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ORIGINAL PAPER

Sedimentology-based reconstructions of paleoclimate changes in the Central Andes in response to the uplift of the Andes, Arica region between 19 and 21°S latitude, northern Chile

Fritz Schlunegger · Florian Kober · Gerold Zeilinger · Ruedi von Rotz

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Abstract We focus on the sedimentological record of the Middle Miocene to modern deposits in the Andes of northern Chile between 19 and 21°S. These sediments, deposited at the Western Escarpment of the Central Depression, indicate successively more moisture on the western margin of the Altiplano and the Western Cordillera where the sources are. At the Pacific Coast, 20-Ma-old exposure ages and salic gypsisols reflect an existing and ongoing hyperarid climate. We interpret the increased divergence of climates between the Coast and the Altiplano as consequence of the Andean rise to elevations higher than approximately 2,500 m a.s.l., when the topography of the Altiplano was sufficiently high and areally extensive to attract Atlantic moisture. Accordingly, the inferred general increase in run-off was closely coupled with the uplift of the Andes if the steady rise model applies. In case that the rapid rise model for Andean uplift is correct, the inferred changes in sediment transport would have occurred independently of uplift, requiring an alternative, yet unknown driver.

Keywords Andes · Arica area · Stratigraphy · Paleoclimate change

F. Schlunegger (✉)
Institute of Geological Sciences,
University of Bern, Bern, Switzerland
e-mail: fritz.schlunegger@geo.unibe.ch

F. Kober
Department of Earth Sciences, ETZ Zürich, Zurich, Switzerland

G. Zeilinger
Geological Institute, University of Potsdam, Potsdam, Germany

R. von Rotz
ETZ Zürich, Oshakati, Namibia

Introduction

The search for possible links between the uplift of the Andes and the development of paleoclimate has received much attention during the past years but has yielded partially conflicting interpretations. The controversy focuses on the questions about (1) when and where the hyperarid climate along the Pacific coast and in the Atacama Desert commenced, (2) how this extremely dry climate can be reconciled with the perennial water run-off in rivers that have their sources in the Western Cordillera and the western margin of the Altiplano Plateau, and (3) how the development of paleoclimates can be related to the uplift of the Andes (e.g. Strecker et al. 2007). For instance, Alpers and Brimhall (1988) and Sillitoe and McKee (1996) related changes in weathering rates and conditions of supergene mineralization partially to a Miocene phase of uplift. Also, according to these authors, the establishment of the Antarctic ice cap at ca. 15 Ma and the increasing upwelling intensity in the Pacific exerted an additional control on climate in northern Chile. They considered that these effects were amplified by the uplift of the Andes to half of their current elevations. In contrast, Early Miocene evaporates deposited in the Central Depression (Hartley and Chong 2002) and surface exposure ages older than 20 Ma (Dunai et al. 2005; Kober et al. 2007; Evenstar et al. 2009) suggest that aridity in northern Chile commenced earlier and was presumably not linked with the Andean rise (e.g. Clarke 2006). Nevertheless, short-lived pluvial phases did leave their signature in the hyperarid realm along the Pacific coast as recorded by fluvial conglomerates (Kiefer et al. 1997; Evenstar et al. 2009).

A further debated question targets the chronology of the Andean rise. In a recent publication, Barnes and Ehlers (2009) discussed two end-member models including (1) the rapid rise model where the Andes raised by approximately 2.5 km between ca. 10–6 Ma and (2) the model of a continuous rise between ca. 40 Ma and the present. Barnes and Ehlers (2009) considered the latter model to be more consistent with published geochronological, geomorphological, and geochemical data.

Here, we contribute to the ongoing debate about recorders of potential climate shifts in northern Chile and how these changes can be related to the rise of the Andes. We focus on the stratigraphic records of sedimentary basins on the western flank of the Central Andes (Arica region, approximately 19–21°S; Fig. 1). We use these sedimentological archives to infer a continuous increase in run-off of rivers with sources in the high Andes since the Miocene. We do not discard the possibility that the interpreted trend of more run-off was interrupted by dry phases. We then relate this change in hydrology and sediment transport to the results of paleoclimate models and conclude that the recorded general increase in run-off was closely coupled with the uplift of the Andes if the steady rise model (Barnes and Ehlers 2009) applies. In case that the rapid rise model for Andean uplift is correct, the inferred changes in sediment transport would have occurred independently of uplift, requiring an alternative, yet unknown driver.

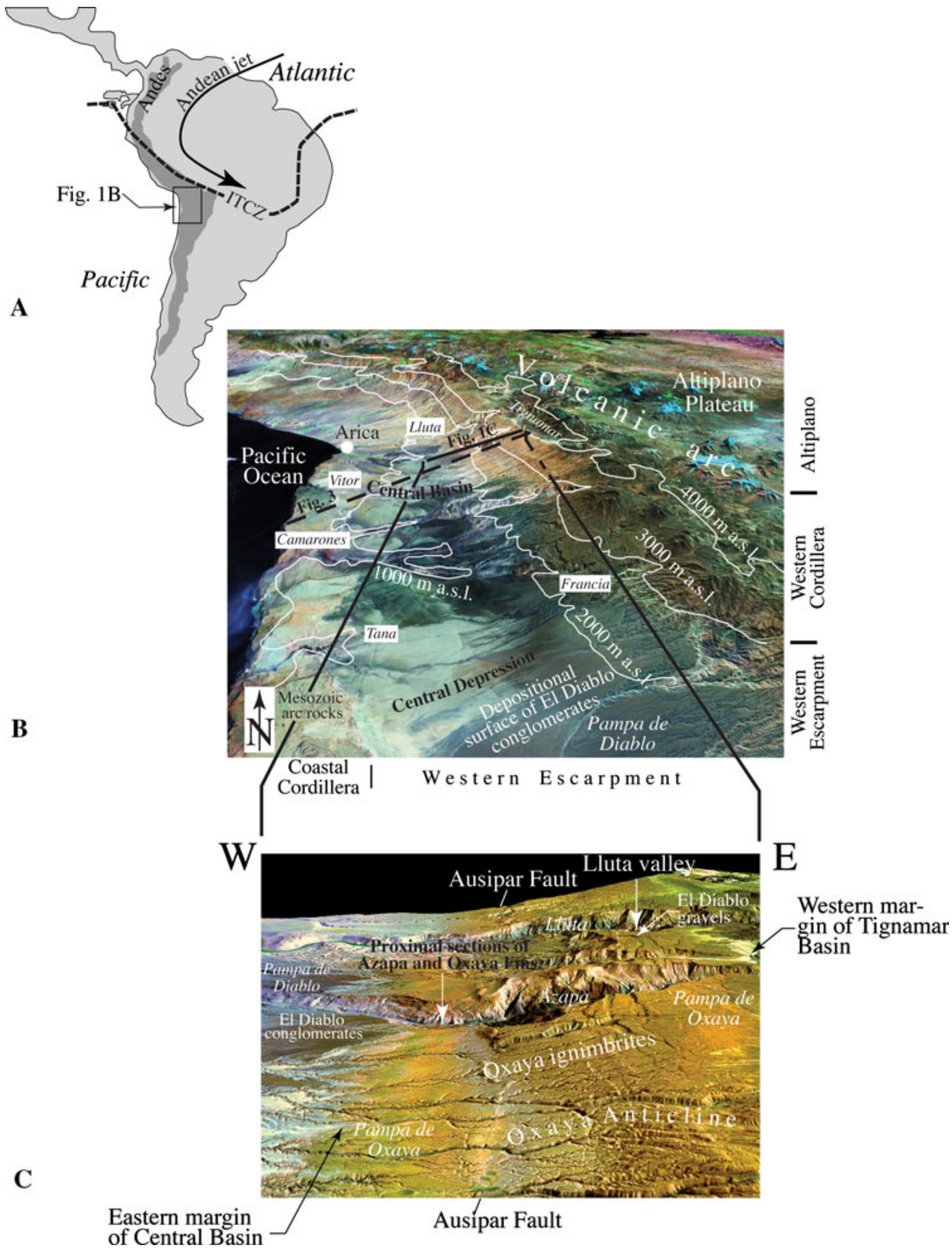

Fig. 1 **a** Figure of South America illustrating the current wind system that carries moisture to the Subandes of Bolivia and to the Western Cordillera. Note that the position of the ITCZ (intertropical convergence zone) shows the situation during austral summer. **b** 3D perspective of a satellite TM scene of northern Chile illustrating the location of sedimentary sections, the Quebradas, and the overall geomorphic setting. **c** shows details of the Oxaya anticline and the Ausipar fault including the 'pampas' and the windgap on the hinge of the Oxaya anticline (where El Diablo gravels were deposited)

Setting

The Andes of northern Chile (Fig. 1) comprise (1) the Coastal Cordillera with Mesozoic tholeiitic arc rocks and marine backarc sediments (Allmendinger et al. 2005; García and Hérail 2005), (2) the Western Cordillera that is the western margin of the Altiplano plateau, and (3) the Altiplano plateau. The Western Cordillera forms the modern arc and hosts andesitic stratovolcanoes of Miocene to modern ages (Wörner et al. 2000, 2002). The Western Escarpment links the Western Cordillera with the coast and is subdivided into a lower and upper segment separated by the Oxaya Anticline (Fig. 1c). This anticline formed in response to transpressional thrusting along the Ausipar fault between the Late Oligocene and the Pliocene (García and Hérail 2005; Zeilinger et al. 2005). The rocks of the Western Escarpment comprise a Mesozoic basement of granites and granodiorites and a suite of Miocene fluvio-volcanoclastic deposits (Azapa, Oxaya, Huyalas, and El Diablo Formations). The depositional surfaces of these units form pediplains or 'pampas'. They developed between ca. 20 and 7–8 Ma (e.g. Alpers and Brimhall 1988; García and Hérail 2005; Kober et al. 2006) and can be correlated several tens of kilometres along strike (Fig. 1b, c). The 'pampas' are cut by perennial braided rivers with sources on the Altiplano (e.g. Lluta, Camarones) and in the Western Cordillera (e.g. Azapa), with up to 1,500-m-deep 'Quebradas' (Fig. 1). Incision was initiated between 7.5 and 8 Ma (von Rotz et al. 2005), or possibly 10 Ma (Hoke et al. 2004, 2007; Schildgen et al. 2007) in response to surface uplift. Valley dissection has proceeded upstream by parallel retreat (García and Hérail 2005; Kober et al. 2006; Schlunegger et al. 2006; Schildgen et al. 2007).

