Palaeo-geoecological significance of Pleistocene trees in the Lluta Valley, Atacama Desert

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Abstract

In the Lluta Valley, northern Chile, climate is hyperarid and vegetation is restricted to the valley floors and lowermost footslopes. Fossil tree trunks and leaves of predominantly *Escallonia angustifolia*, however, are abundant up to ~15 m above the present valley floor, where they are intercalated with slope deposits, reflecting higher water levels in the past. A total of 17 samples have been radiocarbon dated, yielding ages between 38 and 15k cal a BP. The youngest ages of 15.4k cal a BP are interpreted as reflecting the beginning of river incision and lowering of the valley floor, impeding the further growth of trees at higher parts of the slopes. The most plausible scenario for this observation is intensified river incision after 15.4k cal a BP due to increased stream power and runoff from the Rio Lluta headwaters in the Western Cordillera and Altiplano corresponding to the highstand of the Tauca and CAPE wet phase.

KEYWORDS: Atacama desert; climate change; fluvial dynamics; late Pleistocene; northern Chile.

Introduction

The Atacama Desert in northern Chile is one of the driest deserts on earth. Rainfall along the coast between Arica and Iquique is ~1 mm a^{-1} (Schulz *et al.*, 2011). Cosmogenic ^{21}Ne exposure dates on surfaces in Quebrada Tiliviche near Pisagua (19°35′S) indicate the onset of extreme hyper-aridity probably as early as 25–22 Ma (Dunai *et al.*, 2005). Hyperarid conditions might have persisted through most of the Neogene as the Andes reached their current elevation around 15 Ma, creating the pronounced rain-shadow effect still in place today (Alpers and Brimhall, 1988; Houston and Hartley, 2003), even though ages around 10 Ma have also been proposed (Jordan *et al.*, 2014). As a consequence, the landscape in the Atacama Desert is characterized by very smooth slopes and interfluves which do not sustain noteworthy plant growth, and are characterized by extremely low erosion rates (Kober *et al.*, 2007). In contrast, the main rivers in northern Chile, such as the Río Lluta, reach the Pacific via canyon-like valleys (Figs 1 and 2a). Downcutting via headward migration of erosional fronts (i.e. knickzones) probably commenced at ~8–11 Ma in response to surface uplift (García and Hérail, 2005; Schlunegger *et al.*, 2006; Schildgen *et al.*, 2007, 2010; Thouret *et al.*, 2007; García *et al.*, 2011), and had lowered the valley floor to near-modern elevations by ~2.7 Ma in proximity to the Pacific coast, as evidenced by the Lauca Ignimbrite deposits (Schröder and Wörner, 1996; Uhlig, 1999; Schlunegger *et al.*, 2006; García *et al.*, 2011). This implies relative long-term stability of the valley floor elevation along the graded river reach beneath the knickzone (Fig. 1e), and dominant sediment bypass in wide braided river channels and floodplains. In this setting, vegetation is restricted to the lowermost footslopes and marginal valley floors, representing modern ‘treelines’ (Fig. 2a). Fossil tree trunks and leaves, however, are abundant up to ~15–20 m above the present valley floor of the Lluta Valley in northern Chile, where they are intercalated with slope deposits, suggesting past changes in water availability and humidity. Therefore, these deposits may provide new information on changes in discharge and/or sediment supplies over late Quaternary timescales. Here we present a comprehensive radiocarbon-based chronology for these stratified slope deposits in the Lluta Valley, consider potential mechanisms of their formation, and discuss their palaeoclimatic and tectonic significance.

Study area

Geologically, northern Chile is characterized (from west to east) by a Coastal Cordillera, Central Depression, Precordillera and the Western Cordillera (Fig. 1b). Directly north of Arica, the Coastal Cordillera is completely absent, whereas south of Arica it is characterized by a steep escarpment and up to 1000-m-high cliffs, deeply incised by some of the major rivers in northern Chile (Fig. 1b,c). With their headwaters in the Western Cordillera of the Andes, these rivers reach the Pacific via canyon-like valleys such as the Quebrada de Camarones, Quebrada de Vitor, Quebrada de Azapa or the Valle de Lluta which have incised up to 1000 m into the surrounding Tertiary pediments and peneplains of the Precordillera and Central Depression (Fig. 1). Further south, between ~19°30′S and 26°30′S, most rivers are endorheic and terminate in the hyperarid Atacama Desert. Climatic conditions in northern Chile and the Atacama region are generally hyperarid, and are characterized by a strong meridional gradient in annual precipitation with 0.4 mm at the coast to 237 mm at Putre (3650 m a.s.l.) and values of >350 mm in the highest parts of the catchment (DGA, 2004). The region's hyperaridity owes its existence to a combination of: (i) the extreme rainshadow effect of the high Andes, blocking advection of tropical/subtropical moisture from the east; (ii) limited influence of winter storm tracks from the south due to the presence of the semi-permanent South Pacific Anticyclone; and (iii) the generation of a temperature inversion at ~1000 m by the cold, north-flowing Humboldt Current that limits the inland (upslope) penetration of Pacific moisture. Precipitation variability in both summer and winter is modulated primarily by Pacific sea surface temperature gradients and the associated upper-air circulation anomalies (Vuille *et al.*, 2000; Garreaud *et al.*, 2003). A significant fraction of the inter-annual variability of summer precipitation is currently related to the El Niño Southern Oscillation (Vuille, 1999). Thus, wet summers on the Andean Altiplano are associated with an El Niño Southern Oscillation-related cooling of the tropical Pacific (i.e. La Niña phase). Rainfall and discharge maxima occur mainly during the 'Invierno Boliviano' (December–March; DGA, 2004; Houston, 2006) in relation to the South American Summer Monsoon system (Lenters and Cook, 1997; Schulz *et al.*, 2011), which transports moisture from the Amazon lowlands over the Andes down to ~2800 m a.s.l. on the western Andean slopes, but does not cause significant rainfall in the central Atacama (Rech *et al.*, 2006).

