ABSTRACT
The intermontane Quebrada de Humahuaca Basin (Humahuaca Basin) in the Eastern Cordillera of the southern Central Andes of NW Argentina (23°–24°S) records the evolution of a formerly contiguous foreland-basin setting to an intermontane depositional environment during the late stages of Cenozoic Andean mountain building. This basin has been and continues to be subject to shortening and surface uplift, which has resulted in the establishment of an orographic barrier for easterly sourced moisture-bearing winds along its eastern margin, followed by leeward aridification. We present new U–Pb zircon ages and palaeocurrent reconstructions suggesting that from at least 6 Ma until 4.2 Ma, the Humahuaca Basin was an integral part of a largely contiguous depositional system that became progressively decoupled from the foreland as deformation migrated eastward. The Humahuaca Basin experienced multiple cycles of severed hydrological conditions and subsequent re-captured drainage, fluvial connectivity with the foreland and sediment evacuation. Depositional and structural relationships among faults, regional unconformities and deformed landforms reveal a general pattern of intrabasin deformation that appears to be associated with different cycles of alluviation and basin excavation in which deformation is focused on basin-internal structures during or subsequent to phases of large-scale sediment removal.

INTRODUCTION
To understand the spatiotemporal evolution of tectonically active range fronts in mountain belts, it is essential to unravel the relationships between styles and rates of tectonic deformation, surface uplift, and the distribution of precipitation and surface processes that reflect relief and local climatic conditions. This evolution may be partially recorded by the sedimentary deposits preserved in intermontane basins in the peripheral sectors of an orogen, in the compartmentalized basins within broken forelands, or farther away in adjacent foreland basins.

Sediment accumulation within contiguous foreland basins is predominantly determined by the flexural response of the crust to the topographic load from an adjacent fold-and-thrust belt and from the sediments derived from the orogen (e.g. Beaumont, 1981; DeCelles & Giles, 1996). As a fundamental characteristic of foreland basins, protracted deformation and coeval deposition progressively extend into the previously undeformed, distal foreland regions, with the orogenic deformation front and associated sedimentary facies patterns advancing in a systematic spatiotemporal pattern (e.g. DeCelles & Giles, 1996). In contrast, broken foreland basins may develop in regions where shortening is accommodated along reactivated high-angle structures inherited from former tectonic regimes (Jordan & Allmendinger, 1986; Jordan & Alonso, 1987), often leading to highly diachronous and spatially disparate basement uplifts (reviewed in Strecker et al., 2011). Isolated range uplifts promote much more subdued flexural subsidence with accommodation space that is limited to the margins of the individual ranges (Strecker et al., 2011). If these tectonic characteristics are paired with arid climate conditions, headwater basins can become isolated from the downstream fluvial network, leading to sediment accumulation between uplifting ranges (Meyer et al., 1998; Sobel et al., 2003; Hilley & Strecker, 2005). Over geological timescales, an array of isolated to variably connected and laterally restricted depocentres may develop, forming a landscape similar to the partially coalesced basins observed in Cenozoic orogenic plateaus and their flanks, such as the southern part of the Andean Altiplano-Puna Plateau or the Tibetan Plateau and the adjacent Qilian Shan in Asia (Meyer et al., 1998; Sobel et al., 2003; Alonso et al., 2006; Strecker et al., 2009).
The dynamics of basin hydrology in these environments may depend on a type of competition between uplift of downstream ranges, which favours fragmentation of the fluvial network, and headward incision, which promotes the persistence or re-integration of rivers draining the periphery of these orogens (Sobol et al., 2003; Hilley & Strecker, 2005; Garcia-Castellanos, 2007). As a result, changes in climatic conditions or tectonic rates may cause these marginal basins along the flanks of an orogenic plateau to transition between conditions in which fluvial connectivity is promoted or basins are hydrologically isolated from their downstream watersheds. These alternations in the fluvial network are expected to influence the rate and tempo of sediment removal from the interior of the orogen to the unrestricted parts of foreland basins.

The Andean broken foreland areas of the northern Sierras Pampeanas, the Santa Bárbara System and parts of the Eastern Cordillera of NW Argentina (Fig. 1) illustrate the complex morphology resulting from tectonic uplift, basin formation and basin excavation along the eastern flanks of the orogenic Altiplano-Puna Plateau. While field studies in this region show that rivers connecting intermontane basins with the foreland are often interrupted due to spatial and temporal changes in deformation, climate and the erodibility of exposed bedrock (e.g. Hilley & Strecker, 2005), predicting the combinations of driving factors responsible for alternating states of basin isolation and fluvial connectivity is still difficult. Deposits preserved in the intermontane basins are often deformed, faulted and frequently show syntectonic growth as a result of initial foreland fragmentation and out-of-sequence deformation, demonstrating clear tectonic influence on basin sedimentation (for a summary see Strecker et al., 2011; Hilley et al., 2005). Moreover, regional unconformities show that large volumes of sediment have been rapidly removed from these basins once they have been re-captured (Hilley & Strecker, 2005; Strecker et al., 2009). These superposed processes raise an interesting and as yet unexplored possible feedback between the re-integration of these intermontane basins with the foreland through fluvial connectivity and renewed faulting within the orogenic realm following the removal of sedimentary loads. While these relationships among tectonics, sedimentation and erosion have been suspected to exist in many intermontane basins of the NW Argentine Andes (Strecker et al., 1989, 2009; Hilley & Strecker, 2005; Alonso et al., 2006), the timescales for individual filling and excavation cycles have remained poorly constrained.

A rich record of frequently intercalated volcanic ashes in the sediments of the southern Humahuaca Basin of NW Argentina (~23.5°S, Fig. 1) provides the requisite chronology to quantify temporal associations among tectonics, climate and sedimentation on the scale of a single intermontane basin. In our study, we present new chronostatigraphic (206Pb/238U zircon and AMS 14C), structural and sedimentological data for various preserved conglomeratic basin fills within the Humahuaca Basin and document that (a) the transition between a largely continuous foreland depositional environment and a subsequent fault-bounded intermontane basin is related to more pronounced surface uplifts to the east after ~4.2 Ma; (b) the intermontane basin stage has been characterized by multiple cycles of basin filling and subsequent sediment removal; and, although speculative, (c) out-of-sequence reactivation of faults within the basin may be closely linked with sediment evacuation.

