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The paradigm of paraglacial megafans of the San Juan river basin, Central Andes, Argentina

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A B S T R A C T

The spatial distribution and several morphometric characteristics of the Quaternary alluvial fans of the San Juan River, in the province of San Juan, at the Central and Western part of Argentina, have been studied to classify them as paraglacial megafans, as well to ratify its depositional environmental conditions. The high sedimentary load exported by San Juan river from the Central Andes to the foreland depressions is estimated about 3,682,200 hm^3. The large alluvial fans of Ullum-Zonda and Tulum valleys were deposited into deep tectonic depressions, during the Upper Pleistocene deglaciation stages. The outcome of collecting remotely sensed data, map and DEM data, geophysical data and much fieldwork gave access to morphometric, morphographic and morphogenetic data of these alluvial fans. The main drainage network was mapped on processed images using QGis (vers.2.0.1). Several fan morphometric parameters were measured, such as the size, the shape, the thickness, the surface areas and the sedimentary volume of exported load. The analyzed fans were accumulated in deep tectonic depressions, where the alluvium fill reaches 700 to 1200 m thick. Such fans do not reach the large size that other world megafans have, and this is due to tectonic obstacles, although the sedimentary fill average volume surpasses 514,000 hm^3. The author proposes to consider Ullum-Zonda and Tulum alluvial fans as paraglacial megafans. According to the stratigraphic relationships of the tropical South American Rivers, the author considers that the San Juan paraglacial megafans would have occurred in the period before 24 ka BP , possibly corresponding to Middle Pleniglacial (ca 65–24ka BP). They record colder and more humid conditions compared with the present arid and dry conditions.

1. Introduction

All Andean rivers have sustained human civilizations foreland for more than 5000 years and have provided fertile oasis for agriculture. The oasis in the San Juan and Mendoza valleys are good examples where water management strategies were quite advanced along with the flood protection measures. The studied area lies within the Western Argentine Arid Zone which is a part of the "South American Arid Diagonal." The Andes are an important barrier to moisture coming in from the Pacific Ocean, consequently, the adjacent region is recorded with low precipitation, arid conditions and sparse vegetation are predominant. An alluvial fan is a deposit whose surface forms a segment of a cone that radiates downslope from the point where the stream leaves the source area (Bull, 1977). Alluvial fans have greatly diverse sizes, slopes, types of deposits, and source area characteristics which are widespread in the dryer parts of the world (Bull, 1977, 1991). The alluvial fan environment is important to man. Crops are grown on fans and water is pumped from fan deposits. In contrast, a megafan is a fan-shaped sedimentary system covering an area of several hundreds to thousands of square kilometers (Bull, 1991). Its features are quite different from the same so-called depositions developed in the piedmonts or in the perimountainous environments. The longitudinal slope is extremely low in comparison with the classic small piedmont fans. Its development indicates an absence of obstacles and this situation facilitates its longitudinal development. The study of alluvial fans has many practical applications. In this study case, they are the areas with free aquifers in the basin (LLoret and Suvires, 2006). Several mega-fans may be cited such as the Kosi mega-fan that covers large areas in North Bihhar, India and Nepal (Gohain and Parkash, 1987) with a radius greater than 60 km. The Kosi river, in the Indo Gangetic plain, builds a mega-fan as a result