The catchment of the Río Lluta comprises an area of ~3400 km^2, with a river length of approximately 150 km (Fig. 1c). The highest peaks in the upper catchment are the 'Nevados de Putre' (5861 m a.s.l), 'Volcán Tacora' (5988 m a.s.l.) and 'Volcán Tarapacá' (5860 m a.s.l.). The Lluta River originates in the Western Cordillera at an altitude of about 3900 m a.s.l. and reaches the Pacific Ocean ~4 km north of Arica at 18°24′55″S, 70°19′35″W (Fig. 1c). Whereas a pediplain developed on top of the Coastal Cordillera during the Paleogene ('Tarapacá Pediplain'; Mortimer and Sarič, 1975), river incision in northern Chile commenced at ~8–11 Ma in response to surface uplift (García and Hérail, 2005; Schildgen *et al.*, 2007, 2010; Thouret *et al.*, 2007; García *et al.*, 2011). In the Lluta Valley incision had lowered the valley floor nearly to modern elevations by 2.7 Ma, as evidenced by the Lauca Ignimbrite deposits (Schröder and Wörner, 1996; Uhlig, 1999; García *et al.*, 2011). Today, the Lluta Valley long-profile exhibits a ~30- km-long, steep and narrow knickzone of mixed bedrock–alluvial channel morphology, which divides the Lluta River into an upstream and downstream segment of wider valley floors (Fig. 1e). Beneath the knickzone, the valley floor is up to 1200 m wide, encompassing a gravelly braided river channel and variably wide floodplains. Only very few remnants of older terraces are visible, but they have not been studied up to now and their age and genesis are unknown. Today, the floodplain is subject to intensive irrigation and agricultural use (Fig. 2a). The Lluta River has incised 1–3 m into this valley bottom, which seems to have been the active floodplain for most of the Holocene. Apart from agriculture, *Escallonia angustifolia* and *Schinus molle* are the dominating trees of the riparian plant communities near the current valley floor. *Schinus molle* can live from groundwater, with root systems of 10–20 m in length, whereas *Escallonia angustifolia* needs surficial running water and humidity. Surface discharge along the Rio Lluta is highly seasonal and can reach mean monthly flows of ~16 $m^3 s^{-1}$ in February at the Pacific coast (DGA, 2004), and sediment loads up to 1700 tonnes per day have been measured during peak flow episodes (Campos Ortega *et al.*, 2007). The annual distribution of discharge is strongly controlled by precipitation in the Andean headwaters of the Lluta River in the Western Cordillera (Fig. 1c), which is mainly built up by volcanic and sedimentary sequences (García *et al.*, 2011). In the Central Depression and the Precordillera, the geology is characterized by Oligo-Miocene sediments and ignimbrites (Azapa, Oxaya, El Diablo and Huaylas formations, Tobar *et al.*, 1968; Seyfried *et al.*, 1995; Uhlig, 1999; García *et al.*, 2011). Uplift of the Precordillera has induced major landslides, and parts of the Oxaya Formation collapsed >2.5 Myr ago building up the large Lluta Collapse deposit (Seyfried *et al.*, 1998; Wörner *et al.*, 2002; Strasser and Schlunegger, 2005; García *et al.*, 2011). All profiles presented here are situated in the area of the Lluta Collapse (Fig. 1c,d), east of Poconchile and along Chile's National Road 11 (18°27′6″S, 70°4′1″W; ±750 m a.s.l.). Along this segment of the valley, profiles can be studied easily along road cuts. However, the fossil trunks and leaves exist in a far broader area, from the coast and the mouth of the Lluta River up to > 1000 m a.s.l. along the valley floor. Further upstream of our study area the main road soon leaves the valley and crosses to the southern Azapa Valley. The smaller road which continues in the Lluta catchment runs on the present valley floor. We concentrated our investigation on the easily accessible part with open profiles.

Methods

Fieldwork consisted of detailed investigation of road cut exposures in the lower slopes along the southern side of the Lluta Valley east of Poconchile (Fig. 1c,d). An exhaustive sampling campaign was conducted on the organic horizons situated at 30–50 km from the coast (Figs 2–4). As the up to 50-cm-thick leaf deposits could be identified as almost completely consisting of leaves of *Escallonia angustifolia*, no further in-depth study of the palaeovegetation was undertaken. Trunks, which are completely imbedded within the leaf deposits, were not identified botanically. Profiles of these slope sedimentary sequences were described in the field. Profile location as well as an approximate elevation were documented with a hand-held GPS. Organic layers, mostly leaves and trunks, were stratigraphically sampled at five locations for ^{14}C dating (Profiles km 36.2, km 36.5, km 37.0, km 37.5 and km 37.7; Table 1; ten samples), and were analysed at the radiocarbon laboratory of the Institute of Physics at the University of Bern. To check for spatial validity and chronological accuracy of these results, a set of additional samples was collected from exposures situated in a wider area (Profiles LVW-1, LVW-2, LVW-3, LVW-4, LVW-5, LVW-6 and LVW-7; Table 2; seven samples) and analysed with the accelerator mass spectrometer MICADAS at the LARA laboratory at the University of Bern (Szidat *et al*., 2014). All results were calibrated with CALIB version 7.0 (Stuiver and Reimer, 1993, 2011) and the SHcal13 calibration curve (Hogg *et al.*, 2013). These dates are referred to as 'cal a BP' or 'k cal a BP'.

Results

The slopes along the Lluta Valley are very smooth and undissected without any sign of linear erosion (Fig. 2a). In the hyperarid setting of northern Chile, these slopes are the combined product of the slow salt- and gravity-related surficial displacement of material (salt-creep), granular flows, and the lack of linear fluvial erosion (Mortensen, 1927; Abele, 1987, 1990). These hillslope deposits are made up of well-sorted, horizontally stratified and cross-bedded sandy and coarser detritus, lacking a sedimentary matrix, with a thickening of the layers downslope. Stratification is on the order of millimetres, dipping parallel to the surface. These slope sediments are frequently intercalated with layers of fossil organic material such as trunks and leaves (Figs 2b–d and 3). Trunks and branches do not show signs of transport and are well preserved (Figs 2d and 3d). Therefore, they are more or less in an *in situ* position. It is particularly in the surroundings of Poconchile where this organic material is nicely recognizable along road cuts. In one case the slope sediments have buried the Ah-horizon of a palaeosol (Fig. 2e). The fossil organic material reaches up to ~9 m above the present distribution of living trees at the intersection of the modern valley floor and slopes (Fig. 3a), which is generally up to 11–15 m (exception: profile LVW-2 at 17.9 m and Profile LVW-7 at 20.3 m) above the valley bottom. Further upslope, no trunks or leaves have been found. Most documented profiles contain several layers of organic material, reflecting an alternation of tree growth and sedimentation (Figs 2 and 4). All radiocarbon ages from these organic layers and a bAh horizon are summarized in Tables 1 and 2. The profiles documented in the photographs (Fig. 2) and sketches (Fig. 4) can be characterized as follows:

