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# Holocene evolution and geochronology of a semiarid fluvial system in the western slope of the Central Andes: AMS $^{14}$C data in El Tránsito River Valley, Northern Chile

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In this paper, we discriminate the contribution of the different sediment sources into a river situated in the semiarid region of northern Chile, differentiating the ones driven by the paraglacial response from the ones yielded to the tributary-junction alluvial fans or the ones coming from the hillslopes. The sedimentary infilling is accurately described in the main landforms such as alluvial fans, alluvial terraces and landslides in the current valley floor where twenty-six $^{14}$C AMS samples were picked up. The $^{14}$C age data indicate that the aggradation in the uppermost part of the valley immediately postdates the glacial retreat at ~15,000 $^{14}$C years cal. B.P. and spans the whole Holocene starting at 11 ka. B.P. and finishing about 2 ka B.P. The main sources for lateral inputs are debris flows from tributary catchments in the portion where the river is embedded in between 1000 and 2000 m a.s.l as well as catastrophic landslides. Additionally, an extensive detailed geomorphological mapping is provided to discuss the meaning of the ages together with an assessment of where the samples came from. Finally, the dataset and field criteria provided in this work contribute to better perform paleoclimatological interpretations for the semiarid fluvial systems of northern Chile. These interpretations usually consider the increased influence of the westerlies during the Holocene and the span of time that the paraglacial response delivers glacigenic sediments into the system.



## 1. Introduction

The geomorphic activity of the fluvial systems that drain the Andean ranges into the Pacific Ocean has been studied from different perspectives. Most of them highlight, according to the statements given by Kondolf and Piégay (2003), the relief driven by tectonics, the lithological controls and variations of the hydrology related with climate or by human impact. Previous descriptions of the main fluvial systems, that drain the western slope of the Andes of central Chile, were described by Darwin (1876) and Paskoff (1970, 1977) based on geomorphological field descriptions.

The study area is situated between the 28-29ºS in the southernmost portion of the Atacama Desert. The higher tributaries of El Tránsito River represent a glaciated landscape that, from $^{10}$Be age data, results from successive glacial oscillations between 22,000 and 14,000 years B.P. (Aguilar, 2010; Zech et al., 2006) and the definitive and rapid glacial retreat after that time. Previously, for El Tránsito River, Aguilar et al. (2014) discussed the values of the erosion rates (30 m/Myr and 50 m/Myr) highlighting the lateral supply behaviour of the valley infilling as one of the main local sources (debris flows and landslides), against fluvial sediments coming from the whole river basin and including the paraglacial sediments yielded after the glacial retreatment approximately 15 Ka. ago. Previous work in El Turbio River (30ºS) situated in the semiarid Region of northern Chile (Riquelme et al., 2011) had pointed out that the infill of that river was strongly controlled by the paraglacial response caused by the glacial retreat during the late Pleistocene.

The paraglacial response has been documented in many rivers in the world with the presence of glaciers in their uppermost sections (e.g. Church and Ryder, 1972; Hobley et al., 2010; Ballantyne, 2002). Furthermore, different interesting perspectives on Quaternary landscape evolution have been raised for the Andean watersheds. Antinao and Gosse (2009) indicated that the Quaternary landscape

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evolution is strongly influenced by landslides associated with seismotectonic activity and point out that the sediment yield by slides are three time greater during periods of an increase in shallow seismicity. Furthermore, Colombo (2005), based on prior works, proposes that torrential rainfalls controlled by El Niño Southern Oscillation (ENSO) are responsible of most of the sedimentary inputs in the tributary-junction alluvial fans. The sediment supply from the tributaries has been documented for the actual dynamics (Cabré et al., 2015) for El Tránsito River and for many others in the Central Andes as the ones described in Sepúlveda et al. (2006, 2014) and Moreiras (2006).

The objective of this study is to understand the dynamics for 110 km of the thalweg profile going from the high ranges towards along the main valley downstream in order to understand the large-scale dynamics of the fluvial system during the Holocene. We need to assume that the local effect on the river profile represents an important tool for understanding differences in sediment supply in the different segments of El Tránsito River.

## 2. Study area

The study area is situated in the Frontal Cordillera near 29ºS in Chile (Fig. 1). The former studies in El Tránsito River by Aguilar (2010); Aguilar et al. (2011, 2014), introduce the insights for understanding the behaviour and geomorphic dynamics for this river system which flows from the high mountain region (~5600 m a.s.l.) downstream towards the Pacific Ocean (Fig. 1B). Geomorphology and stratigraphy of the uppermost segment of the El Tránsito Valley define a segment with glacial features corresponding to several glacial phases during the late Pleistocene (Zech et al., 2006; Aguilar, 2010; Ammann et al., 2001; Veit, 1996; Grosjean et al., 1998). In El Encierro Creek (Zech et al., 2006; Aguilar, 2010; Grosjean et al., 1998) we can find moraine deposits, *rouches moutonnées*, rock glaciers and 'U'-shaped hanging valleys (Fig. 2A). The $^{10}$Be surface exposure dating has been done in moraines and streamlined subglacial landforms from the Encierro Valley (Zech et al., 2006; Aguilar, 2010). Results show a correlation between glacial phases in South America shown in Kull et al. (2002), Clapperton et al. (1997), Espizua (1999) and Ammann et al. (2001). These glacial features occurred before 15 ka B.P. and resulted from episodes of increased moisture during the late Quaternary, which have been related to a northward shifting of the Southern Westerlies (Veit, 1996; Lamy et al., 2000; Ammann et al., 2001); alternatively, it has been interpreted as the result of a strengthening of the South American Monsoon related to the 'Central Andean Pluvial Event' (CAPE) (e.g., Zech et al., 2006, 2008; Quade et al., 2008; Riquelme et al., 2011).

