# NERC Geophysical Equipment Pool Project 831 Scientific Report

**Ruth A.J. Robinson**
School of Geography & Geosciences, University of St Andrews, St Andrews, KY16 9AL, UK

## Longitudinal river profile development and landscape response in NW Argentina

*This research is part of a larger project* quantifying the timing of deposition in Quaternary alluvial fill units in a tectonically active, narrow valley in NW Argentina, and identifying how both climate and tectonics influence and control the rates of erosion and sedimentation over the last 120ky. Detailed measurements of river profile elevation permit an assessment of how river profiles adapt to climatic or tectonic perturbation; the profile data are used to quantify the rivers' response time to perturbation and to test the applicability of erosion laws that are based on equilibrium states of rivers.*

* The larger project in NW Argentina includes collaboration with Bill Phillips (Idaho), Joel Spencer (Kansas), Manfred Strecker (Potsdam) and Ricardo Alonso (CONICET, Salta).

## Abstract

In actively uplifting mountain belts, landscape evolution is largely limited by bedrock river incision. Over the last twenty years, progress has been made in modelling the dynamics of bedrock channels using the stream-power (or shear-stress) incision model (Howard and Kerby, 1983) and modified versions incorporating sediment supply (e.g., Sklar and Dietrich, 2008). Although the bedrock erosion equation is incorporated into landscape evolution models, its parameterisation arises from the assumption that rivers are in equilibrium with uplift rates or climate. Elevation data of river longitudinal profiles in northwest Argentina were collected using a Leica SR530 differential-GPS system in order to quantify how the river profiles are adjusting to tectonic and climatic perturbations, and to capture the fluvial morphology in its transient state. Additionally, the profiles of abandoned terraces are compared to the active river channels to gauge the evolution of river profiles through time. Our previous research conducted in northwest Argentina's Quebrada de Humahuaca has produced a chronological framework of basin behaviour over the last ~120,000 years and the calculation of rates of denudation through time. This framework, and the elevation data collected as part of this study, allow us to further evaluate the response times and behaviour of the river profiles to uplift and/or climate perturbations.

This high resolution topographical dataset permits a test of theoretical models of fluvial incision; bed slope and catchment area data were analysed and rivers draining the western side of the valley ("equilibrium rivers") define linear relationships between slope and area with concavity indices (0.31 ± 0.05 to 0.48 ± 0.05) that are similar to those calculated in previous studies. However, the slope-area relationships for eastern catchments are composite "equilibrated zones" where sub-basins with alluvial rivers are in the process of being reactivated by faults, and completely non-linear in zones where slope rises and falls over bedrock knickpoint which traverse faults. Concavity indices deviate from the equilibrium range of values and demonstrate that the stream-power model would be an unsuitable predictor of profile evolution for these rivers.

## Background

Chronologies of sedimentation and erosion are required to fully understand landscape development and the coupling of river behaviour and hillslope processes in non-marine settings. High resolution datasets of topography are also required in order to refine the currently used erosion laws in order that their predictions are accurate over a wider range of landscape states. Despite the fact many rivers in tectonically active regions are in a transient state, until recently, most landscape evolution models have applied algorithmns that assume the rivers are in dynamic equilibrium. Landscapes tend towards a steady state where uplift is balanced by incision and the curvature of the channel profile is unchanging though time (Kirby and Whipple, 2001). Transient behaviour in bedrock channels is expressed as upstream-propagating knickpoints separating zones that are graded to different equilibrium states. The ability of a system to reach equilibrium depends on the response time of the landscape (Willett, 2002). Estimated response times to tectonic or climatic perturbations range from 0.25 to 2.5Ma (Whipple, 2001); this implies that, on timescales of up to ~$10^5$ years, many rivers undergoing active uplift will be in a transient state (Pratt-Sitaula and Burbank, 2004).

