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Orogenic-orographic feedback and the rise of the Central Andes

L.A. Evenstar [a,*], A.J. Hartley [b], A.E. Mather [c]

[a] School of Applied Science, University of Brighton, UK
[b] Department of Geology and Geophysics, University of Aberdeen, Aberdeen, UK
[c] Department of Geography, Earth and Environmental Sciences, University of Plymouth, UK

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ABSTRACT

The rise of large mountain ranges is considered to be driven by tectonics potentially coupled with climate driven-erosion, although the role of this coupling remains uncertain. The arid climate of the Central Andes allows us to strengthen our understanding of the relative roles of these processes in mountain range development globally. Here we compile estimates of exhumation, sedimentation, aridity and surface uplift across the Central Andes for the last 50 Ma. We aim to place constraints on the relative timing of rock uplift (displacement of rocks with respect to the geoid), exhumation (displacement of rocks with respect to the surface) and surface uplift (displacement of the earth's surface with respect to the geoid). We show that initial rock uplift of the Andes extends back at least 50 Myr. This rock uplift generated orographically driven precipitation on windward slopes leading to increased exhumation but limited preservation of surface uplift. Eastward propagation of the mountain range resulted in increasingly extreme orographic effects on the leeward side amplifying aridity, reducing exhumation and increasing preservation of surface uplift. Essentially, surface uplift shows a ∼5-10 Myr lag behind initial rock uplift as the Andes grow asymmetrically through time. We suggest that an eastward propagating pattern of exhumation, aridity and surface uplift with time, reconciles previous contradictory models of Andean uplift.

One Sentence Summary: Uplift of the Central Andes is reconstructed over the last 50 Myr and the precise relationship between roles of tectonics and climate established.

1. Background

The relief of mountain ranges is commonly attributed to a combination of climate change and/or tectonics (e.g., England and Molnar, 1990; Avouac and Burov, 1996; Willett, 1999; Whipple, 2009). The precise role of these processes in controlling mountain range development is difficult to distinguish, as criteria characteristic of each specific driving mechanism are often challenging to isolate and reconstruct, particularly through time (England and Molnar, 1990; Koons, 1990). Because of this ambiguity in recognising tectonic vs climatic drivers in controlling mountain range relief, a range of different theories may be equally valid. For example, in the Central Andes, slow, long term uplift (gradual surface uplift initiated in the late Eocene) is favoured by some workers (e.g., Barke and Lamb, 2006; Barnes and Ehlers, 2009) whereas late, rapid uplift (surface uplift from the Middle Miocene onwards) is favoured by others (e.g., Garzione et al., 2006; Ghosh et al., 2006; Garzione et al., 2017).

In the present day Central Andes shortening is driven by convergence of the Nazca and South American plates and is manifested presently in both the eastward propagation of the Sub-Andean thrust belt into the foreland of Argentina and Bolivia (Horton and DeCelles, 1997) and westward directed compressional structures in the forearc (Victor et al., 2004; Farías et al., 2005). The prevailing climate within the Central Andes (20-30°S) is arid due to large-scale atmospheric circulation and continentality (Fig. 1). The movement of air masses over the Andes creates small deviations from this background arid climate with enhanced orographic effects (Fig. 1A; Bookhagen and Strecker, 2008). For example, along the windward, eastern flank of the Andes precipitation and erosion is focused between 500 and 3500 m altitude (Fig. 1A; Bookhagen and Strecker, 2008). Both at higher elevations and west of 3500 m altitude, orographic effects result in a progressive decrease in precipitation, exhumation and associated sedimentation in surrounding basins in the hinterland (Fig. 1A). We refer to this potential relationship between uplift and climate as the orogenic-orographic feedback effect (Willett, 1999). We integrate data from low temperature thermochronology (Fig. 2 and 3E), rates of sediment accumulation (Fig. 3C) and dated supergene copper enrich-

* Corresponding author.
E-mail address: l.evenstar@brighton.ac.uk (L.A. Evenstar).

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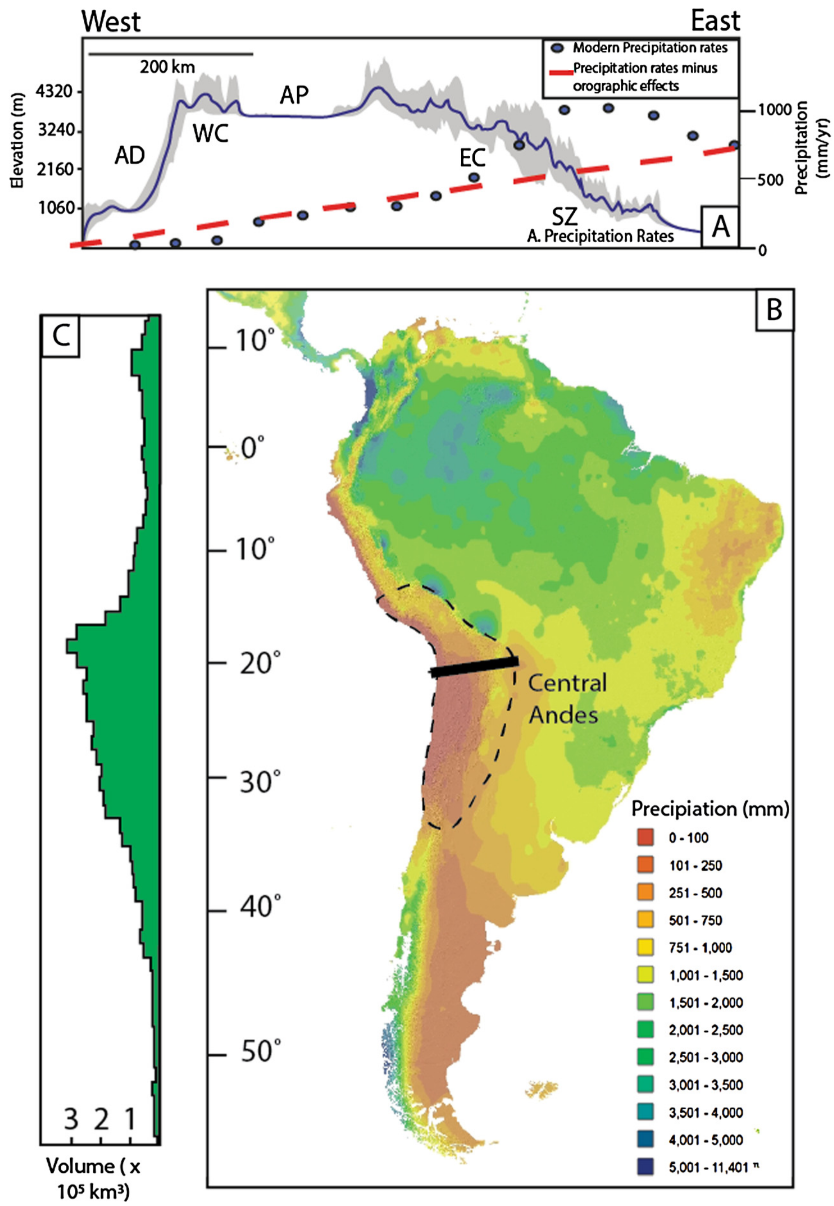