REGIONAL AND GEOLICAL SETTING

The Humahuaca Basin (Jujuy Province) is the northernmost intermontane sedimentary basin in an array of reverse-fault bounded basins within the Eastern Cordillera of NW Argentina along the eastern Puna Plateau margin, the southern extension of the Bolivian Altiplano (Fig. 1). The Humahuaca Basin is surrounded by high-elevation mountain ranges exceeding 5,000 m a.s.l. that consist of smaller reverse and thrust fault-bounded blocks. The Sierra Alta separates the basin from the internally drained and arid Puna Plateau to the west, while the Tilcara ranges constitute the boundary with the humid foreland depositional system to the east. At present, the Humahuaca Basin is connected to the foreland via a narrow, fault-bounded bedrock gorge to the south, through which the Río Grande exits the basin (Figs 2 and 9). Here, the course of the Río Grande firstly follows and then obliquely crosses the trace of the west-dipping reverse fault that bounds the southern sector of the Tilcara ranges.

Basement blocks constitute the basin-bounding ranges that have been uplifted along north to north–northeast striking, bivergent thrust and reverse-fault systems (Rodríguez-Fernández et al., 1999; Kley et al., 2005; Fig. 2). At the latitude of the Humahuaca Basin, the eastern margin of the neighbouring Altiplano-Puna Plateau records a middle Eocene to Oligocene deformation history, influenced by pre-existing crustal heterogeneities and structures that were reactivated during Cenozoic compression (Coutand et al., 2001, 2006; Deeken et al., 2006; Hongn et al., 2007; Insel et al., 2012). Between 10 and 8 Ma, the eastern plateau margin apparently attained sufficient elevation and relief to intercept moisture-bearing easterly winds; this topography constituted a major orographic barrier to atmospheric circulation on a hemispheric scale, resulting in the aridification of the orogen interior and the establishment of humid conditions on the eastern flanks (Allmendinger et al., 1997; Kleinert & Strecker, 2001; Starck & Anzótegui, 2001; Strecker et al., 2007; Uba et al., 2007; Carrapa et al., 2008; Mulch et al., 2010; Vezzoli et al., 2012). During the Mio-Pliocene, deformation migrated into the present-day Eastern Cordillera, where the formerly contiguous foreland basin was partitioned by regional range uplifts. This deformation is spatially disparate, highly diachronous (reviewed in
The basement rocks exposed along the flanks of the Humahuaca Basin comprise tightly folded late Proterozoic to early Palaeozoic low-grade metasediments of the Puncoviscana Formation (Turner, 1960; Omarini, 1983). These units are unconformably overlain by Cambro-Ordovician sandstones and quartzites of the Mes/C19on and Santa Victoria groups (Moya, 1988; Sánchez & Salfity, 1999; Aceñolaza, 2003). An angular unconformity separates these sediments from the late Cretaceous to Palaeogene Salta Group related to the Cretaceous Salta Rift (Salilty, 1982; Galliski & Viramonte, 1988; Marquillas et al., 2005). The most prominent strata of these sequences exposed in the southern Humahuaca Basin are continental red beds of the Pirgua Subgroup, white sandstones and yellow-coloured marine carbonates of the Lecho Formation and the stromatolitic Yacoraite Formation (Balbuena Subgroup), respectively, and fluvial deposits of the Lumbera Formation (Santa Bárbara Subgroup). For detailed reviews, see Marquillas et al. (2005) and Sánchez & Marquillas (2010).

These lithologies are typically overlain by early Cenozoic foreland sediments such as the Quebrada de los Colorado Formation (middle Eocene–Oligocene), the deposits of the Orán Group (Miocene–Pliocene) or equivalent strata (Gebhard et al., 1974; Russo & Serraiotto, 1978; Díaz & Malizia, 1983; Vergani & Starck, 1989; Coutand et al., 2001) in the Puna and present-day foreland regions to the east of the study area. However, these sediments have mostly been removed in the highly exhumed Eastern Cordillera (Jordan & Alonso, 1987; Kley et al., 2005). A regional exception to this general pattern is a ca. 6-km thick succession of middle Eocene to Pliocene foreland and intermontane basin deposits in the Cianzo Basin of the Eastern Cordillera, 20 km east of the town of Humahuaca (details in Siks & Horton, 2011). Strata overlying the Salta Group in the Humahuaca Basin largely consist of weakly consolidated, mainly conglomeratic deposits that reflect a complex history of deposition, erosion and deformation that spans the late Miocene and Quaternary.

Three major units have previously been described: the Maimará Formation (Salilty et al., 1984), the Uquia Formation (Castellanos, 1950; Marshall et al., 1982; Walther et al., 1998) and thick conglomeratic fills of Quaternary age (Tchilinguirian & Pereyra, 2001; Robinson et al., 2005; Strecker et al., 2007; Sancho et al., 2008). In the following sections, we will refine this stratigraphic framework for the southern part of the Humahuaca Basin and focus our attention on its distinct volcanic ash-bearing conglomerates and sandstones that document sustained deposition, deformation and erosion in the basin, and which provide excellent stratigraphic markers to assess the late Miocene and Quaternary basin evolution.

**METHODS**

We used stratigraphic and structural analysis, together with detailed geological mapping of exposed units (Fig. 3), regional unconformities, sediment provenance, lateral facies pinch-outs and lithological contacts to document the tectono-sedimentary history of the southern Humahuaca Basin. A similar approach is used in an ongoing chronostratigraphic study of the northern Humahuaca Basin (Streit et al., 2012).
Despite apparent similarities between the various synorogenic lithologies, spatiotemporal changes in the sediment sources result in distinct differences among the conglomeratic fill units in the Humahuaca Basin. We characterized the compositional differences of the fills by counting at least 100 clasts from within a 0.25-m² grid in key stratigraphic units. To deduce sediment provenance and transport directions for ancient river systems, we measured ~1,600 imbricated clasts at 33 localities. Where possible, we measured the orientation of at least 50 clasts per site, applied corrections for structural dip and displayed them in unidirectional rose diagrams using OSXStereonet software (by N. Cardozo & R. Allmendinger).

Fig. 2. (a) Simplified geology of the Humahuaca Basin and surroundings and (b) geological cross section after Rodríguez-Fernández et al. (1999) and own data. Black box indicates the area mapped in detail (Fig. 3a).
Fig. 3. (a) Geological map of the central study area between Tilcara and Purmamarca in the southern Humahuaca Basin. Triangles represent U–Pb zircon sample locations (see Table S1) and thick black lines show the position of measured stratigraphic sections from Fig. 6. Map is rotated clockwise by 20°. (b) Simplified late Cenozoic chronostratigraphy of the study area. Unless otherwise indicated, values represent averaged U–Pb zircon ages from this study. a40Ar/39Ar-biotite (Strecker et al., 2007); bOSL-quartz (Robinson et al., 2005; Sancho et al., 2008); cAMS14C (this study). (c) Subsurface interpretations of severely deformed strata. Shown are pseudo-fault-plane solutions calculated from fault-kinematic indicators documenting thrust kinematics during the Pliocene. Pv, Puncoviscana Fm; Sa, Salta Group; M, Maimará Fm; T, Tilcara Fm; Q, Quaternary gravels.
To provide a chronological base for different tectonic and sedimentological events, we dated 12 volcanic ash deposits interbedded in the Mio-Pleistocene basin strata using U–Pb zircon geochronology. Samples were crushed, sieved, and treated with standard heavy-liquid and magnetic separation techniques to isolate zircon crystals. About 30 crystals per sample were handpicked, mounted in epoxy, polished, and cleaned, and then gold-coated for microprobe analysis. Crystals free of inclusions or cracks were selected for U–Pb analysis using the CAMECA IMS 1270 ion microprobe at the University of California in Los Angeles, following protocols described in Schmitt et al. (2003) and Grove et al. (2003). The 206Pb/238U ages have been corrected for common Pb and initial disequilibrium. The uncertainties in U–Pb ages, estimated from the reproducibility of standard AS3 zircons (1,099.1 Ma; Paces & Miller, 1993), were 2.2% and 2.7% (1 standard deviation) for the analytical sessions in July 2009 and June 2010, respectively.