Crustal thickening, surface uplift and exhumation of the central Andes commenced in the Eocene (McQuarrie et al. 2005, 2008; Ege et al. 2007), and the Altiplano plateau had its modern width at 20 Ma at the latest (Barnes et al. 2006). Exhumation rates in the Eastern Cordillera accelerated between 15 and 11 Ma (Gillis et al. 2006) when folding of the Bolivian Subandes (Fig. 2a) started (Uba et al. 2007). On the western side of the Andes in northern Chile, depositional growth strata and onlap relationships between dated units were inverted to rock and surface uplift estimates (Parraguez 1998; Victor et al. 2004; Farías et al. 2005; Zeilinger et al. 2005). According to these studies, the Altiplano started to rise in the Eocene, reached an altitude of ca. 2,000 m a.s.l. at 8 Ma, and rose to its present elevation (3,500–4,000 m) at 2.7 Ma at the latest (Fig. 2b). Similarly, Ghosh et al. (2006) and Garzione et al. (2008) proposed a model of rapid uplift of the Altiplano plateau from originally 2,000 m a.s.l. to the present-day elevation between 10 and 5 Ma. This model is mainly based on δ^{18}O and δD values from authigenic minerals (Garzione et al. 2006) and is corroborated by geomorphic investigations (Hoke et al. 2007) and the physiognomy of fossiliferous plants (Gregory-Wodzicki et al. 1998). Recently, Bershaw et al. (2010) present δ^{13}C and δ^{18}O data form mammal teeth that support the rapid rise model. According to these authors, however, the Altiplano plateau reached its modern elevation at 8 Ma in the La Paz region, and at approximately 3.6 Ma in the Uyuni area ca. 400 km farther south, implying heterochronous plateau uplift. Based on a compilation of a large variety of published data regarding stable isotope records, the chronology of incision in the Western Escarpment, and cross-cutting relationships between dated deposits and thrusts, Barnes and Ehlers (2009) concluded that the Andes most likely rose continuously between 40 Ma and their present elevation (Fig. 2b). This model of continuous uplift and related crustal thickening is corroborated by trace element concentrations in magmatic rocks in southern Peru and northern Chile. In particular, Mamani et al. (2010) interpreted these data to indicate continuous crustal thickening and magma generation between 30 Ma and the present.

The restoration of the location of the arc at different times (Wörner et al. 2000, 2002) reveals that the arc shifted ca. 20–50 km farther east during the Miocene and has remained in a stationary location since then (Fig. 2c) (Mamani et al. 2010). The arc delineating the Western Cordillera has been the source area of the deposits found in the sedimentary basins in the Western Escarpment (e.g. Central Basin, Central Depression, Tignamar Basin; García and Hérail 2005; Fig. 1b).

Stratigraphy

Miocene to modern sediments accumulated in isolated and partially hydrologically closed basins that are located in the lower Western Escarpment east of the Costal Cordillera (Central Basin near Arica, Central Depression farther south) and in the upper Western Escarpment at the foothills of the Western Cordillera (Tignamar Basin, Figs. 1b, 3).

The deposits in the Central Basin comprise the Late Oligocene to Early Miocene Azapa Formation, the Early Miocene Oxaya Formation, and the Middle to Late Miocene El Diablo Formation (Fig. 3; Kohler 1999; Wörner et al. 2002; García and Hérail 2005; Farías et al. 2005). Further deposits in the Central Basin include strath terrace conglomerates deposited on the shoulders of the deeply incised valleys and modern fluvial gravels (Fig. 4). The sedimentary fill of the Tignamar Basin is made up of the Middle to presumably Late Miocene Huyalas Formation (Kohler 1999) (Fig. 3). Sedimentological sections encompassing Early (Azapa and Oxaya Formation) and Middle

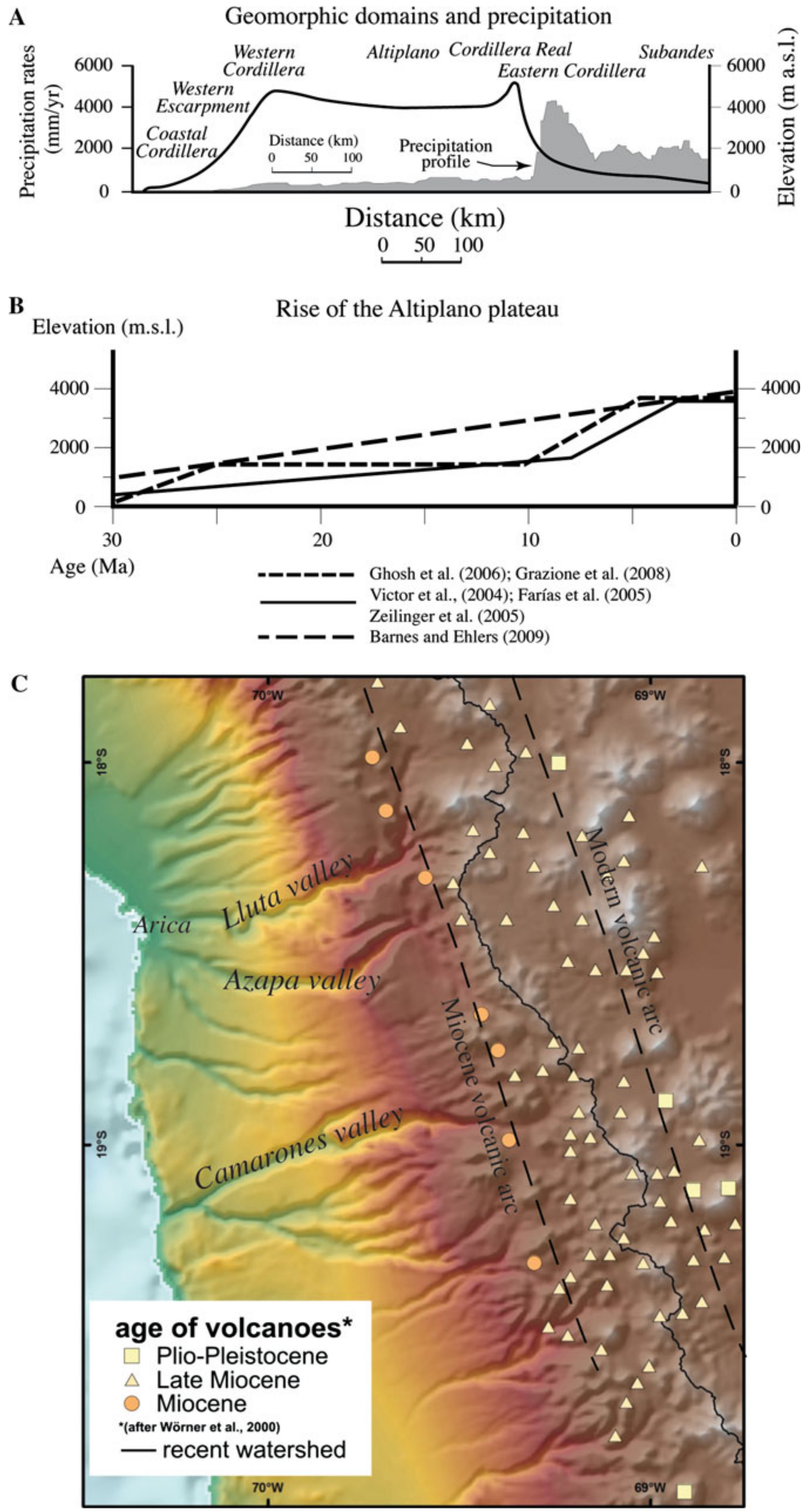

Fig. 2 **a** Geomorphic section across the Central Andes with mean elevations extracted from the SRTM 90-m digital elevation model within an 80-km-wide swath. This section also shows the major tectono-geomorphic domains including TRMM rainfall data (Bookhagen and Strecker 2008). **b** Various scenarios of the uplift of the Altiplano plateau. **c** Locations of the volcanic arc between the Miocene and the present (taken from Wörner et al. 2000; Mamani et al. 2010). Note that the volcanic arc defines the drainage divide

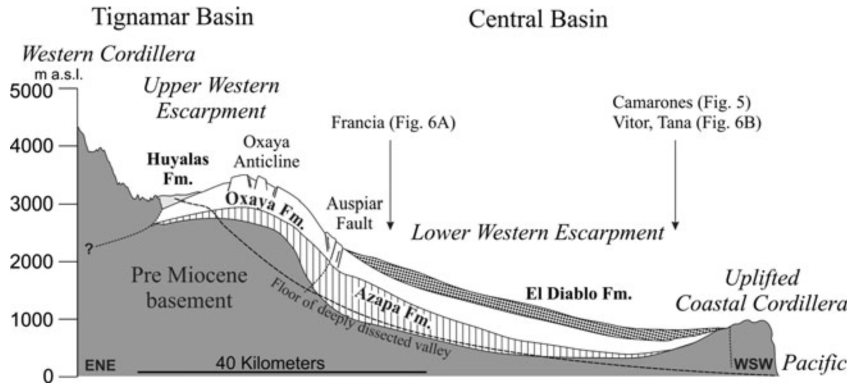

Fig. 3 Schematic geologic-stratigraphic section across the Andes of the Arica area between the Costal Cordillera and the Western Cordillera. The Central Basin (Kohler 1999) is the northern extension of the Central Depression (Fig. 1). See Fig. 1b for location of section