Fig. 1. A) Cross section across Central Andes showing main morphotectonic units; Atacama Desert (AD), Western Cordillera (WC), Altiplano (AP), Eastern Cordillera (EC), and Sub-Andean zone (SZ). Swath profiles shows the mean elevation with grey area highlighting the elevation of the Q1-Q3 across a 50 km wide range. Precipitation values across the Central Andes at 19° in blue dots (Precipitation profiles across the Andes in all regions shown in supplementary material) (Houston and Hartley, 2003). Red dashed lines show the precipitation rates due to continentality minus the orographic effect on precipitation at (Houston and Hartley, 2003). B) Mean annual precipitation, overlain on shaded-relief map of western South America. Precipitation map of South America showing the orographic effect in the Central Andes C) Volume of Andes above sea level calculated from 18 latitude bins (Montgomery et al., 2001). (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

ment (Fig. 2 and 3D) as different temporal and spatial proxies for climate, to reconstruct the relationship between surface uplift, exhumation, sedimentation and aridity through time and across the different morphotectonic provinces of the Central Andes over the last 50 Myrs (see Supplementary Material for full datasets over this region). These data are used to propose a potential orogenic-orographic feedback effect that we argue facilitates the preservation of uplift in the Central Andes over this time period.

2. Morphology and tectonics

Within the Central Andes (15° to 27°S), a series of morphotectonic regions are recognised (Fig. 1A). The central region comprises the Altiplano (AP), an internally drained plateau which reaches widths of up to 250 km with an average elevation of 3700 m (Fig. 1A). The western side of the plateau is bordered by the Western Cordillera (WC) with peak heights of up to 6 km and hosts the modern magmatic arc. The cordillera descends sharply westward towards the Pacific Ocean. South of 18°S, the Atacama Desert (AD) rests at the base of the Western Cordillera and forms a strip up to 100 km wide parallel to the Pacific coast. The eastern edge of the AP is bounded by the >5 km high peaks of the east-verging thrust belts of the Eastern Cordillera (EC) and the Sub-Andean zone (SZ) to the east.

3. Climate and erosional history of the Andes

Globally, within the arid climatic realm in particular (i.e. hyper arid to sub humid), a significant positive relationship has been demonstrated to exist between precipitation and erosion (e.g., Hooke, 2000). Studies indicate that the erosional impact of further increases in precipitation tends to be buffered by the role