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of the high rainfalls (1500 mm year) of the reception basin; much unlike the fans in arid regions where the annual rainfall is low (Singh et al., 1993). In this case of study, the mega-fans are an important source of water to recharge the ground water reservoir. Some of them are located throughout the territories of Ecuador, Peru, Bolivia and Argentina (Iriondo, 2010). These were formed by the accumulation of sediments carried by the river networks from the Andes. The collectors of these networks cross the mountain ranges and deposits fans from the piedmonts to long distances towards the east (Iriondo, 1988). The mega-fan of Paraná covers half of the northwest of the province of Corrientes in Argentina and the south of Eastern Paraguay. These large reliefs would have been formed in the Pliocene but remain active until the present (Iriondo, 2007). In the northern part of Argentina, different mega-fans have been identified, such as: the Salado River (650 km long by 150 km wide) and the Bermejo, Pilcomayo, Parapetí and Grande rivers which extend to the countries of Paraguay and Bolivia. On the other hand, Andes foreland region present large landforms fill with thick alluvium deposits resulting in glacial smelting (Dorn, 1994). In the area under study, Ortiz et al. (1977) describes the great alluvial fans of the Mendoza and Tunuyán rivers which lie to south of San Juan basin. Rocca (1969) carried out an important hydrogeological study of the Ullum-Zonda (U:Z) and Tulum (T) valleys. This author found two large aquifers coincident with the alluvial fans of San Juan river. These fans constitute the most important ground water reservoir of San Juan province (Lloret and Suvires, 2006). The paper presents the location, shapes, morphometric data and the Digital Elevation Models (DEM) of the alluvial fans of the San Juan River. The morphometric characteristics of width, length, surface, basin and fan areas as well as the values of the thickness of the sedimentary fill of the U-Z and T fans are published herein. In conclusion to label them as paraglacial megafans, due to their size, thickness, sedimentary fill and genesis at the time they were formed.

2. Characteristics of the study area

The area is located in the Province of San Juan, which is at the central-western part of Argentina, between 31° S and 32° S latitude and 67°–70° 30′ W longitude, from 800 to 600 m a.s.l. altitude. Fig. 1. The climate is arid to desertic (Bwk, Koeppen) where daily and seasonal temperatures vary greatly. The extreme absolute temperatures reached 45 °C and −4 °C. The annual mean temperature ranges from 14 °C to 19 °C. The annual rainfall values range within 100–124 mm. The moist winds blowing from the Atlantic Ocean are stopped by the eastern extreme of Pampean Ranges. The prevailing winds are from the S, while others, far less frequent or intense, blow from the W, NW and NE. The Tulum valley contains the main irrigated oasis in the province of San Juan and therefore is densely populated with about 700,000 inhabitants. This territory contains four large regional morphostructural units which coincide with four geological provinces (from W to E): Principal Cordillera, Frontal Cordillera, Precordillera and Pampean ranges, Fig. 1.

These mountainous areas are separated from each other by longitudinal block basins occupied by intermountain alluvial plains, great alluvial fans and fertile valleys. The geometry of the subduction of the Nazca plate below the South American plate controls the Quaternary deformations and the topography of the Andean Ranges which extend for more than 8000 km along the edge of South America between 4° S and 46° 30' S (Costa et al., 2006). The considered area is found on a subduction section of a very low angle between 5° and 10°, located between 27° S and 33° S. In the Fig. 1, we can see the Precordillera range, that is an Andean thrust and fold belt with a typical thin skin structural style developed in an Early Paleozoic carbonate platform and overlying Paleozoic rocks (Ramos, 1996). The structural vergence is located to