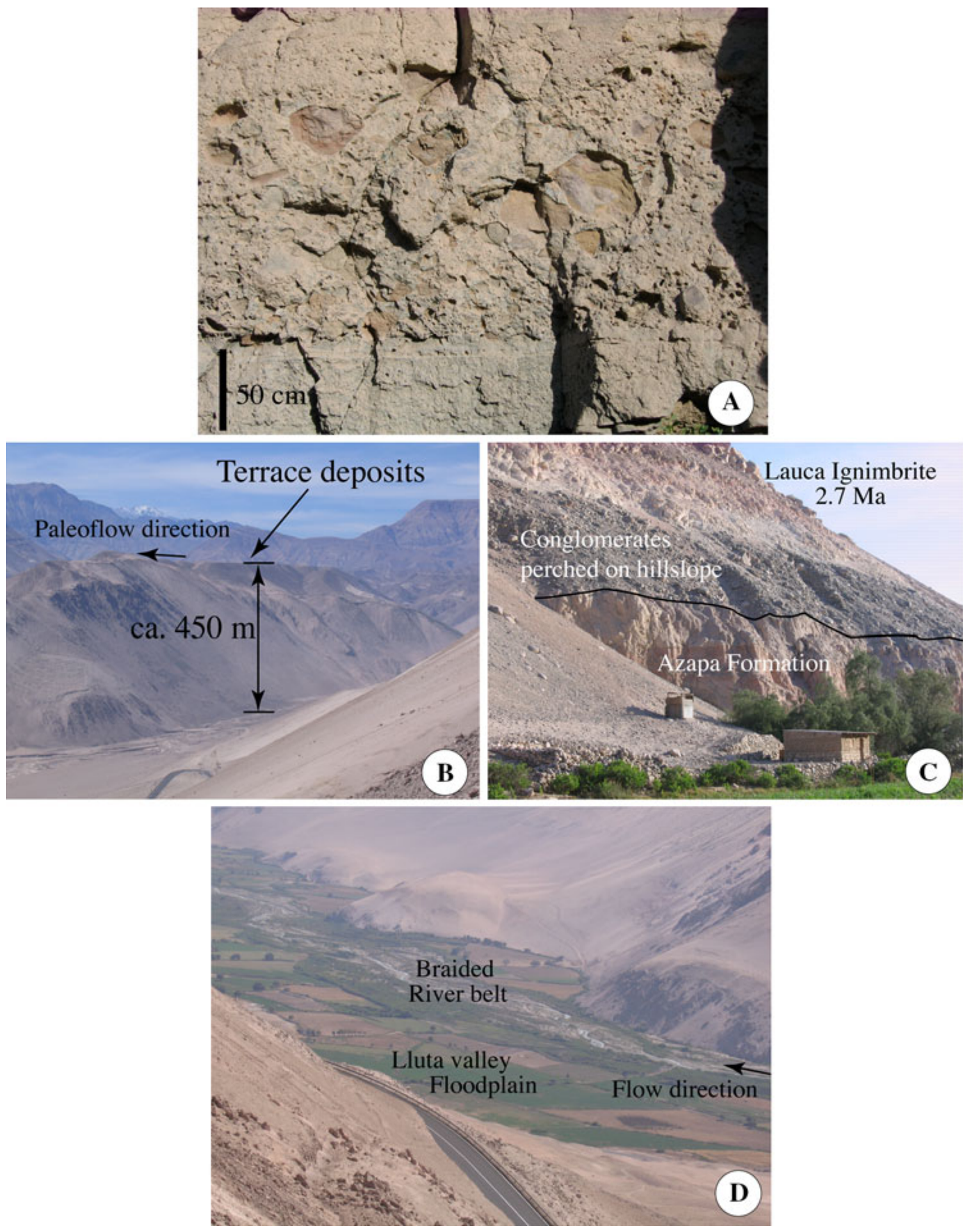

Fig. 4 **a** Sedimentary fabric of the Azapa Formation in Lluta valley (18°21′S, 69°52′W, 1,372 m a.s.l). **b** Cut terrace in Lluta valley (18°23′S, 69°55′W, 1,440 m a.s.l.). **c** Gravel sheet perched on hillslope in Lluta valley (18°23′S, 69°56′W, 1,013 m a.s.l.). **d** View of Lluta valley

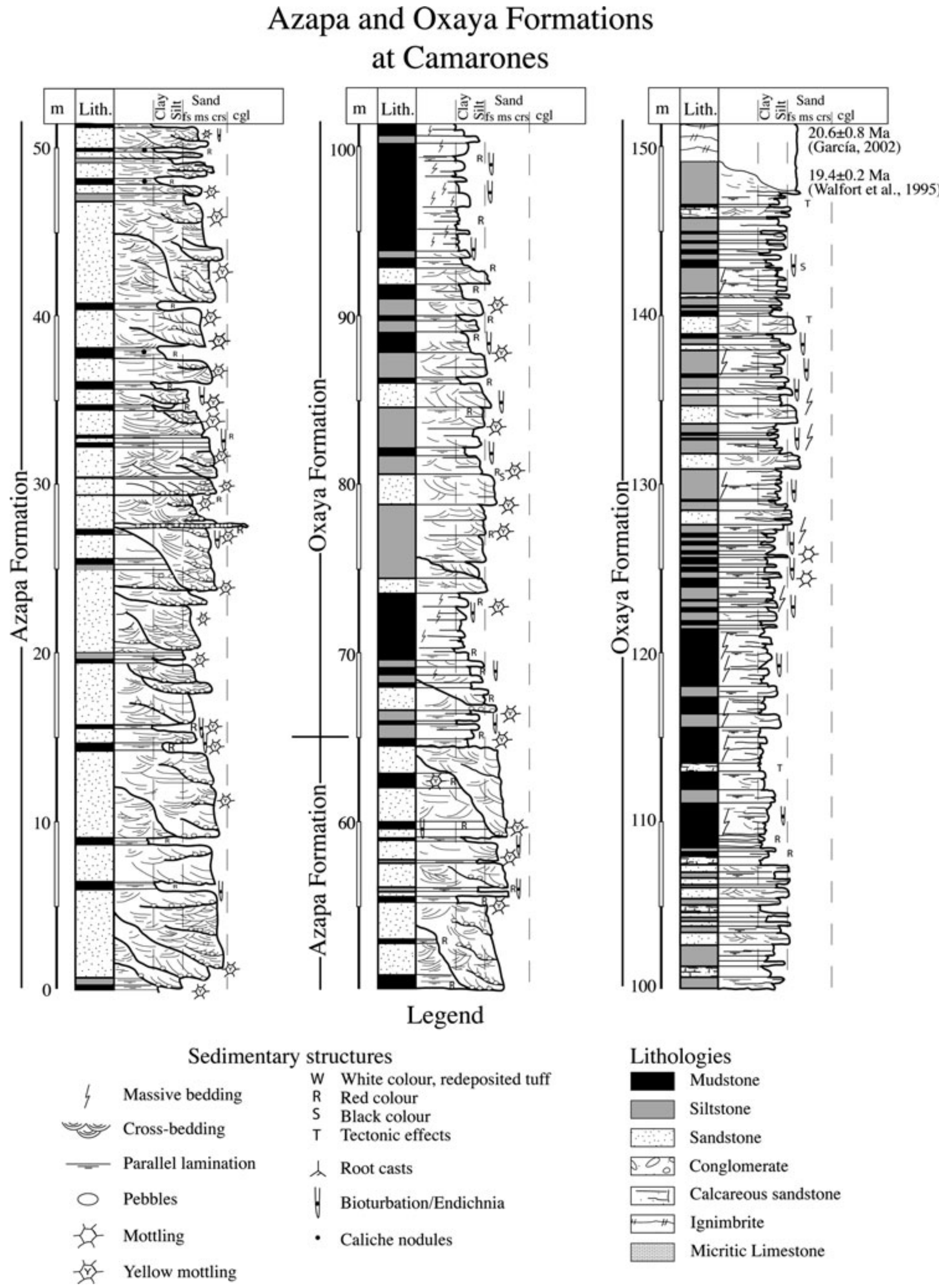

Fig. 5 Details of the sedimentological section measured at Camarones (base of section: 15°05′S, 70°05′W, 502 m a.s.l, top of Sect. 19°04′S, 70°03′W, 772 m a.s.l.). The chronologic ages are taken from the magnetostratigraphic investigations by von Rotz et al. (2005)

Miocene units (Huyalas Formation and lower member of El Diablo Formation) were analysed in detail by Kohler (1999) and Farías et al. (2005). We complement these data with detailed sedimentological logging of the Oxaya and Azapa Formations at distal sites near the coast (Camarones section, Figs. 1b, 5), and of the upper member of the El Diablo Formation at both proximal (Francia section) and distal positions within the Central Basin (Tana and Vitor sections; Figs. 1b, 6). Sedimentological sections were measured at a scale of ca. 1:100 in an effort to reconstruct the development of the sedimentary environments and inferred sediment transport. Special attention was paid on identifying key clasts that bear information on the provenance of the material.

Sedimentology

Early Miocene: Azapa and Oxaya formations

In the Central Basin adjacent to the Ausipar Fault (Fig. 3), the Azapa Formation is >300 m thick. The base of the formation is not exposed. This unit is an alternation of 3- to 5-m-thick matrix-supported breccias (Fig. 4a) and 2-m-thick massive-bedded and parallel-laminated sandstones,