RESULTS

U–Pb zircon geochronology

Most analysed samples show complex zircon age distributions. This could be due to protracted pre-eruptive crystal residences (e.g. Schmitt et al., 2003), or post-eruptive reworking in which case mixing and contamination with detrital crystals during emplacement would lead to the presence of multiple age populations. We therefore systematically omitted older ages from our calculations of an average zircon crystallization age. The statistically uniform younger age population was then used as an approximation for the depositional age, while acknowledging that this is likely to overestimate the eruption age because of pre-eruptive zircon crystallization (e.g. by ~0.1 Ma for the large-volume Atana ignimbrite; Schmitt et al., 2001).

Most samples yielded consistent 206Pb/238U ages for the majority of crystals, as indicated by near-unity values for the mean square of weighted deviates (MSWDs), suggesting only minor reworking. In some cases, however, only a small percentage of crystals defined a coherent young population; in these cases, we have interpreted the 206Pb/238U zircon age as the maximum age for deposition. Results are shown in Figs 3–5, and summarized in Table S1.

Late Miocene to Pleistocene stratigraphy

Maimarí Formation

The ochre to yellow beds of the Maimarí Formation unconformably overlie the older lithologies exposed in the basin, including the Proterozoic Puncoviscana Formation. The Maimarí Formation generally comprises arkosic sandstones and interbedded cobble conglomerates, and is at least 250-m thick (Fig. 6). The matrix-
to clast-supported conglomerates are composed of well-rounded pebbles and cobbles, and occasionally boulders, mainly from Proterozoic (23.5% Pz) and Palaeozoic (64.5% Pz) sources (Puncoviscana Fm. & Mesón Group). This unit also contains clasts of limestones and sandstones from the Cretaceous to Palaeogene Salta Group (12% Cz) and a minor proportion of lithic-rich, late Miocene to Pliocene ignimbrites with the nearest known exposures confined to the Puna Plateau to the west (e.g. Riller et al., 2001).

The most complete section is exposed in the Quebrada de Maimará, west of the town of Maimará (Figs 3 and 6), where the successions has been thrust eastward over Pliocene conglomerates. Fossil-rich clay beds and siltstones dominate the basal 50 m of this section and contain freshwater ostracods (Limnocythere sp.; Fig. 8b) and intact calcic encrustations of charophyte oogonia. The following 200-m thick sequence of interbedded sandstones and conglomerates is intercalated with at least seven volcanic ash layers.

About 75 m of faulted strata of the Maimará Formation is also exposed at Incahuasi, located about 10 km south of the Quebrada de Maimará. This section unconformably overlies palaeo-relief developed in the Proterozoic to Palaeozoic basement and comprises several metre-thick banks of moderately consolidated fine-grained arkosic sandstones that are frequently intercalated with rhyolitic ash layers, debris-flow deposits and conglomeratic channel fills (Fig. 6). Further exposures of the Maimará Formation exist east of the town of Tilcara, along the Río Huasamayo, where the Maimará Formation has been thrust over late Pleistocene conglomerates (e.g. Saltif et al., 1984; Marrett et al., 1994; Fig. 8a).

The presence of ignimbrite clasts sourced in the Puna supports the notion of an eastward fluvial transport across the present-day Sierra Alta, the major mountain range that now constitutes the eastern margin of the Altiplano-Puna Plateau west of the basin. The notion of a western provenance is in agreement with our palaeocurrent estimates that demonstrate an east–southeast-directed palaeo-drainage system at that time (Fig. 7). We therefore conclude that the former fluvial network must have drained eastward across both ranges that now delimit the basin.

Our U–Pb zircon ages from various volcanic ashes (08HUM03; 08HUM05; 08HUM07; 09HUM12; 10HUM02; 10HUM21; 10HUM23; Figs 4 and 6; Table S1) constrain that this depositional setting existed at least between 5.92 ± 0.12 Ma (MSWD = 1.4; n = 14) and 4.18 ± 0.11 Ma (MSWD = 0.68; n = 10).

Tilcara Formation

In the southern Humahuaca Basin, the Maimará Formation is overlain by a series of metre-thick interbedded conglomerate, fanglomerate and sandstone beds, at least 250-m thick, which also contain volcanic ash layers. The transition to subsequent lithologies is always characterized by a pronounced regional unconformity, rendering all measurements of total sediment thickness minimum estimates (Figs 8c, d). In contrast to the Maimará Formation, the poorly consolidated strata comprise well-rounded and well-imbricated pebble- to boulder-sized clasts with only a minor quantity of Salta Group clasts.

Fig. 5. 207Pb/206Pb vs. 238U/206Pb zircon data for Tilcara and Quaternary gravel samples, uncorrected for common Pb and regression lines with a fixed y-axis intercept corresponding to common Pb (207Pb/206Pb = 0.83). See caption of Fig. 4 for additional information.
but no ignimbrites (27.5% P\textsubscript{V}; 71% P\textsubscript{Z}; 1.5% C\textsubscript{R}). Carbonate cementation of conglomerates occurs in metre-thick beds. The nearly filled pore spaces, within such beds, suggest advanced pedogenic K-horizon formation (e.g. Gile et al., 1966; Machette, 1985), a common feature associated with conglomerate deposits in the semi-arid environments of the southern Central Andes (e.g. Strecker et al., 1989). Clast-imbrication measurements record a change to a southerly direction of sediment transport (Figs 6 and 7). While on average, this change demonstrates a rotation of ca. 20° towards the south (Fig. 7), palaeocurrent directions measured along continuous sections reflect a dramatic reorganization of the fluvial system by more than 90° (Fig. 6).

