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Evenstar, LA

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Using spatial patterns of fluvial incision to constrain continental-scale uplift in the Andes.

L.A. Evenstar*, A.E. Mather2 and A.J. Hartley3

1School of Environment and Technology, University of Brighton, UK,
2Department of Geography, Earth and Environmental Sciences, University of Plymouth, UK,
3Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen, UK,

Abstract

Geomorphic archives, particularly longitudinal river profiles, are increasingly used as a proxy to reconstruct uplift rates in mountainous regions. Within the Atacama Desert, Northern Chile, slow, long-term erosion creates exceptional preservation of fluvial and alluvial surfaces. This enables river incision patterns to be used on a continental-scale (>250 km) along the western margin of the Andes (18°00’S to 20°15’S) and over a time frame from Miocene to Present day. The data show marked compartmentalisation of fluvial system behaviour with changes in incision rates from south to north creating 3 distinctly different regions. Within these different sectors, incision rates are broadly consistent between rivers suggesting a regional rather than a river specific control on rates. In Sector 1 (18°05’S to 19°20’S) the fluvial systems are exorheic with a terminal base level (the lowest base level to which the river system can erode) in the Pacific Ocean and span the Coastal Cordillera, Longitudinal Valley, Precordillera and western edge of the Western Cordillera. This constrains the total uplift over these regions to a minimum of 1200 m in 11 Myr with incision rates of ~200-120 m/Myr consistent with rapid but sustained uplift of the Andes in the Late Miocene. In Sector 2 (19°20’S to 19°50’S), to the immediate south, the rivers are shorter and terminate in the Longitudinal Valley, spanning only the Longitudinal Valley and eastern part of the Precordillera with low incision rates of 50 to 25 m/Myr. Comparison of incision rates between Sector 1 and 2 can constrain the uplift of the Coastal Cordillera to 60m/Myr which is in keeping with previous studies from the region. In southernmost Sector 3 (19°50’S to 20°10’S), the fluvial systems terminate in the Longitudinal Valley and span only the Longitudinal Valley and eastern part of the Precordillera with low incision rates of 50 to 25 m/Myr.
Differences between Sectors 2 and 3 are attributable to drainage loss by tectonic beheading of catchments through uplift of the Cordillera de Domeyko fault system, placing a minimum constrain on uplift in this region of 50 to 25 m/Myr. This study demonstrates the applicability of large-scale fluvial archives to access not just the timing of uplift on a continental scale, but also the relative uplift of individual tectonic provinces.

Keywords; Andes; Paleosurface; Atacama; Desert Pavement; landscape evolution; climate; base levels; fluvial incision, fluvial archives, terraces.

1. Introduction

Fluvial geomorphological archives are being increasingly used to reconstruct climate and deformation (e.g. Macklin et al., 2002, Bridgeland et al., 2012, Stokes et al. 2017, Evenstar et al. 2018; Stokes et al., 2018). These archives comprise dominantly erosional (e.g. strath terrace) through to depositional records (e.g. distributive fluvial systems) and can be regionally extensive (e.g. pediment systems). The common theme is that these types of geomorphic archive have low angle surface expressions which can be reconstructed to enable surface deformation to be quantified (e.g. Gesch et al., 2014; Demoulin et al 2017, Stokes et al., 2018). Typically the majority of these studies concentrate on a single pediment surface over small basin scale or focus on trunk drainage or tributaries along a single river system (e.g. Anton et al., 2014, Martins et al., 2017, Evenstar et al., 2018). Whilst correlation of fluvial system behaviour has been attempted across regional scales (>100’s km) to examine climate controls (e.g. Macklin et al, 2002), flooding records (e.g. Benito et al., 2000) and uplift rates (Litchfield and Berryman 2006) this has typically been restricted to time-scales younger than the Pliocene. The few studies that look at regional scale deformation over longer timescales tend to utilise modelling of profiles or terrace patterns due to limited preservation of the fluvial system (e.g. Demoulin et al., 2007, Boulton et al., 2014). Where appropriate records are well preserved (e.g. in arid landscapes), availability of high-resolution satellite data sets facilitate regional geomorphic reconstruction over much wider spatial and temporal scales than was previously possible.

The Atacama is the most arid and potentially, oldest desert region in the world (Hartley et al., 2005, Dunai et al., 2005). The long term sustained arid climate leads to preservation of ancient landscapes, some of which are dated back to the Late
Oligocene (Dunai et al. 2005, Evenstar et al. 2009, Evenstar et al. 2017). Several of these surfaces are identified as being generated following abandonment of fluvial incision events associated with fluctuating climate and long-term uplift of the Andean mountain chain (Evenstar at al. 2017). Within hyper-arid fluvial systems, as a function of their low geomorphic erosional efficiency, even modest vertical crustal uplift is likely to be more directly expressed as surface uplift, and thus more likely to be recorded within fluvial archives (e.g. Demoulin et al., 2017). In the central Andes (Atacama Desert) the sustained dominance of extreme aridity is expressed by the presence of near linear to convex hypsometric curves that are typical of areas experiencing ineffective fluvial incision (Montgomery et al., 2002). This incision, in response to tectonic uplift, is documented in the fluvial archives, and along with the past climate (e.g. Dunai et al., 2005; Evenstar et al., 2009; Evenstar et al., 2017), these fluvial archives are increasingly well understood (Victor et al., 2004, Farias et al., 2005, Jordan et al., 2014, van Zalinge et al., 2017) and can be exploited to examine continental scale uplift. These approaches have documented vastly different rates of fluvial incision in northern Chile from 100 m/m.y. (Hoke et al., 2007) to 10 m/m.y (Cooper et al., 2016) since the Middle Miocene leading to different models for timing of Andean uplift.