The Quebrada de Humahuaca (Fig. 1) is one of several intramontane reverse-fault bounded basins situated in the Andean Eastern Cordillera fold and thrust belt, between the arid Puna Plateau to the west and humid foreland to the east (Hilley et al., 2005). The major phase of deformation in the Puna Plateau ended ~4 Ma (Allmendinger et al. 1997), but deformation has continued in the Eastern Cordillera (Reynolds et al., 2000). Pliocene to Quaternary changes in the stress field from a NW-SE to a NE-SW contraction orientation (Marrett and Strecker, 2000), extensive faulting and folding of upper Pliocene units, and faulting and folding of Quaternary sediments reflect that deformation is ongoing in the Eastern Cordillera. Average uplift rates since ~7.5 Ma are poorly constrained between 0.4-0.64 mmyr$^{-1}$ (Hilley et al, 2005) and current estimates of shortening for the region are 8-11mm/yr (Echavarria et al., 2003). Uplift on an intra-valley thrust fault in the field area and dating of displaced sediments indicates this region has been tectonically active in the last 68 ka with an uplift rate of ~0.3mm/yr, and terrace warping suggests that deformation has been ongoing throughout the Quaternary (Robinson et al., submitted). Over the last ~1Ma, but on different timescales, sedimentation and erosion patterns are influenced by tectonically modified fluvial profiles which increase relief and river incision, as well as promoting upstream aggradation, headward capture, and increased landslide frequency during humid or high seismicity periods (Hermanns & Strecker, 1999; Hermanns et al. 2000; Hilley and Strecker, 2005).

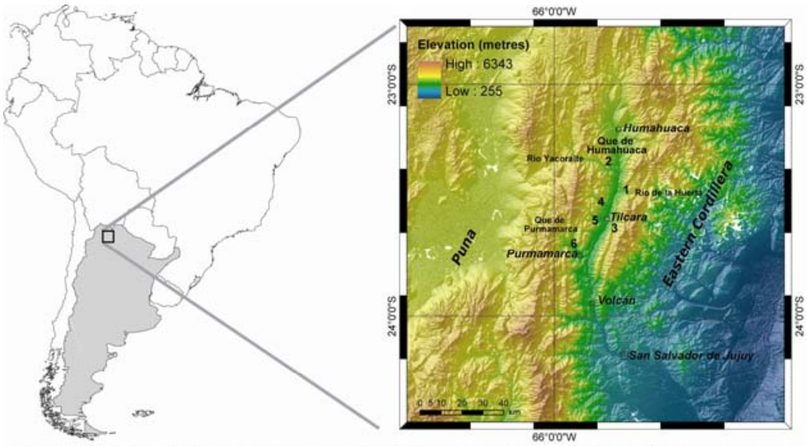

Figure 1. Study location in NW Argentina. Numbered tributary sites (1-6) are the focus of the larger research project. This study focuses on the tributaries at sites 1, 3, 4, and 5.

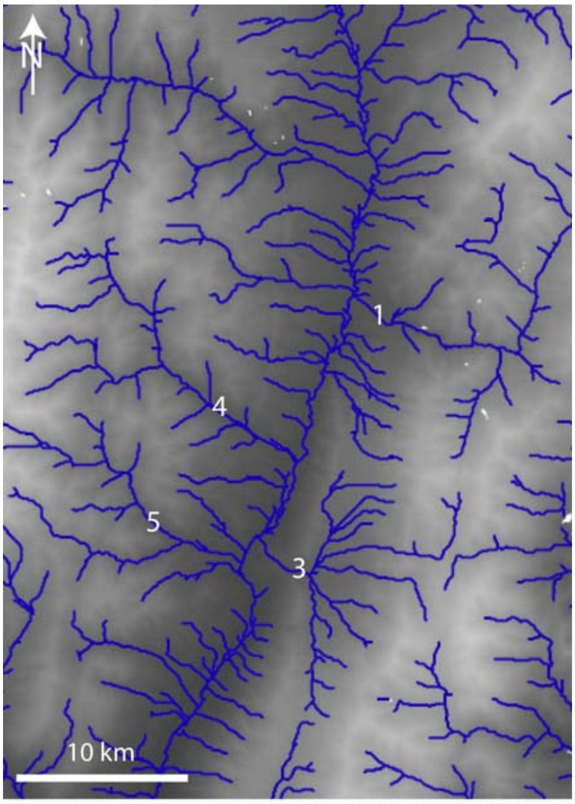

Figure 2. Drainage network derived from the SRTM (NASA) 90 m DEM showing the tributaries (1, 3, 4, 5) that are the focus of the higher resolution dGPS study.

