressive restraining bend kinematically related to ENE-striking deformation, that reactivated previous structures, Recreo and Dean Funes faults (figures 4, 8c). The hill’s uplift produced the division of the Laguna Grande - Laguna de Ambargasta and the diversion of the Saladillo River to the east, from where it is then known as the Dulce River, and flows to Laguna Mar Chiquita. The diversion of the Saladillo River cut off the water supply to the Laguna Grande - Laguna de Ambargasta, which then became salt flats (figure 8c).

5. Discussion
The study region was subjected to transpressive deformation related to the Pampean orogeny, which experienced an oblique dextral collision [53]. Evidence of dextral transpression occurred during the Pampean orogeny (515 Ma) were found in the Sierra Norte de Córdoba and Guamanes milonitic area [48, 32].
Figure 7. Normal faults in the Dean Funes Fault and Copacabana Range area, a) are normal faults in the granite rock that were reactivated during Quaternary. Two Quaternary sequences are affected by this conjugate faults, consistent with a near EW strike deformation, b) southeast of the Copacabana Range, low angle normal faults are consistent with the near EW compression. These faults are cutting off the sedimentary layers of the upper Cretaceous Río Copacabana Formation.

During the Cenozoic orogeny, the area also experienced dextral transtension and dextral transpressions; the Sierra Baja de San Marcos Fault show evidence of reactivation with left lateral displacement in the Holocene [18] (figure 5a). The positive reliefs Dorsal Mujer Muerta, Altos de Otumpa, Alto San Guillermo, Alto de Mansilla, are geomorphological expressions that show the Quaternary EW strike deformation of the easternmost of the Sierras Pampeanas portion. This deformation was conducted in the study area by the transcurrent dextral slip of pre-existing NS strike structures, generating the formation of the basin of the salinas and the Alto de Mancilla positive relief (figures 1, 2, 8c).
Figure 8. Three pictures illustrate the morphotectonic process that gave origin to the lakes, the hills and salt flats. 8a) Shows the drainage to the south of the Sali-San Bernardo River, giving origin to the Laguna Grande. 8b) Shows the raising of the Guasayán Range and Dorsal Mujer Muerta. These positive prominences led to the capture of the Sali River diverting it to the east and unloading its water through the Saladillo River in the Laguna de Ambargasta. 8c) The progressive raising of the proto-mountain ranges and new topographic high (Alto de Mancilla, Altos de Otumpa and Alto San Guillermo) are observed, leading to the diversion of the Saladillo River to form with the Dulce River, thus known as the Laguna Mar Chiquita. The old lakes are also transformed into the Salinas Grandes and Salina de Ambargasta. The transfer area between the Dulce and Salado River is indicated, as is the diversion of the Salado River to the east.

There is evidence that by 1770, the Salado River diverted its course to the west, flowing into the Laguna Mar Chiquita and then returning to its normal riverbed [54]. Events of the Dulce River floods changed its course to the Salado River; they were observed in 1825 and 1905 [55, 39], and presently it
naturally flows into the Salado River [38]. The existence of the Salinas Grandes and Laguna San Francisco is a concrete evidence of the prior existence of a big lake (Laguna Grande) that was filled by San Bernardo River (figure 2). San Bernardo salt flat is concrete evidence that the Sali River drained into the Salinas Grandes (figures 2, 8a). Later the Sali River shifted its course eastward due to the lifting of the relief, filling the Laguna de Ambargasta with the Saladillo River [38] (figure 8b). The continuous rise of the relief diverted the Sali River southward to actually form the Laguna Mar Chiquita [38] (figure 8c). Villagers from the area of Recreo know from their grandfathers that the San Bernardo salt flat could once be crossed by boat from one bank to the other, because there was a river. Today the banks of the salar is connected with a road and the villagers cross it by car. According to the data obtained from [55, 54, 39, 38, 40], it is probable that the definite disengagement of the Dulce River from the Laguna Grande-Laguna de Ambargasta occurred 250–300 years ago.

6. Conclusions

The progressive deformation of the Sierras Pampeanas to the east is apparent in the topographic elevations of the Llanura Chaqueña (Altos de Otumpa, Alto San Guillermo, Dorsal Mujer Muerta, Alto El Recreo, Alto de Mancilla) interfering and diverts surface runoff drainage. In the near future, this hills will evolve to be a new range, rising separate and independent from the current ranges by a vast depression that will then be filled with sediment.

Morphotectonic processes that generated the current landscape were produced by transtensive-transpressive ENE tectonic events, generating the reactivation of previous NS strike faults with a right lateral displacement, after the Pleistocene era. The beginning of the deformation of Salinas Grandes and Ambargasta depression occurred by ENE transtension that reactivated the Clodomira and Pocho faults with releasing bend geometry (figures 3, 8). The Sali River discharges into the Laguna Grande through the San Bernardo river (figure 8a). As the deformation progressed, the near EW compression reactivated two separated strike-slip fault segments (Recreo and Dean Funes faults). This faults converged and overlapped with step-over restraining bend geometry, generating the pop-up structures of Alto de Mancilla (figure 3). The Sali River was diverted to the east and discharges into the Laguna Ambargasta through the Saladillo River (figure 8b) and then diverted to the Laguna Mar Chiquita (figure 8c).

The geometric relationship of structures associated with the NS fault of the western edge of Alto El Recreo and Dean Funes Fault are consistent with a near EW crustal shortening. The arrangement of the sedimentary layers of the Rio Sali (Middle Miocene), Las Cañas (Pliocene) and Concepción (Pleistocene) Formations on both sides of the fault on the eastern edge of the Guasayan Range, are consistent with a transpressional system. The domino structures in the hills of Alto El Corito and Alto La Higuerita are consistent with a near EW crustal shortening and transpressional system reactivated dextral strike-slip faulting.

It is probable that the definite disengagement of the Dulce River from the Laguna Grande and Laguna de Ambargasta occurred ca. 250 to 300 years ago. The transference area between the Dulce and Salado rivers, to the north of the Laguna Mar Chiquita, shows that the raising of the eastside of the Sierras Pampeanas is on-going. This implies that in the near future, the Dulce River could be completely captured by the Salado River, with its disengagement from the Laguna Mar Chiquita. The decreased hydraulic contribution that supplies the lake, in addition to an increase in evapotranspiration, will lead to the formation of the Salina de Mar Chiquita.

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