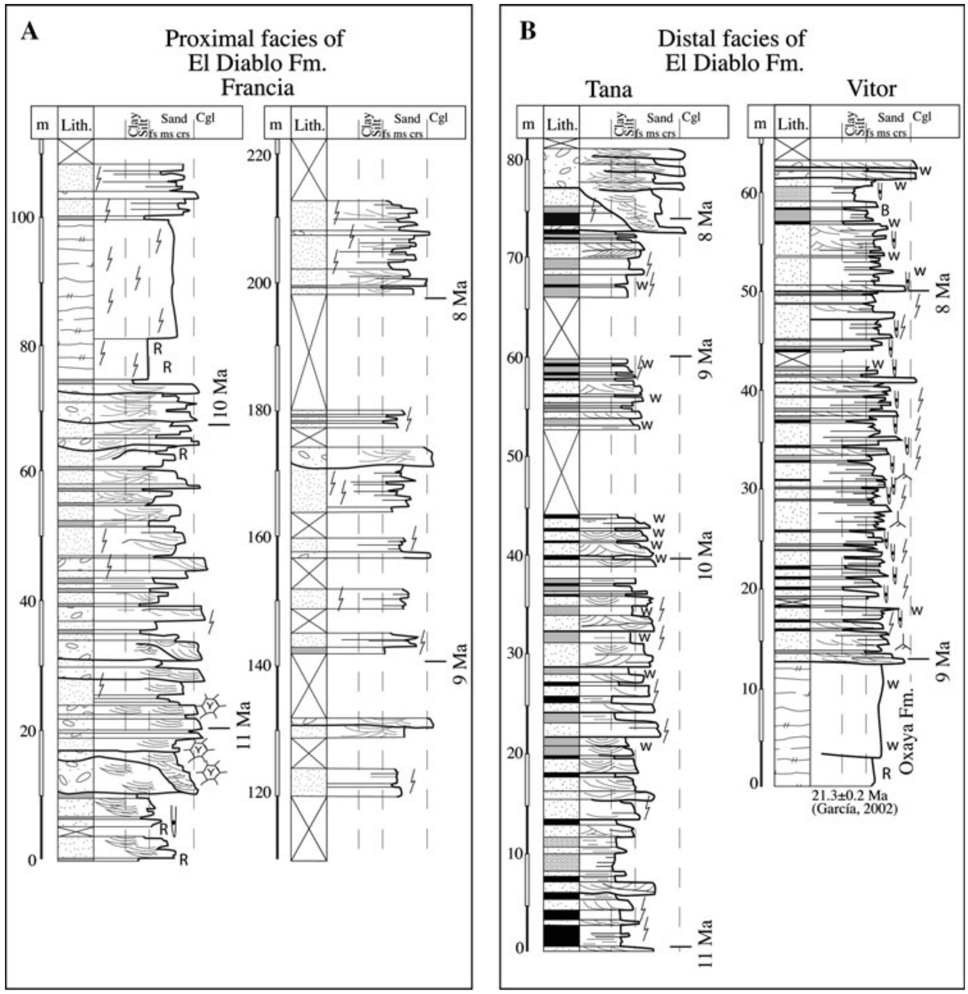

Fig. 6 Details of the sedimentological section measured at **a** Francia (base of section: 19°24′S, 69°36′W, 1643 m a.s.l, top of section 19°25′S, 69°36′W, 1880 m a.s.l.), and **b** Tana (base of section: 19°27′S, 69°56′W, 997 m a.s.l, top of section 19°27′S, 69°56′W, 1,073 m a.s.l.), and Vitor sections (base of section: 18°46′S, 70°14′W, 581 m a.s.l, top of section 18°45′S, 70°15′W, 653 m a.s.l.). The chronologic ages are taken from the magnetostratigraphic investigations by von Rotz et al. (2005). See Fig. 5 for legend

suggesting deposition by episodic debris flows and flash floods (Nemec and Postma 1993; Blair 1999a). Clast types include andesitic and rhyolitic constituents derived from the volcanic arc. Also at this location, the overlying Oxaya Formation is a ca. 400-m-thick stack of welded ignimbrites and covers the whole Western Escarpment including the Oxaya Anticline (Fig. 3) (Wörner et al. 2002). The Azapa and Oxaya Formations onlap the Mesozoic basement of the Coastal Cordillera south of Arica (von Rotz et al. 2005; Fig. 3). At Arica, the Coastal Cordillera is submerged beneath the Pacific Ocean, which inhibits a reconstruction of the geometric relationships between Azapa/Oxaya Formations and the basement.

At Camarones near the coast, the Azapa Formation comprises a 20-m-thick basal unit. It is made up of matrix-supported, 1- to 3-m-thick breccia beds with mafic, ultramafic, and rhyolitic clast types, suggesting deposition by debris flows (Blair 1999a, b) with sources in the adjacent Costal Cordillera. The overlying ca. 65-m-thick succession (Fig. 5) comprises an amalgamated stack of fine-to medium-grained sandstone beds. The deposits are trough- and cross-bedded, moderately sorted, and display basal scours, rip-up clasts, and volcanic pebbly lags. Individual sandstone beds, 2–4 m thick and 6–20 m wide, have ribbon geometries (Friend 1983; Blair 1999b). Massive, cm- to dm-thick mudstone interbeds are yellow/red mottled and display bioturbation, root casts, and caliche nodules. The overlying Oxaya Formation is 85 m thick (Fig. 5) and comprises dm-thick massive mudstone beds that are occasionally mottled, and rhyolites at the top. Interbedded dm- to m-thick fine-grained sandstone sheets are normal graded and display planar contacts, parallel lamination or a massive fabric. The sandstone beds of the Azapa and Oxaya Formations were most likely deposited by low-energy *ephemeral* flows in straight channels (ribbon sandstones) or by unconfined flows on a mudflat (sandstone sheets) (Friend 1983). Channels were bordered by floodplains with calcic vertisols testifying semiarid conditions (Rech et al. 2006).

Middle to Late Miocene: Huyalas formation

The Middle to presumably Late Miocene Huyalas Formation accumulated on the top of the Oxaya Formation in the Tignamar Basin (Figs. 1b, 3). The deposits in this basin, bordered to the west by the Oxaya Anticline and to the east by the foothills of Western Cordillera, are a >100-m-thick succession of conglomerates, sandstones, and mudstones (Kohler 1999). At the base, this unit consists of a ca. 50-m-thick alternation of moderately sorted coarse-grained sandstone beds and fine-grained, clast-supported conglomerates. The conglomerates and sandstones reveal erosive bases with up to 50-cm-deep and 3- to 4-m-wide scours, implying deposition in shallow channels of a braided river system (Miall 1985). Individual conglomerate interbeds are matrix supported and were deposited by debris flows (Nemec and Postma 1993; Blair 1999a). The presence of a braided river system together with the occurrence of interbedded debris flow units implies that sediment transport occurred by both episodic *ephemeral* and continuous *perennial* flows (Miall 1985). The overlying ca 20-m-thick succession is an alternation of diatomites, siltstones and fine-grained sandstone beds several centimetres thick with root casts, suggesting the presence of a shallow lake (Kohler 1999). The lacustrine diatomites are overlain by m-thick matrix-supported, poorly sorted breccias that were deposited by one or multiple debris flows. The presence of a lacustrine environment implies that the Tignamar basin was hydrologically closed for some time, hosting a perennial lake.

Middle to Late Miocene: El Diablo formation

The El Diablo Formation, deposited between the Middle and Late Miocene, comprises two members. They record a coarsening and thickening upward megasequence, starting with alternated conglomerates, breccias, sandstones, and mudstones at the base (lower member), and ending with conglomerates and mudstone interbeds at the top (upper member) (Farías et al. 2005). The conglomerate and breccia composition, characterized by abundant andesite clasts, implies that the material was derived form stratovolcanoes in the Western Cordillera (Pinto et al. 2004). The El Diablo unit is thickest (>300 m, Pinto et al. 2004; Farías et al. 2005) at the eastern border of the Central Basin (Fig. 3). It overlies the Oxaya Formation with a hiatus that increases in length towards the coast (see discussion of chronologies below), where the deposits onlap and partially cover the Costal Cordillera (von Rotz et al. 2005), linking the Central Basin with the Pacific Ocean. El Diablo sediments also overlap the Oxaya Anticline as documented by El Diablo gravels and boulders in wind gaps on top of the Oxaya Anticline (Fig. 1c; Zeilinger et al. 2005).

The sedimentological properties of the lower and upper member of the El Diablo Formation were described by Farías et al. (2005). According to these authors, the lower member comprises an up to 100-m-thick alternation of conglomerates, breccias, sandstones, and mudstones. Breccia beds are between 10 and 20 m thick. The clasts are subangular and display a massive, clast- and/or matrix-supported fabric. The sedimentary properties imply episodic transport by granular and debris flows (Nemec and Postma 1993; Blair 1999a). Interbedded sandy gravels and conglomerates are 5–10 m thick. They are massive and horizontally bedded and generally display a clast-supported fabric, implying transport by unconfined flows in the upper flow regime (sheetfloods; Miall 1985). Sandstones are present as 5- to 20-m-thick tabular beds and are cross-bedded, suggesting deposition by continuous flow in the lower flow regime. Centimetre-thick mudstone interbeds are massive with desiccation cracks, suggesting deposition on floodplains (Miall 1985). Similar to the Huyalas Formation, the lower member of the El Diablo unit records sediment transport by predominantly episodic *ephemeral*, and partially also by continuous *perennial* flows.

The upper member of the El Diablo Formation is exposed in both proximal (Francia) and distal positions (Vitor, Tana). At Francia, it is a >200-m-thick alternation of clast-supported, massive- and cross-bedded conglomerates, massive- and cross-bedded sandstones, and massive mudstones (Fig. 6a). These sedimentological properties suggest deposition by a braided river system where run-off was predominantly *perennial*. At Tana and Vitor near the coast (Figs. 1b, 6b), the El Diablo sediments total several tens of metres. There, the base of the sections are characterized by parallel-laminated mudstones, organic-rich dolostones, and massive sandstones with gypsum pseudomorphs, rootlets, and bioturbation, implying deposition in a lacustrine environment (Platt 1992). Up-section, cross-bedded, well-sorted conglomerates with imbricated, rounded clasts imply deposition by *perennial* rivers on a braidplain (Rust 1978; Miall 1985).

