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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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ABSTRACT

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.

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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 Mather, 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

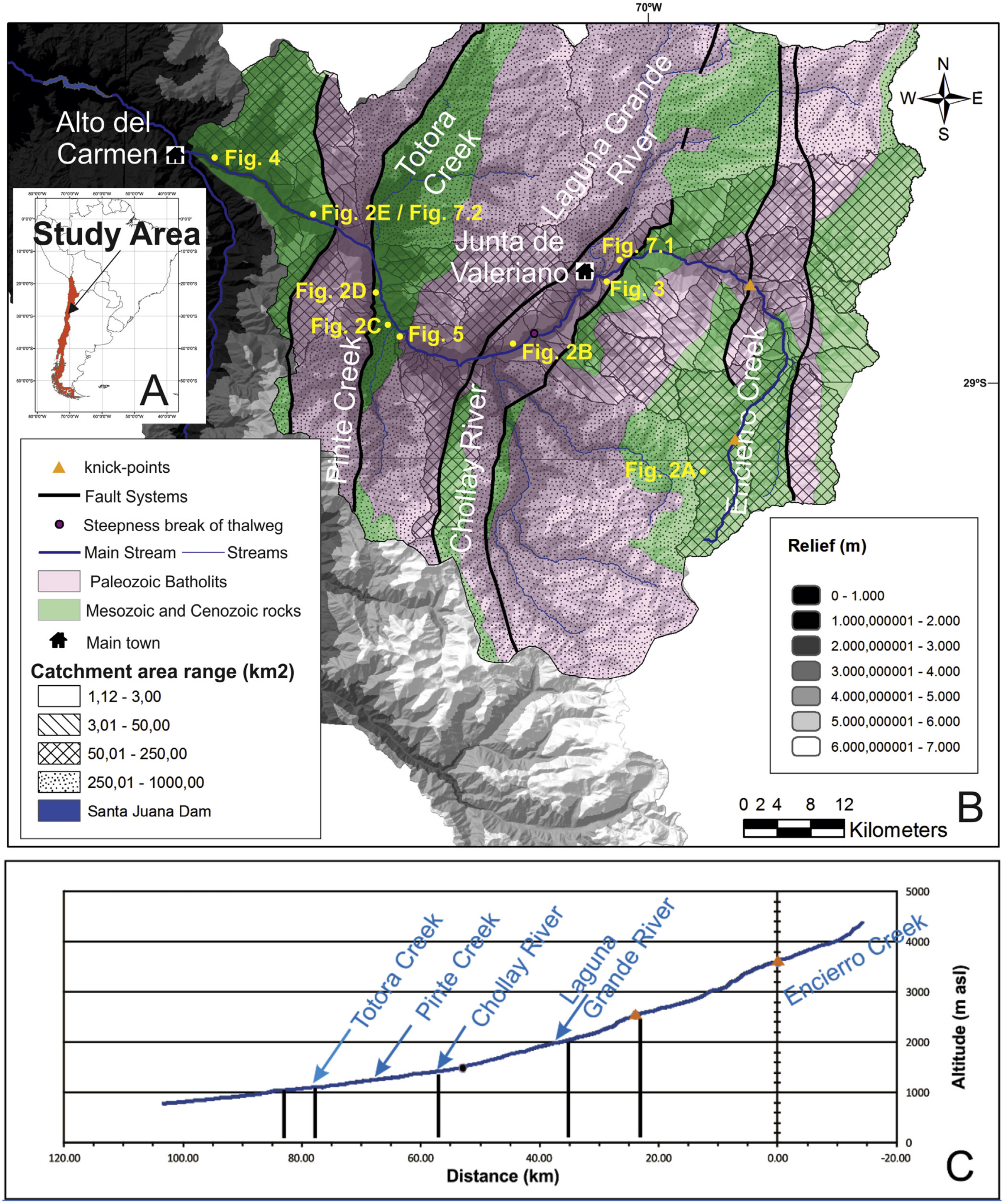

Fig. 1. Context maps on the study area. A. Map of the study area in South America. B. Map of the study area over a shaded relief map from a Digital Elevation Model. Tributary basins have been hierarchized based on their area size. The bigger catchments appear with local names. C. Thalweg profile of El Tránsito River valley showing the location of confluence with the main larger tributaries, knick-points, steepness break and main faults.

thalweg profile, a valley floor whose width varies between 200 and 400 m. Nevertheless, between Pinte Creek and Totora Creek it reaches up to 800 m wide, and presents a relatively flat plain in which the river has a braided pattern with numerous lateral inputs from colluvial slopes (Fig. 2D). The thalweg profile in Fig. 1D presents two knick-points in the section between Encierro Creek and