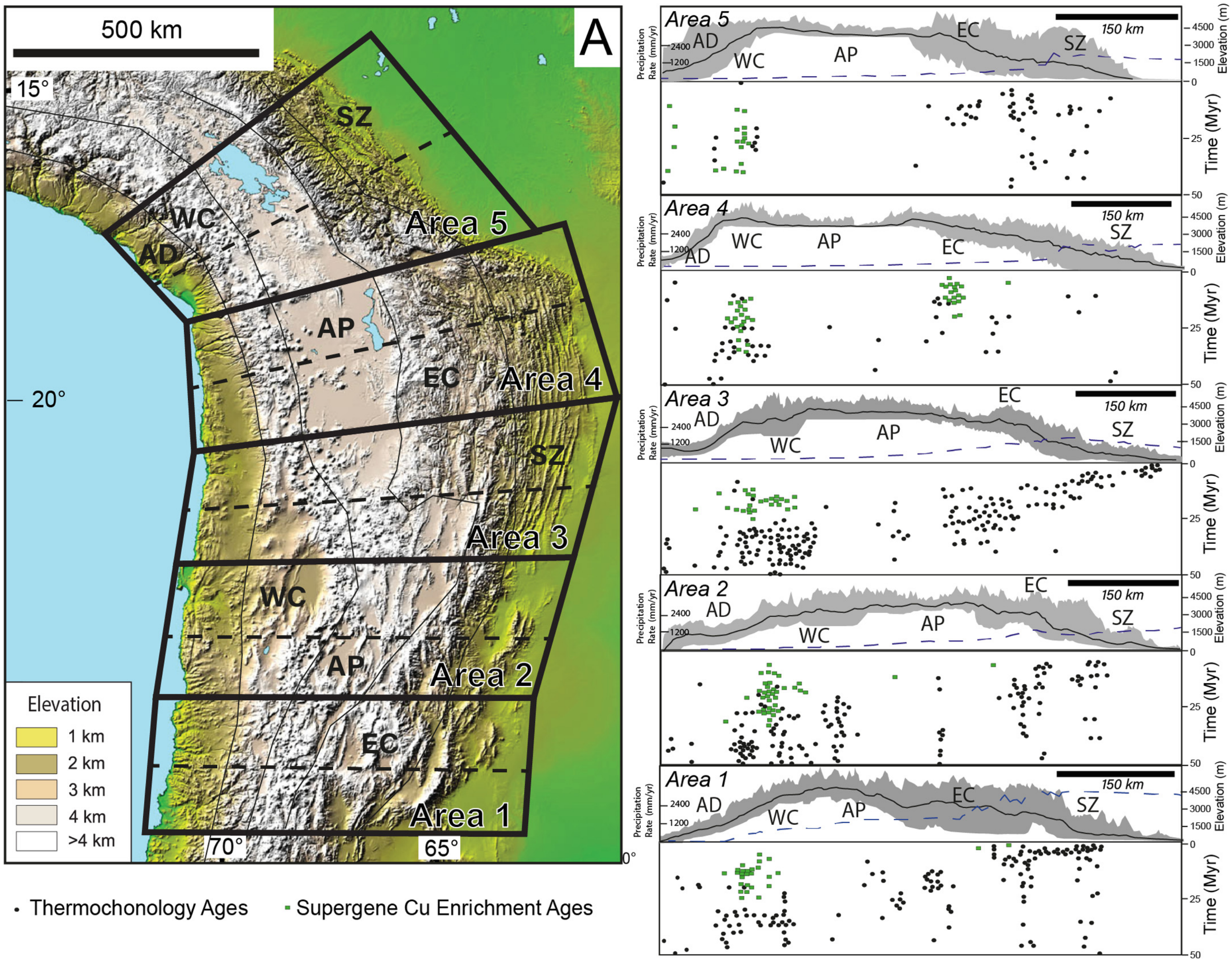

Fig. 2. Reconstruction of supergene enrichment ages and exhumation data across a west to east transect in the Central Andes. Left; The Central Andes is separated into 5 areas running from south to north (area 1-5). Right; Each area shows the swath profiles across the region with the mean elevation with grey area highlighting the elevation of the Q1-Q3 across a 50 km wide range with precipitation rates, thermochronology ages (Apatite fission track, Apatite U-Th/He and Zircon U-Th/He are differentiated in Fig. 3 and detailed data available is supplementary materials), and supergene copper enrichment ages were projected along the strike of the tectonic grain relative to the east-west profile in each individual area (detailed data available in supplementary materials).

of enhanced vegetation cover on slope stabilisation (e.g., Hooke, 2000). Within the modern-day Andes, changes in precipitation and the associated relationship with erosion rates are thus particularly apparent (Schaller et al., 2018). For example, along the SZ, in the Central Andes, precipitation is enhanced due to orographic effects (Bookhagen and Strecker, 2008). In the southern Central Andes (19° to 27°S) orographic effects promote a change from <500 mm/yr (assuming no topography) to 500-1000 mm/yr (Houston and Hartley, 2003) (Fig. 1A). This places the SZ at the higher end of semi-arid to dry subhumid climate conditions where erosion rates peak (West of the SZ the climate becomes increasingly arid to the AD which has one of the lowest erosional rates in the world (Dunai et al., 2005; Kober et al., 2007)). Whilst it is noted that precipitation rates vary from north to south across the Central Andes (see Fig. 2), the overall pattern is one of increased precipitation in the eastern foothills of the Andes due to enhanced orographic effects.

Low temperature thermochronological studies can be used to constrain the timing of rock exhumation and fluctuations in erosion over orographic relief (Reiners and Brandon, 2006). They record the time a mineral passes through a given closure temperature interval, which varies for different methods (e.g. Apatite fission track ∼ 110°C, Apatite U-Th/He ∼ 75°C and Zircon U-Th/He ∼ 200°C (Ehlers et al., 2005)). The effective closure temperature depends on the geothermal gradient which can vary both spatially and temporally through time and be affected by local deformation kinematics (Reiners and Brandon, 2006) and long wavelength surface topography (Braun et al., 2012). We combine all previous low temperature thermochronological data from the Central Andes (see supplementary material) as a proxy for rock exhumation assuming a broadly similar subsurface thermal structure across the region and only vertical rock advection. Although we recognise that this approach is an oversimplification which may over- or under-estimate times of exhumation in certain areas, we contend that the clustering of datapoints along transects in time, highlights the time periods when exhumation was highest (Fig. 2). This rock exhumation data combined with sediment accumulation rates in adjacent basins (recording erosion in proximal source terrains), can be used as a proxy to infer increased erosion rates that we argue are a function of orographically driven precipitation rates (the higher end of semi-arid to dry subhumid climate conditions where erosion rates peak) (Bookhagen and Strecker, 2008; Norton and