Strath terrace deposits and modern gravels

The deeply dissected valleys of the Western Cordillera host well-sorted, clast-supported conglomerate sheets with imbricate clasts that are perched on hillslopes at various elevations (Fig. 4b, c). The sedimentary fabric of these deposits is identical to that found in Quaternary terrace deposits farther south (e.g. Pisco valley, Peru; Steffen et al. 2009) and on modern longitudinal gravel bars of rivers with sources in the Western Cordillera (Fig. 4d). As outlined previously, these rivers have a perennial water discharge. Accordingly, we interpret the sedimentary fabric of the gravel sheets on hillslopes including the Quaternary terrace deposits to record the presence of perennial braided rivers as is the case today. Furthermore, the petrographic composition of the gravel sheets shifts towards increasing contribution of plutonic clasts including granites and granodiorites (Fig. 7). These constituents are identical to the

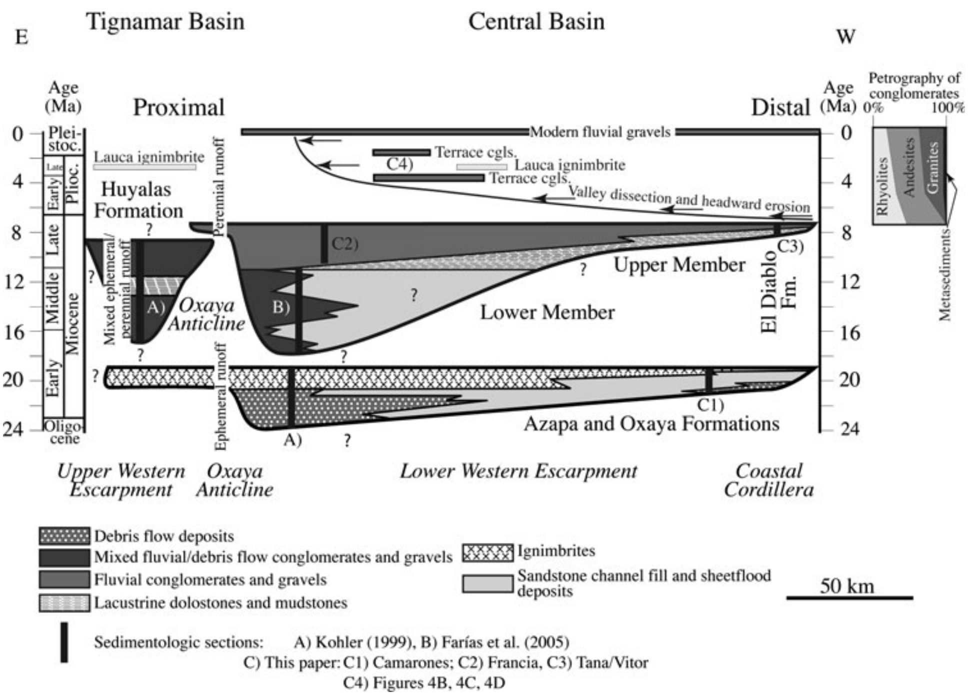

Fig. 7 Chronologic (Wheeler) diagram of Miocene to present deposits in the western slope of the Andes between 19 and 21°S latitude

Mesozoic granitic/granodioritic basement of the Western Escarpment. This change in the clast composition reflects a normal unroofing sequence recording the successive dissection of the deep valleys.

Chronology

As the chronological framework of the deposits (Fig. 7) is important for the scope of this paper, details regarding ages and potential biases are presented in this section. The ignimbrite sheets of the Oxaya Formation have been dated by various authors. Wörner et al. (2000) assigned ages of approximately 21.8 and 22.7 for the base of this unit near Arica where the Oxaya Formation is an amalgamated stack of ignimbrite sheets. Approximately 100 km farther south, the top of the Oxaya Formation is represented by the Ignimbrita Moquella and was dated to 17.4 ± 0.6 Ma based on K–Ar ages of biotites (Naranjo and Paskoff 1985). Ignimbrite sheets of older ages, also forming the top of the Oxaya Formation and the base of the El Diablo unit (García and Hérail 2005), are exposed at Vitor (21.3 ± 0.2 Ma K–Ar ages of biotites, García 2002) and Camarones (20.6 ± 0.8 Ma K–Ar ages of biotites, García 2002; and 19.4 ± 0.2 Ma Ar–Ar ages of sanidines, Walfort et al. 1995). The Azapa unit contains no ignimbrite interbeds and has thus no radiometric ages. Using these chronological constraints and the results of detailed magnetostratigraphic investigations into the Camarones section (von Rotz et al. 2005), a time interval between approximately 23 and 17 Ma is assigned for the ephemeral deposits of the Azapa and Oxaya Formations (Fig. 7).

Constraints for bracketing the age of the Huyalas Formation are provided by an intercalated ignimbrite dated to 16.8 ± 1.5 Ma (García et al. 1996) or to 10.55 ± 0.05 Ma (Wörner et al. (2000), by mammalian fossils (*Typotheriopsis* sp, *Nothoungulata*, Mesotherridae), suggesting an age between 8 and 9 Ma (Salinas et al. 1991), and the 2.73 ± 0.11-Ma-old Lauca ignimbrite (Walfort et al. 1995) overlying the Huaylas with an angular unconformity. Accordingly, the Huaylas Formation spans a time interval between the Middle and presumably Late Miocene (Fig. 7).

Ages for deposition of the El Diablo Formation are based on (1) chronometric investigations into Oxaya ignimbrite sheets *underlying* this unit, (2) 8.2 ± 0.5 Ma (Muñoz and Sepúlveda 1992) and 9.0 ± 1 Ma (Naranjo and Paskoff 1985) whole rock K–Ar ages of the Lava de Tana *overlying* the El Diablo unit at Francia (Pinto et al. 2004), and (3) a 8.2 ± 0.8 Ma Rb–Sr age of biotites extracted from a dm-thick interbedded tuff at Tana (von Rotz et al. 2005). Using these age brackets and based on detailed magneto-polarity investigations into the upper member at Francia, Tana and Vitor (von Rotz et al. 2005), the El Diablo unit most likely spans the time interval between approximately 17 and 8 Ma at proximal position, and between ca. 9 and 8 Ma at distal sites near the coast (Fig. 7).

Strath terrace conglomerates postdate sediment accumulation of the upper member of the El Diablo Formation. In the Lluta valley, the 2.7-Ma-old Lauca ignimbrite was deposited on the valley floor and onlaps a ridge forming a terrace level (Fig. 4c). In other places, terrace conglomerates are perched on Lauca ignimbrite fragments (Fig. 4d). These constraints bracket the incision of the valley and the accumulation of terrace conglomerates. Accordingly, incision started between 8 and 7 Ma (top of El Diablo Formation) and continued before and after 2.7 Ma (Lauca ignimbrite) until the present (Fig. 7).

The age constraints outlined previously yield strongly heterochronous facies relationships (Fig. 7). Interestingly, the ages indicate a depositional gap between ca. 17 and 9 Ma in the Central Basin near the coast. During this time span, however, sediment was deposited at proximal sites near the Western Cordillera, from where the depocentres migrated westward towards the Coastal Cordillera. A further important implication is the time transgressive character of braidplain deposits recorded by the El Diablo conglomerates. In particular, fluvial conglomerate deposition commenced approximately at 11 Ma at proximal sites (Francia), and at ca. 8 Ma farther west near the coast (Tana, Vitor), implying progradation of the braidplain over a 3-My-long time span.

Discussion

In the next paragraphs, we discuss the stratigraphic and sedimentological data with particular emphasis on the development of the basins and the paleoclimate implications. Because the major scope of the paper lies on the reconstruction of run-off and precipitation patterns in relation to the rise of the Andes, more attention will be given to the climatic implications of the sedimentological data.

Evolution of Tignamar and Central Basins

The evolution of the Central and Tignamar Basins is strongly controlled by the combined effect of surface erosion in the Western Cordillera where the alluvial material was sourced and structural deformation in the Western Escarpment. The highest thicknesses of the Azapa and Oxaya unit near the Ausipar fault, together with successive thinning of these deposits towards the coast where they onlap the Coastal Cordillera, delineate a wedge-shaped geometry. This suggests that the development of the basin was strongly linked with transpressional faulting along the Ausipar fault (Kohler 1999), although the details are not clear. Interestingly, sedimentation was stalled at distal sites of the Central Basin during the same time that deposition occurred at the foothill of the Western Cordillera, both in the Tignamar Basin and at proximal sites of the Central Basin (Fig. 7). Because the deposits at Tignamar imply a hydrologically closed system, we interpret that folding of the Oxaya Anticline (Fig. 1b) partially closed the pathway to the Central Basin farther west for a limited time span. A further scenario includes enhanced subsidence rates near the Western Cordillera in response to faulting and loading along the Ausipar and related faults. We use these scenarios to explain the continued accumulation of deposits at the foothill of the Western Cordillera and the hiatus between the Oxaya and El Diablo Formation at distal sites.

Fragments of El Diablo conglomerates in windgaps on the Oxaya Anticline (Fig. 1c) implies that this unit records the communication link between the Tignamar and Central Basins. Because the El Diablo conglomerates also onlap and partly cover the Coastal Cordillera, the rivers feeding this unit must have responded to surface uplift relative to the Pacific Ocean. This was certainly the case when surface uplift forced the rivers to incise into previously deposited El Diablo conglomerates (García and Hérail 2005). The result of surface uplift and continued fluvial incision was the termination of El Diablo accumulation in the Central Basin, the formation of the spectacular valleys and the deposition of gravel sheets perched on the hillslopes at various elevations.

Most important, however, is the nearly complete stratigraphic record in the Arica area that provides ideal conditions for paleoclimate reconstructions. In this regard, the inferred change from ephemeral to mixed perennial–ephemeral and finally to perennial sediment transport is a key. It indicates a continuous increase in run-off from streams with sources in the Western Cordillera, as is detailed below.

Paleoclimate implications

Western Altiplano margin and Western Cordillera

The increase in run-off and inferred stream power and the progradation of braidplains that is interpreted from the sedimentological development (Fig. 7) could be related to (1) glaciers on the stratovolcanoes and the related increase in run-off and transport of gravels during deglaciation, (2) continuous steepening of stream gradients in response to the Andean rise, (3) increase in water discharge through eastward shifts of drainage divides, and (4) increase in precipitation rates on the Altiplano and the Western Cordillera where the headwaters are. Each of these changes in hydromorphological and paleoclimate parameters can explain the various incision depths of the Quebradas (e.g. Hoke et al. 2004; Farías et al. 2005; Thouret et al. 2007), but they are not equally capable of elucidating the deposition and progradation of El Diablo conglomerates (Fig. 7). In particular, (1) the modern valley floor of the Azapa system hosts a braided river with well-sorted longitudinal gravel bars (Schlunegger et al. 2006), despite the absence of glaciers in the source area; (2) the Andean rise did steepen the Western Escarpment (Isacks 1988), but not the Coastal Cordillera where stream gradients remained flat and where gravels were deposited (i.e. steepening of the Western Escarpment cannot be invoked to explain an increased stream power near the Costal Cordillera); (3) eastward shifts of drainage divides did increase the catchment size and presumably water discharge of the Lluta and Camarones rivers, but did not alter the size of the Azapa catchment where the modern drainage divide ends in the Western Cordillera and has thus not shifted eastwards (Fig. 2c). We are therefore left with the scenario of increasing precipitation rates on the Altiplano and the Western Cordillera, in the source areas of the rivers. Accordingly, the change in water discharge leading to ephemeral deposits during the Early Miocene, mixed ephemeral and perennial deposits during the Middle Miocene, and finally to perennial deposits thereafter is considered to indicate a continuous shift towards a more humid climate in the Western Cordillera and the western margin of the Altiplano where the sediment sources are. Note that Gaupp et al. (1999) reconstructed multiple cycles of dry and humid periods on the Altiplano of the Arica region since 8 Ma. However, due to the deficiency of post 8-Ma-old deposits between the western Altiplano margin and the coast (Fig. 7), we are currently not able to resolve these oscillations in the sedimentary record. Even in the absence of these deposits, the conclusions by Gaupp et al. (1999) do not contradict our interpretation of an increasing trend of precipitation rates in the headwaters of the rivers since the Middle Miocene, nor does it conflict with the assignment of higher and more continuous run-off, and thus in the transport of clasts even at the coast.