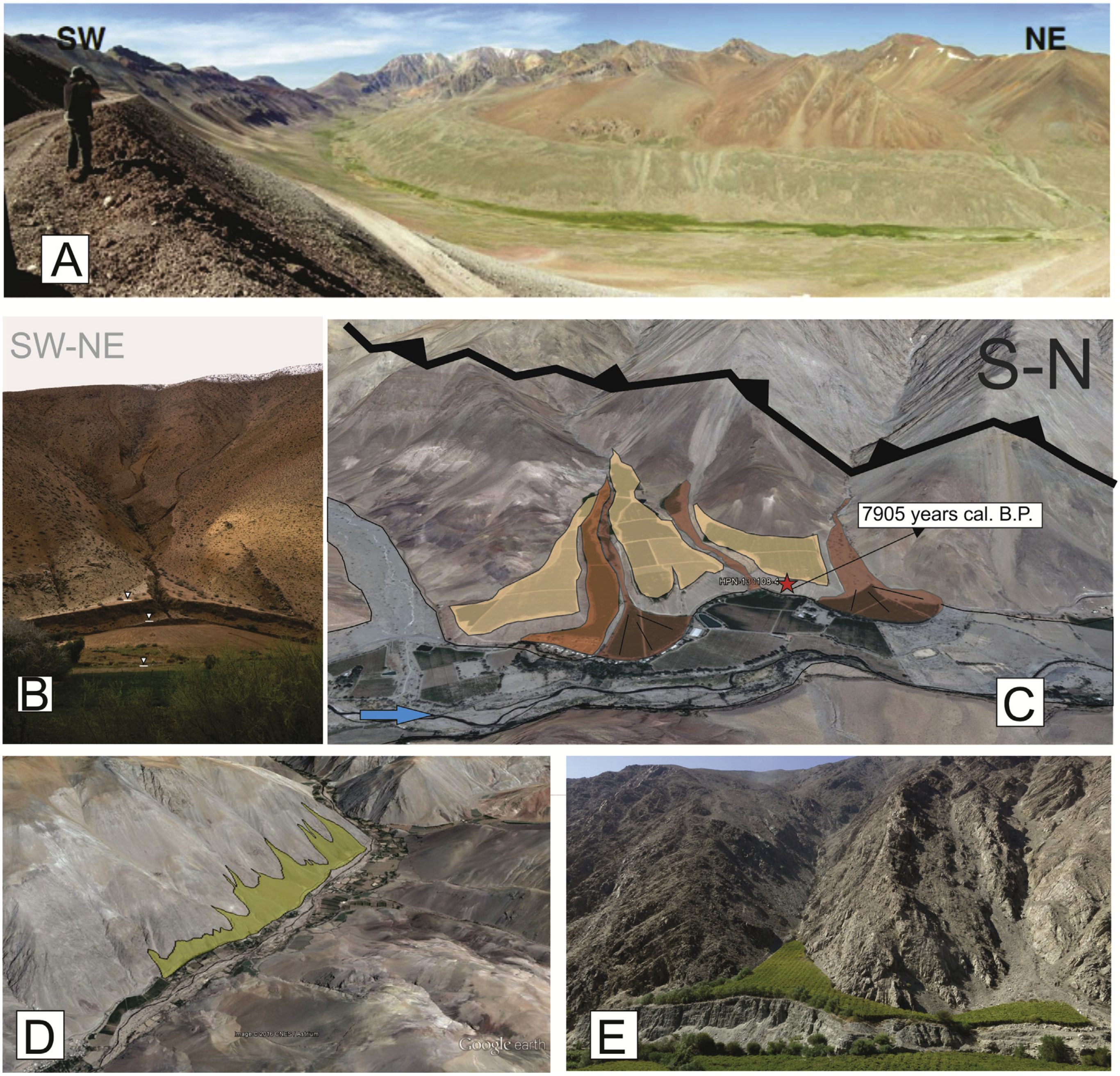

Fig. 2. Geomorphic features present in the study area. A. General view of Encierro Creek showing the glacial geomorphology and till deposits. B. Tributary-junction alluvial fan showing telescopic-like pattern with three different base levels (white triangles). C. Alluvial fan close to Pinte-Totora Fault system with the location of radiocarbon age, image courtesy of the Google Earth archive (07-08-2013). D. Presence of colluvial sediments in the southern hill of El Tránsito river between Pinte Creek and Totora Creek, image courtesy of the Google Earth archive (07-08-2013). E. Trimmed alluvial fan within Totora Creek and Carmen River.

Chollay. In this segment, it is possible to identify a knick-point that coincides with the western branch of the La Coipa-Potro Fault System and with a change in the bedrock lithology. This change is related to the boundaries between Mesozoic rocks and Paleozoic Batholits (Fig. 1C). Downstream of this point, no major steepness break is observed at the considered resolution. Thus, the thalweg exposes a rectilinear to slightly exponential longitudinal profile. Downwards, the thalweg profile shows a steepness break at 1500 m a.s.l. at the Chollay River.

The study area considers 52 tributary catchments of the El Tránsito River valley that have been classified into three categories depending on their area size (Fig. 1C). This classification is useful in terms of differentiating the basins with higher amounts of sediment yielding to the valley floor (fan-building on toe) with the basins with no tributary-junction alluvial fans building on the valley. From Fig. 1C, it is also possible to observe that in the segment between the Totora Creek and Carmen River there is a greater density of small basins (3–50 km^2). Furthermore, two of the larger catchments in the El Tránsito River basin drain into the segment between the Chollay River and Totora Creek. The morphometric analysis of these catchments shows differences between valley floor and crests that reach 2000 m. The catchments with ranges above 250 km^2 have summits greater than 5000 m a.s.l. and their thalweg profiles are gentle.

Table 1
Radiocarbon data and ages from the study.