Here, we utilise freely available satellite remotely sensed data, together with longer term geological and geomorphological erosional and depositional records to reconstruct and quantify the last 11 Myr of pediment and fluvial landscape erosion along the western side of the Central Andes orogen, a classic subduction zone setting. The low erosional efficiency of this landscape means that the surface uplift is preserved in excellent detail. The present study seeks to establish a continental scale view of the fluvial incision and how this varies parallel to the Andean Mountain chain. Using this we aim to establish the main controlling factors on incision rates in order to better understand their use in constraining continental scale uplift within the Central Andes.

2. Study area: landscape components and depositional record
The study region runs along the western margin of the Central Andean mountain range from 18°00'S to 20°15'S (Figure 1a). This region consists of several different morphotectonic provinces; the Coastal Cordillera, Longitudinal Valley, Precordillera and Western Cordillera (Figure 1a). The Coastal Cordillera runs along the coast of the Pacific Ocean and is characterised by the eroded Jurassic magmatic arc. The Coastal Cordillera is absent around the border between Chile and Peru (18°30'S) but
increases in width and height towards the south (Madella et al., 2017). The Coastal Cordillera shows exhumation back to the Eocene (Juez-Larre et al., 2010). However the timing of uplift of this range is poorly constrained with rates varying from 0.001 mm/yr to 0.1 mm/yr proximal to the coast (Regard et al. 2010; Garcia-Perez et al., 2018) to 0.05 mm/yr to 0.07 mm/yr inland (Hartley et al., 2000; Dunai et al., 2005; Cosentino and Jordan 2017). On the regional scale the mountain range was still at or close to sea level in the Late Oligocene forming the regionally extensive Tarapaca surface that graded down to sea level (Noble et al., 1985, Delouis et al., 1998, Dunai et al., 2005; Thouret et al., 2007). The mountain range is believed to have uplifted continuously from the late Oligocene at an average rate of 0.05 mm/yr to 0.07 mm/yr (Delouis et al., 1998; Hartley et al., 2000; Dunai et al., 2005; Cosentino and Jordan 2017). To the east, the Coastal Cordillera borders the Longitudinal Valley, a deep fore arc basin infilled with Oligocene to Miocene aged sediments derived from the Andean mountain range to the east (Evenstar et al., 2009; Hartley & Evenstar 2010). The top of the basin is characterized by an elevated low-relief relict landscape termed the Pacific Paleosurface (PPS) (Evenstar et al., 2017). The Longitudinal Valley is characterized by a series of westward propagating reverse faults or monocline folds which have been active from ~30 to 5 Ma (Víctor et al., 2004, García 2005, Fariás et al., 2004). To the east of the Longitudinal Valley lies the Precordillera. This rises in elevation from 2000 to 4000 masl and is characterized by a series of westward propagating, north-south striking thrusts and folds related to the Domeyko fault system (Figure 1). The Precordillera forms the foothills to the modern magmatic arc in the east, termed the Western Cordillera with peaks up to 6000 m.

The Precordillera and Longitudinal Valley are infilled by volcaniclastic and fluvial sediments, which were predominantly deposited syn-tectonically (Figure 2). The oldest sediments in the region are the Azapa Formation, a series of alluvial conglomerates dated at ~35 to 22.7 Ma (Wörner et al., 2000; Wotzlaw et al., 2011; van Zalinge et., 2017). Overlying the Azapa Formation in the Longitudinal Valley, and unconformably overlying the basement in the Precordillera, are a series of ignimbrites and volcaniclastic sediments termed the Oxaya Formation (22.7 Ma -19.7 Ma) (Wörner et al., 2000; van Zalinge et., 2017). North of 19°00'S, these deposits are predominantly formed by thick ignimbrite sheets (up to 1000 m) (van Zalinge et al., 2017). In the area around the Lluta Quebrada, the ignimbrite sequence forms the top of the stratigraphic succession in the Longitudinal Valley (Figure 2 and 3). In contrast, towards the south, the ignimbrite sheets thin and are intercalated with more fluvial sediments (Hartley and Evenstar, 2010). South of Quebrada Lluta, the volcaniclastic
sediments in the Longitudinal Valley are conformably overlain by the El Diablo Formation (Figure 2), a series of fluvial sediments dated at 16 -11 Ma (Evenstar et al., 2017). Within this region the El Diablo Formation is overlain by the Tana lava dated at 8.8 ± 0.5 Ma (Mortimer et al., 1974) and 8.2 ± 0.5 Ma (Muñoz and Sepulveda, 1992) constraining the age of the end of the El Diablo Formation to 11-8 Ma.