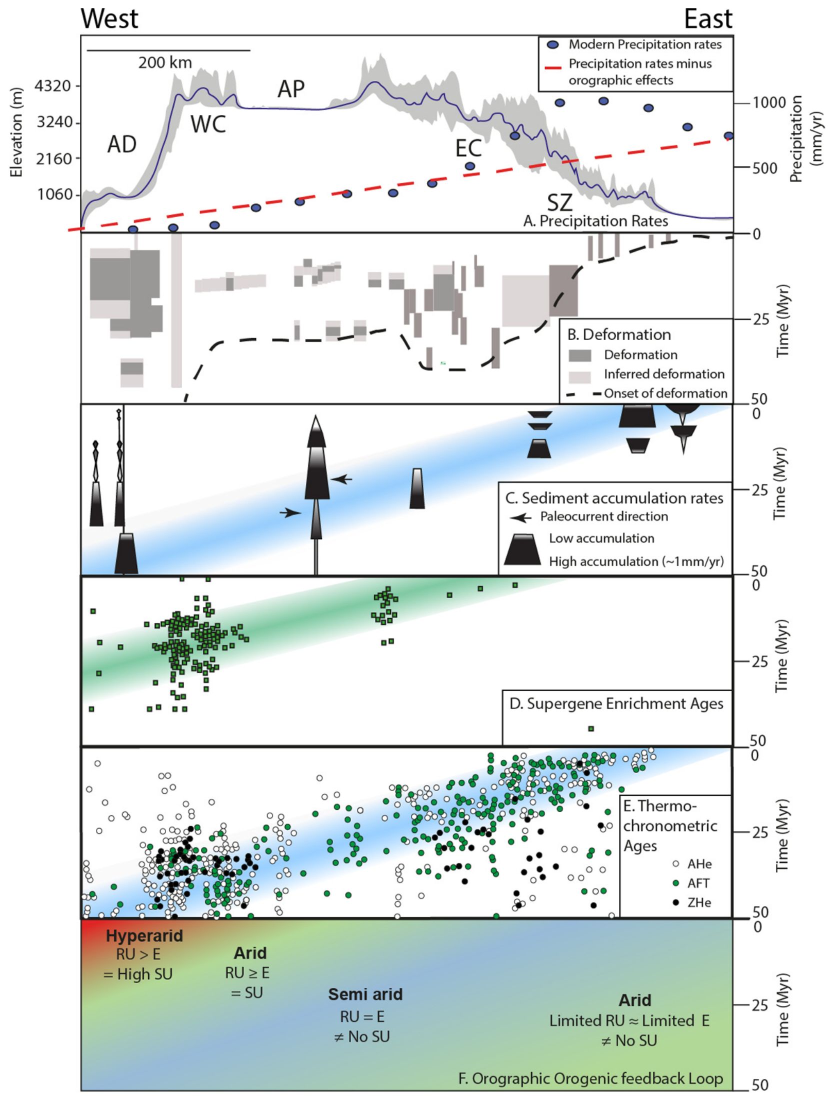

Fig. 3. Reconstruction of deformation, sediment accumulation rates, supergene enrichment ages, exhumation and paleoelevation data across a west to east transect in the Central Andes. A) Cross section of across Central Andes showing main morphotectonic units; Atacama Desert (AD), Western Cordillera (WC), Altiplano (AP), Eastern Cordillera (EC) and Sub-Andean zone (SZ). Swath profile shows the mean elevation with grey area highlighting the elevation of the Q1-Q3 across a 50 km wide range. Precipitation values across the Central Andes in blue dot (Houston and Hartley, 2003). Red dashed lines show the precipitation rates due to continentality minus the orographic effect on precipitation (Houston and Hartley, 2003). B) Summary of deformation studies across the Central Andes modified from Oncken et al. (2006) to include studies; Sáez et al., 1999; Charrier et al., 2013; Wörner et al., 2002; van Zalinge et al., 2017. C) Relative Sediment accumulation rate summaries constructed from Area 3 and 4 in Fig. 2 (Reynolds et al., 2000; Echavarria et al., 2003; Garzione et al., 2006; Hampton and Horton, 2007; Uba et al., 2009; Jordan et al., 2014 and reference within Evenstar et al., 2017), and D) Summary of supergene copper enrichment ages across the Andes with main phase of enrichment highlighted in light green (table of data available in supplementary material). E) Summary of thermochronology ages across Andes with main phase of exhumation highlighted in light blue (table of data available in supplementary material). F) Summary sketch of the migration of the orographic-orographic feedback effect through time, RU = rock uplift, E = erosion, SU - surface uplift.

Schlunegger, 2011, Fig. 2 and Fig. 3C and E). Using low temperature thermochronological data and sediment accumulation rates for the last 50 Myr, the passage of this orographically generated erosion event can be reconstructed (Fig. 2 and 3). Data shown in Fig. 2 are separated into 5 east-west transects that show limited along strike (north-south) variation and are summarised in Fig. 3E. These data record the migration of a distinct pulse of enhanced erosion across the Central Andes (Fig. 3 C, E and G), that initiated in the Early Eocene along the western edge of the Andes and migrated eastwards to the Sub-Andean zone at the present day. For example, in the Oligocene in the AP, sediments sourced from the WC record increased accumulation rates which correspond to a period of increased thermochronological ages in the WC (Fig. 3C and E). An additional increase in Early Miocene sediment accumulation in the AP sourced from the east corresponds to an increase in thermochronological ages in the EC (Hampton and Horton, 2007; Barnes et al., 2008; Anderson et al., 2018) (Fig. 3C and E).

The sedimentation and exhumation data in Figs. 2 and 3 illustrate that there are only a limited number of dates that are younger than the main data clusters, this is interpreted to represent a rapid decrease in erosion and highlights a diachronous pattern in exhumation. This shows exhumation and sedimentation in proximal basins largely ceasing by the Early Oligocene in the WC and by the Middle Miocene in the EC. This rapid decrease in erosion is detached from deformation rates which continue till the Late Miocene to present day (Fig. 3B and E). For example, deformation continued after the Middle Miocene along the western edge of the Andes (Sáez et al., 1999; Wörner et al., 2002; Oncken et al., 2006; Charrier et al., 2013; van Zalinge et al., 2017) but, due to the low erosion rates associated with enhanced aridity (Dunai et al., 2005; Evenstar et al., 2017), this tectonic signature is preserved solely in the geomorphology.