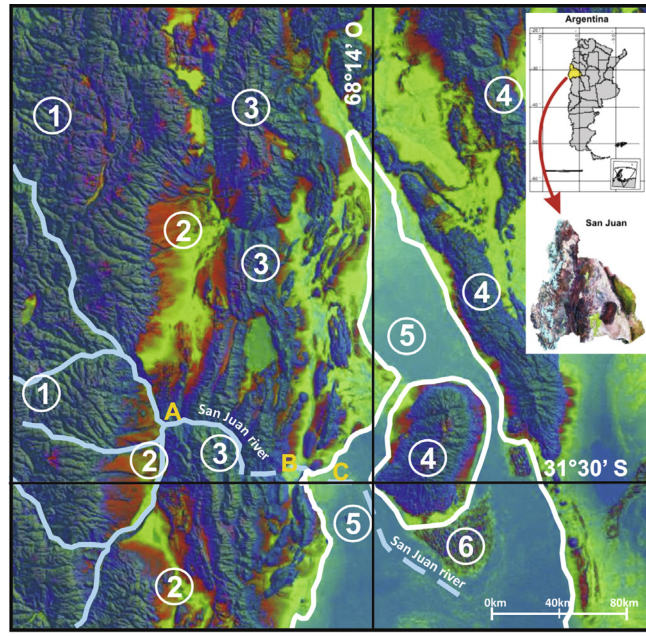

Fig. 1. Study area located of Central Andes foreland basin, San Juan Province, Argentina. San Juan river basin drains major morpho-structural units of geological provinces of Central Andes, which are presented from west to east: 1 Frontal Cordillera, 2 longitudinal tectonical depression of Iglesia-Calingasta-Barreal valleys; 3 Precordillera; 4 Pampean ranges; 5 longitudinal tectonical depression of Bermejo and Tulum valleys; 6 Structural high of Medanos Grandes sand sea. Sites: A: Las Juntas, B: Ullum-Zonda valley; C: Tulum valley.

the east in the Front Range, Western and Central Precordillera, while the vergence in the Eastern Precordillera is to the west (Ramos et al., 2002). The Chica de Zonda and Marquezado ranges belong to Eastern Precordillera while the Alta de Zonda range, the Cerro Blanco and Cerro de la Sal belong to Central Precordillera (Fig. 1). The Desaguadero river is the main fluvial collector of the Central Andes that, in the last century, drained to the Atlantic Ocean. Presently, however, and due to greater dryness conditions and increased water use and consumption, it has become an endorreic system. It has a length of 1498 km; it is born around

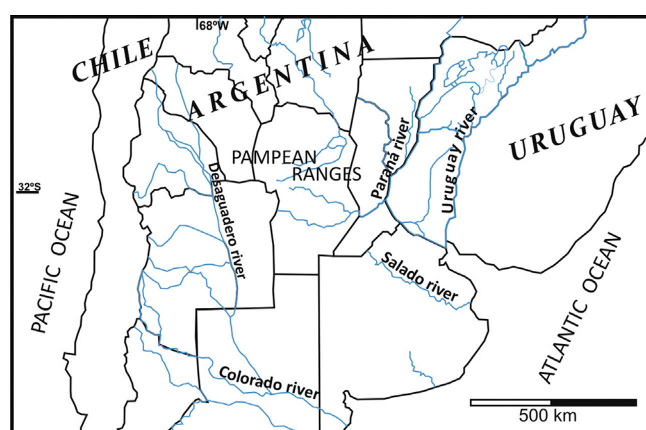

Fig. 2. Large rivers in Central Andean and Tropical regions of Argentina. These rivers drain a diverse geological and climatic regime. The Desaguadero – Colorado river forms the most important river system in this region. The Ullum-Zonda and Tulum basins are drained by San Juan river. These basins have been filled with thick alluvium sediments derived from Andean chain during most of the Upper Pleistocene event. The Desaguadero-colorado river debouched in the Atlantic Ocean years ago.

6700 m a.s.l., and drainage a surface around 260,000 km^2. The module of the San Juan river is 63 m3/sec (average discharge) and it drains an area about 26,000 km^2. Its general course flows from west to east, crossing the Precordillera range and continues further eastwards across tectonic depressions. The final concentration of all of the runoff from the Central Andean section reaches the Atlantic by a single collector trunk, the Colorado river (Suvires et al., 2012). Fig. 2.

3. Methods and materials

The area was analyzed using remotely sensed data, map and DEM data, geophysical and fieldwork data. The main drainage network of the San Juan river was mapped on processed images using QGis (vers.2.0.1), obtaining Figs. 1–3. Fig. 3 is the local cartography showing the U-Z and T alluvial fans and its sectors among Loma de Las Tapias, sierra Alta de Zonda, sierra Chica de Zonda, sierra de Marquesado and the Ullum reservoir. The apex of (U-Z) fans is located between Cerro de la Sal and Cerro Blanco while (T) fans were developed from Zonda canyon (A in Fig. 3). The recent channel of San Juan river drains Tulum valley starting from Ullum canyon (B in Fig. 3). Several palaeochannels inside alluvial fans were identified in Fig 3 (1, 2, 3, 4, 5 channels). Zonda canyon is the abandoned course of the San Juan river between Easter Precordillera. Some Digital Elevation Models (DEM) of the both larger alluvial fans (Ullum-Zonda: U-Z, and Tulum: T) were also constructed (Fig. 4a) from www.wist.echo.nasa.gov/api source. The morphometric data were measured from topographic maps and aerial photographs to 1:50,000 (Table 1). The data of the thickness of the alluvium deposits were extracted from geophysical-geoelectric and resistivity antecedents (Rodriguez et al., 2002; Lloret and Suvires, 2006; Zambrano and Suvires, 2008). The alluvial fans slopes across U-Z and T valleys were made according topographic data, obtaining Fig. 4b.