This study focuses on the PPS which is formed from numerous distributive fluvial systems, which can be found in the Longitudinal Valley and in parts of the Precordillera (Evenstar et al., 2017). North of 19°20'S, the PPS is deeply dissected (up to 1,700 masl) by five main rivers (Lluta, Azapa, Victor, Camarones and Tana) that drain to the Pacific Ocean (exorheicly drained) with a terminal base level of 0 masl (Fig. 1). Analysis of the fluvial profiles of Quebrada Tana shows that the main knickpoint is within the Coastal Cordillera (Garcia et al., 2011; Evenstar et al., 2017; Kirk-Lawlor et al., 2013), suggesting that it has not yet adapted to the new terminal (0 masl) base level, with the upper reaches of the river still grading down to the former terminal base level within the Longitudinal Valley at 1000 masl (Kirk-Lawlor et al., 2013; Evenstar et al., 2017). The timing of when fluvial regions north of Quebrada Tana became exorheicly drained is considered to be diachronous from the Early to Mid Miocene (Evenstar et al., 2017). South of this region, the main rivers (Aroma, Tarapaca, de Parca and Tambillo) terminate within the Longitudinal Valley (endorheicly drained) with terminal base levels of ~1000 masl and incise the PPS towards the Western Cordillera by up to 1000 masl (Hoke et al., 2007).

The PPS can be traced for over 600 km (south to north) within the Longitudinal Valley. The surface has been mapped in detail using remote sensing techniques and constrained in age using cosmogenic isotope dating techniques in Evenstar et al. (2017). This research demonstrates that the PPS is in fact formed from an amalgamation of geomorphic surfaces (both erosional (inset) and depositional (overlying)) spanning a range of ages from the Late Oligocene to present day (Evenstar et al., 2009; 2017). The timing of formation of the surface is related to regional climate while the geographical location of the individual components that comprise the surface are controlled by regional tectonic activity (Evenstar et al., 2017). Within the present study we examine the youngest three geomorphic surfaces; Aggradational Surface 4 (AS4), Degradational Surface 3 (DS3) and Degradational Surface 2 (DS2) (Terminology after Evenstar et al., 2017 and shown in Figure 2 and 3). Aggradational surface 4 (AS4) represents the end of deposition of
the El Diablo formation and is dated at 11 Ma using *insitu* exposure ages (Evenstar et al., 2017). Degradational surface 3 (DS3) is an erosion system which cuts into the underlying sediment fill of the basin (El Diablo Formation and Oxaya Formation). The surface comprises a relict dendritic drainage pattern abandoned at ~7 Ma (*insitu* exposure ages, Evenstar et al., 2017). Degradational System 2 (DS2) cuts into the older geomorphic surface DS3 and is characterized by a trellis drainage pattern. The abandonment of this surface is constrained at ~3 Ma (Evenstar et al., 2017). Along the Quebrada Lluta, lies a large (26 km$^3$) landslip deposit, the Lluta collapse, which disrupts various surfaces. This feature shows westward collapse into the Longitudinal Valley and is believed to have formed at ~3 Ma (Wörner et al., 2002; Kober et al., 2007; Evenstar et al., 2017).

The timing and rate of uplift of the Andes is still ambiguous, with two favoured end-member models (Fig. 2); (1) rapid, late Miocene uplift, with surface uplift of ~2.5 km between 11 and 6 Ma (e.g. Garzione et al., 2006; Ghosh et al., 2006, Garzione et al., 2008); and (2) slow and steady uplift that started in the late Eocene (e.g. Victor et al., 2004; Hartley et al., 2007; Barnes and Ehlers, 2009; Evenstar et al., 2015; van Zalinge et al., 2017). Thus, the eastern edge of the PSS has experienced substantial cumulative surface uplift regardless of which model is taken throughout the Miocene and Pliocene. Several studies have used the main fluvial systems in the region to calculate regional uplift of the Andes across the region (e.g. Farías et al., 2005, Hoke et al., 2007; Schildgen et al., 2002; Schildgen et al., 2009). However, more recent climate modelling of this region has cast doubt on this interpretation suggesting higher incision rates could be due to increased orographically generated precipitation (Ehlers and Poulsen, 2009).

Along the western margin of the Andes, the PPS has been undergoing uplift since at least the Early Miocene (Evenstar et al., 2015) and likely extends back further to the early Oligocene (Barnes and Ehler 2009, van Zalinge et al., 2017). The uplift of the region is modified locally predominantly north-south fault systems (Figure 1) (Wörner et al. 2002; Victor et al. 2005; Farías et al. 2005; van Zalinge et al. 2017) with minor amounts of surface uplift expressed as regional tilting (Farías et al. 2005). However, there are no marked changes in regional tectonic uplift from North to South over the study area with similar rates and timing of uplift (2500m to 3200m of uplift during 25 Ma to 8 Ma) reported from 18°S to 22°S in Northernmost Chile by numerous authors (Wörner et al., 2002; Victor et al., 2005; Farías et al., 2005; Jordan et al., 2014; Evenstar et al., 2015; van Zalinge et al., 2017).
3. Study area climate

The past climate of the region is reasonably well constrained (Fig. 2). The climate has been arid to semi-arid since at least the late Jurassic (Hartley et al., 2005), arid since the late Oligocene and predominantly hyperarid since the mid Miocene (Evenstar et al., 2009, Jordan et al., 2014, Evenstar et al., 2017, Rech et al., 2019). Since the Oligocene, short intervals (< 1 myr) of slightly more humid conditions have been recorded (Evenstar et al., 2009, 2015, 2017; Jordan et al., 2014) (Fig. 2). These humid intervals are within the range of an arid climate with annual mean precipitation rates less than 100 mm/yr, below the threshold for the establishment of significant vegetation cover (Jordan et al., 2014). As a result of the long-lived regional persistent climatic aridity, the PPS is exceptionally well preserved, providing a unique opportunity to examine the development of regionally extensive paleo-fluvial surfaces in a non-vegetated regime over geologic time-scales.