In all but the northern most profile, supergene copper enrichment post-dates the age of exhumation and rapid sediment

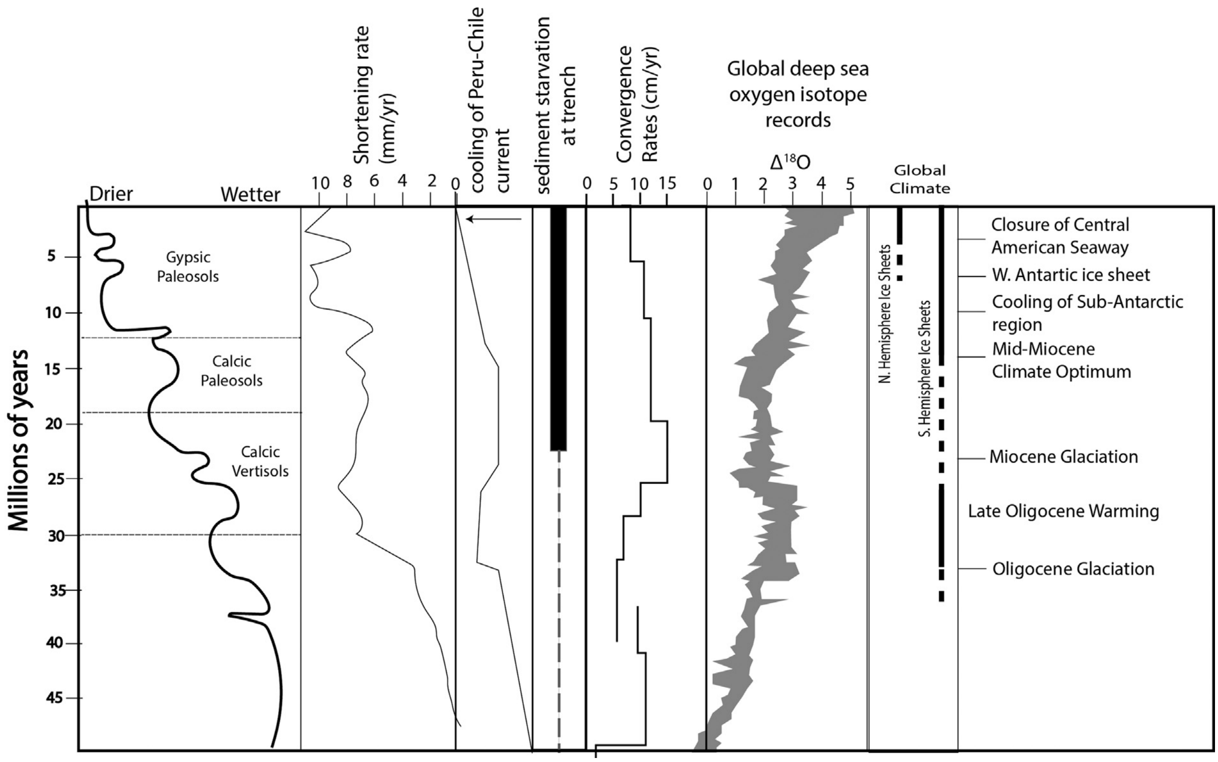

Fig. 4. Summary of both local and global climate combined with shortening and convergence rates of the Nazca and South American plates. Climate in the Atacama Desert (AD) from Jordan et al., 2014; Evenstar et al., 2017 and Rech et al., 2019. Shortening rates for Andean mountain chain (Oncken et al., 2006). Cooling of Peru-Chile current (Lamb and Davis, 2003); Sediment starvation at trench based on timing of uplift of the Coastal Cordillera (summarised in Evenstar et al., 2017); Convergence rates of the Nazca plate and Central South America Plate (Oncken et al., 2006); Global deep-sea isotope records (Zachos et al., 2001).

accumulation rates (Fig. 2 and Fig. 3D). Supergene copper mineralisation occurs where meteoric water migrates from the surface to the water table (recharge) requiring precipitation of at least 100 to 200 mm/yr (Clark et al., 1990; Shaw et al., 2021). For supergene copper deposits to be formed and preserved requires very low erosion rates (Sanchez et al., 2018) that are most commonly found under semi-arid to arid climatic conditions (Hooke, 2000), whereas the cessation of enrichment records a decrease in precipitation to <100 mm/yr at the transition from arid to hyper-arid conditions (Clark et al., 1990; Shaw et al., 2021). The timing of the age of supergene copper enrichment (and subsequent cessation) across the Central Andes is shown in Fig. 2 and 3D. Data are separated into east to west transects and display limited along strike (north-south) variability except in the northernmost area where thermochronological and supergene enrichment data are limited (Fig. 2). Supergene copper enrichment started in the AD in the late Eocene and migrated eastwards through time, occurring in the WC from Early Oligocene and EC in the Late Miocene. Supergene age dates immediately postdate the thermochronological age data and high sediment accumulation rates. The cessation of enrichment can also record the switch to hyperaridity which was also diachronous, finishing in the Mid-Miocene in the AD and substantially later in the late Miocene along the western edge of the WC. This climatic signature is supported by sedimentological data, sedimentation rates, paleosol type and paleosurface analysis (Fig. 4) within the AD, where a long term drying trend from the higher end of semi-arid in the Eocene to Early Miocene, arid to semi-arid from Early Miocene to Mid-Miocene and arid to hyper-arid from Mid-Miocene to present day is recorded in numerous studies (Jordan et al., 2014; Evenstar et al., 2017; Rech et al., 2019) (Fig. 4).