Two ashes sampled in the lower part of the section (08HUM01 and 08HUM08) yielded overlapping U–Pb zircon ages of 3.66 ± 0.20 (MSWD = 1.6; n = 6) and 3.52 ± 0.08 Ma (MSWD = 0.44; n = 8; Fig. 5; Table S1). Because these age determinations are statistically indistinguishable, we consider them to represent the same ash horizon. A second ash layer from the upper section (09HUM05) yielded a significantly younger 206Pb/238U zircon age of 2.50 ± 0.10 Ma (MSWD = 1.4; n = 9; Fig. 5; Table S1).

Previous stratigraphic and palaeontological studies have shown that in the northern Humahuaca Basin, strata of the Maimará Formation are overlain by the fossil-bearing fluvial Uquía Formation. This unit comprises mud and sandstones with occasional conglomeratic beds and interbedded volcanic ash horizons (Castellanos, 1950; Reguero et al., 2007). Clast counts for the Uquía Formation at a limited number of outcrops reveal ~10% Proterozoic rocks (Puncoviscana Fm.) and ~90% Palaeozoic rocks (Mesón Group). Age determinations of a basal volcanic ash from the Uquía Formation (3.54 ± 0.04 Ma; Marshall et al., 1982) and from within the upper third of the section (zircon fission-track age ~2.5 Ma; Walther et al., 1998) are in good agreement with our chronology of the Tilcara Formation. Furthermore, palaeomagnetic results from the Uquía Formation (Marshall et al., 1982) imply that its uppermost strata may be as young as ~1.5 Ma. As the topmost section of the Tilcara Formation is not preserved, we are unable to determine an upper depositional age limit. However, we infer that the timing of deposition was similar in both sub-basins. We consider this assumption to be valid because (a) we do not find any evidence of other deposits between 2.5 and >1 Ma in the southern Humahuaca Basin, and (b) the oldest Quaternary sediments that cover both formations uniformly may be as old as ~1 Ma. It is therefore quite possible that the (unpreserved) top of the Tilcara Formation in the southern basin is temporally equivalent to the ~1.5-Myr old top of the Uquía Formation to the north.

Although chronostratigraphic investigations in the northern Humahuaca Basin are still ongoing (Streit et al., 2012), we have sufficient evidence for lithological differences between the corresponding Plio-Pleistocene deposits in the two sub-basins to establish a new lithological unit in the southern basin: the Tilcara Formation. Our
Fig. 8. (a) Thrust fault near Tilcara along the Río Huasamayo, juxtaposing late Miocene Maimará deposits against Quaternary gravels. Arrows and dashed lines indicate the vertical displacement (up to 20 m) of a formerly contiguous terrace surface. (b) SEM image of *Limnocythere* sp. from the lower beds of the Maimará Formation. (c) Deformed bedding-parallel erosion surfaces in the Tilcara Formation preserved below Quaternary landslide deposits. Tectono-sedimentary relationships suggest an episode of river incision and excavation prior to deformation. (d) Another example of the marked regional unconformity between the Tilcara Formation and Quaternary gravels. (e) Thick conglomeratic fill unit (Quaternary gravels) near the town of Tumbaya. (f) Panoramic view towards the east showing well developed geomorphic surfaces along the western flanks of the Tilcara ranges at successively lower elevation.
radiometric ages show that deposition of this unit took place between ~4.2 and 2.5 Ma and by correlation may have lasted until approximately 1.5 Ma.

Landslide deposits

We identified multiple voluminous landslide deposits south of Maimará village that unconformably cover older units along the eastern basin margin (Fig. 3a). These deposits predominantly consist of Palaeozoic and Cretaceous to Eocene rocks, and overlie previously exhumed Palaeozoic rocks that dip steeply westward. Multiple, pervasively shattered rock sheets with no stratigraphic context are located 60 m above the valley floor and appear to be sourced in the eastern basin-bounding range. In places, the landslide deposits have been subsequently covered by sub-horizontally bedded conglomerates of Pleistocene age. The depositional age of the landslide deposits can, therefore, be only crudely constrained to be older than the Pleistocene conglomerates.

To the west of the Río Grande and north of Incahuasi (Fig. 3a), a voluminous Quaternary landslide deposit that extends for approximately 3.5 km to the north has been preserved covering an erosional palaeo-landscape in the previously deposited and folded units. The deposit comprises two distinct source lithologies: (a) basal conglomerates whose clast composition, size and general appearance match the conglomeratic sections of the Maimará Formation; and (b) Proterozoic basement, found only in the upper section of the landslide. In both parts, the rocks are heavily sheared and fractured, with the degree of cataclasis increasing with depth, culminating at the bottom where underlying undifferentiated sediments have been injected upward into the fully disintegrated rocks. The contact between the two units comprising the landslide deposit is very sharp and resembles a thrust fault identical to the relationships that can be observed along the present-day basin-bounding Sierra Alta to the west. The landslide deposit is covered by ash-bearing fanglomerates that have been dated to ~1 Ma (see section below), which were subsequently tilted by faulting.

Quaternary gravels

The youngest deposits in the southern Humahuaca Basin constitute thick gravel fills covering palaeotopography in the previously deformed and eroded units. Two lithological units can be distinguished on the basis of clast compositions. The first unit comprises dark grey to black...
fangle conglomerates that were derived exclusively from source regions to the west. These sediments consist predominantly of angular to subangular clasts of the Puncoviscana Formation, together with less abundant clasts from the Proterozoic basement of the Sierra Alta. At several locations corresponding to more distal sectors of the inferred alluvial fans, the flanges intersect with well-stratified layers of pebble conglomerates, graded sands and unconsolidated silty clay. The layers are characterized by lateral, east–west-oriented pinch-outs. By analogy with the present-day depositional environment of the Rio Grande and from the geometry of the pinch-outs, we infer that the former fluvial system also drained southward. The youngest zircons from a trachy–dacitic ash deposit in the upper part of a deformed succession 2 km north–west of Incahuasi yielded mid-Pleistocene ages (1.06 ± 0.10 Ma; n = 2; 08HUM11; Fig. 5; Table S1), which we infer to represent a maximum depositional age.

The second unit in the Quaternary gravels comprises a group of grey alluvial-fan deposits and fluvial conglomerates (Fig. 8e) that are widely distributed within the Humahuaca Basin, its tributary valleys and in the basin outlet region to the north of Volcán village (Figs 2 and 9). These gravels typically consist of approximately equal proportions of Proterozoic and Palaeozoic clasts with minor contributions from Cretaceous lithologies, representing the present-day exposure of rock types in the surrounding source areas. The oldest conglomeratic fill in this unit forms an abandoned geomorphic surface to the east of the town of Tilcara, which is up to 400 m above the present-day baselevel and has an 40Ar/39Ar biotite age of ~800 ka, taken from a volcanic ash layer in the lower third of the section (Strecker et al., 2007). Other investigators have further differentiated these gravels and document at least one additional, separate fill unit at lower elevations, corresponding to a third basin-filling episode between 93.8 ± 7.9 and 65 ± 4 ka (Tchilinguirian & Pereyra, 2001; Robinson et al., 2005; Sancho et al., 2008). In the south of Tilcara, this younger fill unit has been episodically downcut during the last ~65 ka, which has resulted in fluvial terrace surfaces at successively lower elevations (Fig. 8f). In the tributary Quebrada de Purmamarca in the south–west of the study area, even younger deposits, up to 250-m thick, constitute massive basin fills that have been dated 47.6 ± 2.8 ka (OSL, Robinson et al., 2005) and, although at the limit of the dating method, at 49.55 ± 1.7 ka BP (23° 40.9’ S, 65° 34.5’ W; AMS 14C; this study).