- At km 36.2 (Figs 2c and 4), leaves from a single organic layer at ~80 cm in the profile are dated to 23.9 ± 0.1k cal a BP.
- The profile at km 36.5 (Figs 2b and 4) shows at least five organic layers and a layer of whitish volcanic ash. A wood fragment from the lowermost exposed organic layer at 250 cm below the surface yielded an age of 37.1 ± 0.4k cal a BP. Two samples from leaf-dominated layers at 120 and 50 cm have ages of 28.9 ± 0.1 and 18.3 ± 0.1k cal a BP, respectively. The uppermost 30 cm of the profile contains reeds, faecal pellets and abundant ceramics. The reed sample was dated to 0.5 ± 0.01k cal a BP (~AD 1406–1439), thus reflecting the locally strong influence of pre-Colombian cultures in the Lluta Valley.
- At km 37.0 (Figs 2d and 4), a thick leaf deposit at a depth of 80 cm is dated to 19.4 ± 0.1k cal a BP. Wood from the same layer yielded an age of 19.5 ± 0.1k cal a BP.
- At km 37.5 (Fig. 4) leaves at a depth of 100–120 cm below the surface are dated to 15.6 ± 0.1k cal a BP.
- At km 37.7 (Figs 2e and 4), the profile consists of a volcanic ash layer and an organic layer at the bottom intercalated with stratified slope deposits. Approximately 110 cm below the surface, a dark, greyish palaeosol (bAh-horizon) indicates a period of relative surface stability at 15.4 ± 0.4k cal a BP. It is directly overlain by leaves with an age of 16.1 ± 0.1k cal a BP. Both the palaeosol horizon and the leaf layer are truncated by the palaeochannel of a gully or small creek. The palaeochannel is filled by stratified slope deposits without organic layers and is no longer visible at the surface.

In summary, all dated wood and leaf samples belong stratigraphically to the Upper Pleistocene between ~15 and 38k cal a BP. In all profiles, the lowermost layers are the oldest ones, becoming younger towards the surface. ^{14}C ages from leaves and wood from the same layer are in good accordance with this. No age inversions between layers occur. The results from ^{14}C dating of seven additional samples (Table 2), which were processed using two different methodologies, are internally consistent, and range between ~16 and 35k cal a BP. Hence, they corroborate the chronological results obtained from the other profiles.

Discussion

The modern upper limit of living trees (‘treeline’, Figs 3a and 5) is characterized by a zone of non-climatic struggle between valley floor vegetation that depends on the presence of perennial surficial water and groundwater in the Rio Lluta floodplain deposits, and the vegetation-bare hillslopes with extreme aridity and active gravitational processes, mainly surficial creep, induced by wetting and drying of salt (Abele, 1987, 1990). This seems to be the present-day process, reflecting the dry environmental conditions on the slopes. Small gullies, as in profile km 37.7 (Fig. 2e), may have formed in a very short period, indicating linear erosion on the slope after 16.1–15.4k cal a BP. They are filled with stratified slope deposits, which formed under dry conditions, comparable to those of today. Thus, in the marginal floodplain and on the lowermost slopes, accumulating organic matter, leaves and wood debris are successively covered by sediments of salt-creep, ultimately forming stratified deposits of alternating organic material and slope debris. The distribution of these deposits including the fossil trees and leaves is restricted to the lowermost slopes ~15–20 m above the modern floodplain in relative proximity to the modern treeline, indicating that the presence of fossilized vegetation remains does not reflect wetter climatic conditions at a local scale and extensively vegetated hillslopes, for example as the result from substantially increased precipitation. A wider distribution of organic material and related palaeosols could be expected if more humid climatic conditions had prevailed at low elevations in the Atacama Desert, but has not been observed in the numerous hillslope quarries. In combination with the clear dominance of tree taxa in the organic layers, and the lack of hillslope taxa in the fossil record, this implies a higher palaeo-'treeline' (treeline A, Figs 3a and 5). In our profiles, the available radiocarbon dates from organic remains within the stratified slope deposits range between ~38 and 15.4k cal a BP and thus reflect tree growth up to ~9 m above the modern 'treeline' for this timeframe. In contrast, the youngest and stratigraphically uppermost organic layers consistently date to ~15.4k cal a BP, and no younger radiocarbon ages are available. Based on our model of quasi-continuous formation of stratified slope deposits along the marginal floodplain, this suggests a ~9-m downslope shift of the 'treeline' (from treeline A to B, Fig. 5) after ~15.4k cal a BP in relation to a major drop of the valley floor at that time.

Several scenarios could explain this drop on the order of ~ 9 m at our study site along the Rio Lluta: (i) the re-organization of the valley floor and river long-profile as the result of tectonics, (ii) the influence of global sea-level oscillations through the last glacial cycle, (iii) blocking of the valley by mass wasting (landslides, alluvial fans from tributaries, etc.) or dunes, (iv) reduced runoff and/or groundwater recharge in the Rio Lluta catchment due to drier climatic conditions in the Western Cordillera of the Andes, or − vice versa − (v) river incision induced by intensified runoff from the Western Cordillera and increased stream power.

Neotectonic activity is common throughout the Andean forearc and the Coastal Cordillera, even though the exact mechanisms and magnitudes of deformation related to stress accumulation and release during the seismic cycle are not yet fully understood (Allmendinger and González, 2010; A. Madella *et al.*, unpubl. data). Marine terraces dating to 140 ka are found up to 250 m a.s.l. in northen Chile and up to 300 m a.s.l. in southern Peru (Regard *et al.*, 2010), indicating variable uplift rates of up to 2.1 m ka^{-1}. In the area immediately north of Arica at the mouth of the Rio Lluta, however, the Coastal Cordillera is absent (Fig. 1a). In contrast, the broad Rio Lluta–Tacna plain seems to indicate relative subsidence rather than uplift. However, the discovery of ca. 10 ka raised fluvial terraces directly at the mouth of the Rio Lluta does suggest the occurrence of uplift, at least at the coast (A. Madella *et al.*, unpubl. data). Nevertheless, this uplift is unlikely to explain the 9-m lowering of groundwater table in the study reach because it occurred ca. 5000 years later. In addition, the study area is characterized by the lack of active structures (A. Madella *et al.*, unpubl. data), which implies that the smooth slopes and related deposits that embed the fossil wood are not affected by any tectonic deformation. This observation indicates that a tectonic disturbance alone could not be the major control for the onset of incision in this area.

During the Last Glacial Maximum (LGM), global sea level was ca. 125–135 m lower than today (Sidall *et al.*, 2006; Lambeck *et al*., 2014). Today, the valley floor at our study site is ~750 m a.s.l. and up to 30–50 km inland from the coastline. The gradient at Poconchile is ~25 m km^{-1} and gradually decreases to ~15 m km^{-1} along the coast. During the LGM sea-level lowstand, the coastline would have been ~20 km west of the modern coastline (Becker *et al*., 2009), indicating even lower gradients of around ~6 m km^{-1}. Additionally, sea level approached the LGM lowstand gradually over the last glacial cycle, in combination probably limiting the potential for significant upstream migration of a knickpoint. In contrast, the postglacial rise of global sea level was rapid between ~20 and 8 ka with a particularly rapid increase around 15 ka (Lambeck *et al*., 2014). As a consequence, upstream valley floor aggradation and a tendency of increasing water levels would be expected. However, our results clearly indicate a decrease in water levels and/or valley floor elevations, suggesting that sea-level changes were probably not a major control on the observed drop in treeline after 15k cal a BP, particularly considering that our study site is located at altitudes >750 m a.s.l. The same holds true for a possible incursion of salinized groundwater and a corresponding lethal effect on the vegetation, following sea-level rise. This scenario cannot explain dying trees at >750 m a.s.l.