Additional support for more precipitation on the Altiplano and the Puna Plateau is potentially provided by oxidation and supergene enrichment that started at 12 Ma. However, this data has to be treated with care because of multiple potential controls on supergene enrichments as discussed by Hartley and Rice (2005) and Clarke (2006). Farther east in the Subandes, run-off, sediment discharge, and accumulation rates increased at the same time (Uba et al. 2007; Mulch et al. 2010).

Western Escarpment and Coastal Cordillera

For the Western Escarpment and the Costal Cordillera, shifts in weathering and surface erosion patterns are also related to paleoclimatic changes, however, with the opposite trend. In particular, 20-Ma-old floodplain deposits with calcic vertisols in the Azapa (Western Escarpment) and El Loa Formations (Atacama Desert, 23°S latitude) are considered to represent poorly drained, vegetated floodplains with seasonal precipitation rates >200 mm/year (Rech et al. 2006). At 10–8 Ma, the formation of >3-m-thick salic gypsisols have been used to suggest a paleoclimate shift to hyperaridity (<20 mm/year precipitation; Rech et al. 2006). Similarly, there are a number of reasons to infer a shift to a hyperarid climate: (1) contemporaneous cessation of supergene oxidation in the Atacama Desert (Sillitoe and McKee 1996; Arancibia et al. 2006), (2) termination of channel incision by rivers with sources in the Coastal Cordillera (Kober et al. 2006), (3) cessation of Atacama Gravel accumulation by braided rivers with sources in the Western Escarpment (Nalpas et al. 2008), and (4) termination of supergene enrichment and mineralization in the Late Miocene, or even later (Fig. 8). However, modifications in paleosoil development, cessation of conglomerate deposition, and termination of supergene enrichment can also be interpreted differently. In particular, faulting, surface uplift, and valley dissection are considered to lower groundwater tables and geomorphic baselevels, which in turn slows down, or even terminates supergene enrichment and conglomerate accumulation (e.g. Clarke 2006). Furthermore, Dunai et al. (2005) and Evenstar et al. (2009) interpreted hyperarid conditions in the coastal region and the Western Escarpment at least since the Oligocene/Early Miocene based on >20-Ma-old surface exposure ages. Additional supporting evidence is Miocene ^{21}Ne exposure ages near the coast (Kober et al. 2007). In a recent paper, Reich et al. (2009) dated two major phases of supergene enrichment of copper deposits in the Atacama Desert. They related the second phase, lasting between 2 Ma and the Pleistocene, to the ascent of ground waters form the basement. Accordingly, geochemical and geomorphic archives yield no clear answer as to whether or not paleoclimate changed between the Miocene and the present in the Western Escarpment and the Coastal Cordillera. It is more likely that paleoclimate was hyperarid since 20 Ma at the latest and stayed extremely dry afterwards. One drawback of this summary of spatial and temporal distribution of records of hyperaridity (Fig. 8) is that the large spatial scatter of the paleoclimate proxies precludes the assignment of a distinct and unequivocal age for a paleoclimatic change. It is possible that aridisation was time transgressive as orography might have been formed at different magnitudes and rates in different locations (e.g. Bershaw et al. 2010).

Hartley and Chong (2002) and Evenstar et al. (2009) used stratigraphic archives in the Central Depression (Fig. 8) to reconstruct several paleoclimate oscillations between 22 and 2 Ma. They also found evidence for an accentuated shift to hyperaridity at ca. 4 Ma that Hartley (2003) related to global cooling. It is likely that the global cooling at 4 Ma resulted in an additional enhancement of precipitation contrasts between the high Andes and the regions near the Pacific (Hartley 2003). For the Altiplano Plateau, Gaupp et al. (1999) inferred multiple oscillations

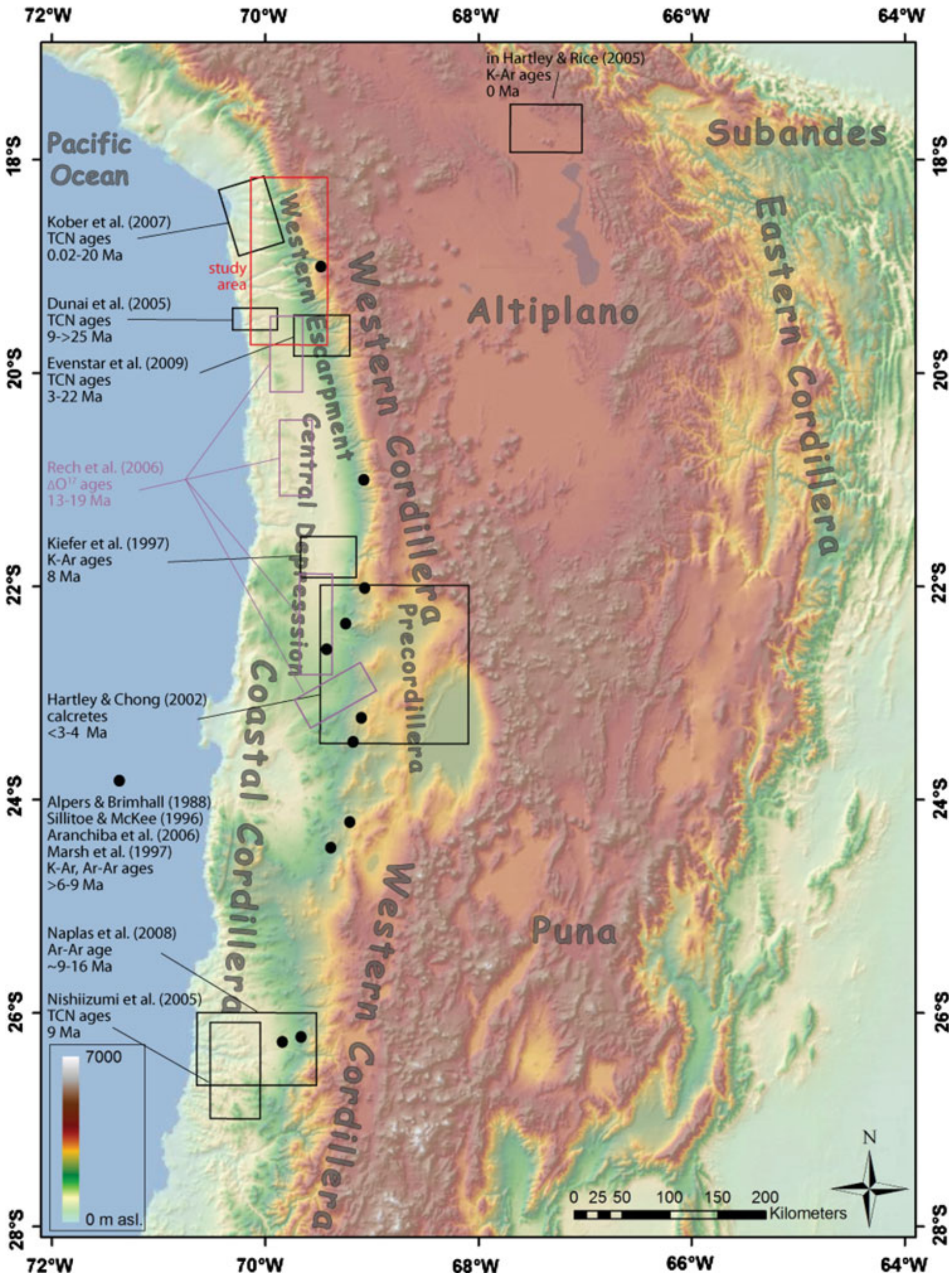

Fig. 8 Overview figure illustrating the locations for which an onset of aridisation has been postulated by the various authors. The TCN methodology comprises the determination of exposure ages with terrestrial cosmogenic nuclides (e.g. ^{26}Al, ^{10}Be, and ^{21}Ne). Note that the 13–19 Ma ages of Rech et al. (2006) chronicle the formation of calcic vertisols, implying either precipitation rates >200 mm/year or supply of groundwater sourced in the Western Cordillera

between semihumid and semiarid conditions from sedimentological archives between 8 Ma and the present. Similarly, Allmendinger et al. (1997) reported stratigraphic evidence for paleoclimate cyclicities for earlier time intervals. We are currently not able to resolve these inferred climate variabilities with available data. Instead, we simply infer a general enhancement of precipitation on the Western Cordillera and Western Altiplano margin between 19 and 21°S since the Miocene and thus increased divergence of climates between the Coast/Western Escarpment and the Altiplano margin/Western Cordillera (Fig. 9).