4. Surface uplift history of the Andes

Thirty-one paleoelevation studies in the Central Andes utilising paleoclimate and paleoaltimetry proxies (e.g., Ghosh et al., 2006; Scott et al., 2018; for full list see supplementary material) geomorphic analysis of erosion surfaces (e.g., Victor et al., 2004; Barke and Lamb, 2006; for full list see supplementary material) and reconstruction of fluvial incision rates (e.g. Schildgen et al., 2007; Evenstar et al., 2020; for full list see supplementary material) are compiled for the Western Cordillera, Altiplano and Eastern Cordillera in Figs. 5 and 6. The latter two, erosional surfaces and fluvial incision rates, can be used as proxies for the timing of surface uplift in regions which are highly active with large rivers (Demoulin et al., 2017 and references within). To assess these estimates of surface uplift, the range in proposed ages and rates of surface uplift and published errors, were divided into three east-to west oriented transects running from north to south (Fig. 5). These three transects include the three main morphotectonic provinces (WC, AP and EC) (Fig. 5). Three of the paleoclimate and paleoaltimetry proxies (Singewald and Berry, 1922; Muñoz and Charrier, 1996; Graham et al., 2001) may be subject to unconstrained systematic errors due to assumptions about the modern climate elevation relationship (Ehlers and Poulsen, 2009) however the remaining twenty eight studies have either been reinterpreted subsequently to take into account these variation or include them in their initial data. Fig. 5 shows only limited along strike (north-south) variation and the data is summarised in Fig. 6. The clustering of the data permit an interpretation of diachronous surface uplift from west to east through time (Fig. 6). The WC shows initial uplift in the Oligocene with substantial surface uplift (50% of present day) prior to the Mid-Miocene and continued uplift from the Mid-Miocene to present day (e.g., Evenstar et al., 2020; Hoke et al., 2007). Within the AP, surface uplift was potentially initi-

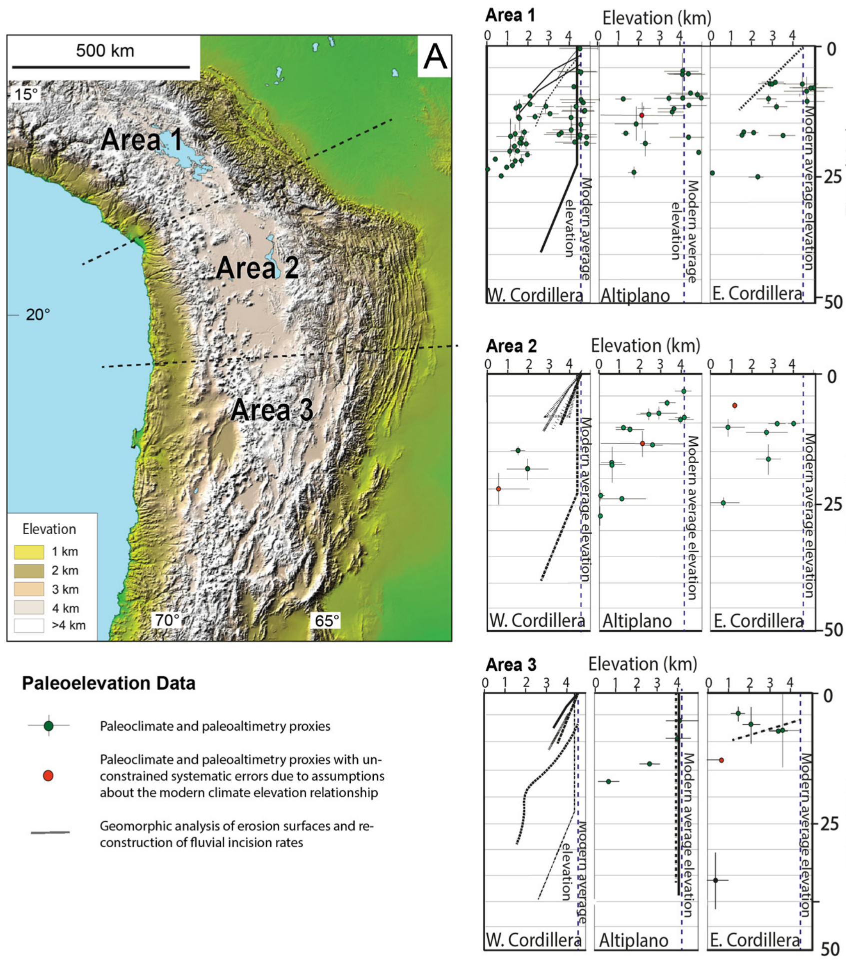

Fig. 5. Summary of paleoelevation data (detailed data available in supplementary material) across the Central Andes. Left; shows the location of each study in the Central Andes. The Central Andes is separated into three areas (1-3) running north to south to highlight the limited spatial difference along strike. Right; Paleoelevation data from each area separated into east to west morphotectonic provinces; Western Cordillera (W. Cordillera), Altiplano and Eastern Cordillera (E. Cordillera) to shows the similar uplift histories regardless of along strike variations. Light grey highlights the max-min range in paleoelvation across all areas in each morphotectonic province (WC, AP and EC) with the dark grey defining a grouping of data related to surface uplift.