4. Alluvial fans of san juan river

4.1. Morphology and morphometric data

Fluviatile deposits make up the greater part of the Quaternary sedimentary fill of the Ullum-Zonda and Tulum tectonic basins and have been transported and laid down by shifting courses of the San Juan river. These sediments have intercalations of windblown sands and loess and contain the developable aquifers in both valleys. Fig. 3, shows the Ullum-Zonda and Tulum alluvial fans, developed into longitudinal tectonic depression. In each one of these depressions, where an important topographic break occurs, the San Juan river built two large and thick alluvial fans. Fig. 3. In the former, where the free aquifer is placed, the sediments are gravels and sands with good permeability, locally with discontinuous intercalations of silts and silty clays (Lloret and Suvires, 2006). The development of Ullum-Zonda alluvial fan was limited to the east by the mountain range of Eastern Precordillera. One gap through Eastern Precordillera ridge, called Zonda gorge, facilitated the fact that this same river, after passing this mountain ridge, formed the large alluvial fan in the Tulum valley. Both large fans are relict landforms that show high detrital loads and water volumes released in deglaciation stages.

Tulum alluvial fan has a greater surface development that the Zonda one and reaches the foot of the Sierra Pie de Palo. To the south of this ridge, the fan spreads out until it reaches the Bermejo-Desaguadero plains, where the Bermejo- Desaguadero-Salado river is located. The gap that connected both depressions (UZ and T) during the Upper Pleistocene was Zonda canyon (Figs. 3 and 4a (A), where relicts of terraces can be observed (Suvires, 1995). The elevation of the Eastern Precordillera through the Villicum-Zonda fault (VZ in Figs. 3 and 4a. b) disconnected both valleys and interrupted the drainage through the Zonda canyon (Suvires, 2013). Today the San Juan river passes from Zonda to Tulum valley through Ullum canyon (B in Fig. 4), to the north of the Sierra Marquezado.