**Structures**

Three east–vergent, basement-involved fault systems define the structural framework of the Humahuaca Basin: (a) the basin-bounding Purmamarca Thrust Fault to the west; (b) a set of thrust-and-reverse faults within the Tilcara ranges to the east; and (c) the Tumbaya Fault in the basin centre, close to the Rio Grande (Fig. 9).

The Purmamarca Thrust Fault juxtaposes Proterozoic basement of the Sierra Alta over Meso-Cenozoic sediments along the western basin margin and has developed a characteristic deformation pattern in the overthrust lithologies, involving steep eastward dips, or overturned strata. Moreover, multiple splays have developed from that fault extending into the basin, offsetting the Cenozoic strata (Figs 2 and 3). The Sierra Alta belongs to a set of subparallel basement ranges that have been uplifted along bivergent thrust and reverse faults. Apatite fission track thermal modelling suggests that exhumation of the easternmost ranges constituting the Sierra Alta began between 15 and 10 Ma (Deeken et al., 2004).

Present-day elevations of the eastern basin-bounding Tilcara ranges are attributed to shortening, crustal thickening and block rotation along multiple major east-verging thrust faults located within the range (Rodríguez-Fernández et al., 1999; Fig. 2). Because fault activity was mainly restricted to areas east of the Humahuaca Basin, the Proterozoic basement and overlying Palaeozoic to Mesozoic strata along the western flanks of the range were affected by westward tilting of this basement block.

At Molle Punco, near Tumbaya (Figs 2 and 9), Proterozoic rocks of the Puncoviscana Formation are thrust over the Palaeozoic successions of the Mesón Group along the Tumbaya Fault. The Tumbaya Fault can be traced into the northern Humahuaca Basin, intersecting the course of the Rio Grande repeatedly. In the southern Humahuaca Basin, this fault is responsible for an uplifted central range (Fig. 3a) that causes the narrowing of the basin. The surface expression of the fault and associated basement exposure gradually decrease northward, but the fault location can still be inferred from west-dipping Cenozoic basin strata in its hanging wall.

The sedimentary strata and landforms in the southern Humahuaca Basin attest to protracted deformation during the Plio-Pleistocene (see section below and Fig. 3c). The deformation includes thrusting of Precambrian to Mesozoic rocks over the conglomerates of the Maimará basin. 

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**Fig. 11.** Conceptual model of foreland-basin fragmentation. (a) The Maimará Formation is deposited into an exposed basement palaeotopography in a largely continuous depositional system since ~a. 6 Ma. (b) Surface uplifts to the east led to re-routing of the fluvial network and deposition of the Tilcara Formation into an intermontane basin after 4.2 Ma.
Formation along the Purmamarca Thrust Fault and associated folding, and the subsequent tilting of late Miocene to Pleistocene basin sediments in the hanging wall of the Tumbaya Fault until after 1 Ma.

Shortening within the basin was further accommodated by a number of mesoscale structures, mostly affecting the Maimará and Tilcara formations. Tight to open folding and the development of generally east-vergent and shallow-dipping thrust systems led to multiple stacked repetitions of the Miocene-Pliocene strata within the basin (Fig. 3). These thrusts are often associated with the development of drag folds, and shortening is in places accommodated by antithetic west-vergent faults. This pronounced Plio-Pleistocene strain accommodation in the southern Humahuaca Basin is mainly observed in the west of the Río Grande between the Purmamarca and Tumbaya faults.

**Tectono-sedimentary relationships and deformation of basin sediments**

The Maimará Formation rests unconformably on deformed sandstones of the Palaeogene Lumbrera Formation (upper Salta Group) and Proterozoic to Palaeozoic basement rocks. This unconformity and onlap relationships between the Maimará Formation and the underlying, irregularly shaped basement surface suggests deposition on palaeotopography that was sculpted into these rocks prior to ~6 Ma. To date, no evidence has been observed supporting an unconformable relationship between the Maimará Formation and the intermontane Tilcara Formation. The Tilcara Formation is always cut by a marked regional unconformity that in many places has been subsequently altered and obscured by continued deformation, erosion and deposition. Lateral correlation with the Uquía Formation in the northern Humahuaca Basin suggests that deformation following the initial incision occurred after ~1.5 Ma. Near the Tumbaya Fault at Incahuasi (Figs 3a and 9), this deformed unconformity resembles fluvial erosion surfaces sculpted into the Tilcara Formation that are tilted at ~20–30°W, parallel to bedding (Fig. 8c). These unconformable relationships and the vestiges of an erosional palaeotopography in the Tertiary sedimentary rocks are well preserved under a >1.06 ± 0.1 Ma conglomeratic fill unit that dips 10°–15°W. Basal remnants of this earlier fill unit have a depositional age of about 0.8 Ma.

A subsequent conglomerate unit (~94–65 ka at Tilcara and ~50 ka near Purmamarca) filled palaeotopography, covering the channel of the former trunk stream, which is now being re-excavated. This >200-m thick fill unit terminates in a smooth terrace surface that is connected with the mountain fronts. At Purmamarca, these gravel beds are generally not affected by fault displacement or other deformation. Near Tilcara, however, a prominent thrust fault close to the eastern margin of the basin (Fig. 8a) juxtaposes the Maimará Formation with young terrace-forming sections of the Quaternary strata (Salifity et al., 1984; Marrett et al., 1994). Here, deformation resulted in vertical offsets between 15 and 20 m, which translates into an average vertical displacement rate of 0.27 ± 0.04 mm/a during the last 65 kyr. Horizontal displacements of ~40 m (Sancho et al., 2008) suggest shortening rates of 0.62 ± 0.04 mm/a. Although these rates are only approximations, they emphasize the importance of protracted tectonic activity in the Humahuaca Basin within the interior of the orogen, which is compatible with the characteristics of regional shallow crustal seismicity (e.g. Bevis & Isacks, 1984; Cahill et al., 1992). It is noteworthy that this youngest deformation followed a major phase of gradual basin evacuation.