4. Methodology and Approach

4.1 Reconstructing regional fluvial palaeo-surfaces.

Relict paleo-surfaces of the PPS combined with the elevation data in the Longitudinal Valley were used to identify and extrapolate geomorphic surfaces (pediments and valley bottoms) throughout the past ca. 11 Myr. Four regional elevation profiles (A-D) were constructed across the PPS, one parallel to the drainage (A-East to West) and three perpendicular to the drainage (B, C and D-North to south) (Fig. 3). The landscape profiles were constructed using DEM data from Shuttle Radar Topography Mission (SRTM) data with 30 m resolution (Figs. 3 and 4). Profile A is 45 km long and runs from east to west at 18°45'S (Fig. 3). The three other topographic profiles are 260 km long and run parallel along the eastern edge of the Longitudinal Valley from southern Peru at 18°05'S towards northern Chile at 20°15'S (Location in Figure 3 and cross sections in Figure 4). These profiles cross three of the main paleo-surfaces mapped within the regions (AS4, DS3 and DS2) (Fig. 3). On each profile the remnant parts of the various paleo-surfaces (as mapped by Evenstar et al, 2017) are highlighted (Figs.3 and 4). Using the preserved remnants of these surfaces (palaeosurface residual highs, inset terraces and valley bottom elevations) we can extrapolate the line of maximum incision levels of the main quebradas across the region (Figs.3 and 4).
Surface AS4 is formed as a series of relict distributive fluvial systems with a low gradient slope and is preserved on the west edge of profile A forming a plateau (Fig. 3). Using the slope of AS4, the surface can be projected towards the east (Fig. 3). Within profiles B-D, AS4 is preserved in the south as a series of relict inselberg surfaces which can be correlated across the southern region to reconstruct the paleo fluvial surface (Fig. 4). Towards the north of Quebrada Camarones, the preservation of the AS4 surface decreases and the surface cannot be accurately mapped north of Quebrada Lluta.

Surface DS3 formed as a tributary fluvial system incised into AS4. It is well preserved within the central parts of profile A cutting into AS4 and forming a low angle erosional surface. This surface can be projected to the east using the slope angle (Fig. 3). Within profiles B-D, DS3 is mapped as a series of relict inselberg highs north of Quebrada Lluta (Figs. 4 and 5A-B). These highs in profiles B-D can be linked across the region forming a single surface down to Quebrada Camarones. South of this point, where AS4 is preserved, DS3 incises into AS4 and forms a series of lower terraces (Figs. 4 and 5C).

Surface DS2 is preserved along the eastern edge of Profile A cutting into DS3 and forming a low angle erosional surface (Fig. 3). Within Profiles B to D, this surface forms the lowest incision surface north of Quebrada Lluta that can be correlated across this region (Figs. 4 and 5A-B). Towards the south, this surface is constrained within the main quebradas and forms a series of terraces. The Lluta ignimbrite is preserved along these terraces and has previously been used to reconstruct the relict river profiles at 2.7 Ma along the Quebrada Lluta which can be linked with this surface (Kober et al. 2006).

In the southernmost part of the region the laterally traced fluvial archives are correlated with the depths and timing of water table drops in the Cerro Colorado mine that have been reconstructed using hematite age-dates from drill core (Cooper et al. 2016) (Fig. 4). Throughout the region, the present-day fluvial cross-profiles were reconstructed utilising the lowermost incisional points within the modern-day perennial rivers (Fig. 4).

4.2 Palaeo-surface age constraints.
Age constraints on the surfaces are based on previously published *insitu* exposure age dating (Kober et al., 2007, Evenstar et al., 2009, Evenstar et al., 2017), dated volcanics (Wörner et al., 2002, Kober et al., 2006, Hoke et al., 2007) and hematite age-dates from drill core (Cooper et al., 2016). These constraints are shown where they intersect the elevation profiles in Figure 4.

Surface AS4 is constrained as having formed between ~16-8 Ma (Hoke et al., 2007, Evenstar et al., 2015). Within Quebrada Aroma (Fig. 1), the Nama ignimbrite is interbedded with sediments that underlie surface AS4 placing an upper age constraint of 16.27 ± 0.16 Ma on this surface (Pinto et al., 2004, Victor et al., 2004; Farias et al., 2005; Pinto et al., 2007). Proximal to Quebrada Tana (Figs. 1 and 4), the Tana lava overlying this surface is dated at 8.8 ± 0.5 Ma (Mortimer et al., 1974 and 8.2 ± 0.5 Ma; Muñoz and Sepulveda, 1992) placing an upper age constraint on the surface (Hoke et al., 2007). This surface is further constrained by *insitu* exposure age dating to ~11 Ma (Fig. 4) (Evenstar et al., 2009, Evenstar et al., 2015 and Evenstar et al., 2017).