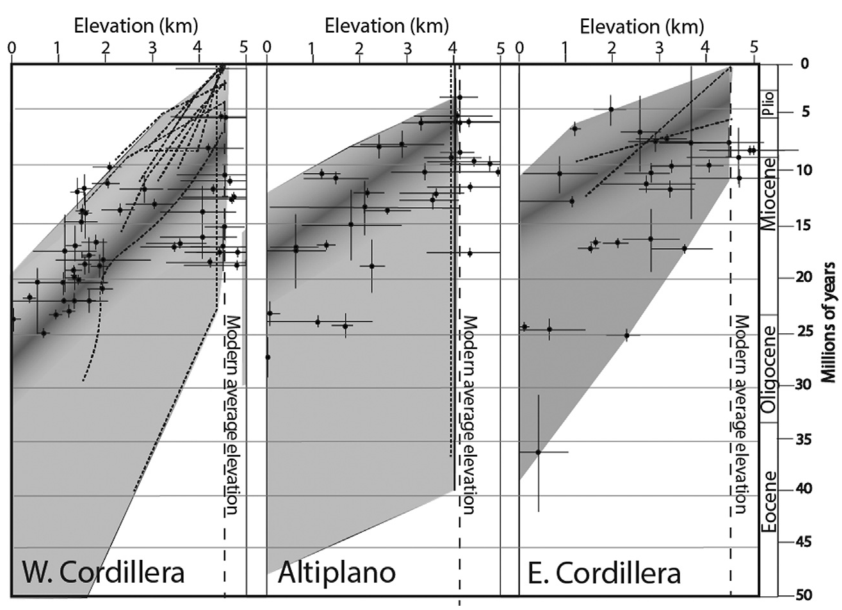

Fig. 6. Summary of all paleoelevation data (presented in Fig. 5) across the Central Andes separated into the three main morphotectonic provinces; Western Cordillera (W. Cordillera), Altiplano and Eastern Cordillera (E. Cordillera). Light grey highlights the max-min range in paleoelvation across all areas in each morphotectonic province (WC, AP and EC) with the dark grey defining a grouping of data related to surface uplift.

ated in the Early Miocene, reaching current elevations by the Late Miocene (Garzione et al., 2008, 2017). In the EC, paleoelevation data are more limited and varied. Potentially up to 2 km of uplift is interpreted to have occurred from the mid-late Miocene and which continues to the present day (Whipple and Gasparini, 2014; Garzione et al., 2017). In summary, both the initiation and main phase of surface uplift in the Central Andes is consistent with a diachronous eastward migration from the WC through the AP into the EC.

5. Discussion

The combination of data sets presented above helps place constraints on the relative importance of climate and tectonics in creating the Central Andean orogen over the last 50 Myrs. The exhumation, deformation and sediment accumulation datasets record a pulse of enhanced exhumation across the Central Andes initiated in the Early Eocene along the western edge of the Andes and which migrated eastwards to the Sub-Andean zone to the present day. Succeeding this, exhumation and sediment accumulation rates decrease diachronously, ceasing by the Early Oligocene in the WC and the Middle Miocene in the EC suggesting a shift to drier conditions which is supported by an increase in preserved supergene copper enrichment at this time. This corresponds to estimates of surface uplift as interpreted from paleoelevation studies (Fig. 6). The cessation of supergene enrichment, but not surface uplift, in the Mid-Miocene in the AD and substantially later in the late Miocene along the western edge of the WC records the final switch to hyperaridity in the region.

Here we propose a model to explain these datasets and attempt to reconcile previous uplift models. The formation of the Andes would have generated substantial relief, a prerequisite for high exhumation rates, however the arid background climate acted as a control to limit exhumation. Uplift generated an orographic effect on the eastern, windward side of the proto-Andes changing the hinterland climate from arid to semi-arid. This will have increased erosional rates and limited net surface uplift, as rock uplift will have been counterbalanced by erosion (Fig. 3E and F). As topography grew and migrated eastwards, orographic precipitation was suppressed on the western side of the proto-Andes shifting the climate to more arid conditions (Fig. 3F and 7). This is recorded by the decrease in exhumation and sedimentation rates and an increase in formation and preservation of supergene copper enrichment deposits (Fig. 3 and 7). Increased aridity and decreased erosion led to a progressive increase in surface uplift, leading to a positive feedback mechanism where lateral (eastward) expansion of the orogen generated increasingly arid conditions in the west, ultimately promoting hyper-aridity in the AD in the Mid-Miocene (Fig. 4 and 7). In the AD, WC and AP deformation and uplift continued whilst aridity increased but no associated exhumation and very limited coarse sediment deposition occurred - indicating that exhumation effectively became decoupled from deformation and uplift due to increased aridity (Fig. 3B). Importantly, these observations indicate that the orogenic-orographic feedback effect which dominates the Central Andes at the present day has been in place since the mid Eocene, migrating ~600 km from west to east over ~50 Ma and is responsible for the proposed asymmetrical uplift profile of the Andes.

The orogenic-orographic feedback effect outlined above could explain apparent discrepancies between the principal end-member models for Andean uplift: slow and gradual since the Eocene vs. rapid and late from the Miocene onwards (Barnes and Ehlers, 2009). It is clear that rock uplift or growth of the Andes has occurred since at least the Eocene in the west (AD and WC). However, where initial rock uplift took place, it was counter-balanced by higher erosion in a relatively more humid climatic setting, leading to potentially overall low surface uplift rates (Fig. 6 and 7). Substantial surface uplift only occurred as the climate became drier following rock uplift with a lag time of ~5-10 Myr and migrated eastward through time. This potential time lag could allow discrepancies between previously proposed uplift models (e.g. Garzione et al., 2006; Hartley et al., 2007) to be explained. For example, thermochronological data, sedimentation rates, crustal thickening and shortening all record long-term rock uplift rates. In contrast, palaeobotany, clumped isotopes, fluvial incision rates and paleosurface uplift rates all record surface uplift that post dates rock uplift (Ghosh et al., 2006; Garzione et al., 2006), and as a result, may not necessarily reflect long-term rock uplift rates. Consequently, whilst the observations and interpretation from the different techniques maybe correct, the nature of the uplift they record differs such that the discrepancy between slow versus rapid uplift of the Andes can be explained. Other models (e.g., Lamb and Davis, 2003) suggest that Andean uplift was promoted by global climate cooling which increased aridity, decreased erosion and reduced sediment supply to the subduction zone, thus increasing plate friction along the basal megathrust and driving uplift. Friction along the basal megathrust is important for dictating and sustaining the relief of the mountain range (e.g. Dielforder et al., 2020) but climate is more likely to control the preservation of the mountain belt and ultimately the range width. For example, the late Oligocene onset of sediment starvation at the trench (Madella et al., 2018) is more closely linked with the timing of aridity along the western margin generated by orographic effects than with global cooling patterns, which show cooling some 10 Ma later from the Mid Miocene onwards (Fig. 4). This suggests