**DISCUSSION**

Foreland basin fragmentation and orographic barrier development

Crustal deformation corresponding to the region of the present-day interior of the Puna Plateau initiated in Eocene to Oligocene time (e.g. Kraemer et al., 1999; Carrapa et al., 2005; Deeken et al., 2006; Hongn et al., 2007; Letcher, 2007; Fig. 10). While individual ranges were uplifted, thick synorogenic strata buried the region that now constitutes the Eastern Cordillera and adjacent regions to the east (Reynolds et al., 2001; Deeken et al., 2006; DelPapa et al., in review). Today, these sediments are only rarely preserved in the uplifted Eastern Cordillera and the south-eastern flanks of the present-day Puna Plateau (Jordan & Alonso, 1985; Bossi et al., 2001; Coutand et al., 2001; Kley et al., 2005; Mortimer et al., 2007) and none appear to have been retained in the southern Humahuaca Basin. A regional exception is a ca. 6-km thick succession of middle Eocene to Pliocene foreland and intermontane basin deposits in the Cianzo Basin (Fig. 9), about 20 km east of the town of Humahuaca, where deformation and severely drainage conditions have been documented at ca. 10 Ma (Siks & Horton, 2011). Similarly, the Tres Cruces Basin in the Puna (Fig. 9) to the west has retained thick Cenozoic deposits (e.g. Boll & Hernández, 1986; Coutand et al., 2001). In both cases, major reverse faults enclosing the basins have helped to preserve the Cenozoic sedimentary record. These regional relationships support the notion of widely distributed early Tertiary sediments in the area of the Eastern Cordillera and regions farther east. Their general absence in these high-elevation sectors of the orogen thus suggests their removal during regional exhumation in the realm of the Eastern Cordillera at about 15–10 Ma (Deeken et al., 2004, 2006; Coutand et al., 2006; Siks & Horton, 2011).

The earliest synorogenic strata recognized in the southern Humahuaca Basin belong to the Maimará Formation and were deposited on a palaeotopography of exposed Proterozoic and Paleozoic basement. Deposition of Maimará sediments after a prolonged period of exhumation and deformation along the former orogenic flanks clearly documents that by ca. 6 Ma (and possibly some time...
earlier), new topographic conditions had evolved that would have promoted sedimentation in the study area. Our palaeocurrent and provenance data including ignimbrite clasts from currently isolated areas in the Puna interior and clasts from the Eastern Cordillera document that these sediments were sourced from the west. As the Humahuaca Basin and the Puna are not connected anymore, this observation confirms that thrusting in the Sierra Alta had not completely interrupted eastward-draining rivers at about 6 Ma and that the final disruption of the fluvial network must have occurred later.

We do not record any sedimentary evidence for uplift of the Tilcara ranges at the time when the Maimar Formation was deposited. This suggests that the Humahuaca Basin was part of an unrestricted foreland, and that surface uplift of the eastern ranges started later, coupled with the deposition of the Tilcara Formation. Alternatively, one could envision a scenario with an eastward-directed antecedent fluvial network that may have traversed the uplifting Tilcara ranges and transported sediment towards the regions farther east. In both settings, more pronounced surface uplift in Plio-Pleistocene time would have ultimately forced the full establishment of intermontane basin conditions and the formation of an efficient drainage divide, with rivers routing sediments towards the south. Although not documented in this study, a lateral correlation between the Maimar Formation and the upper sections of the Orán Group east of the ranges can not be excluded. Sediments of the Orán Group may yield additional information to further elaborate these interpretations in future.

Nevertheless, Orán Group sediments exposed in the Zapla anticline to the south-east of the Tilcara ranges (Fig. 9), record a major pulse in deformation prior to 5 Ma (Reynolds et al., 1994, 2000; reviewed in Kley & Monaldi, 2002). This is consistent with our palaeocurrent data from the Tilcara Formation that record a distinct early Pliocene changeover of fluvial transport towards a data from the Tilcara Formation that record a distinct Monaldi, 2002). This is consistent with our palaeocurrent

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Palaeo-environmental evidence from the Miocene-Pliocene palaeontological and sedimentary record prior to pronounced uplift indicates that climatic conditions during that time were relatively humid. While the Uquía Formation is well known for its fossil assemblage indicating subtropical to tropical warm, humid conditions (Alonso et al., 2006; Reguero et al., 2007; Reguero & Candela, 2008), ostracods analysed in this study additionally attest to the existence of permanent freshwater bodies in the lower Maimar Formation, clearly indicating that topography and relief conditions must have been subdued. Calcic rhizocrencretions and nodules in the upper section of the Maimar Formation indicate regional wet-dry seasonality, a characteristic, which is maintained in the overlying Tilcara and Uquía formations. In stark contrast are the more arid conditions and the efficient orographic barrier to the east observed in the Humahuaca Basin today. Stratigraphic relationships and inferred palaeoclimatic indicators suggest that aridification may be a relatively young phenomenon, related to the uplift of the Tilcara ranges.

The timing of tectonic uplift and associated aridification appears to have been diachronous and basin-specific throughout the southern Central Andes, and determined by the individual behaviour of the basin-bounding faults. Although such environmental shifts are a hallmark of virtually all intermontane basins along the eastern flank of the Puna Plateau and generally took place during the Pliocene (Bossi et al., 2001; Kleinert & Strecker, 2001; Starck & Anzótegui, 2001; Coutand et al., 2006; Hain et al., 2011), our observations demonstrate that in the Humahuaca Basin, the change to drier conditions probably occurred as late as Plio-Pleistocene time.

**Basin-fill evolution and deformation in the Humahuaca Basin**

The abrupt change in palaeoflow directions during the deposition of the Tilcara Formation at ~4.2 Ma and the associated facies change from distal to rather proximal sources (upward coarsening; Figs 3 and 6) record the tectonically induced reorganization of east-flowing river networks that formerly traversed the Tilcara ranges (Fig. 11). By analogy with neighbouring intermontane basins (e.g. the Toro and Lerma basins), the strata of the Tilcara Formation are interpreted as heralding the attainment of an intermontane basin stage. At that time, deposition in the Humahuaca Basin must have taken place under conditions of restricted fluvial connectivity with the foreland; otherwise, the deposition of over 250 m of sediment within the basin may not have been possible. Others have suggested that protracted internal drainage (e.g. Sobel et al., 2003) or restricted external drainage (e.g. Hilley & Strecker, 2005) appear to be related to the combined effects of high uplift rates, exposure of resistant rocks and aridity. In this context, the following mechanisms for basin aggradation between 4.2 and ~1.5 Ma may be envisioned: (1) increased surface-uplift rates in the Tilcara ranges, associated with activity along a reverse fault that obliquely crosses the outlet region, and/or exposure of more resistant rock types reducing the fluvial transport efficiency within the basin; and (2) a change in global and/or regional climatic conditions towards increased aridity, reduced runoff and transport capacity.