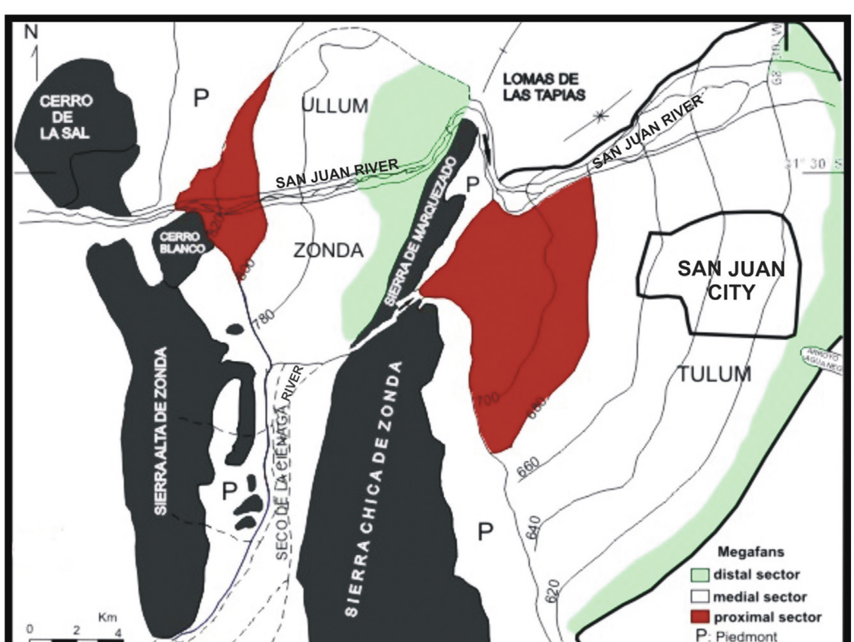

Fig. 3. Geomorphology features of the Ullum-Zonda and Tulum megafans into homonymous valleys (31° 30′ S and 68° 30′ W). The Tulum megafan deposits are characterized by at least two episodes: one of fluvial activity corresponding to Middle Pleniglacial and later the Holocene aeolian event. The gap that connected both depressions (UZ and T) during the Upper Pleistocene was Zonda canyon. The elevation of the Eastern Precordillera through Villicum-Zonda fault (VZ) disconnected both valleys and interrupted the drainage through the Zonda canyon. Today the San Juan river passes from Zonda to Tulum valley through Ullum canyon, to the north of the Sierra Marquezado.

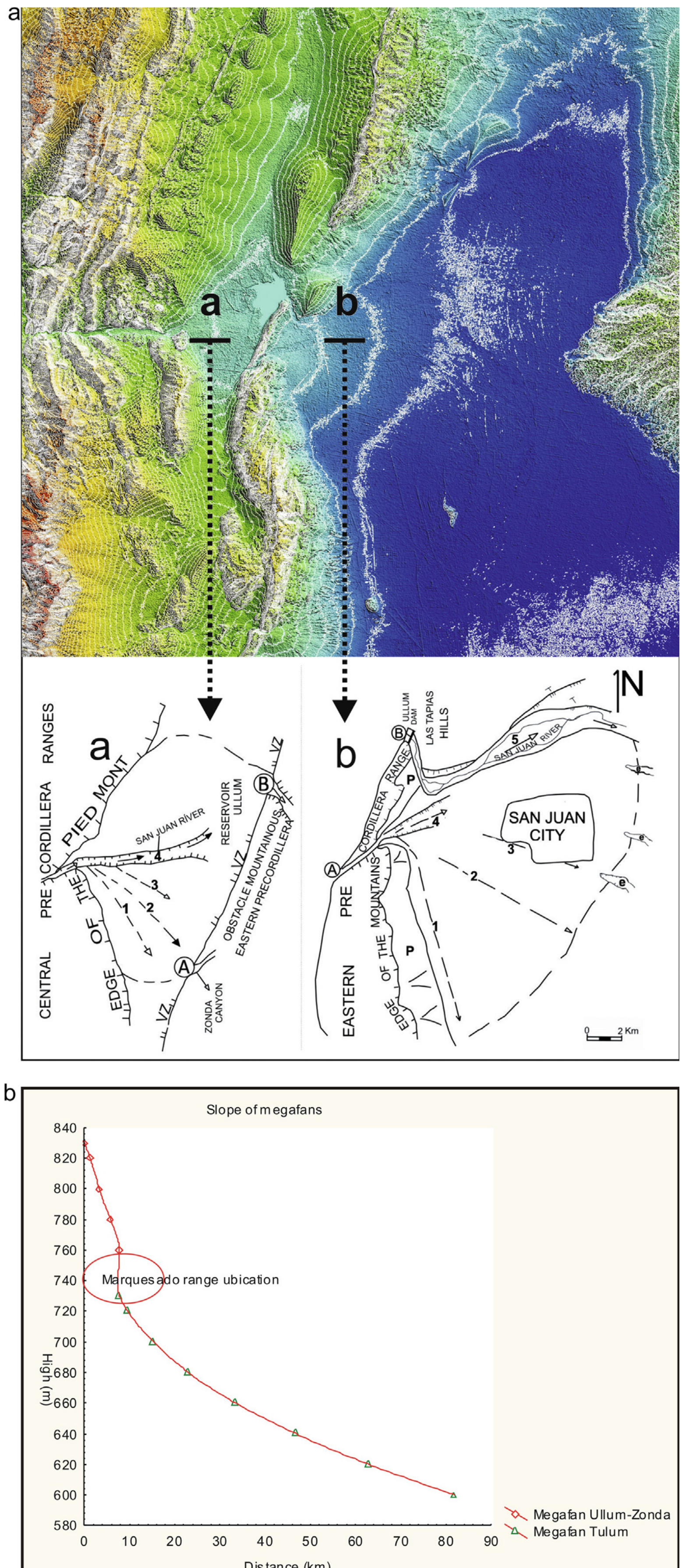
a
a
b
PRE CORDILLERA RANGES
CENTRAL
PIED MONT
OF THE EDGE
SAN JUAN RIVER
RESERVOIR ULLUM
OBSTACLE MOUNTAINOUS EASTERN PRECORDILLERA
VZ
ZONDA CANYON
A
B
1
2
3
4
b
N
ULLUM DAM
LAS TAPIAS HILLS
SAN JUAN RIVER
SAN JUAN CITY
CORDILLERA RANGE
PRE
EASTERN
EDGE OF THE MOUNTAINS
P
5
0 2 Km
b
Slope of megafans
Higth (m)
Distance (km)
Marquesado range ubication
Megafan Ullum-Zonda
Megafan Tulum
840
820
800
780
760
740
720
700
680
660
640
620
600
580
0 10 20 30 40 50 60 70 80 90