Landslides or alluvial input from tributary rivers might have caused local blocking of the Lluta River. So far, no age control on visible landslides in the valley is available. Because fossil trunks and leaves exist from the coast, a few metres above sea level to far into the catchment up to >1000 m a.s.l., and due to the complete lack of limnic sediments indicating former lake conditions, this catastrophic explanation does not seem realistic. Additionally, the vertical sequence of ^{14}C ages in the profiles would have to be interpreted as several blocking periods, with each (younger) one resulting in higher lake levels, which also has no indication in the sediments.

Pleistocene dunes might have blocked the Lluta River during periods of low sea level such as the LGM. The rising sea level after 15 ka might have hindered new dune formation, allowing the Lluta River to incise into the valley bottom. However, as no major dune system has yet been be identified and datings are not available, these considerations are speculative. In addition and similar to the potential effect of landslide blocking, the dated profiles are situated at an altitude of >750 m a.s.l., where a direct effect of blocking dunes in the lower part of the valley does not seem to be very likely.

The temporal coincidence between a well-known wet phase on the Altiplano and the initiation of valley lowering along the Rio Lluta suggests an environmental driver. In this context, some authors report wet LGM conditions in the Western Cordillera/Altiplano (e.g. Baker *et al*., 2001a,b; Bobs *et al.*, 2001; Rigsby *et al.*, 2005; Steffen *et al.*, 2009). In turn, a drop in treeline after ~15.4k cal a BP would consequently point to drier conditions. Most published proxies, however, point to wet climatic conditions on the Bolivian Altiplano, commonly referred to as the ‘Tauca Period’ (Servant and Fontes, 1978). Palaeolake Tauca was a freshwater lake, indicating enhanced precipitation between 18.1 and 14.1k cal a BP, with highest lake levels from 16.4 to 14.1k cal a BP (Servant and Fontes, 1978; Sylvestre *et al.*, 1999; Placzek *et al*., 2006, 2013). Lake levels dropped after 14.1k cal a BP with a minor, secondary highstand during the minor Coipasa phase, between 13 and 11k cal a BP (Placzek *et al.*, 2006). Nester *et al.* (2007) and Gayo *et al.* (2012) report perennial stream discharge in the endorheic basins of the Atacama (Pampa del Tamarugal, 19°30′ to 22°S) between 16.4 and 13.7k cal a BP and consider this the most important groundwater recharge event of the past 18 ka. It might appear as a contradiction that the alluvial fans in the Pampa del Tamarugal reacted with aggradation, whereas the Río Lluta eroded and incised at the same time. However, this can be easily explained by the different geomorphological systems; the fans in the endorheic basins of the Atacama are generally inactive during dry periods. There, increased precipitation leads to erosion in the catchment and corresponding accumulation on the fans. In a perennial river system with a much larger catchment area like the Río Lluta, it depends on the balance between water energy and material transported to react with accumulation or incision. After 15.4k cal a BP, there was probably a more consistent and/or elevated discharge available to allow for incision. At the Río Salado catchment (22°S), rodent middens from 3000 m a.s.l. have been interpreted as a two-fold precipitation increase at 17.5–16.3k cal a BP (Latorre *et al.*, 2006). A number of palaeowetland deposits additionally point to a major wet phase between >15 and 9k cal a BP (Betancourt *et al.*, 2000; Latorre *et al*., 2002, 2003; Rech *et al*., 2002, 2003; Quade *et al*., 2008). The regional climatic pattern reflected in all these records has been summarized as the ‘Central Andean Pluvial Event’ (‘CAPE’; Quade *et al.*, 2008). The onset of the CAPE (ca. 18k cal a BP) occurred 2000–2500 years before the lowering of the valley floor in the Lluta valley (15.4k cal a BP), as reflected in the youngest ages of the fossil leaves and trunks, but coincides well with the highstand of Lake Tauca and the wet period in the Pampa del Tamarugal at about 16.4–14k cal a BP. It is unlikely that fluvial incision at our study sites started at exactly the time when precipitation started to increase on the Altiplano. Instead, environmental changes in the catchment are progressively propagated through the fluvial system. This leads to a time lag (i.e. response time) which varies from catchment to catchment (compare e.g. Romans *et al*., 2016) and was probably ~2000 years in duration after the onset of the CAPE in the Lluta Valley. Glacial ice modelling and dating of glacial advances also indicate rainfall increases of up to 100% in the Central Andes during the Tauca period (Kull *et al.*, 2002, 2008; Zech *et al*., 2007, 2008, 2010). In contrast, the preceding period before and around the LGM (44–17 ka) was probably cold and dry in this area, as inferred from the small number of middens and the widespread lack of wetland deposits of this age, and palaeobotanical studies on fossil plants contained in them (Latorre *et al*., 2002; Quade *et al.*, 2008).

In summary, the most plausible scenario for a ~9-m drop in treeline is river incision and lowering of the valley floor after 15.4k cal a BP due to increased stream power and runoff from the Rio Lluta headwaters in the Western Cordillera and Altiplano, and corresponding to the highstand of the CAPE and Tauca wet phase.

Conclusions

Along the large valley systems in the hyperarid Atacama Desert of northern Chile, vegetation is markedly restricted to the floodplains and valley floors. As such, the treeline is non-climatic and is only indirectly controlled by precipitation via groundwater availability and humidity at the valley floor. Despite the notion of long-term climatic stability along the lower reaches of the Lluta River, the observation of fossil tree remains, leaves and organic material intercalated with slope deposits significantly above the modern treeline indicates a drop in treeline elevation. Our radiocarbon-based chronology for these organic deposits suggests that this drop occurred at ~15.4k cal a BP, and was probably related to ~9 m of incision triggered by a pulse of increased discharge during the CAPE, which was characterized by significantly increased tropical moisture and precipitation totals in much of the Central Andes.

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Abbreviations. CAPE, Central Andean Pluvial Event; LGM, Last Glacial Maximum.

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Figure 1. Study area. (a) Overview; (b) northern Chile with morphotectonical units; (c) Lluta Valley with location of the study area; (d) location of studied profiles; (e) longitudinal profile of the Río Lluta. Triangle in (c) marks the location of dated wood at the coast, according to A. Madella (pers. comm.).