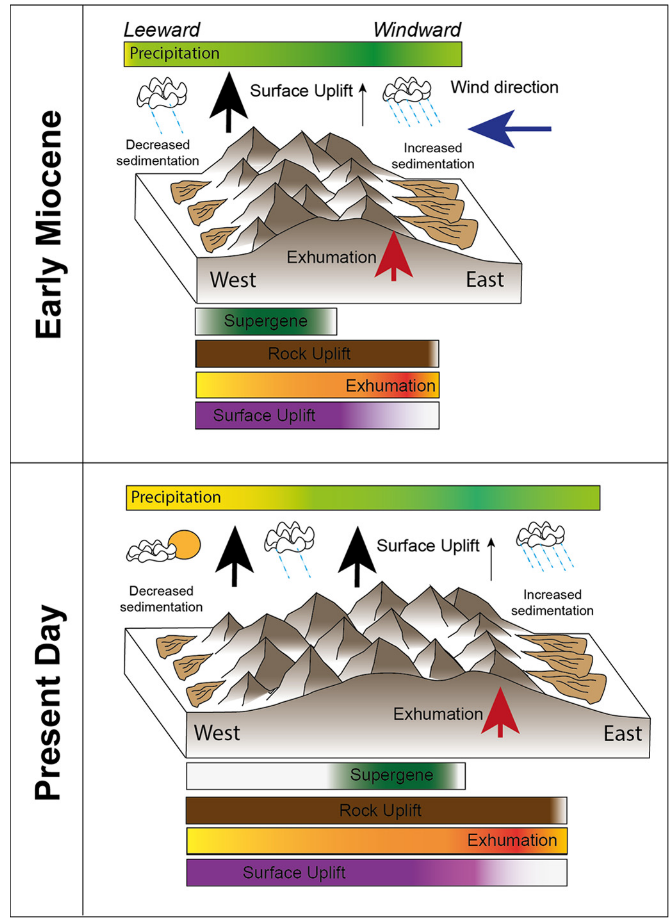

Fig. 7. Summary figure of interaction of the orographic-orogenic feedback effect with the asymmetric growth of the Andes. Asymmetric growth of the Central Andes and its interaction with the climate from the Early Eocene to the present day.

that increased friction along megathrusts on the leeward side of mountain chains may be a symptom of the orogenic—orographic feedback effect rather than the cause.

The data sets presented here show that one of the key features in the formation of the Central Andean orogen is latitude. Location within the southern hemisphere arid to semi-arid region means that orogenic processes are susceptible to subtle fluctuations in precipitation rates generated by orographic relief. The prevailing aridity thus allows orographic-orogenic effects to be more clearly traced within the Central Andes than in other, more-humid orogenic systems where vegetation and associated effects may mask the erosional rainfall-signature as the orogeny approach a steady-state (Willett, 1999).

6. Conclusions

Tectonics driven by plate boundary forces play a first order control on deformation and ultimate height of the Andes but do not necessarily result in the preservation of uplift and width of the mountain belt which is controlled by climate. An analysis of low temperature thermochronology, sediment accumulation rates, supergene enrichment and paleoelevation data provides a record of the spatial and temporal distribution of surface and rock uplift for the last 50 Myr in the Central Andes. This allows identification of the orogenic-orographic feedback effect where initial uplift and associated orographic effects impact the background climate driving high erosional events on the windward side while reducing erosion on the leeward side. This leads to asymmetrical growth of the orogen as progressive accretion of ranges on the windward side generates increased aridity on the leeward side as they become gradually distant from the erosional focus. In essence, surface uplift lags significantly behind initial deformation through this orographic-orogenic feedback effect. In the Andes, this growth is from the west to east, has led to the continual eastward extension of the Central Andes over at least the last 50 Ma.

Previous work has attributed a single uplift history from individual studies for the entire Central Andes (Garzione et al., 2008). We show that uplift rate and magnitude varies spatially along the >700 km width of the Andes and can be explained by the orogenic-orographic feedback effect. With initial rapid rock uplift and associated exhumation on the east flank of the Andes leading to potentially limited surface uplift through to slow gradual surface uplift associated with increasingly dry climate leading to a decrease in erosion.

The orogenic-orographic feedback is recognised as an important control on the asymmetry and steady state erosion in mountain ranges (Willett, 1999; Willett and Brandon, 2002). Within the Central Andes, as a result of the low erosion rates and high preservation potential of related surface deformation, the feedback effect can be recognised over long term times scales (<10 Myr). This provides opportunity for a clear understanding of the roles of tectonics and climate in driving orogenic development which will potentially be applicable to other mountain ranges.

CRediT authorship contribution statement

L.A. Evenstar: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft. **A.J. Hartley:** Conceptualization, Investigation, Visualization, Writing – original draft. **A.E. Mather:** Conceptualization, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data is available in the main text or the supplementary materials. Any additions material requests should be directed to L.A. Evenstar.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2022.117931.

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