Table 1
Different parameters of each fan were measured such as: transverse radius, longitudinal radius, area (km^2), and the sedimentary fill volume (hm^3), using QGIS and Google satellite images, whose results are shown in Table 1. The data of thickness average alluvium fill (m) were extracted from geophysical data antecedents. The alluvium deposit of the Tulum fan is over several hundreds of meters thick; the highest values – 700 to 800 m-were determined at the alluvial fan edge. The high sedimentary load exported by San Juan river from the Cordillera to the foreland depressions was calculated in 3,682,200 hm^3.

Alluvial fan	W–E longitudinal radius (km)	N–S cross radius (km)	Area (km^2)	Average thickness of alluvium fill (m) (source: Geophysical data antecedents.CRAS)	Volume of sedimentary fill of each one fan. (Area × thickness) (hm^3)
Tulum	23	35	805	400	322,000
Ullum-Zonda	15	16	240	800	192,000
Total values					514,000

Some morphometric parameters of each alluvial fan into homonymous basin were calculated. The volumes of alluvium sedimentary fills were calculated of both fans. The average thicknesses of alluvial fan deposit were founded into the geophysical studies. Both megafans contain more than 514,000 hm^3 of alluvium fill.

Several small paleochannels of the San Juan river were identified (1, 2, 3, 4 on Fig. 4a). The Digital Elevation Model (DEM) (Fig. 4a) shows down there a sketch of both large fans. The U-Z fan is interrupted by the presence of the sierra Chica de Zonda and sierra de Marquezado while the Tulum fan grows to the east, without being restricted by any mountain range. Due to this fact, the latter mentioned fan covers a greater extension than the former fan. Tulum and Ullum-Zonda fans present downstream change in their patterns, from gravelly-sandy braided or sandy braided to meandering, each one being characterized by different bed features and channel processes. At present, the high and receding flow and the dune sands are the main processes that shape the river bed, Fig. 4a.

Different morphometric parameters of each fan were measured such as: transverse radius, longitudinal radius, area (km^2) and the sedimentary fill volume (hm^3). These parameters were measured using QGIS and satellite images, whose results are shown in Table 1. The data of thickness average alluvium fill (m) were extracted from geophysical data antecedents. The Ullum-Zonda fan (U-Z) has its apex at the Cerro Blanco at 805 m a.s.l and reaches 0.6% slope, while the Tulum fan apex is located at the Zonda gorge at about 730 m a.s.l and reaches 0.2% slope, Fig. 4b.