Distance from glacier front (Km)	Sample	North	East	Sample Material	Geomorphological setting	Stratigraphic background (depth of samples in cms)	13C/12C ratio (‰)	Conventional Radiocarbon age (years)	Intersection with calibration curve (14C years cal. B.P.)	2 Sigma calibration	
10	HPN-170108-1	6794036	418043	plant material	alluvial terrace	interbedded in an alluvial terrace composed by fine-grained sediments	−25.4	138.3±-0.7 pMC	*25	–	–
10	HPN-170108-1-OS	6794036	418043	organic sediments	alluvial terrace	interbedded in an alluvial terrace composed by fine-grained sediments	–	–	*25	–	–
26	HPN-180108-3	6805757	409325	organic sediments	alluvial terrace	interbedded close to the top of an alluvial terrace by fine-grained sediments (−100)	23.7	2410 ± 40	2360	2700	2640
30	HPN-180108-6	6807010	405808	charcoal	alluvial terrace	interbedded in a debris cone within clay and silts	23.8	9550 ± 50	10915	11120	10700
33	HPN-081107-16b	6806386	402140	organic sediments	alluvial terrace	lower section of an alluvial terrace mainly composed by fine sediments	25.6	5890 ± 40	6720	6790	6640
34	HPN-081107-16a	6806386	402140	organic sediments	alluvial terrace	upper section of an alluvial terrace composed by fine sediments (−110)	23.3	9530 ± 50	10760	11090	10680
34	HPN-081107-16a-AS	6806386	402140	alkali soluble sediment organics	alluvial terrace	upper section of an alluvial terrace composed by fine sediments (−80)	24.9	9170 ± 50	10270	10490	10230
35	HPN-081107-17	6806203	401100	organic sediments	alluvial terrace	interbedded in an alluvial terrace (−150)	NA	7740 ± 50	8540	8600	8420
36	MA131109-1	6805290	400558	organic sediments	alluvial terrace	interbedded in an alluvial terrace composed by coarser and fine-grained sediments (−400)	23.7	3980 ± 40	4430	4530	4400
36	MA141109-1	6805290	400558	organic sediments	alluvial terrace	interbedded in an alluvial terrace composed by coarser and fine-grained sediments (−500)	25.7	5940 ± 40	6750	6880	6670
36	MA141109-2	6805290	400558	organic sediments	alluvial terrace	interbedded in an alluvial terrace composed by coarser and fine-grained sediments (−1000)	25.8	9020 ± 60	10210	10250	10150
39	HPN-091107-20	6804247	398160	organic sediments	alluvial terrace	sample on sandy lens at the top of the alluvial terrace (−150)	22.2	2480 ± 40	2595	2730	2360
39	HPN-120108-2-AS	6798654	394460	organic sediments	alluvial terrace	interbedded in an alluvial terrace composed by fine sediments	22.7	9690 ± 50	11170	11220	11070
39	HPN-120108-2	6798654	394460	charcoal	alluvial terrace	interbedded in an alluvial terrace composed by fine sediments	20.7	9360 ± 60	10580	10720	10420
47	HPN-091107-22	6798070	393676	Organic sediments	alluvial terrace	interbedded in fluvial gravels hanged high (50 m) above the current floodplain (−200)	21.7	4620 ± 50	5320	5470	5290
48	HPN-071107-14	6797544	393226	organic sediments	alluvial terrace	upper section of an alluvial terrace composed by fine sediments. This terrace is overlain by coarser facies (−300)	NA	4620 ± 50	5320	5470	5290
55	HPN-071107-12	6794289	386224	organic sediments	alluvial terrace	interbedded in alluvial terrace (−150)	21.5	7550 ± 50	8380	8420	8310
58	HPN-071107-11	6793577	383540	organic sediments	alluvial terrace	interbedded in alluvial terrace (−150)	23.2	710 ± 40	670	700	640
65	GA140109-1	6796179	377938	organic sediments	lacustrine	sample below lacustrine facies intergranular carbonaceous matrix (−3100)	24.3	12360 ± 80	14210	14720	14050
68	HPN-130108-4	6798842	375902	charcoal	alluvial terrace	interbedded in a debris cone (−3000)	22.7	7060 ± 50	7905	7970	7790
85	HPN-041107-8L	6811560	366380	organic sediments	alluvial terrace	interbedded in an alluvial terrace (−2500)	24.2	3870 ± 40	4290	4420	4150
90	HPN-031107-7	6814272	363793	organic sediments	alluvial terrace	interbedded in a debris cone (−200)	22.7	4310 ± 40	4860	4960	4830
94	HPN-021107-2	6816163	359818	organic sediments	alluvial terrace	interbedded in a debris cone (−300)	23.9	6970 ± 70	7800	7950	7670
98	HPN-021107-1	6818155	355672	organic sediments	alluvial terrace	interbedded in an alluvial terrace by fine sediments (−150)	24.0	5510 ± 40	6300	6400	6280
99	HPN-280707-1b	6818400	354769	organic sediments	alluvial terrace	sample from the top of a fluvial terrace composed by fine-graided sediments (−120)	24.2	5300 ± 50	6090	6260	6250
102	HPN-101107-23	6820317	353459	wood	alluvial terrace	sample from fine sediments interbeddeds 2 m downwards of the alluvial surface (−200)	23.1	150 ± 40	*135	290	0

4.2. *Terraces and alluvial fans at toe of small-medium catchments*

In the El Tránsito River valley there is a discontinuous presence of alluvial terraces (Fig. SDF-2 to SDF-7). The formation of these terraces is mainly due to stream capture, and it is possible to identify three levels of terraces in the confluence areas of tributaries.

The facies present in the alluvial terraces consist of well-stratified fine sediments with poorly sorted interbedded gravel beds. These coarser facies present poorly rounded clasts, poorly sorted gravels and matrix supported. The absence of roundness in clasts suggests that these particles were hardly transported and indicates the nearby presence of lateral sediment inputs into the trunk valley (Fig. 3). The stratigraphic arrangement comprises well defined planar boundaries between different fine facies and erosional boundaries among the coarser facies. Fine sediments are mainly silty sands and silty muds, and it is also possible to identify distinct developed soil horizons. Within these buried soils there is an important carbonate inter-particle cementation, which gives a whitish appearance. Charcoal layers where ^{14}C samples have been picked up are typically included in these buried soils, presenting lateral continuity in the outcrops (Fig. 3). Stratification, which is not always well preserved, shows convolute stratification in layers where it is possible to observe rootlet traces or disrupted stratification, presumably caused by freeze-thawing processes (Fig. 3). Ferruginous crusts and calcite envelopes are usually observed around the gaps where root or plants were established.

Alluvial fans at the tributary outlet of medium and small catchments are present in the entire study area (Fig. SDF-2 to SDF-7). The presence or absence of these alluvial fans is related to the catchment area size. In basins ranging from 3 km^2 to 250 km^2 we observe tributary junction alluvial fans, whereas in bigger ones (>250 km^2), fans are absent. We identify a segment of the El Tránsito River valley within Totora Creek and Carmen River where there is a major fan presence (sixteen fans in 30 km). Twelve of these fans are preserved in the northern edge of El Tránsito River and four in the southern slope (Fig. SDF-2, SDF-3). The spacing distribution of fans in the upper segments of the El Tránsito River varies and shows a greater density downstream (Fig.SDF-2). Alluvial fans show trenching on the fan head and toe incisions by the main river up to 70 m height (Fig. 2C, E). Infilling sediments correspond mainly to the ones removed from the catchments. Even