Surface DS3 is constrained using *insitu* exposure age dating across the region to ~7 Ma (Kober et al., 2006, Evenstar et al., 2009, 2017). Several of the *insitu* exposure ages lie on the landscape cross-profiles either on top of the residual palaeosurfaces in the north or on the incised terrace surfaces in the south and are highlighted in Figures 4 and 5C. Proximal to the Cerro Colorado mine DS3 links with the depth and age of dated hematite within drill core at 7 Ma which records the paleowater table level (Cooper et al., 2016) (Figure 4).

Surface DS2 was dated at ~3 Ma based on *insitu* exposure age dating (Fig. 4) (Kober et al., 2006, Evenstar et al., 2009, 2017). The surface age can be further constrained using the preservation of the Lluta ignimbrite (dated at 2.7 Ma; Wörner et al., 2002) along fluvial terraces within Quebradas Lluta and Azapa (Fig. 4). Proximal to the Cerro Colorado mine this surface is linked to dated hematite (3 Ma) within drill core (Cooper et al., 2016) (Fig. 4).

### 4.3 Reconstructing regional mean incision rates.

The reconstructed fluvial paleo-surface profiles combined with the dating constraints described above can be used to calculate the regional fluvial incision rates over the last 11 million years (Fig. 6A). The difference in elevation between the paleo-fluvial
surfaces and modern river were extrapolated for each surface across the region (Fig. 6B). Using the difference in elevation of the surfaces and the modern river, divided by the time since the surfaces had been abandoned the mean fluvial incision rates along the main quebradas were calculated (Fig. 6C). In this way, we are able to reconstruct relative incision rates for the PSS.

5. Results

Profile A runs 45 km from east to west at 18°45’S in Figure 3 and highlights the general relationship of the surfaces within the region. AS4 is predominantly preserved in the west of the Longitudinal Valley and shows an average depositional slope of 5° to the west. Cutting into AS4 within the centre of the Longitudinal Valley, DS3 incises 90 m and shows a similar depositional slope angle. To the east of DS3, DS2 cuts 90 m into and erodes DS3, with a higher slope angle of 10° to the west. Figure 4 highlights the overall relationship of the main fluvial archives from North to South. AS4 forms the highest elevation surface across the region and is predominantly preserved in the southern parts of the elevation profiles. DS3 cuts into AS4 forming a lower elevation surface across the region. Cutting into both AS4 and DS3, DS2 forms at the lowest elevation of all the preserved paleo-fluvial surface in the Longitudinal Valley. The modern river system forms at the base of the valleys with the lowermost elevations across the region. All the surfaces generally show an increase in elevation towards the east and south across the region (Figure 3 and 4). The changes in elevation show a step like increase from north to south and can be separated into three different sectors (1 to 3 on Figure 4). Sector 1 runs from (18°05’S) to Quebrada Tana (19°20’S), Sector 2 from Quebrada Tana (19°20’S) to Quebrada Tarapaca (19°50’S) and Sector 3 from Quebrada Tarapaca (19°50’S) to Quebrada Juan de Morales (20°10’S). Within each sector the change in elevation is broadly similar and affects a number of different rivers rather than being river specific. Sector 1 shows the highest changes in elevation across the region between the different fluvial surfaces which decrease within Sector 2 and is the lowest within Sector 3.

Figure 6A shows the current elevation of the fluvial systems in cross section B. AS4 shows a single laterally extensive surface which undulates across the region from ~2750 masl in Sector 1, to ~2500 masl in Sector 2 and ~2650 masl in Sector 3. DS3 forms a laterally extensive surface with an average height of 2350 masl across Sector 1 and 2 and increasing in elevation to ~2700 masl in Sector 3. DS2 varies in
elevation from 1800 masl at the northern tip of the elevation profile to ~ 2000 masl in Sector 2 and increases in height to ~2600 masl in Sector 3. The modern fluvial systems vary in height from 1400 masl to 1500 masl in Sector 1 to Sector 2 to ~2000 masl and ~2500 masl in Sector 3.

Using the difference between the paleo fluvial surfaces and modern fluvial systems the change in fluvial incision through time can be more clearly illustrated (Fig. 6B). and combined with the age constraint the fluvial incision rates through time can be calculated (Fig. 6C). Overall, fluvial incision shows higher rates from 3 to present day. However, there are marked differences across the study area. Sector 1 show the highest rates of fluvial incision through time from 120 m/Myr at 11-7 Ma to 150 m/Myr at 7-3 Ma to ~200 m/Myr at 3-0 Ma. Sector 2 show lower incision rates through time of 50 m/My for both 11-7 Ma and 7-3 Ma and higher rates of 100-50 for 3-0 Ma. Sector 3 show the lowest rates of fluvial incision throughout the area with 25 m/Myr from 11-7 Ma, 30m/Myr from 7-3 Ma and 50 m/Myr from 3-0 Ma.