The thickness of U-Z fan (according to electric resistivity surveys) surpasses 1200 m and its base has not been reached by wells (Rodríguez et al., 2002). On the other hand, the Tulum fan distal rim ends to the east and to the south into the alluvial plain of the San Juan River. In the alluvial plain, the permeable intervals are fine gravels, gravelly sands, and sands that form string–shaped bodies deposited in meandering river channels. These sediments are interbedded with bank deposits, made up of fine silty or clayed sands, silts, and clays. The alluvium deposit of the Tulum fan is over several hundreds of meters thick; the highest values – 700 to 800 m-were determined at the alluvial fan edge. The high sedimentary loads exported by San Juan river from the Frontal Cordillera and Precordillera to the foreland depressions, were estimated in 3,682,200 hm^3; they were accumulated in the tectonical depressions as alluvial fans. The ratio existing between the hydrographic basin area of San Juan river (Ab) and the total area of both fans (Af) is about 31.7. This number may be interpreted due to the depositional features of andean rivers, which are fed by snow falls very far from here. The average longitude of the San Juan river channel is estimated to be about 180 km (Lt), whereas the longitude of the river along both valleys (Lf) (U-Z and T) is only of about 34 km. On the contrary the neighboring small alluvial cones piedmonts do not surpass 5 km.

4.2. *Quaternary palaeoenvironmental evolution*

Unfortunately, the Early and Middle Pleistocene fluvial records of the Central Andes region is still almost unknown except for some information from the subtropical zone in the Parana and Uruguay basins (Iriondo, 1993). The rivers with headwaters in the highlands of the Central Andes, like San Juan river, carried abundant sediments that were coarser than the present-day load (Milana, 1994; Suvires, 1995; Colombo et al., 2000; Lloret and Suvires, 2006; Harvey, 1997). The aeolian activity, in response to an increase of the aridity in the Central Andes, modified the original fluvial relief. Simultaneous events of the neotectonic activity contributed to origin new topographies and changes in the location of the rivers (Lloret and Suvires, 2006). High structures of Neotectonic origin, located to the south of the Sierras Pampeanas (unit 6, Fig. 1) are covered by large sand fields. Also, the medium and distal sectors of the Tulum alluvial fans are partially covered by occasional dunes and sandy loamy plains (Suvires et al., 2012). The aridity in South America reached its maxima during the Upper Pleniglacial (MIS 2) when the aeolian sedimentation was still active along the Venezuelan and Colombian Llanos and over parts of central and northern Amazonia. The Upper Pleniglacial was also a time of extensive aeolian activity in response to increasing aridity in Central Brazil, Chaco (Latrubesse et al., 2012; Iriondo, 1993) and Pampa (Iriondo and Garcia, 1993). During the last glacial, in the Pampean region (Argentina) a sand sea with large dunes was formed and loessic sediments were deposited in the Chaco region. The aeolian activity peaked during the Upper Pleniglacial. The best records of large tropical South American Rivers come from the period before 24 ka BP, possibly corresponding to the Middle Pleniglacial (ca 65–24 ka BP). The Middle Pleniglacial is characterized by abundant precipitation in the Andes and a continuing change towards dry conditions in the lowlands, including the cratonic areas (Latrubesse, 2000, 2003). The Middle Pleniglacial–early Upper Pleniglacial episode of fluvial sedimentation is well recorded in the Upper Parana basin. Some authors suggest that the alluvial sedimentation could have been directly associated with glacial advances and enhanced rainfall in the central and northern Andes where the rivers deposited sand and gravel (Dumont et al., 1992;

Fig. 4. a. Digital Elevation Model (DEM) shows down there a sketch of Zonda (a) and Tulum (b) megafans. Both alluvial fans constitute the most important ground water reservoir of San Juan province within tectonical depression. The Tulum valley (b) contains the main irrigated oasis in the province of San Juan and it is densely populated with about 700,000 inhabitants (San Juan city). Several palaeo-channels of San Juan river were outlined (1, 2, 3, 4). To the North of the city, the modern channel of San Juan river runs across Ullum canyon (5). Tulum alluvial fan has a greater surface development that the Zonda one and reaches the foot of the Sierra Pie de Palo. To the south of this ridge, the fan spreads out until it reaches the Bermejo-Desaguadero plains, where the Bermejo-Desaguadero-Salado river is located. P: piedmont area. Fig. 4 b. Slopes of alluvial megafans. The Ullum-Zonda fan (U–Z) has its apex at the Cerro Blanco at 805 m a.s.l and reaches 0.6% slope, while the Tulum fan apex is located at the Zonda gorge at about 730 m a.s.l and reaches 0.2% slope. The Marquesado range is the obstacle between both valleys.