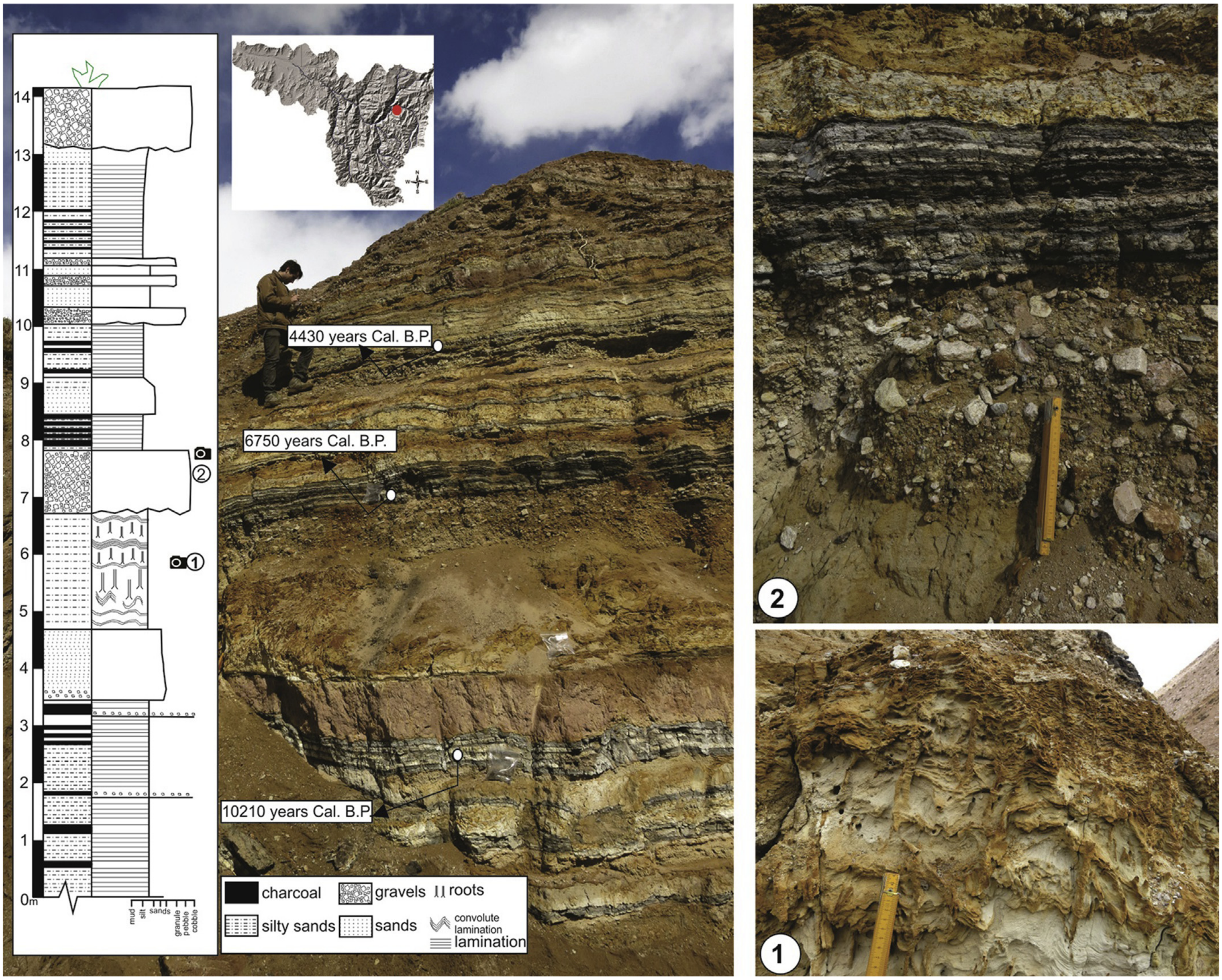

Fig. 3. Stratigraphic section in alluvial terrace situated near Junta de Valeriano town (Fig. 1) on a Digital Elevation Model of the El Tránsito River valley. The location of samples of radiocarbon ages is on the log picture and photographs of specific facies (photos 1 and 2) are discussed in detail in text.

though there are differences in the facies assemblage among the fans of this valley, the stratigraphic arrangement in alluvial fans is mainly composed of coarser facies (Fig. 4). These are composed of massive gravel deposits, occasionally boulder size gravel up to 60 cm in diameter, matrix supported, relatively well stratified with planar stratifications, gently erosive beds, poorly rounded clasts, poorly sorted, sandy to silty matrix supported and sandy facies with crossed stratification.

Twenty-five samples were picked up from buried soils, fine sediments within the alluvial terraces and from wetland deposits. Some samples from the alluvial fans correspond to charcoal layers picked in the upstream portion of the fans, mainly in the segment between El Encierro Creek confluence and Chollay River confluence. The ^{14}C ages for the wetland deposits found in the alluvial terraces range between 11170 years cal. B.P. to 2360 years cal. B.P. As an example, we picked up three samples (MA131109-1, MA141109-1, MA141109-2) in the same stratigraphic column where is possible to constrain that the aggradation for this segment has a continuous infilling from 10210 years cal. B.P. to 4430 years cal. B.P. (Fig. 6C). The significance of ^{14}C ages in alluvial terraces is discussed further.

4.3. Rockslides

These features are present in the segment within the Chollay River and Totora Creek albeit they are greater between Chollay River and Pinte Creek (Fig. SDF-3, SDF-4). This is somehow related to the highly-fractured bedrock close to the Pinte Totora Fault System. Rock avalanche deposits lie on the hillslope and they are usually preserved in the opposite slope of the rockslide scarp (Fig. 5A, B, 5E). These chaotic deposits are composed entirely of clasts from the bedrock, with angular blocks showing mass-flow facies and injections, or dykes of fine sediments in the basal zone (Fig. 5G). Most of the rockslides are 40 m above the floodplain in the hillslopes. It is possible to observe one of these ancient rockslides underlying lacustrine facies close to Pinte Creek about 15 m above the actual floodplain (Fig. 5E, F). The stratigraphic arrangement of the lacustrine deposits dammed by the rockslide comprises silty muds facies with some sandy channelized layers with a maximum thickness of 30 m (Fig. 5C, F). The reworking of the natural dam is evidenced by massive coarser facies that are poorly sorted coevally with lacustrine facies. Then, lacustrine facies onlap the barrier dam deposit (Fig. 5D, F). We picked a sample of organic sediments within the sand matrix at the bottom of this lacustrine sequence (GA-140109-1) which has an age of 14210 ^{14}C years cal. B.P., so, this rockslide is at least 14.2 ka. B.P.