Figure 2. Field impressions from the Lluta Valley. (a) Overview, agriculture on the valley floor and dry slopes; (b–d) stratified slope deposits with intercalated wood and leaves; (e) gully, filled with slope deposits and older, buried organic soil horizons (note: green triangles mark organic layers with fossil trees, logs and leaves; white triangle marks volcanic ash).

Figure 3. Field impressions from the Lluta Valley. (a) Overview with palaeo-‘treeline’; (b) organic layers in surface parallel position; (c) detail of leaf deposit; (d) leaves of dominating *Escallonia angustifolia*.

Figure 4. Sketch of profiles with ^{14}C dates. All dates are given as k cal a BP (Table 1).

Figure 5. Sketch, showing the evolution of the slopes and the valley bottom, the incision of the Río Lluta and the changes in ‘treeline’ due to lowering of the valley bottom.

Table 1. ^{14}C results from samples VEC 06/.

Sample name	Latitude	Longitude	Profile	Height	Depth	Material	Lab code	$\delta^{13}C$ (‰)	^{14}C age (a BP)	Age (cal a BP)	Age (k cal a BP)

	(°S)	(°W)		above valley floor (m)	(cm)													
VEC 06/35	−18.40221	−70.01646	36.2	12	80	Leaves	B-9016	−25.0	±	0.2	19 870	±	70	23 746	23 993	23.9	±	0.1
VEC 06/39	−18.40357	−70.01371	36.5	11.5	15	Reed	B-9012	−10.2	±	0.2	510	±	20	503	520	0.5	±	0.0
VEC 06/36	−18.40357	−70.01371	36.5	11.5	50	Leaves	B-9013	−23.6	±	0.2	15 120	±	90	18 192	18 459	18.3	±	0.1
VEC 06/37B	−18.40357	−70.01371	36.5	11.5	120	Leaves	B-9014	−23.2	±	0.2	24 900	±	100	28 732	29 001	28.9	±	0.1
VEC 06/38	−18.40357	−70.01371	36.5	11.5	250	Wood	B-9015	−24.4	±	0.2	33 090	±	180	36 733	37 514	37.1	±	0.4
VEC 06/34A	−18.40553	−70.00944	37.0	12.5	80	Leaves	B-9010	−23.4	±	0.2	16 120	±	60	19 298	19 511	19.4	±	0.1
VEC 06/34B	−18.40553	−70.00944	37.0	12.5	80	Wood	B-9011	−20.7	±	0.2	16 180	±	60	19 378	19 583	19.5	±	0.1
VEC 06/33	−18.40787	−70.00493	37.5	13.5	110	Leaves	B-9009	−24.2	±	0.2	13 080	±	70	15 457	15 757	15.6	±	0.2
VEC 06/30	−18.40865	−70.00325	37.7	13.5	115	TOC fAh	B-9007	−21.1	±	0.2	12 930	±	220	15 073	15 782	15.4	±	0.4
VEC 06/32	−18.40865	−70.00325	37.7	14	110	Leaves	B-9008	−23.4	±	0.2	13 420	±	80	15 973	16 226	16.1	±	0.1

Table 2. ^{14}C results from samples LVW-, presented with 95% confidence limits.

Sample name	Latitude (°S)	Longitude (°W)	Height above valley floor (m)	Depth (cm)	Material	Lab code	$\delta^{13}C$ (‰)	^{14}C age (a BP)			Age (cal a BP)		Age (k cal a BP)		
LVW-1	−18.45164	−70.05891	8.3	30	Wood	BE-1754.1.1	−18.5	30 593	±	140	34 300	34 897	35	±	0.3
						BE-1754.1.2	−19.8	30 842	±	178					
						BE-1754.2.1*	−20.5	30 936	±	285					
LVW-2	−18.40407	−70.03452	17.9	10	Wood	BE-1755.2.1*	−19.0	13 826	±	212	16 094	17 330	16.7	±	0.6
LVW-3	−18.40036	−70.02080	14.5	20	Wood	BE-1756.1.1	−20.1	18 641	±	41	21 999	22 588	22	±	0.3
						BE-1756.1.2	−18.9	18 415	±	51					
						BE-1756.2.1*	−22.5	18 891	±	216					
LVW-4	−18.40273	−70.01611	11.6	60	Wood	BE-1757.1.1	−19.7	25 547	±	81	29 294	29 842	30	±	0.3
						BE-1757.1.2	−18.4	25 495	±	99					
						BE-1757.2.1*	−20.4	25 326	±	234					
LVW-5	−18.40552	−70.00953	11.6	80	Wood	BE-1758.2.1*	−18.9	23 704	±	227	27 427	28 234	27.8	±	0.4
LVW-6	−18.40552	−70.00953	11.3	60	Wood	BE-1759.2.1*	−21.1	16 132	±	214	18 919	19 948	19.4	±	0.5
LVW-7	−18.39513	−69.96443	20.0	40	Wood	BE-1760.1.1	−18.0	14 576	±	30	17 538	17 880	18	±	0.2

* Due to advanced degradation, these samples were prepared using the simplified acid–base–acid (ABA) method and corrected for an average age offset of −454 ± 209 years by comparison with the base–acid–base–acid–bleaching (BABAB) method, i.e. the standard method for wood analysis (Szidat *et al.*, 2014).