Paleoclimate change and the rise of the Andes

At present, moisture is derived from the Atlantic by the low-level Andean jet that is deflected towards the Subandes (Fig. 1a) where most moisture is lost due to orographic effects (Bookhagen and Strecker 2008) (Fig. 2a). Moisture is also transported across the Altiplano to the Western Cordillera (Strecker et al. 2007, Fig. 1a), which currently experiences semiarid/semihumid conditions with precipitation rates between 300 and 500 mm/year (Salino et al. 2002; Garreaud et al. 2003; Houston and Hartley 2003). Circulation models for moisture transport reveal that the

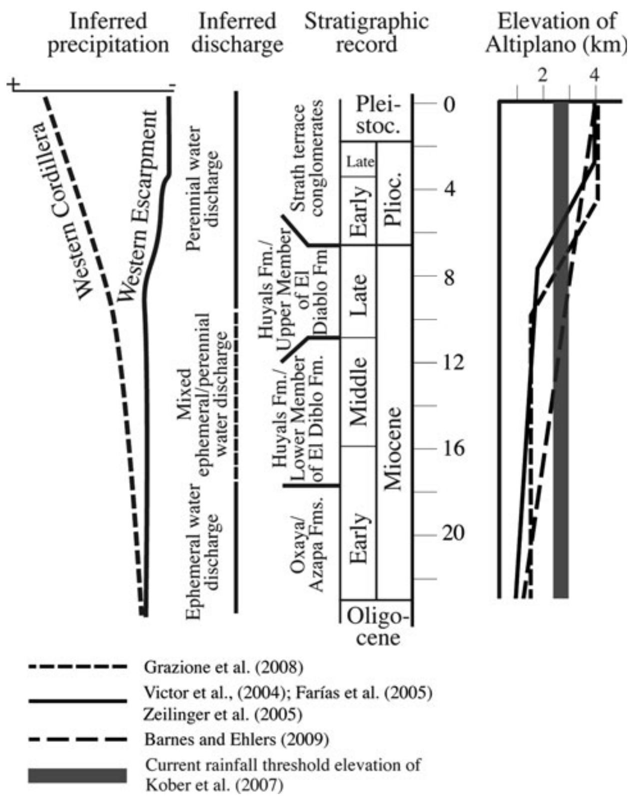

Fig. 9 Summary figure of relationships between Andean rise, paleoclimate changes, and modification of sediment transport and erosion

Altiplano/Puna plateau provides areally extensive and sufficiently high topography to deflect the Andean jet towards the south, thereby attracting and intercepting moisture from the Atlantic (Insel et al. 2010). Because uplift of the Andes increased the elevation exposure of the plateau (Strecker et al. 2007), it modified the wind pattern on the eastern side, but also the atmospheric circulation over the Pacific Ocean (Ehlers and Poulsen 2009; Sepulchre et al. 2010). The effects are: (1) high orographic precipitation gradients in the Eastern Cordillera (Lenters and Cook 1995; Bookhagen and Strecker 2008), (2) enhanced convective precipitation on the Altiplano and the Western Cordillera, and (3) blocking of westerly flow from the Pacific (Insel et al. 2010). Sepulchre et al. (2010) and Ehlers and Poulsen (2009) proposed that a 2,000–2,500 m height is sufficient to modulate the wind and precipitation pattern. The same threshold elevation was used by Rech et al. (2006) to explain the interpreted shift to a hyperarid paleoclimate. Kober et al. (2007) identified a threshold elevation between 2,500 and 3,000 m a.s.l. above which climate forcing on surface erosion becomes important. Accordingly, we consider the relationships between Andean uplift and climate to have become important since the Middle Miocene (Fig. 9) when run-off of rivers with sources in the high Andes started to change from ephemeral to perennial, leading to progradation of conglomerates to distal sites (Fig. 7). We acknowledge, however, that lateral and latitudinal variations in surface uplift have to be considered as was recently shown by Bershaw et al. (2010). Accordingly, the inferred topographical interference with the wind pattern was most likely time transgressive, which might explain some of the discrepancies of the paleoclimate reconstructions. We emphasize, therefore, that our preferred relationship between paleoclimate change and Andean uplift mainly applies to the Andes near Arica and could potentially be extended across strike towards the Eastern Cordillera near Coroico (16°S, 67°W; e.g. Mulch et al. 2010).

Note that this scenario partially challenges the model of a climate-driven acceleration of uplift (Lamb and Davis 2003), particularly during the Late Miocene. This model requires a reduction of sediment discharge to the trench, which is not corroborated by the inferred increase in run-off and sediment transport. However, starvation of sediment accumulation in the trench could have been due to the blockage of sediment discharge behind the Coastal Cordillera, which was hydrologically closed in some locations. Also, the inferred deflection of the wind system and modulation of the precipitation pattern is not accepted by all geologists, and much more data regarding paleoclimate development need to be collected before a conclusive assessment of this question is possible. Bearing this in mind, we note that our preferred interpretation is supported by stratigraphic archives and paleoclimate models and does not conflict with published geomorphic and geochemical data.

Conclusions

As previously mentioned by Alpers and Brimhall (1988), we consider that the uplift of the Andes resulted in more precipitation in the Eastern Cordillera, enhanced convective storms and a wetter climate on the Altiplano particularly in the segment between 19 and 21°S latitude. Similar to these authors, we conclude that these paleoclimate conditions successively changed when the Andes rose above a threshold elevation of 2,000–2,500 m a.s.l. during the Middle Miocene. This estimate of the time span during which the inferred threshold elevation was reached applies for the Central Andes between Arica and Coroico only and needs to be considered with caution when analysing locations farther south. Our conclusion of an uplift-driven change in run-off and sedimentary response strongly relies on the continuous rise model for the uplift of the Andes. In case that uplift occurred during a short time span between 10 and 8 Ma, then the change in sediment transport and inferred modification in run-off was presumably not related to the rise of the Andes, and other, yet unknown, controls (e.g. an early change of the paleoceanic and atmospheric circulation in the eastern Pacific) have to be sought.

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References

Allmendinger RW, Jordan TE, Kay SM, Isacks B (1997) The evolution of the Altiplano-Puna plateau of the Central Andes. Ann Rev Earth Planet Sci 25:139–174

Allmendinger RW, González G, Yu J, Hoke G, Isacks B (2005) Trench-parallel shortening in the Northern Chilenean Forearc: tectonic and climatic implications. Geol Soc Am Bull 117:9–104

Alpers CN, Brimhall GH (1988) Middle Miocene climatic change in the Atacama Desert, northern Chile; evidence from supergene mineralization at La Escondida. Geol Soc Am Bull 100:1640–1656

Arancibia G, Matthews SJ, Pérez de Arce C (2006) K-Ar an $^{40}Ar/^{39}Ar$ geochronology of supergene processes in the Atacama Desert, Northern Chile: tectonic and climatic relations. J Geol Soc London 163:107–118

Barnes JB, Ehlers TA (2009) End member models for Andean Plateau uplift. Earth-Sci Rev 97:105–132

Barnes JD, Ehlers TA, McQuarrie N, O'Sullivan PB, Pelletier JD (2006) Eocene to recent variations in erosion across the central Andes fold-thrust belt, northern Bolivia: implications for plateau evolution. Earth Planet Sci Lett 248:8–133

Bershaw J, Garzione CN, Higgins P, MacFadden BJ, Anaya F, Alvarenga H (2010) Spatial-temporal changes in Andean plateau climate and elevation from stable isotopes of mammal teeth. Earth Planet Sci Lett 289:530–538

Blair TC (1999a) Sedimentary processes and facies of the waterlaid Anvil Spring Canyon alluvial fan, Death Valley, California. Sedimentology 46:913–940

Blair TC (1999b) Sedimentology of the debris-flow-dominated Warm Spring Canyon alluvial fan, Death Valley, California. Sedimentology 46:941–965

Bookhagen B, Strecker M (2008) Orographic barriers, high-resolution TRMM rainfall, and relief variations along the eastern Andes. Geophys Res Lett 35:L06403

Clarke JDA (2006) Antiquity of aridity in the Chilean Atacama Desert. Geomorphology 73:101–114

Dunai TJ, González López GA, Juez-Larré J (2005) Oligocene/Miocene age of aridity in the Atacama Desert revealed by exposure dating of erosion sensitive landforms. Geology 33:321–324

Ege H, Sobel ER, Scheuber E, Jacobshagen V (2007) Exhumation history of the southern Altiplano plateau (southern Bolivia) constrained by apatite fission track thermochronology. Tectonics 26:TC1004

Ehlers TA, Poulsen CJ (2009) Influence of Andean uplift on climate and paleoaltimetry estimates. Earth Planet Sci Lett 281:238–248

Evenstar LA, Hartley AJ, Stuart FM, Mather AE, Rice CM, Chong G (2009) Multiphase development of the Atacama planation surface recorded by cosmogenic 3He exposure ages: implications for uplift and Cenzoic climate change in western South America. Geology 37:27–30

Farías M, Charrier F, Comte D, Martinod J, Hérail G (2005) Late Cenozoic deformation and uplift of the western flank of the Altiplano: evidence from the depositional, tectonic, and geomorphic evolution and shallow seismic activity (northern Chile at 19°30′S). Tectonics 24:TC4001

Friend P (1983) Towards the field classification of alluvial architecture or sequence. In: Collinson JD, Lewin J (eds) Modern and ancient fluvial systems. Int Assoc Sed Spec Publ 6:345–354

García M (2002) Evolution Oligo-Miocène de l'Altiplano occidental (arc et avant-arc du nord du Chili, Arica): Tectonique, volcanism, sédimentation, géomorphologie et bilan érosion-sédimentation. Géologie Alpine, Laboratoire de Géodynamique des Chaînes Alpines, Université Joseph Fourier—Grenoble 1, pp 118

García M, Hérail G (2005) Fault-related folding, drainage network evolution and valley incision during the Neogene in the Andean Precordillera of Northern Chile. Geomorphology 65:279–300

García M, Hérail G, Charretier R (1996) The Cenozoic forearc evolution in northern Chile: the western border of the Altiplano of Belén (Chile). In: 3rd international symposium of Andean geodynamics, Saint-Malo, pp 359–362

Garreaud R, Vuille M, Clement AC (2003) The climate of the Altiplano: observed current conditions and mechanisms of past changes. Paleog Paleocl Paleoec 194:5–22

Garzione CN, Molnar P, Libarkin J, MacFadden B (2006) Rapid late Miocene rise of the Bolivian Altiplano: evidence for removal of mantle lithosphere. Earth Planet Sci Lett 241:543–556

Garzione CN, Hoke GD, Libarkin JC, Whiters S, MacFadden B, Eiler J, Ghosh P, Mulch A (2008) Rise of the Andes. Science 320:1304–1307