Reduced runoff by increased aridity appears unlikely given the record of humid palaeoclimatic conditions. Moreover, the Tilcara Formation belongs to a group of spatially widespread Miocene-Pliocene conglomerates in NW Argentina commonly known as Punaschotter (Penck, 1920). These deposits are more likely related to individual
range uplifts, because their diachronous deposition in various intermontane basins and foreland regions excludes a coeval sedimentary response to regional climate change (McPherson, 2008; Schoenbohm et al., 2008). As glaciation in the Central Andes has not been documented prior to 3.5 Ma (Clapperton, 1979) and subsequent glaciations have been minor due to limited moisture availability (Haselton et al., 2002), it seems also unlikely that the style and deposition of the Tilcara conglomerates in the Humahuaca Basin results from glacial erosion at high elevation. Therefore, although a global trend towards colder and drier climates since mid-Miocene (e.g., Zachos et al., 2001) may have favoured basin isolation, it is unlikely to have initiated basin filling here at 4.2 Ma. We therefore favour the first scenario as the most likely mechanism for initializing partial hydrological isolation of the Humahuaca Basin, which is consistent with the inferred tectonic forcing and severing of the fluvial system. The transition towards coarser grain sizes with the onset of deposition of the Tilcara Formation is thus best explained by erosion of more proximal sources in the uplifting Sierra Alta and Tilcara ranges.

Based on the depositional age estimates from the Tilcara and Uguía formations (i.e. ~4.2–1.5 Ma) and the unconformably overlying Quaternary gravel (~1.06 ± 0.10 Ma), it appears that fluvial connectivity with the foreland must have been re-established in the intervening time period. Although our data are currently insufficient to resolve the processes that led to basin excavation, incision rates at the valley outlet must have been sufficient to preserve external drainage, and sufficient transport capacity must have existed to allow sediment from upstream to bypass the basin while large volumes of sediment were removed. These processes, however, do not necessarily imply more availability of moisture in the Humahuaca Basin itself, but may instead represent efficient headward erosion at the location of the valley outlet, where current precipitation rates abruptly decline upstream towards the Humahuaca Basin (Strecker et al., 2007).

Although later surface processes have often altered the unconformity in the Tilcara Formation, preserved vestiges of deformed erosion surfaces suggest that fluvial incision predated an episode of deformation in the basin. These events were followed by a prolonged phase of restricted hydrological connectivity with the foreland associated with basin filling of up to 400-m thick fluvial and alluvial gravel between >1.06 and <0.8 Ma. Whether this filling episode was linked to tectonically induced basin isolation farther downstream, regional uplift of the Tilcara ranges or the result of climatic forcing remains uncertain. It is, however, conceivable that the ongoing surface uplift of the Tilcara ranges exceeded a regional threshold elevation to form an efficient orographic barrier to cause basin-wide semi-arid conditions (i.e. reduced runoff and transport capacities) as observed today.

These 400-m thick gravels were largely removed from the basin during basin excavation, followed by the deposition of a second major fill, which reached a thickness of approximately 250 m between at least about 94 and 65 ka in the Humahuaca Basin (Robinson et al., 2005; Sancho et al., 2008) and until after ~50 ka in the tributary Quebrada de Purmamarca (this study). This fill unit and all previous deposits now form the substrate for gravel-covered pediments and multiple fluvial terraces that have been sculpted into these deposits. These terrace systems were formed at successively lower elevations (Fig. 8f), indicating renewed incision that may record recent reductions in channel gradients and/or changes in local baselevel with respect to the Andean foreland. These periods of sediment removal are episodic and have occurred some time between 65 and 50 ka and the present day. Faulting that has affected these deposits is an expression of renewed deformation within the basin during, or shortly after an episode of extensive basin excavation in the Pleistocene (Fig. 8a).

Although the last basin-fill episode in the Humahuaca Basin coincides to some extent with more humid phases documented in the Altiplano-Puna Plateau (e.g. Bobst et al., 2001; Placzek et al., 2006), a direct correlation cannot be observed. Due to limited age control on the younger Quaternary deposits and landforms in the Humahuaca Basin, we cannot entirely exclude such a possible correlation. However, aggradation during humid phases requires that sediment generation from hillslopes must increase with precipitation more rapidly than the increase in the transport capacity of rivers that would result from enhanced discharge in rivers during this time.

Interestingly, our observations point towards a systematic behaviour among erosion, deposition and tectonic processes in the Humahuaca Basin, an intriguing relationship that can also be found in other intermontane basins of the NW Argentine Andes (Strecker et al., 1989; Hilley & Strecker, 2005). According to these observations, basin-inner/out-of-sequence deformation occurs during or following episodes of enhanced basin excavation. This is documented at least three times in the stratigraphic record of the southern Humahuaca Basin. First, after ~1.5 Ma, the Tilcara Formation was partly removed from the basin followed by major out-of-sequence thrusting along the basin-inner Tumbaya Fault. Here, deformation ceased prior to 1 Ma, which is documented by the onlap of ~1-Myr old gravels. Second, deformed remnants of these gravels, which lack evidence of syntectonic deposition, might also indicate that deformation occurred in association with the removal of the strata. Third, renewed, but locally limited deformation of young river terraces near Tilcara is observed right after the removal of the youngest Quaternary gravels. Although this phenomenon and the associated mechanisms will require more detailed studies in the future, it is conceivable that the removal of basin fills and the resulting reduction in lithostatic stresses on formerly locked thrust and reverse faults could ultimately result in the reactivation of these faults.

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Regional context of foreland fragmentation and basin-fill evolution

Many intermontane basins along the Puna margin record the partial or complete loss of fluvial connectivity with the foreland through the presence of thick conglomeratic fills (Strecker et al., 2007). Periodic reconnection to the foreland is documented by marked fluvial incision and excavation of these basin fills, reflected in distinct regional unconformities and complex onlap relationships. Virtually all basins in the northern Sierras Pampeanas, the Santa Bárbara System and the Eastern Cordillera of north-western Argentina exhibit similar, but diachronous, patterns of basin-fill and erosion throughout their history (reviewed in Strecker et al., 2007, 2009). The unifying characteristic in the history of these basins is that following the reorganization of fluvial systems by surface uplift, an establishment of orographic barriers results in progressive aridification, interrupted drainages and reduced fluvial transport capacity (Sobel et al., 2003). While the basins in the arid interior of the orogen (the Puna Plateau) have maintained internal drainage systems, resulting in thick sediment accumulations (Alonso et al., 1991; Vandervoort et al., 1995), the intermontane basins along the eastern flank have alternated between restricted external and transient internal drainages, and fully integrated fluvial systems connected with the foreland.