5. Discussion

In a fluvial context, climatic change into wetter conditions promotes a greater effectiveness of sediment transport due to large water discharges (Bull, 1991). The shift in flow regime favours

Fig. 4. Stratigraphic section in alluvial terrace situated near Alto del Carmen town with coarser facies with fine sediments attributed to wetlands deposits. Hammer on the outcrop gives the scale (30 cms).

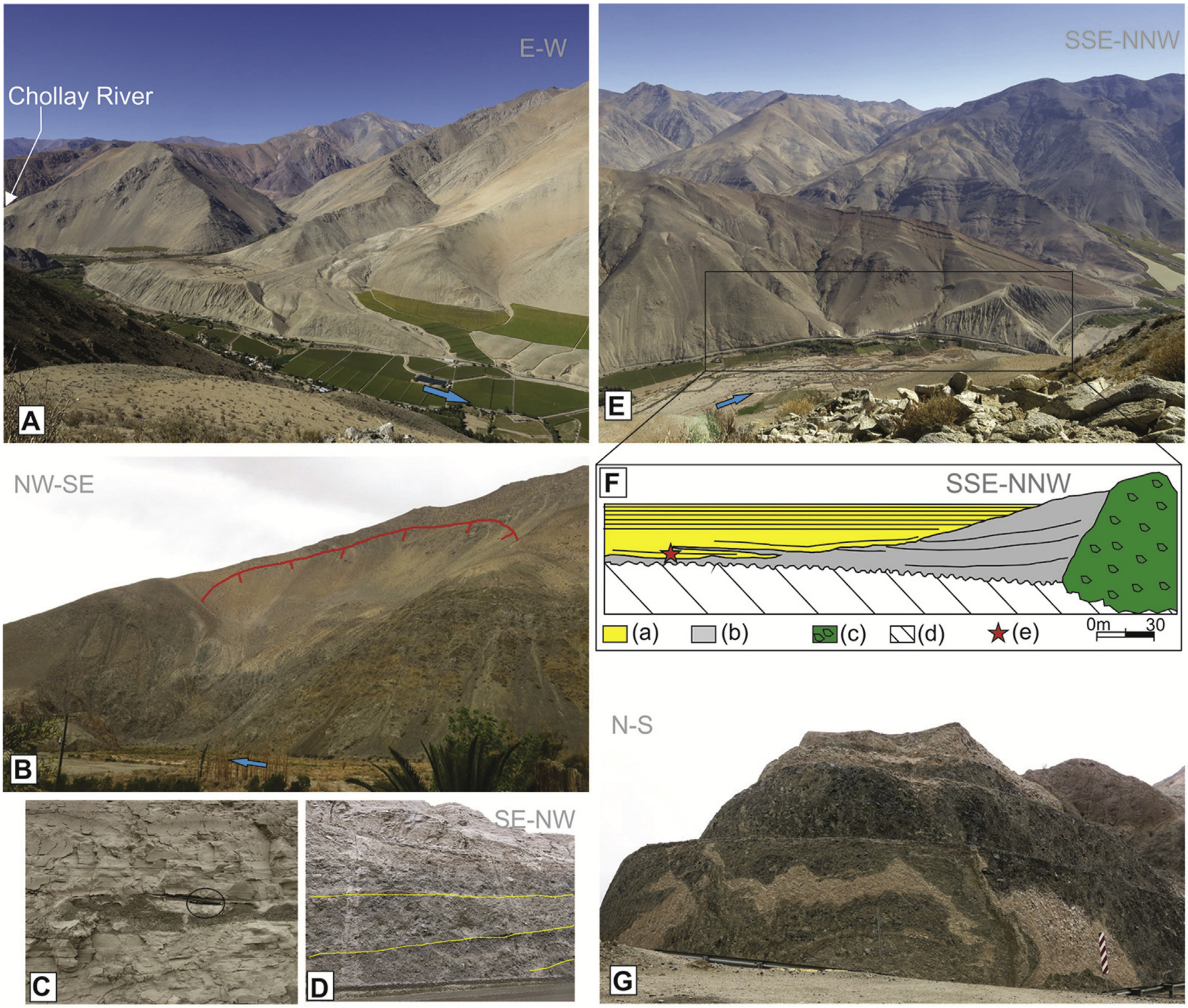

Fig. 5. General view of la Pampa landslide. A. La Pampa landslide. Arrow on the valley floor indicates flow direction. B. Scarp in the hillslope. C. Silty mud facies of lacustrine deposit with coarser gravel bodies. D. Reworked landslide facies upstream the dam with internal discontinuities. E. General view of la Pampa landslide. F. Scheme of stratigraphic relations between different units in la Pampa barrier deposit. Legend for this scheme is: (a) lacustrine facies; (b) reworked barrier facies; (c) barrier dam deposit; (d) bedrock; (e) ^{14}C 14210 years cal. B.P. G. Barrier dam deposit with dykes structures at bottom.

changes in aggradation-incision cycles. Riquelme et al. (2011) proposed that for El Turbio River, a river of the semiarid region of northern Chile south from the studied area presented here, during the Late Pleistocene-Holocene the valley infilling was controlled by the paraglacial response (in the sense of Slaymaker, 2011; Ballantyne, 2002). The fluvial evolution for the El Tránsito River begins with the assumption that after glacier retreat in the highest ranges of this basin, there is a sedimentary response given by a higher water discharge from the ice melting. The reworking of glacial drift sediments, in this case from the ones situated in Encierro Creek, tend to yield fine sediments, named glacigenic sediments, into the system (Ballantyne, 2002). These fine sediments are represented by silts, silty muds and muds in the stratigraphic arrangements studied downstream.