van der Hammen et al., 1992). Wind-circulation models were proposed by Iriondo and Latrubesse, 1994; Latrubesse and Ramonell, 1994; Iriondo, 1997, for the Amazon and the Llanos area for the period close to Late Pleistocene (ca 40–14 ka BP). Cold air masses of the South Pacific Anticyclonic (SPA) circulation were dominant in the Argentinean Pampas and part of the Eastern Chaco during the Middle and Upper Pleniglacial when the climate was dry and cold (Ramonell and Latrubesse, 1991; Iriondo and Garcia, 1993; Latrubesse and Ramonell, 1994). The SPA winds were strengthened by katabatic winds coming from the ice field of the Patagonian Andes (Iriondo and Garcia, 1993). After 14 ka BP, fluvial sedimentation in this region was strongly influenced by the climatic changes associated with the last deglaciation. Major aeolian activity is registered during the Last Glacial Maximum; episodes of aeolian reactivation also occurred during the Holocene. The Maximum Late Glaciation at the center of Argentina, would have been predominant regional aridity conditions (25,000–20,000 y 10,000 y 14C AP) with loess sedimentation (Mehl, 2010; Tripaldi and Forman, 2007). In the piedmont areas of Central Andean foreland, two main cycles of degradation-aggradation are recorded during the Holocene (Zárate et al., 2005; Tripaldi, 2010). Zárate (2002) indicate that terraces deposits were accumulated in the Estacada stream basin at the end of Middle to Late Holocene age, showing changes on fluvial processes and the formation of soil. This soil was interpreted as a change from cold to arid conditions. The pollinic records also indicate that the arid increased in the Middle Holocene (ca. 8000–4000 yBP) (Markgraf, 1983). The last 4000 year, the fluvial sedimentation is evidence of terrace deposits and recent outwash plain. Towards 2800 y 14CBP, the changes of vegetation on upper basin of some rivers, could to be the result of the increase in water of fluvial system (Páez et al., 2010). The abandoned lacustrine deposits of Zonda valley were recorded and dated by Suvires and Gamboa (2011). According to the dating and stratigraphic relationships, this lake-swamp episode would have occurred in the Late Holocene (2840 $\pm$ 80 14CBP) remaining more than 1000 years. The area of the cold and freshwater body would have been around 750 km^2 covering a great part of the U-Z valley.

According to the stratigraphic relationships of the tropical South American Rivers, the author considers that the San Juan paraglacial megafans would have occurred in the period before 24 ka BP (Middle Pleniglacial).

5. Concluding remarks

The different fans of the tributary rivers of the Desaguadero hydrographic system, which begin at the Central Andes, have deposits whose sizes and lithologies are much larger than the ones of the local piedmont fans. These fans's sizes do not equal those examples of the great world megafans (Kosi, Salado, Bermejo). Nevertheless, this deficit can be compensated by the great power of their sediments, since they are located in most cases in tectonic depressions with mountainous obstacles in the direction of the runoff. As a result, the alluvium deposits thickness of the Zonda fan reachs 1200 m. On the other hand, while the Kosi megafan longitudinal radius reaches 60 km, the Tulum fan reaches 50 km. The noted differences occur because the Kosi megafan, located inside the receptions basin, is fed by high rainfalls (1500 mm year), while that U-Z and T alluvial fans are located inside an area with scarce rainfall (100 mm/year), fed by ice and glacial melting. These large alluvial fans are important fluvial archives and aquifers of the deglaciation events possibly corresponding to the Middle Pleniglacial (ca 65–24 ka). According to the stratigraphic relationships of the tropical South American Rivers, the author considers that the San Juan paraglacial megafans would have occurred in the period before 24 ka BP (Middle Pleniglacial). These paraglacial megafans indicate ancient colder and more humid conditions compared with the present arid and dry conditions. They recorded a sedimentary fill volume that surpass 500,000 hm^3.

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