This study focuses on geomorphological and sedimentological descriptions on the fluvial system developed downstream of the lowest altitudinal glacial features. Other fluvial systems in the semiarid region of the western slope on the Andean ranges have been dated with $^{14}$C displaying Holocene ages (Veit, 1996; Riquelme et al., 2011; Houbart, 2015). Veit (1996) has documented buried soils and wetland deposits in the valley floor for El Tránsito River. Thus, whereas the westerlies increased the moisture during the Holocene (7.3 ka. B.P., 5–3 ka B.P., 3–1,8 ka B.P. and 0,27 ka B.P.) carbon-rich layers were accumulated upstream the tributary-junction alluvial fans due to the damming of the main river (Colombo, 2005). Nevertheless, during the drier Holocene periods we find soil formation on the alluvial fans and peat bogs on the valley floor (wetland deposits in this paper) where almost no sedimentation occurred (Veit, 1996).

The importance of the relationship between tributary sediment sources and bedrock geology has been highlighted in many examples around the world (Stokes and Matter, 2015; Gómez-Villar et al., 2006; Wang et al., 2008). Within the study area the bedrock geology is represented by Permian to Lower Triassic batholiths (Ribba, 1985; Salazar, 2012; Salazar et al., 2013 and references therein) and marine, siliciclastic and volcanic rocks ranging from Triassic ages to Neogene (Salazar, 2012 and references therein). The main fault systems with general N-S trends are the Pircas-Zapallo, Pinte-Totora, Chollay-Valeriano and Coipa-Potro that exhumed Paleozoic batholiths, thrusting the Mesozoic and Cenozoic rocks during the Andean orogenesis (Godoy and Davidson, 1976; Moscoso and Mpodozis, 1988; Salazar, 2012; Rossel et al., 2016).

## 3. Data and methods

This study is based on detailed geomorphological mapping, combining Landsat ETM+ images, Google Earth Images, aerial images and fieldwork. This allowed us to determine the main geomorphological features through the El Tránsito River. The fieldwork used classical stratigraphic techniques that provided essential information about the different sedimentary environments developed in this deeply incised drainage system. A total of twenty-six samples for AMS $^{14}$C (Table 1) were collected from different depositional environments related to different morphostratigraphic features to constrain fluvial development during the Holocene. The radiocarbon dating allows us to understand the chronology of the landscape evolution in a fluvial system. Samples were taken from carbon-rich layers within the observed landforms in the main river valley, mainly on alluvial terraces where each sample has been contextualized with its depositional history (Table 1). It is fundamental to avoid samples with contaminant sources of humic acids circulating throughout the soil and root penetration in sediment layers (Törnqvist et al., 1992; Rech et al., 2003) that can lead to misinterpretation of the evolution of the Holocene infilling. Finally, in order to avoid artificial contamination, samples were taken with aluminium foil packets.

Standard procedures were carried out at the Beta Analytic Radiocarbon Dating Laboratory (Miami, USA). All collected samples correspond to bulk organic sediment and were acid washed. Peat and charcoal fractions were analysed separately for two of the samples. Measured radiocarbon age is corrected by the $^{13}$C/$^{12}$C ratio, giving a conventional radiocarbon age. Then, this conventional radiocarbon age is calibrated (version 5.0 of Stuiver and Reimer, 1993 and the INTCAL98 dataset of Stuiver et al., 1998). Differences between the conventional age and the calibrated age are based on cosmic ray variations in time. Calibrated radiocarbon age considers 2-sigma has a 95% probability; these are the results shown in Table 1. For all the age ranges discussed in the text we present the '100%-probable' age ranges.

The samples HPN-170108-1 and HPN-170108-1-OS (Table 1) will not be considered because the reported results indicate an age post-B.P., and their ages have been reported as a % of the modern standard, indicating that the living material from the last 50 years is included in these samples. As indicated above, these younger ages are likely the product of contamination by rootlets intrusion.

## 4. Results

### 4.1. General features

The whole length of the river thalweg analysed is approximately 110 km long. The analysis starts at the point where there is evidence of inheritance of glacial forms (Fig. SDF-7). This fluvial system can be segmented into sections based on the floodplain width, tributaries size, hillslope sediment budget (landslides, colluvial slopes) and by the thalweg slope. The trunk valley shows, along most of the

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