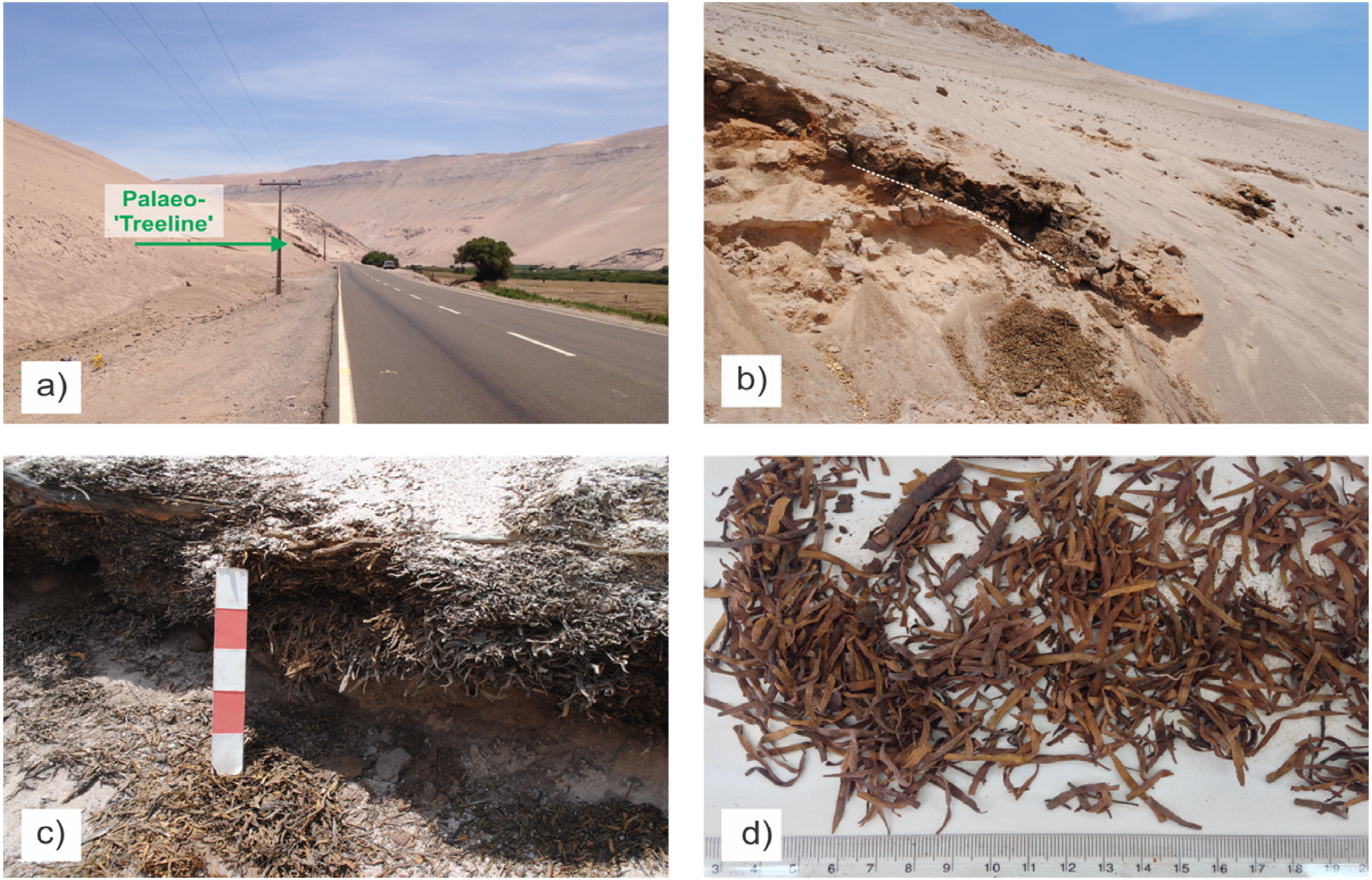
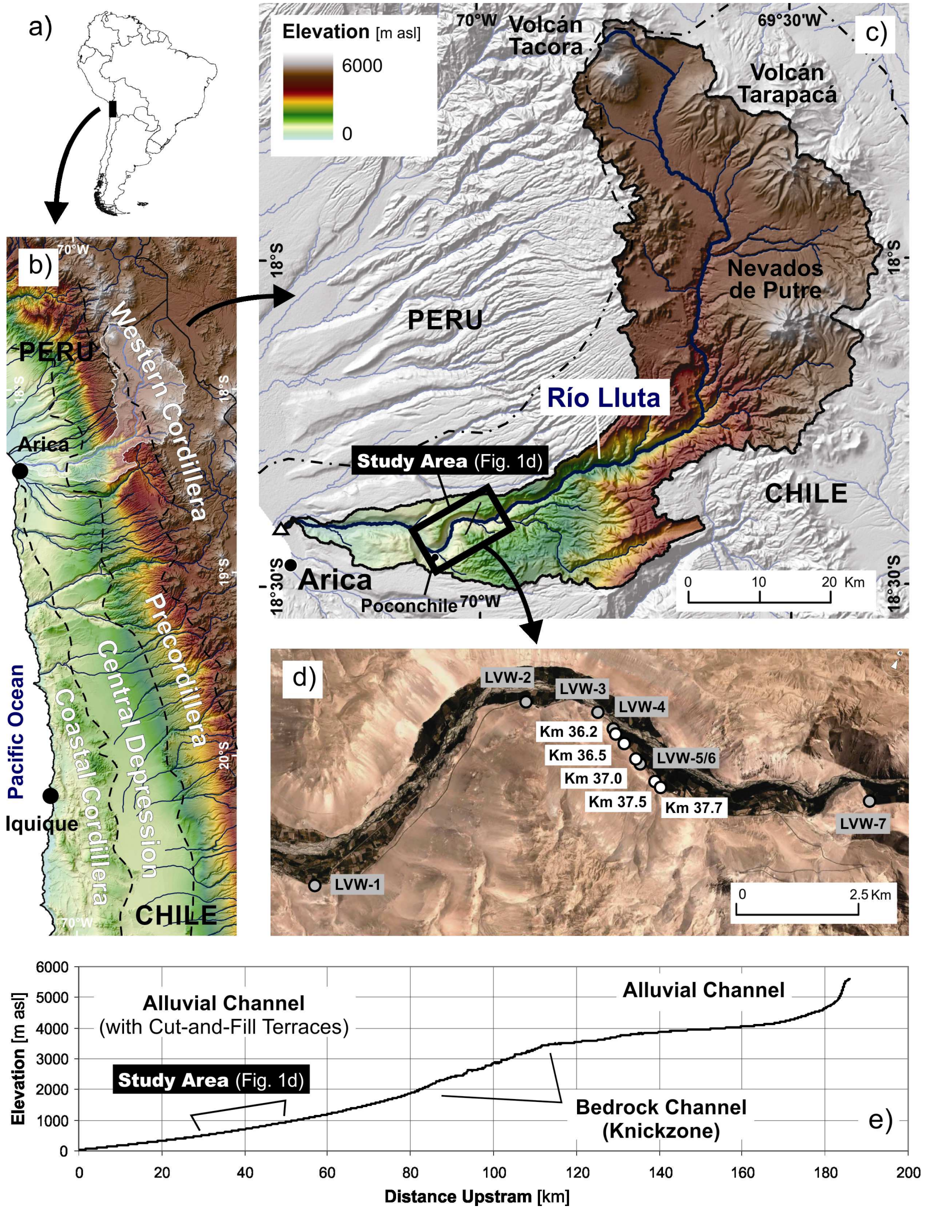
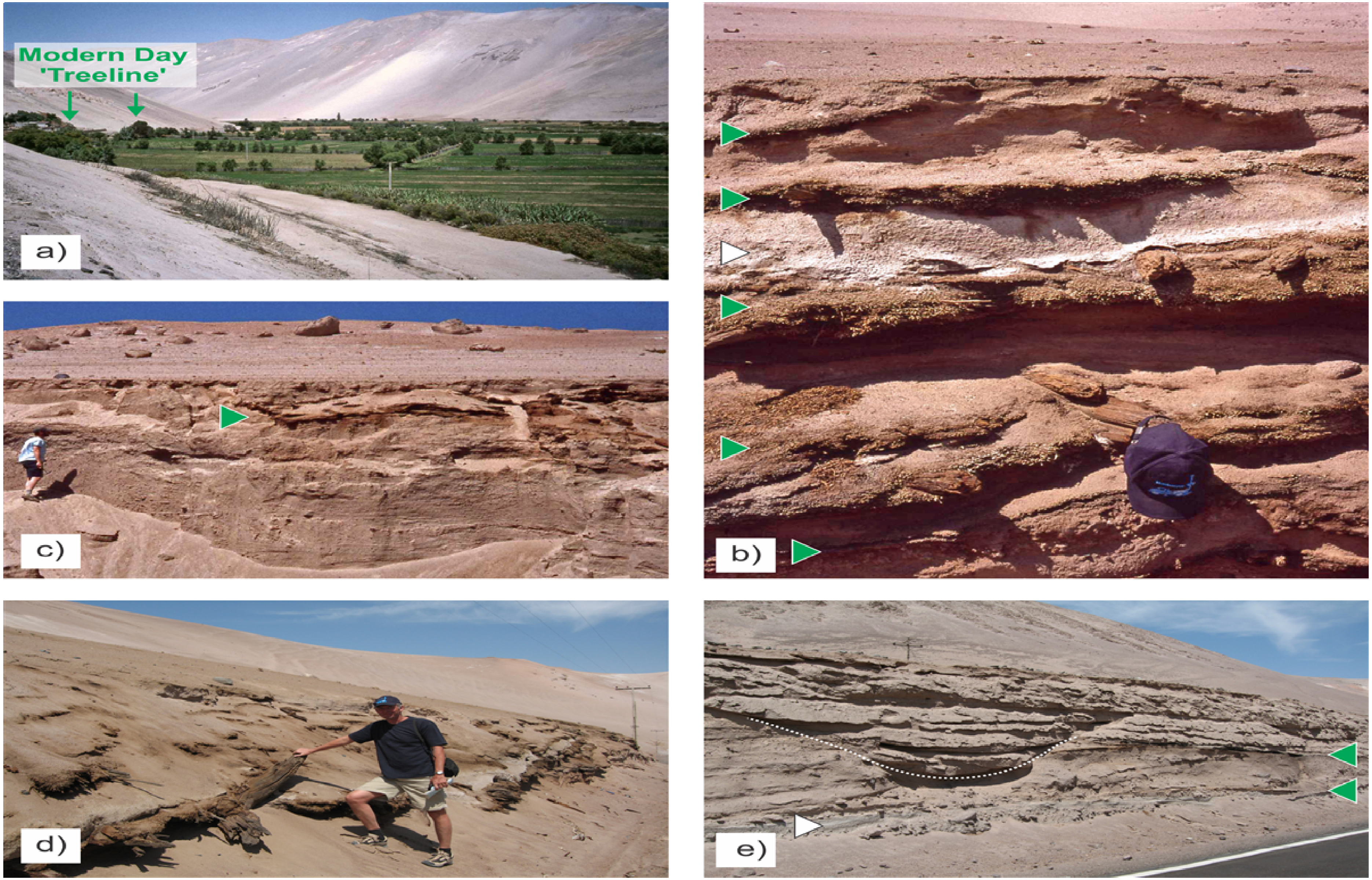