Gaupp R, Kött A, Wörner G (1999) Palaeoclimatic implications of Mio-Pliocene sedimentation in the high-altitude intra-arc Lauca Basin of northern Chile. Paleog Paleocl Paleoec 151:79–100

Ghosh P, Garzione C, Eiler JM (2006) Rapid uplift of the Altiplano revealed through 13C–18O bonds in paleosol coarbonates. Science 311:511–515

Gillis RJ, Horton BK, Grove M (2006) Thermochronology, geochronology and upper crustal structure of the Cordillera Real: implications for Cenozoic exhumation history of the central Andean Plateau. Tectonics 25:TC6007

Gregory-Wodzicki KM, Mcintosh WC, Velasquez K (1998) Climate and tectonic implications of the late Miocene Jakokkota flora, Bolivian Altiplano. J South Am Earth Sci 11:533–560

Hartley AJ (2003) Andean uplift and climate change. J Geol Soc London 160:7–10

Hartley AJ, Chong G (2002) Late Pliocene age for the Atacama Desert: implications for the desertification of western South America. Geology 30:43–46

Hartley AJ, Rice C (2005) Controls on supergene enrichment of porphyry copper deposits in the Central Andes: a review and reinterpretation. Miner Depos 40:515–525

Hoke GD, Isacks BL, Jordan TE, Yu JS (2004) Groundwater-sapping origin for the giant quebradas of northern Chile. Geology 32:605–608

Hoke GD, Isacks BL, Jordan TE, Tomlinson AJ, Blanco Pavez N, Razmezani J (2007) Geomorphic evidence for post-10 Ma uplift of the western flank of the central Andes 18°30′-22′S. Tectonics 26:TC5021

Houston J, Hartley A (2003) The central Andean west-slope rainshadow and its potential contribution to the origin of hyper-aridity in the Atacma desert. Int J Climatol 23:1453–1464

Insel J, Poulsen CJ, Ehlers T (2010) Influence of the Andes mountains on South American moisture transport, convection and precipitation. Clim Dyn. doi:10.1007/s00382-009-0637-1

Isacks BL (1988) Uplift of the Central Andean plateau and bending of the Bolivian orocline. J Geophys Res 93:3211–3231

Kiefer E, Dörr MJ, Ibbeken H, Götze H-J (1997) Gravity-based mass balance of an alluvial fan giant: the Arcas fan, Pampa del Tamarugal, northern Chile. Rev Geol Chile 24:165–185

Kober F, Schlunegger F, Zeilinger G, Schneider H (2006) Surface uplift and climate change: the geomorphic evolution of the Western Escarpment of the Andes of northern Chile between the Miocene and the present. In: Willett SD, Hovius N, Brandon MT, Fischer F (eds) Tectonics, climate and landscape evolution. Geol Soc Amer Spec Paper 398:75–86

Kober F, Ivy-Ochs S, Schlunegger F, Baur H, Kubik PW, Wieler R (2007) Denudation rates and a topography-driven rainfall threshold in northern Chile: multiple cosmogenic nuclide data and sediment budgets. Geomorphology 83:97–120

Kohler I (1999) Syntektonische kontinentale Sedimentation auf der Westabdachung der Anden Nordchiles (18° bis 19°S). Profil 17:1–165. Univ Stuttgart

Lamb S, Davis P (2003) Cenozoic climate change as a possible cause for the rise of the Andes. Nature 425:792–796

Lenters JD, Cook KH (1995) Simulation and diagnosis of the regional summertime precipitation climatology of South America. J Climate 8:2988–3005

Mamani M, Wörner G, Sempere T (2010) Geochemical variations in igneous rocks of the Central Andean orocline (13°S to 18°S): tracing crustal thickening and magma generation through time and space. Geol Soc Am Bull 122:162–182

McQuarrie N, Horton BK, Zandt G, Beck S, DeCelles PG (2005) Lithosperic evolution of the Andean fold-thrust belt, Bolivia, and the origin of the central Andean plateau. Tectonophysics 399:15–37

McQuarrie N, Ehlers TA, Barnes JB, Meade B (2008) Temporal variation in climate and tectonic coupling in the central Andes. Geology 36:999–1002

Miall AD (1985) Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. Earth-Sci Rev 22:261–308

Mulch A, Cornelius U, Strecker M, Schoenberg R, Chamberlain CP (2010) Late Miocene climate variability and surface elevation in the central Andes. Earth Planet Sci Lett 290:173–182

Muñoz N, Sepúlveda P (1992) Estructuras compresivas con vergencia al oeste en el borde oriental de la Depresión Central, Norte de Chile (19°15′S). Revi Geol Chile 19:241–247

Nalpas T, Dabard M-P, Ruffet G, Vernon A, Mpodozis C, Loi A, Hérail G (2008) Sedimentation and preservation of the Miocene Atacama Gravels in the Pedernales-Chañaral Area, Northern Chile: climatic or tectonic control? Tectonophysics 459:161–173

Naranjo J, Paskoff R (1985) Evolución cenozoica del piedemonte andino en la Pampa del Tamarugal, norte de Chile (18°–21°S). Congreso Geológico Chileno 4:149–165, Antofagasta

Nemec W, Postma G (1993) Quaternary alluvial fans in southwestern Crete: sedimentation processes and geomorphic evolution. In: Marzo M, Puigdefábregas M (eds) Alluvial sedimentation, vol 17. IAS Special Publication, pp 235–276

Nishiizumi K, Caffee MW, Finkel RC, Brimhall G, Mote T (2005) Remnants of a fossil alluvial fan landscape of Miocene age in the Atacama Desert of northern Chile using cosmogenic nuclide exposure age dating. Earth Planet Sci Lett 237:499–507

Parraguez G (1998) Sedimentología y geomorfología producto de la tectónica cenozoica, en la Depresión Central, I Región de Tarapacá, Chile. Mem Título thesis Univ Chile, p 108

Pinto L, Hérail G, Charrier R (2004) Sedimentatión sintectónica a las estructuras neógenas en la Precordillera de la zona de Moquella, Tarapacá (19°15′S, norte de Chile). Rev Geol Chile 31:19–44

Platt NH (1992) Freshwater carbonates from the Lower Freshwater Molasse (Oligocene, western Switzerland): sedimentology and stable isotopes. Sediment Geol 78:81–99

Rech JA, Currie BS, Michalski G, Cowan AM (2006) Neogene climate change and uplift in the Atacama Desert, Chile. Geology 34:761–764

Reich M, Palacios C, Vargas G, Luo S, Cameron EM, Leybourne MI, Parada MA, Zúñiga A, You C-F (2009) Supergene enrichment of copper deposits since the onset of modern hyperaridity in the Atacama Desert, Chile. Miner Deposita 44:497–504

Rust B (1978) Depositional models for braided alluvium. In: Miall AD (ed) Fluvial sedimentology. Mem Can Soc Pet Geol 5:605–625

Salino P, Nicolini M, Saulo AC (2002) Chaco low-level jet events characterization during the austral summer season. J Geophys Res 107: NO. D24

Salinas P, Villaroel C, Marshall L, Sepulveda P, Muñoz N (1991) Typotheriopsis sp. (Notoungulata Mesotheriidae), mamifero del Miocene superior en las cercanias Belén, Arcia, Norte de Chile. Congr Geol. Chileno, Resumen, pp 314–317

Schildgen TF, Hodges KV, Whipple KW, Reiners PW, Pringle MS (2007) Uplift of the western margin of the Andean plateau revealed from canyon incision history, southern Peru. Geology 35:523–526

Schlunegger F, Zeilinger G, Kounov A, Kober F, Hüsser B (2006) Scale of relief growth in the Andes of northern Chile. Terra Nova 18:217–223

Sepulchre P, Snyder M, Sloan LC (2010) Impact of Andean Uplift on the Humboldt Current System: a climate model sensitivity study. Paleoceanography (in press)

Sillitoe RH, McKee H (1996) Age of supergene oxidation and enrichment in the Chilenean porphyry copper province. Econ Geol 91:164–179

Steffen D, Schlunegger F, Preusser F (2009) Drainage basin response to climate change in the Pisco valley, Peru. Geology 37:491–494

Strecker MR, Alonso RN, Bookhagen B, Carrapa B, Hilley GE, Sobel ER, Trauth MH (2007) Tectonics and climate of the southern Central Andes. Ann Rev Earth Planet Sci 35:747–787

Thouret J-C, Wörner G, Gunnell Y, Singer B, Zhang X, Souriot T (2007) Geochronologic and stratigraphic constraints on canyon incision and Miocene uplift of the Central Andes in Peru. Earth Planet Sci Lett 263:151–166

Uba CE, Strecker M, Schmitt AK (2007) Increased sediment accumulation rates and climate forcing in the central Andes during the late Miocene. Geology 35:979–982

Victor P, Oncken O, Glodny J (2004) Uplift of the western Altiplano plateau: evidence from the Precordillera between 20° and 21°S (northern Chile). Tectonics 23:TC4004

Von Rotz R, Schlunegger F, Heller F (2005) Assessing the age of relief growth in the Andes of northern Chile: magneto-polarity chronologies from Neogene continental sections. Terra Nova 17:462–471

Walfort B, Hammerschmidt K, Wörner G (1995) New Ar/Ar ages from Tertiary volcanics in the northern Chilenean Andes (18°S): implication for tectonic and magmatic evolution. Terra Nova Abstr 7:354

Wörner G, Hammerschmidt K, Henjes-Kunst F, Lezaun J, Wilke H (2000) Geochronology (40Ar/39Ar, K–Ar and He-exposure ages) of Cenozoic magmatic rocks from northern Chile (18–22°S): implications fro magmatism and tectonic evolution of the central Andes. Rev Geol Chile 27:205–240

Wörner G, Uhlig D, Kohler I, Seyfried H (2002) Evolution of the West Andean Escarpment at 18°S (N. Chile) during the last 25 Ma: uplift, erosion and collapse through time. Tectonophysics 345:183–198

Zeilinger G, Schlunegger F, Simpson F (2005) The Oxaya anticline (northern Chile): a buckle enhanced by river incision? Terra Nova 17:368–375