The paraglacial response in the El Tránsito River, which stills delivering sediment nowadays, is affected by the lateral sediment input (Fig. 6A, C). The distribution of the different geomorphological infill features and ^{14}C data for the El Tránsito River does not display a cascade effect due to a paraglacial response along its entire thalweg profile (Fig. 6C). The main sediment sources for the El Tránsito River infilling are associated with the sediment yielding by the tributaries, which build tributary-junction alluvial fans and construct alluvial terraces, landslide activity on the valley slopes and colluvial sediment present in the whole valley. The sediment input from the catchments into the trunk valley, with the alluvial fan building, finally controls the aggradation in the El Tránsito River valley (Fig. 6B). Thus, the distribution of tributary catchments displays non-uniform distribution of infilling features and ^{14}C ages show a diachronous infilling for this valley. Therefore, local dynamics in semiarid rivers in northern Chile play an important role which highlights the different sediment sources that contribute the aggradation of a semiarid river.

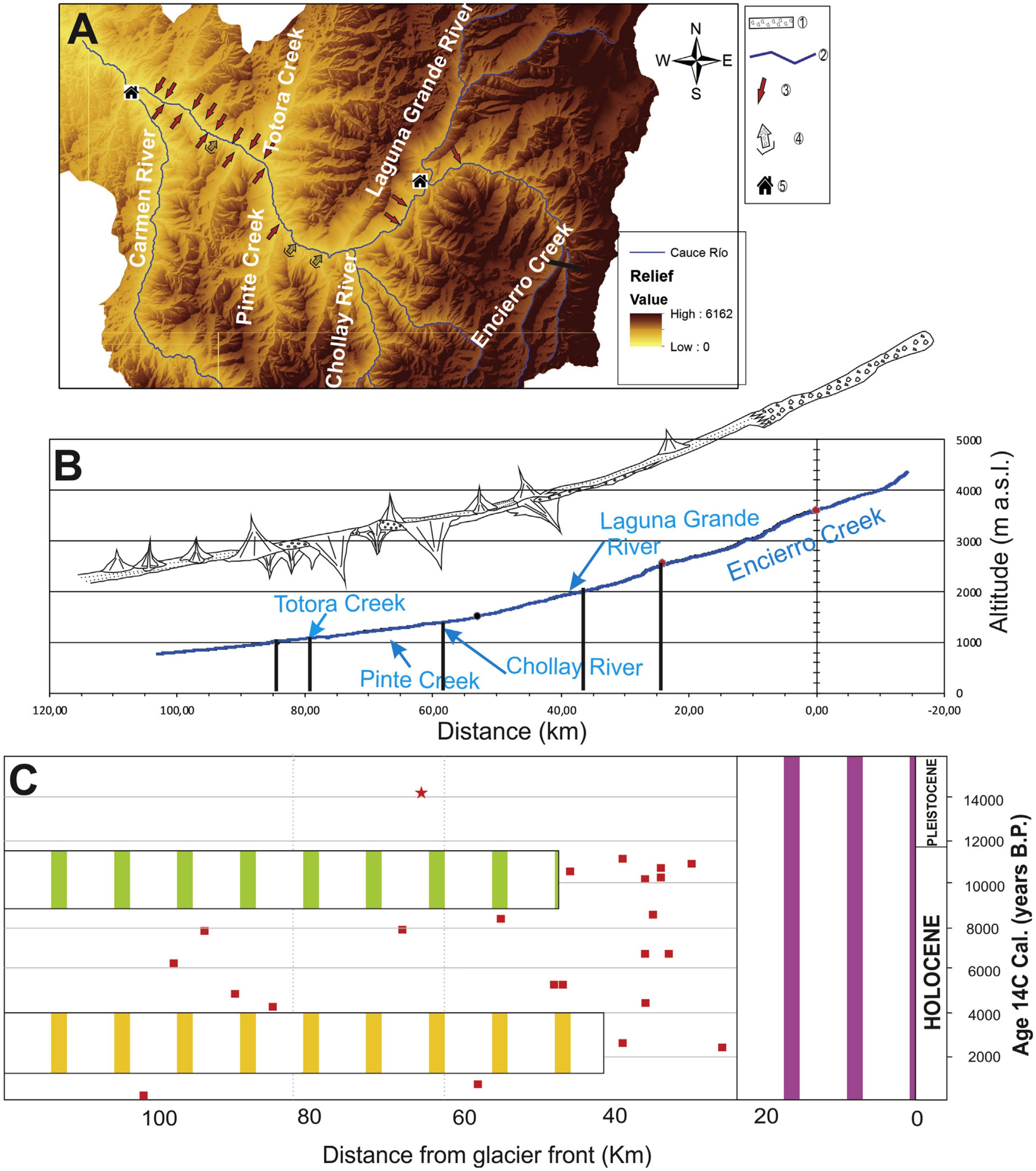

Fig. 6. Schematic figures for discussion. A. Schematic map of El Tránsito River Valley on a hillshade from a Digital Elevation Model. The legend shows: 1) Colluvial sediment storage on hillslopes, 2) Thalweg of El Tránsito River, 3) Tributary junction alluvial fans. 4) Landslides. 5) Main towns. B. Thalweg profile with the spatial relation of the deposits along the river in a schematic cross section. C. Radiocarbon data from Table 1 plotted versus distance from the glacier front (squares-samples in alluvial terraces/star-sample in lacustrine environment). Additionally, three rectangles with different stripe colors are described in the text.

5.1. *Geochronology of the fill evolution for the El Tránsito River valley*

At the end of glaciation, dated about 15,000 years B.P. (Aguilar, 2010; Zech et al., 2006), the fluvial system initiates the sediment yielding downstream according to the paraglacial response of Ballantyne (2002) and Church and Ryder (1972). The fine sediments yielded from the glaciated environment in El Encierro Creek were preserved in the early glacial retreat due a landslide barrier dated in 14,2ka (Fig. 6B). This dam enabled the preservation of the fine sediments in the early Holocene. Otherwise, the river may have transported these sediments downstream.