Palaeo-
'Treeline'
a)
b)
c)
d)

Fig 3 .



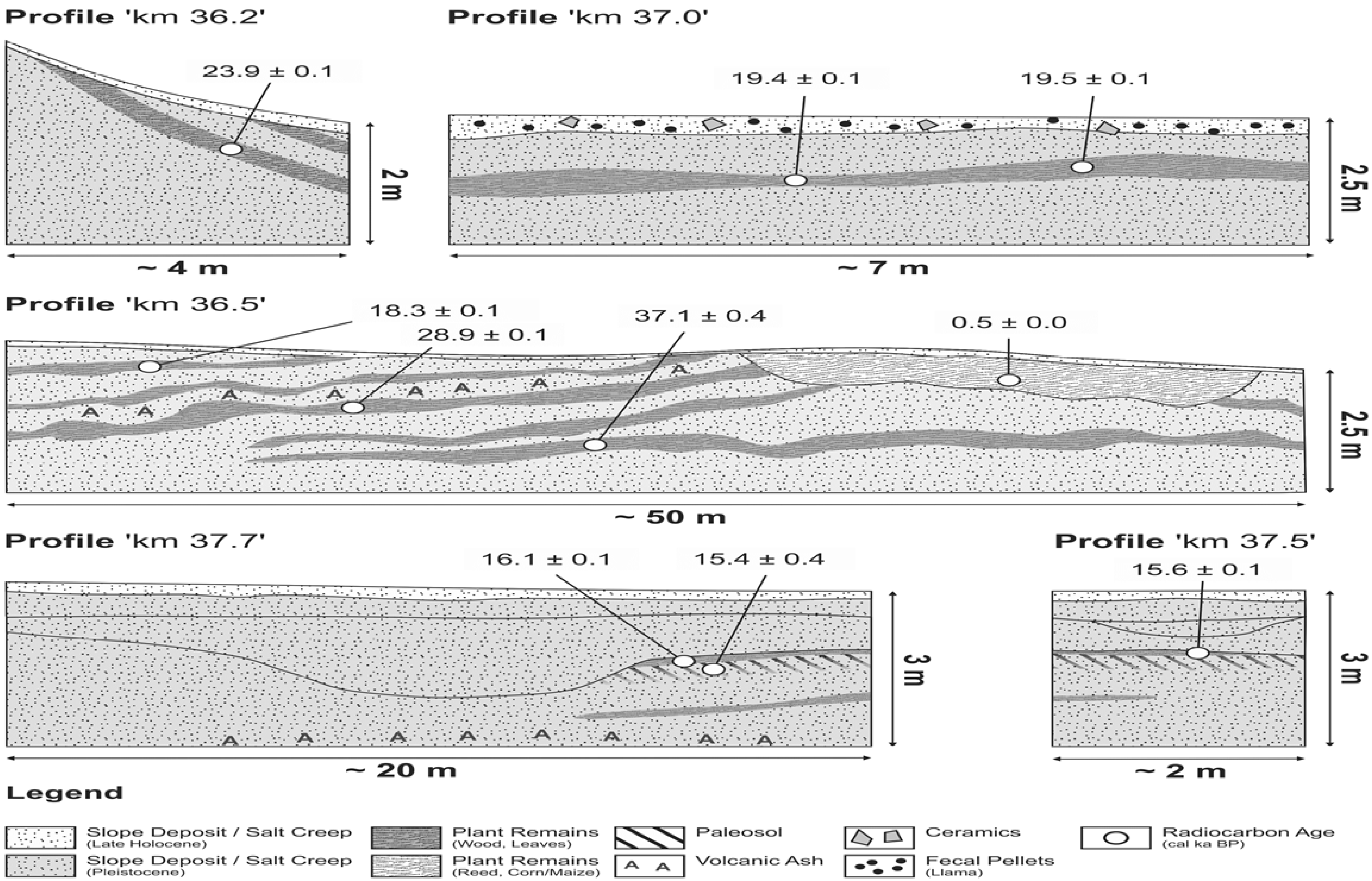
a)
b)
PERU
Western Cordillera
Arica
Pacific Ocean
Iquique
Coastal Cordillera
Central Depression
Precordillera
CHILE
70°W
c)
Elevation [m asl]
6000
0
70°W
Volcán Tacora
69°30'W
Volcán Tarapacá
18°S
Nevados de Putre
PERU
Río Lluta
Study Area (Fig. 1d)
CHILE
Arica
Poconchile
18°30'S
0 10 20 Km
d)
LVW-1
LVW-2
LVW-3
LVW-4
Km 36.2
Km 36.5
LVW-5/6
Km 37.0
Km 37.5
Km 37.7
LVW-7
0 2.5 Km
e)
Alluvial Channel
(with Cut-and-Fill Terraces)
Alluvial Channel
Study Area (Fig. 1d)
Bedrock Channel
(Knickzone)
Elevation [m asl]
Distance Upstream [km]