The Río Grande is the mainstem river running north-south through the quebrada, and in the area of interest, it is fed by three major west-draining tributaries and two east-draining tributaries (Fig. 2). This study examines four of those tributaries, two on each side of the valley. The valley has an asymmetric morphology with steeper drainages and shorter catchments on the eastern side and less steep drainages and longer catchments on the western side (Figs. 2 and 3); drainage orientations on the eastern side additionally show that headward erosion has captured NE-SW trending drainages in small sub-basins to the east of the main valley (Fig. 3). Overall the catchment morphology reflects the eastward migration of deformation and propagation of thrusts since the Miocene, as well as reactivation of the eastern block. Eastern drainages (1-Río de la Huerta and 3-Río Huasamayo) are mixed alluvial-bedrock rivers with multiple knickpoints in the downstream zones, while the western drainages (4-Río de Jueya and 5-Río Huichaira) have longer alluvial reaches with smooth longitudinal profiles (Fig. 2); relative to the east side of the valley, the drainages on the western side have their bedrock-alluvial transition much further upstream.

River profile and terrace elevations with ground coordinates were collected at 1-2m intervals along four tributary profiles using a Leica SR530 differential-GPS system with a fixed base station and a roving receiver, in order to develop a high resolution dataset of elevation (with an uncertainty of ~5cm) in the lower reaches where step changes in elevation occur over 10’s metres; these data were merged with a 90m SRTM in order to extract the catchment areas of the long profiles (Fig. 3). The incised nature of the catchments prevented complete long profiles being measured on all the drainages due to loss of signal exchange between the rover and base station and difficult terrain, therefore, the longitudinal profiles analysed are derived from both the dGPS data and the SRTM 90m DEM data. The resulting longitudinal profiles have high accuracy and precision where measured by dGPS, where elevation changes are greatest and higher resolution measurements are required, but have lower accuracy in upstream zones due to the coarser resolution of the SRTM.

## Base station location

The field work was conducted over 4 weeks in July 2006. A known bench mark was located in the middle of the field area. The base station was set up at the bench mark using one of the Leica receivers; the position of the tripod feet and centrepoint were marked, and the height of the base station was recorded so that the unit could be repositioned in the same place every day. All measurements were made with a roving GPS receiver, and positions were collected in RTK survey mode. The bench mark position and elevation (in POSGAR 1994) were programmed into the base station, but unacceptable positional uncertainties occurred and the base station was allowed to define its own position. Table 1 gives examples of the elevation data for site 4 and a comparison of the benchmark positions; for this example, the stated and dGPS-measured positions differ by 5.01cm in elevation, 16cm in latitude, and 122cm in longitude (1.24 m distance). This affects the accuracy of the data in a global context, but the relative measurements for the river profiles are acceptable for this study. The positional data were analysed on the NERC GEP laptop in Leica Ski-Pro software with assistance from Alan Hobbs (Table 1 provides a sample of data quality).