Dams constructed by rockslides in narrow valleys of semiarid mountainous river catchments in Chile are not triggered necessarily during wetter climate conditions, in line with what Antinao and Gosse (2009) proposed. The triggering mechanisms for these rockslides have been attributed, in active margins, to earthquakes (McPhillips et al., 2014). These are among the most important triggering mechanisms to produce rockslides (Abele, 1984; Antinao and Gosse, 2009; Keefer, 1984; Sepúlveda et al., 2010). Lithological controls, with the presence of active faults, lacking stability on steep slopes given by local geology, geomorphological processes and torrential drainage systems, are one of the most common mechanisms for landslide triggering. Many authors have focused on rockslide features in the Andean ranges (Paskoff, 1970; Deckart et al., 2014; Antinao and Gosse, 2009; Sepúlveda et al., 2010), but studies on the influence of river infilling during the Holocene remains scarce.

The alluvial terraces discriminated in El Tránsito River valley (Fig. SDF-2 to SDF-7) were mainly generated by stream capture. Three levels of terrace were identified in the confluence areas of tributaries. These geomorphological features, a result of the Holocene aggradation of the El Tránsito river and subsequent degradation, show three levels of incision in the segment between Encierro Creek and Laguna Grande River (Fig. 2C, E). See also Fig. 6B.

The ^{14}C ages sampled in alluvial terraces, presented in Table 1, indicate aggradation initiated at 11 ka cal. B.P. and end about 2 ka cal. B.P. (Fig. 6C). To understand why there is a diachronous infilling in the El Tránsito River valley, we should consider that the genesis of alluvial terraces goes together with tributary-junction alluvial fan-building. Hence, we should consider the agents that construct alluvial fans in the trunk valley. Topographical features of catchment areas are fundamental in alluvial fan development (Blair and McPherson, 2009; Stokes and Mather, 2015; Coe et al., 2008; Colombo, 2005). Colombo (2005) presents a model that shows how the sediment provided in the trunk valley dams the river and forms a temporary lake. This damming generates a local aggradation in the trunk valley where it is possible to develop wetlands upstream of the tributary-junction fans (Colombo et al., 2000: Colombo, 2005) (Fig. SDF-8). The activity in the tributary catchments is thought to be driven by rainstorms, which are associated to wetter phases during the Holocene due to the increased influence of the westerlies (Veit, 1996). In the late Holocene it could have been controlled by the activity of the El Niño Southern Oscillation (ENSO) (Vargas et al., 2006: Colombo, 2005 *and references therein*). The ENSO sedimentary record in the coastal ranges of the Atacama Desert present an increase in the second half of the Holocene (Vargas et al., 2006). These torrential rainfalls trigger debris flow and yield important amounts of sediment in the trunk valley. Nowadays, it is possible to note that the dammed stream formed temporary lakes upstream due to the March 2015 torrential rainstorm that triggered debris flows (Wilcox et al., 2016).

The catchment lithology and presence of colluvial sediments, in terms of sediment yield to the tributary-junction fans, plays an important role in sediment yielding (Blair and McPherson, 2009; Coe et al., 2008; Stokes and Mather, 2015). In the case of similar catchment areas, as seen within Pinte Creek-Totora Creek and the Totora Creek-Carmen River, differences in bedrock lithology make the difference in terms of sediment production (Fig. 1B). This controls the sediment that is transported downstream. Therefore, it suggests that segments with dominance of stratified rocks present higher supply rates. In consequence, large sediment volumes are yielded to the trunk valley (Stokes and Mather, 2015). This lithological control promoted the sediment yielding from the tributaries during the torrential rainfall event in March 2015 (Wilcox et al., 2016). Hence, alluvial fan development occurred at tributary catchments toe where the lithology corresponds to stratified Mesozoic rocks (Fig. 1A).

Moreover, the catchment area size defines whether the tributaries provide sediment to the main valley with alluvial fan development. Thereby, along the El Tránsito River valley we observe that in larger catchments there is no alluvial fan-building in the main valley (Fig. SDF-2, SFD-6, SFD-7, SDF-8, SDF-9, Fig. 6A). This suggests that once catchment areas get to a certain size, they have a greater potential to store sediment, suppressing tributary junction fan formation, although there is potential for generating larger flood discharges (Stokes and Mather, 2015). According to this statement, it supports the idea that paraglacial response sent the most of available sediments downstream in a short time (0.3–4 ka B.P.) after the 15 ka B.P. age for moraine formation at El Encierro Creek, and therefore that the Holocene record of aggradations in the El Tránsito River is not only controlled by a paraglacial response. Nevertheless, smaller tributary catchments play an important role with sediment yielding to the main valley. Their catchment area has not evolved and does not have much space to store sediment in the channels (Fig. 6A).

The thalweg profile shows a steepness break 60 km downstream the glacial front of Encierro Creek (Fig. 6B). This, allows us to interpret that the lack of early Holocene ages for the segment downstream this perturbation of thalweg is due to lower incision rates in relation to the high aggradations (green striped box from Fig. 6C). This also restricts the abandonment of the surfaces and leads the valley floor to fill. Finally, this aggradation does not enable us in our field sampling strategy to find the older carbon-rich layers (Fig. 6B, C). Upstream of the steepness break, higher incision occurs during the late Holocene enabling us to sample the lower boundaries of the Holocene. Thus, ages of ~11 ka are found in the upper segment of the El Tránsito River valley. Additionally, the late Holocene (ages <3 ka) are not represented in Fig. 6C inasmuch the ^{14}C sampling was not carried out in the actual floodplain of the El Tránsito River (yellow striped box from Fig. 6C).