Fig1 .



Modern Day
'Treeline'
a)
b)
c)
d)
e)

Fig2 .



Profile 'km 36.2'
23.9 ± 0.1
2 m
~ 4 m
Profile 'km 37.0'
19.4 ± 0.1
19.5 ± 0.1
2.5 m
~ 7 m
Profile 'km 36.5'
18.3 ± 0.1
28.9 ± 0.1
37.1 ± 0.4
0.5 ± 0.0
2.5 m
~ 50 m
Profile 'km 37.7'
16.1 ± 0.1
15.4 ± 0.4
3 m
~ 20 m
Profile 'km 37.5'
15.6 ± 0.1
3 m
~ 2 m
Legend
Slope Deposit / Salt Creep (Late Holocene)
Slope Deposit / Salt Creep (Pleistocene)
Plant Remains (Wood, Leaves)
Plant Remains (Reed, Corn/Maize)
Paleosol
Volcanic Ash
Ceramics
Fecal Pellets (Llama)
Radiocarbon Age (cal ka BP)

Fig4 .

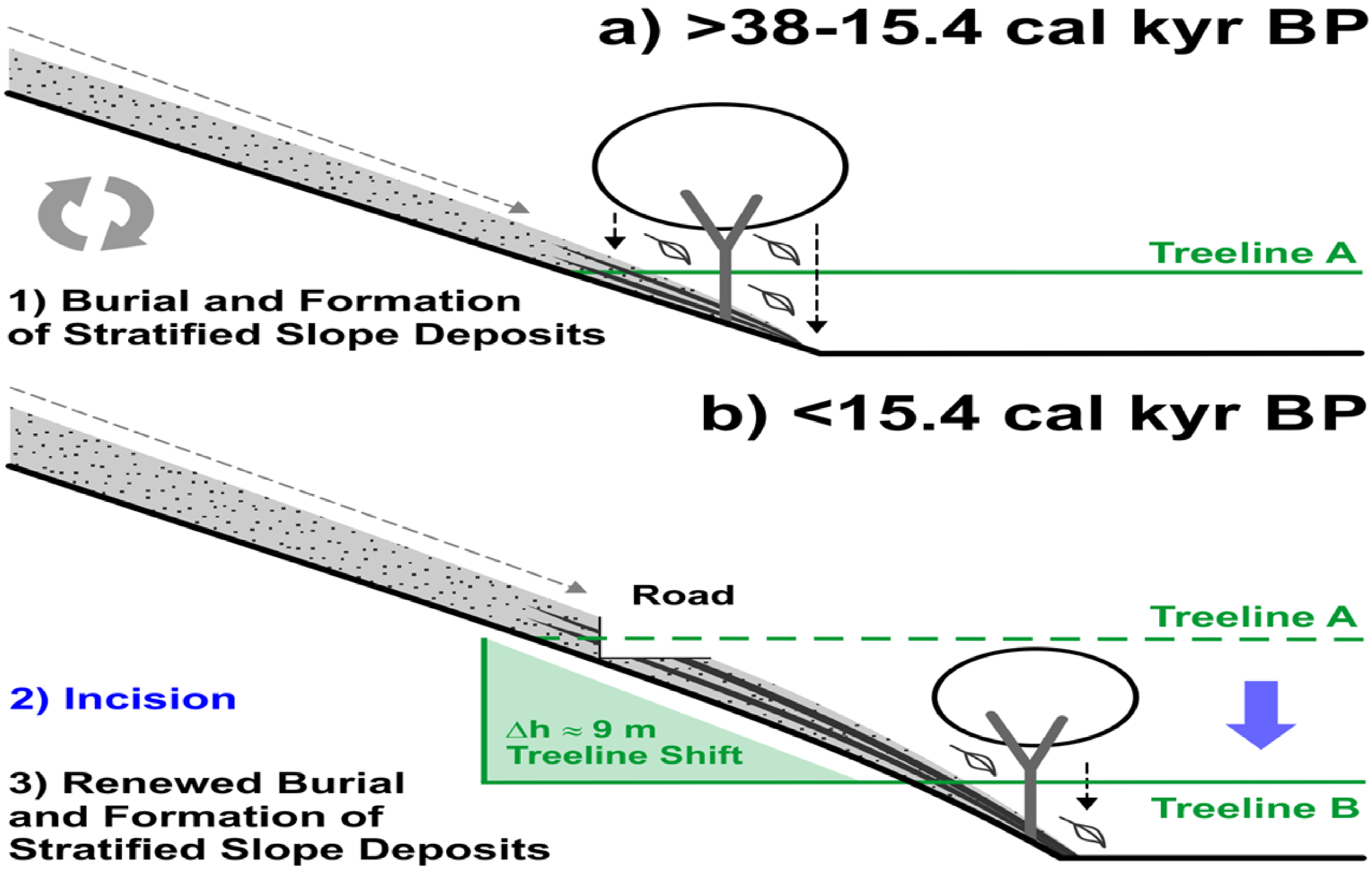

a) >38-15.4 cal kyr BP
Treeline A
1) Burial and Formation of Stratified Slope Deposits
b) <15.4 cal kyr BP
Road
Treeline A
2) Incision
Δh ≈ 9 m Treeline Shift
3) Renewed Burial and Formation of Stratified Slope Deposits
Treeline B

Fig5 .