6. Discussion

The geomorphic archive, using both pediplain and fluvial surfaces, is reconstructed from Northernmost Chile and combined with age constraints to calculate fluvial incision rates over a continental scale (>250 km) and back to the Miocene. These data demonstrate three spatially marked changes in incision rates across the region, from north to south. These distinctly different regions have been termed Sectors 1-3. Sector 1 has the highest rates of fluvial incision through time (ca. 200 to 100 m/Myr), Sector 2 show a lower rate of incision (ca. 100 to 50 m/Myr) and Sector 3 has the lowest rates of incision (<50 m/Myr). These profiles show a generally continuous drop in fluvial incision with slightly higher incision from 3 Ma to the present day. This study shows that along the western margin of the Andes rates of fluvial incision can vary dramatically over distances of 10’s to 100’s km. In Sector 1, incision rates of 100 m/m.y support those proposed by Hoke et al., (2007). However, in contrast to Hoke et al., (2007) the incision shows a marked decrease to the south of Section 1 with substantially lower rates in Section 2 and Section 3. These low rates correlate with the incision rates documented in Cooper et al., (2016) explaining the disparity between these two studies. Below we discuss what controls the variation in incision rates in this region in order to evaluate their use as surface uplift makers.

The spatial extent of the area impacted (i.e. affecting multiple rivers per area
simultaneously) implies an external control. Such a control could take the form of (but
is not limited to) a change in relative terminal base level, climate or regional scale
tectonic uplift through fault blocks, rather than more localised internal river/catchment
specific causes (e.g. internal drainage reorganisation via river capture). Below we
discuss the major external controls on the compartmentalisation of the rivers within
this region.

6.1 Uplift and fluvial incision

Regional tectonic uplift
Fluvial incision rates have been used in numerous studies to help constrain uplift in
tectonically active areas (Maddy et al. 1997; Lave and Avouac 2001; Lu et al. 2004;
Whittaker et al., 2007). Although fluvial incision rates do not necessarily directly
translate to uplift rates as discharge may limit erosional capacity, they do give
minimum constraints. The sustained regional uplift of the Andean mountain chain is
broadly mirrored by continuous tectonically-driven fluvial incision throughout the
Miocene. However, this uplift is predominantly controlled by north-south fault
systems creating variation in uplift from West to East. There are no large scale east-
west trending structures which would generate marked changes in regional tectonic
uplift from North to South accounting for the compartmentalisation of the fluvial
incision rates.

Terminal base level
Comparison of Sector 1 and Sector 2 suggests a marked decrease in fluvial incision
through time and a marked change in terminal base level between the two fluvial
regions. In this part of the Andes the terminal base level is either external (sea level)
north of Quebrada Tana or internal (the Longitudinal valley, 1000 masl) south of
Quebrada Tana. Uniquely, Quebrada Tana acts as an endorheic drainage within the
Longitudinal Valley (Garcia et al., 2011; Kirk-Lawlor et al., 2013; Evenstar et al.,
2017). The timing of when fluvial systems north of Quebrada Tana became
exorheicly drained is diachronous from the Early to Mid Miocene prior to the fluvial
incision documented here (Evenstar et al., 2017). A change in base level would
initially lead to river profile adjustment affecting individual drainages, the absence of
observable river specific differences in the fluvial archives support the idea that in
Sector 1 rivers had an exorheic drainage prior to 11 Ma and so do not explain the
difference in fluvial incision rates between Sector 1 and Sector 2. However, the uplift
of the Coastal Cordillera has not been static during this time period. The uplift rate of
the Coastal Cordillera is poorly constrained, as discussed above. The base level of the fluvial systems in the Longitudinal Valley terminate onto the eastern edge of the Coastal Cordillera and are therefore affected by the regional scale uplift of the mountain range rather than the uplift proximal to the coast which may be more variable. The large scale and long term uplift of the mountain range varies from between 50 m/Myr (0.05 mm/yr) to 70 m/Myr (0.07 mm/yr) (Delouis et al. 1998; Hartley et al. 2000; Dunai et al. 2005; Cosentino and Jordan 2017). The difference between the fluvial incision rate at Sector 1 compared to Sector 2, averaged over 11 Ma is 60m/Myr correlating with this value. Consequently, whilst Andean uplift to the east generated significant fluvial incision within the Longitudinal Valley this was partially offset in Sector 2 and 3 (the endorheicly-drained region) by simultaneous uplift of the Coastal Cordillera in the west. In essence, the rate of fluvial incision is controlled by the east to west length of the fluvial system and whether rivers cut the uplifting north-south trending Coastal Cordillera. The difference between the reach of Sector 1 and Sector 2 is highlighted in Figure 1B.