At present, virtually all of the intermontane basins to the east of the Puna are hydrologically connected to the foreland, often via narrow, deeply incised bedrock gorges (Fig. 1). For example, the Toro Basin at 24.5°S was cut off from the foreland between 8 and 6 Ma and has subsequently experienced at least two cycles of basin filling and excavation (Marrett & Strecker, 2000; Hilley & Strecker, 2005). Similarly, between 5.2 and 2.4 Ma, the uplift of an orographic barrier to the east of the present-day Calchaquí Valley at ~25.5°S caused aridification associated with deposition of the conglomeratic San Felipe Formation, which was subsequently incised, deformed and finally overlain by another conglomeratic gravel after 2.4 Ma (Coutand et al., 2006). After renewed sediment removal, a subsequent gravel unit with complex onlap relationships was deposited that once formed a continuous surface of coalesced alluvial fans and river gravel. River superposition, incision and removal of most of the gravels in the lower Calchaquí Basin document the ongoing erosion of this unit (Coutand et al., 2006; Strecker et al., 2007). The Santa María Basin at ~26.5°S is a result of foreland compartmentalization related to basement uplift to the east that occurred after 6 Ma (Kleinert & Strecker, 2001; Bossi et al., 2001; Sobel & Strecker, 2003), which was followed by aridification, severed fluvial connection to the foreland, deformation, erosion and finally, the deposition of thick conglomerates after 2.9 Ma (Strecker et al., 1989). These units were subsequently incised, as documented by successively lower sediments and fluvial terraces. Further examples of this type of basin development are provided by the El Cajón and Fiambalá basins, at 27°S and 27.5°S, respectively (Mortimer et al., 2007; Carrapa et al., 2008), emphasizing the similarities between the processes and depositional facies that control the evolution of intermontane basins within this environment.

We suggest that the tectono-sedimentary history of the Humahuaca Basin and other intermontane basins in NW Argentina can be best explained through a threshold process described in Sobel et al. (2003), in which active uplift of downstream topographic barriers steepens the channels that traverse these ranges, while aggradation upstream must keep pace with the associated uplift of the channel. As rates of rock uplift increase relative to the transport efficiency (related to precipitation) and bedrock erodibility, internal drainage is favoured. Conversely, low rates of rock uplift in the downstream basement ranges, a high level of erodibility of exposed rock types and pronounced rainfall gradients all promote incision, headward erosion and basin capture. All of these processes ultimately contribute to sustaining fluvial connectivity with the foreland. This, however, is only possible if the narrow outlets of the arid basins are in close proximity to steep rainfall and run-off gradients or if the structural setting is conducive to funnelling moist air into the orogen interior during protracted moist episodes. In turn, this condition would increase precipitation, run-off and erosion, which would ultimately help to achieve or re-establish external drainage conditions. Indeed, on the basis of our chronology, observations and interpretations, we are able to show that the intermontane Humahuaca Basin is the result of progressive rock uplift and associated surface processes in the Eastern Cordillera that commenced at 15–10 Ma and subsequently led to deposition of the Maimará Formation at about 6 Ma. The largely continuous depositional system finally became dismembered after 4.2 Ma when topography of the Tilcara ranges deflected the fluvial network into range-parallel drainage. Until about 1.5 Ma, the basin was characterized by restricted fluvial conditions most likely related to ongoing regional uplifts. Afterwards, the basin was rapidly excavated and internally deformed. The ensuing regional paleotopography in the basin was subsequently refilled between >1.06 and <0.8 Ma. The reason for the initial excavation is not known, but this could have been related to headward erosion and fluvial connectivity, followed by re-established hydrological isolation. The resulting basin fill, then, was largely removed, deformed and replaced by a younger fill that periodically has been excavated some time after ~65 and 50 ka. Excavation, again, seems to have been accompanied by basin-internal deformation, recorded by offset fluvial terraces near Tilcara, while currently the basin is aggrading (Rivelli & Flores, 2009).

SUMMARY AND CONCLUSIONS

In this study, we have combined new provenance and palaeocurrent data from the sedimentary record of the
intermontane Humahuaca Basin of the Eastern Cordillera of the southern Central Andes with 12 new $^{206}$Pb/$^{238}$U zircon age estimates from intercalated volcanic ash deposits to assess its spatiotemporal evolution. This enabled us to improve our understanding of the neotectonic basin and landscape evolution of an intermontane setting in the immediate vicinity of the intra-orogenic Puna Plateau, the world’s second largest plateau, and an important barrier to atmospheric circulation and surface-process regimes. We suggest that the coupled tectonic, erosion and sedimentary processes and associated landscape development in the Humahuaca Basin reflect an environment whose evolution is relevant for the assessment of intermontane basins worldwide, including the North American Laramide province, and the Tien Shan and Qilian Shan basement uplifts in Asia. From our analysis, we draw the following conclusions:

(1) In comparison with the previously developed chronostratigraphy for the Humahuaca Basin, our new U–Pb zircon dates extend the lower boundary of the Maimar Formation into late Miocene, older than 5.92 ± 0.12 Ma, confirms existing ages from the northern basin, and reveals Quaternary fills as old as ~1 Ma.

(2) On the basis of provenance, lithology and spatial distribution, we introduced a new stratigraphic unit, the Tilcara Formation, in the southern Humahuaca Basin that is apparently coeval with the radiometrically and palaeontologically constrained Uquia Formation from the central and northern sectors of the basin. The Tilcara Formation highlights the different depositional environments and source areas between the southern and northern parts of the basin.

(3) The sedimentary units in the Humahuaca Basin record a transition between a partially segmented foreland basin and a fault-bounded intermontane basin in the course of surface uplift to the east. This resulted in a change in fluvial connectivity and the re-arrangement of the formerly eastward-draining river network into an axial, south-directed drainage after ~4.2 Ma.

(4) Repeated hydrological disconnection from the foreland due to tectonism and ensuing aridification in the lee of rising topography repeatedly resulted in restricted fluvial connectivity and possibly transient fluvial isolation and accumulation of at least three basin-fill units during Plio-Pleistocene times. After episodic re-capture, these fills were partially excavated by fluvial incision. This is similar to other intermontane basins along the eastern flank of the Puna where surface uplift resulted in the tectonic defeat of fluvial networks, hydrological isolation and basin aggradation, until renewed river incision exceeded rock uplift at tectonically active basin outlets.

(5) We furthermore observed that major deformation events in the Humahuaca Basin apparently followed a phase of enhanced removal of basin-fill units, a scenario that has been observed in other intermontane basins of NW Argentina. We speculate that this behaviour is related to the reduction in lithostatic stresses acting on subsurface structures during major phases of basin excavation.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table S1. Summary of U–Pb zircon analytical data of volcanic ash samples in the Humahuaca Basin using CAMECA IMS 1270 ion microprobe at UCLA.

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