6. Conclusions

We analysed the geomorphology and stratigraphy of a transect of 110 km along the semiarid valley of Chile to understand the large-scale dynamics of the fluvial system during the Holocene. The higher tributaries 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. Downstream from the glaciated area, the stratigraphic record shows that the valley infill results from a single aggradation cycle during the Holocene, and that the alluvial terraces result from the subsequent degradation. 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. On the other hand, the timing and the stratigraphic arrangement of the infills and the shape of the downstream alluvial terraces are longitudinally segmented, depending on the main geomorphological features and local controls such as sediment inputs from the catchments and rockslide-rock avalanche barriers. These alluvial fan-stream terraces are formed when a stream captures another stream with high base level. Thus, the captured stream suddenly has a new and lower base level and degradation of the floodplain occurs (Huggett, 2007). The genesis of these stratigraphic relationships has been described in Colombo et al. (2000) and Colombo (2005) in the eastern slope of

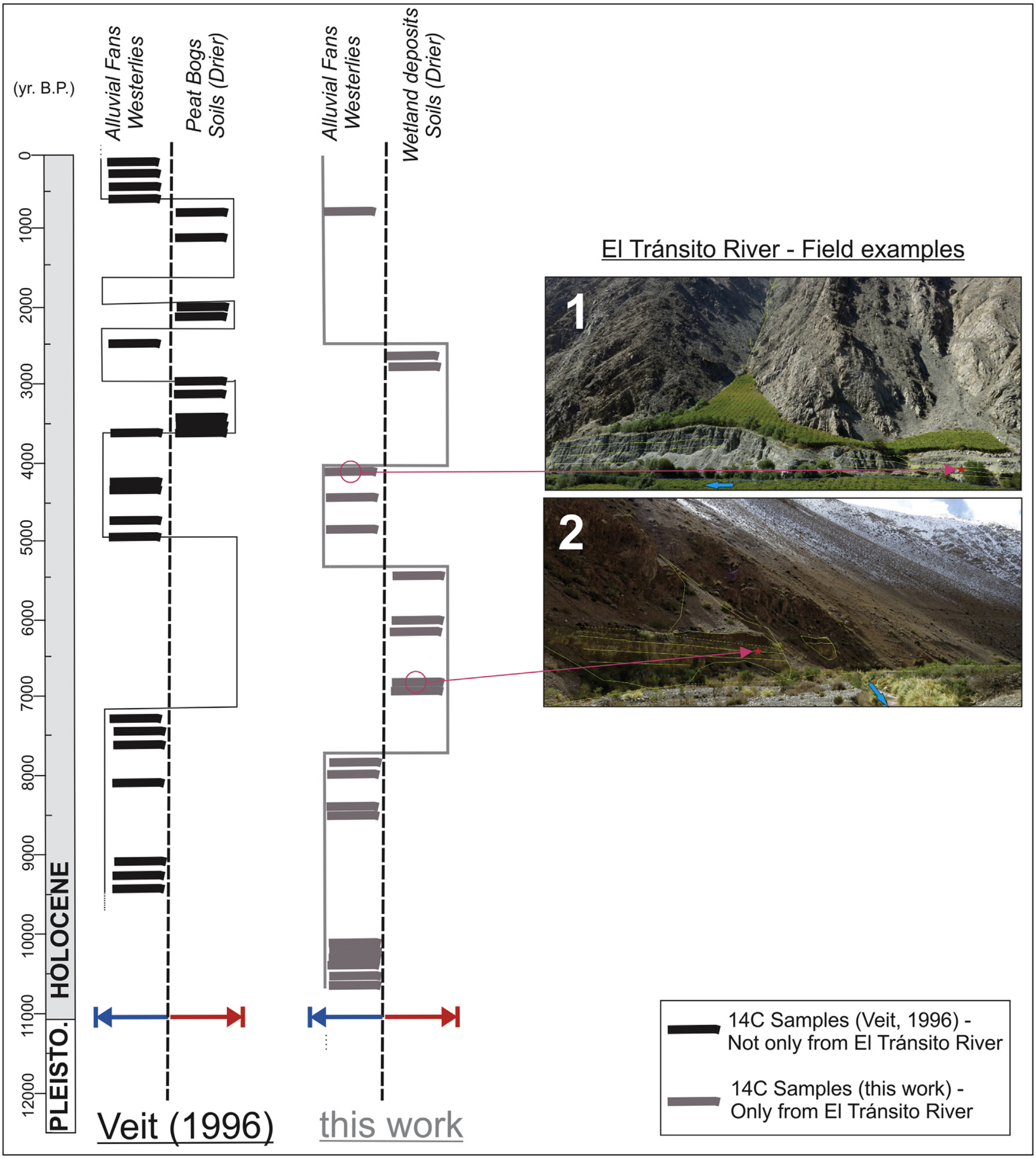

Fig. 7. Holocene changes on moisture from 14C data (this work and Veit, 1996). Blue arrow indicates wetter periods due to an increase of the westerlies influence and red arrow indicates drier periods with less sedimentation on the valley floor. 1) Clear case of sediments being accumulated by obstructions created in the middle portion of the valley segment studied. 2) Clear case of sediments being accumulated as a result of enhanced activity in the mainstream. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the Andean ranges.

This Holocene aggradation cycle is not fully explained by a paraglacial readjustment of glacigenic sediments from the glacial segment due a shift to wetter conditions, which could have enhanced the paraglacial response (Fig. 7). Riquelme et al. (2011) consider climate as a forcing factor that controls the evolution of a fluvial system in the semiarid region of the Andean ranges but this paleoclimatic interpretation should consider that during the

Holocene, the effect on the westerlies (Veit, 1996) promoted tributary catchments sediment delivery (Fig. 7). Hence, shallow seismicity, with the proper geology, could have dammed the fine sediments from the early Holocene during the warmer phases that had promoted the glacial retreatment.

The distribution of tributary catchments agrees with the non-uniform distribution of infilling features and ^{14}C ages (Fig. 6A, B). Thus, the interpretation of 14C ages needs to be in a geomorphic and stratigraphic framework (Fig. 7). Finally, the diachronous infilling for the El Tránsito River valley highlights that: slope dynamics, tributary catchments characteristics present in semiarid rivers in northern Chile and landslide activity should be taken into account when using river stratigraphy for paleoclimatological studies.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2017.04.030.

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