Tectonic beheading

The change in fluvial incision rates from Sector 2 to 3 are more challenging to explain. Both sectors have the same terminal base level within the Longitudinal Valley of ~1000 masl. However, there is a sharp change in the catchment length of major fluvial systems entering the Longitudinal Valley from between the two regions (Fig. 7). Throughout the region, 18°20' S to 22°00' S, the fluvial systems have been constrained by Hoke et al., 2007 as ranging in drainage area from 5 x 10^9 km^2 to 9 x 10^8 km^2 and in length from 30 to 170 km, with both values decreasing towards the south (Fig. 7). Significantly, these data demonstrate a sudden decrease in fluvial lengths from 110 km to 80 km between Sector 2 and Sector 3 (Figs. 1 and 7). This length-gap coincides with a sudden shift in the edge of the watershed from along the western edge of the Western Cordillera to along the Cordillera de Domeyko fault system in the central Precordillera suggesting a tectonically configured watershed. The uplift along the Cordillera de Domeyko fault system beheads the upper part of the drainages within Sector 3, reducing their length by approx. 30 km (Figs. 1 and 7). The affected fluvial systems in this region thus only record the minimum uplift over the Longitudinal Valley and Precordillera as they are no longer connected to the highest elevation areas of the mountain range further east (Fig. 1B). The difference in fluvial incision rates between Sector 2 and Sector 3 of 25 m/Myr to 50 m/Myr therefore place constraints on the uplift generated between the central and eastern
6.2 Alternative controls on fluvial incision

Whilst the observed spatial differences in fluvial incision rates over the region can be largely explained by tectonic controls it is important to briefly explore alternative explanations for these regional differences within the study area that can operate on a similar spatial scale, principally climate and bedrock. It has been suggested that the present-day rivers within the study area vary in erosional capacity from north to south as a function of mean annual precipitation within the source regions (García et al., 2011). Quebrada Lluta has a catchment with a present-day mean annual precipitation rate of 200 mm/yr, Quebradas Azapa, Victor and Camarones have rates of 100 mm/yr and south of Quebrada Camarones the river catchments have rates of < 100 mm/yr (García et al., 2011). However, it is unlikely that latitudinal variations in rainfall are the main cause for incision patterns observed across the region as there is no apparent spatial link between the precipitation rates and the change in fluvial incision rates. For example, there is no change in the fluvial incision between Quebrada Lluta and the rivers to the south, despite Quebrada Lluta draining an area with much higher mean annual precipitation. If precipitation rates do place some control on incision rates it must be at a much smaller scale than the tectonic controls.

Fluvial research demonstrates that the strength properties of bedrock lithology can impact on fluvial system incisional behaviour (e.g. Stokes et al., 2017) and could thus potentially account for spatial variations in incision rates across the study area. However, whilst there is a difference between the major N-S morphotectonic units (thereby presenting an E-W variability in potential erodibility across the region), there is little N-S variation within these units that can account for the observed N-S spatially compartmentalised incision rates.

6.3 Controls on fluvial incision in Northern Chile

Fluvial incision rates have been used in numerous studies to help constrain uplift in tectonically active areas (Lave and Avouac 2001; Lu et al. 2004; Whittaker et al., 2007; Anton et al., 2014; Stokes et al. 2018). The fluvial regions along the edge of the Andes have varying east-west extent over the north-south orientated tectonic provinces. The fluvial incision therefore shows marked compartmentalization across the region with a step like increase from south to north. The varying reaches of the
rivers and the differences in fluvial incision rates between these reaches can therefore be exploited to place minimum constraints on the different tectonic provinces through time.

Sector 1, which spans from the Pacific Ocean to the western edge of the Western Cordillera (Figure 1B), constrains the uplift on a continental-scale along the edge of the Andes. This constrains the uplift of this region (the western side of the Andes) to a minimum of 1200m in 11 Myr. This supports previous models of Late Miocene uplift (e.g. Garzione et al., 2006; Ghosh et al., 2006, Garzione et al., 2008) however in contrast to these models it suggests uplift continued at a slower rate from 7 to 3 Ma and at a higher rates from 3 to 0 Ma (120 m/Myr at 11-7 Ma to 150 m/Myr at 7-3 Ma to ~200 m/Myr at 3-0 Ma).

Sector 2 spans from the Longitudinal Valley to the western edge of the Western Cordillera (Fig. 1B) constraining the uplift over the western margin of the Andes minus uplift of the Coastal Cordillera. Therefore, the difference between Sector 1 and Sector 2 of 60 m/Myr records the uplift of the Coastal Cordillera which corresponds with published uplift rates for the Coastal Cordillera of between 50 m/Myr (0.05 mm/yr) to 70 m/Myr (0.07 mm/yr) (Delouis et al. 1998; Hartley et al. 2000; Dunai et al. 2005).

Sector 3, spans a much shorter extent than Sectors 1 and 2, from the Longitudinal Valley to the Cordillera de Domeyko fault system in the central Precordillera (Fig. 1B). The difference between Sectors 2 and 3, of 25 m/Myr to 50 m/Myr, therefore places a minimum constraint on the uplift generated between the central and eastern edge of the Precordillera along the Cordillera de Domeyko fault system.

7. Conclusions

Within the Atacama Desert, Northern Chile, slow long-term erosion creates exceptional preservation of geomorphic archives (fluvial and pediment surfaces) allowing the long-term reconstruction of fluvial archives on a continental scale. In this study, fluvial profiles are constructed over a wide region (>250 km) along the western margin of the Andes (18°00’S to 20°15’S) and over a time frame from Miocene to Present day. The results reveal that incision patterns reconstructed over a wide area running perpendicular to the main fluvial systems allows a greater spatial and temporal understanding of uplift, specifically;
• Fluvial incision can be reconstructed for ~11 Ma, ~7 Ma, ~3 Ma and the modern day.
• Fluvial incision shows marked spatial compartmentalization across the region with a step like increase from south to north.
• Sector 1 has the highest rates of fluvial incision through time (ca. 200 to 100 m/Myr), Sector 2 shows a lower rate of incision (ca. 100 to 50 m/Myr) and Sector 3 has the lowest rates of incision (<50 m/Myr).
• The main control on the rate of fluvial incision is the extent of the east to west reach of the main rivers across the north to south tectonic provinces.
• Sector 1 spans the entire Coastal Cordillera, Longitudinal Valley and Precordillera to the western edge of the Western Cordillera. This constrains uplift of this region (the western side of the Andes) to a minimum of 1200m in 11 Myr which supports Late Miocene uplift however contrary to these models, it suggests uplift continued at a higher rate from 3 to the present day.
• Sector 2 only spans the Longitudinal Valley and the Precordillera to the western edge of the Western Cordillera. The absence of fluvial systems cutting the Coastal Cordillera accounts for the reduced incision rates of 60 m/Myr which correspond to the published uplift rates for the Coastal Cordillera of 60 m/Myr.
• The eastern edge of Sector 3 is constrained by the Cordillera Domeyko fault system within the Central Precordillera. As such, Sector 3 only places constraints on uplift of the Longitudinal Valley and the western edge of the Precordillera. The absence of the eastern edge of the Precordillera accounts for the decrease in incision rates within this area and places a constraint of uplift generated here in the region of 25 m/Myr to 50 m/Myr.

Most Quaternary fluvial studies tend to be restricted to detailed examination of a single river to understand long-term uplift or climate, mainly due to the scale and intensity of research required to unravel the incision history. Whilst this provides a wealth of knowledge regarding uplift over the reach of the fluvial system, in order to understand orographic scale uplift (and rule out river specific controls) a more regional overview of the fluvial base-level changes is required. Such studies have the potential to address not just the timing of uplift on a continental scale but also any regional spatial controls such as the relative uplift of individual tectonic provinces.
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9. References


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10. Figures
**Figure 1:** a) Sketch of Central Andes showing the five morphotectonic provinces. The main sectors and the fluvial systems within them are highlighted showing catchment area (b) Cross section of main morphotectonic provinces, location shown in Figure 1A. Major tectonic features of the region (Garcia et al., 2004; Victor et al., 2004; Farias et al., 2005; Juez-Larre et al., 2010; Allmendinger and Gonzalez 2014;). Length of reach of the major Sectors (1-3) over the morphotectonic provinces are highlighted.

**Figure 2:** (from left to right) Basic sedimentary overview of the Longitudinal Valley in the study area with the main geomorphic surfaces (AS5, AS4, DS3 and DS2). Climate profile for Longitudinal Valley (Jordan et al. 2014 and Evenstar et al. 2017) with timing for main geomorphic surfaces highlighted and timing of supergene minerals in Atacama (Aranciabia et al. 2009). Elevation profiles for Longitudinal Valley from Evenstar et al. 2015. Solid line represents Late Miocene uplift and dashed line Early Miocene uplift.
Figure 3. (Upper) Large scale map of Northern Chile showing the geomorphic surfaces (1-5) that form the Pacific Paleosurface (PPS). Black lines highlight the topographic cross sections (a-d) in figures 5. Black dashed lines separate regions of Sector 1-3. (Lower) Profile A shows a profile taken west to east across the Longitudinal Valley showing increasing incision of the paleosurfaces to the east through time.
Figure 4; Three cross sections across the region. Locations shown in figure 3.
Profiles b-d are taken NNW to SSE. Black lines show the topographic cross sections across the region. Solid colour lines show the preserved parts of the surface.
with the coloured dashed lines highlight the reconstructed paleo fluvial profiles associated with each surface (AS 4, DS3, DS2 and the modern). Grey areas represent anomalies on the topography profile. Key shows the main features that control the age of the surfaces.

**Figure 5;** A) Google Earth image with 3x vertical exaggeration of DS2 cutting into DS3, leaving DS3 as a series of relict inselberg highs north of Quebrada Lluta. Location of photo of Figure 5B shown, B) Photo of same view taken from the field showing incision of DS3 by DS2 C) Google Earth image with 3x vertical exaggeration of DS3 and DS2 cutting into AS4 forming a lower terrace in Quebrada Camarones with site location of *insitu* exposure age dating in Evenstar et al. 2017.
Figure 6; A- Cross section B showing the different paleo fluvial surfaces draped over an elevation profile. Coloured dots represent locations where the elevation was taken for Figure 6 B-C. B Shows the difference between paleo fluvial surfaces and modern fluvial profiles. C Incision rate through time calculated using the difference in elevation between the paleo fluvial surfaces and modern fluvial system divided by age of paleo fluvial surface.
Figure 7; (Top) Elevation profile along the eastern edge of the Longitudinal Valley from Evenstar et al., 2017 highlighting study area (Sector 1, Sector 2 and Sector 3 (S3)). At the base of the elevation profile the black dots show the main fluvial systems from the Precordillera (the coloured dots relate to the dots in the cumulative drainage area graph below). (Bottom) cumulative drainage area of studied fluvial systems against length of fluvial system, this data was initially presented in Hoke et al. 2007 (supplementary material). A summary of cumulative drainage areas and fluvial length (distance from mouth) (Supplementary material in Hoke et al. 2007 which have been combined and summarized in this paper)