**Table 1.** *Sample of data collected from site 4 (Jueya) and the comparison between the benchmark and dGPS positions.*

| Point Id | Latitude | Longitude | Ell. height | Coordinate quality |
|---|---|---|---|---|
| Auto00001 | 23 30 19.108136 S | 65 25 22.910202 W | 2885.05 | 0.0144 |
| Auto00002 | 23 30 19.104051 S | 65 25 22.916710 W | 2884.95 | 0.0124 |
| Auto00003 | 23 30 19.059086 S | 65 25 22.969218 W | 2885.00 | 0.0152 |
| Auto00004 | 23 30 19.002639 S | 65 25 23.017339 W | 2885.01 | 0.0131 |
| Auto00005 | 23 30 18.967197 S | 65 25 23.042521 W | 2885.17 | 0.0134 |
| Auto00006 | 23 30 18.917410 S | 65 25 23.088172 W | 2885.26 | 0.0173 |
| Auto00007 | 23 30 18.872885 S | 65 25 23.134031 W | 2885.38 | 0.0136 |
| Auto00008 | 23 30 18.840931 S | 65 25 23.167631 W | 2885.50 | 0.0156 |
| Auto00009 | 23 30 18.817882 S | 65 25 23.199131 W | 2885.64 | 0.0101 |
| Auto00010 | 23 30 18.776549 S | 65 25 23.257534 W | 2885.76 | 0.0126 |
| Auto00011 | 23 30 18.734643 S | 65 25 23.318912 W | 2885.86 | 0.0133 |
| dGPS benchmark position | 23 29 57.3280 S | 65 22 15.1576 W | 2606.953 | |
| published benchmark position | 23 29 57.3347 S | 65 22 15.2002 W | 2606.902 | |

## Results and Discussion

The elevation data were analysed in ArcGIS and plotted on the SRTM 90m DEM (Fig. 2). The high resolution dGPS points were merged into the coarser DEM, thus producing a new DEM with high resolution and greater areal coverage. The Hydrology tools in ArcGIS and GRID function in

ArcInfo were used to extract stream networks, catchment areas and slopes following procedures outlines in Wobus et al. (2006) and Snyder et al. (2000). DEMs commonly show scatter in the slope-area plots therefore some smoothing of the data is required. Snyder et al. (2000) analysed different methods of slope averaging and we have adopted the 10m contour interval averaging method. The slope data have been smoothed and regression of bed slope and catchment area data was undertaken to derive concavity and steepness indices for the different rivers (Fig. 4). The western rivers (Jueya and Huichaira, Fig. 4A, C) show a linear relationship between slope and area with concavity indices (0.31 ± 0.05 – 0.48 ± 0.05) in accordance with values predicted from other field studies testing the stream-power incision model (e.g., Snyder et al., 2000). The slope-area relationships for the eastern rivers are complex (Fig. 4 B, D); constant concavity values occur in the sub-basins formed in the footwall of reactivated thrust faults where concave alluvial profiles are undisturbed, but slopes rise and fall dramatically across bedrock knickpoint zones in the downstream reaches of the tributaries. The thrust fault affecting the Huasamayo profile can be seen to affect the most downstream reach of the Huichaira tributary located directly opposite Huasamayo and is affected by hanging wall uplift (Fig. 2, 3). The Huasamayo concavity values are 0.42 ± 0.1 in the upstream sub-basin footwall zone, and as high as 4.3 ± 0.6 in the downstream knickpoint zone; steepness indices range from 0.3 ± 0.1 to 1.1 ± 0.4, and 7.2 ± 1.2 and 17.7 ± 2.8 in the sub-basin and knickpoint zones, respectively. These latter steepness indices are very high relative to typical values from equilibrium rivers (e.g., Snyder etal., 2000; Wobus et al., 2006) and in the eastern rivers, high steepness values are associated with reaches that cross faults, as well as more resistant quartzite lithologies. Steepness is thought to be related predominately to uplift rate (e.g., Kirby and Whipple, 2001) if lithology and precipitation does not vary. These results highlight that the stream-power model with fixed parameters is not capable of accurately predicting profile evolution for rivers in such transient states, something that has been identified in other perturbed river systems (Whittaker et al., 2008). Our results also illustrate that response times on the western and eastern sides of the valley are different because of antecedent and tectonic conditions – the "equilibrated" western tributaries have relatively larger catchments draining a high proportion of erodible substrates (Precambrian shales and Cenozoic sandstones and shales) with less uplift and a thicker alluvial cover, while the eastern tributaries have smaller catchments and drain a high

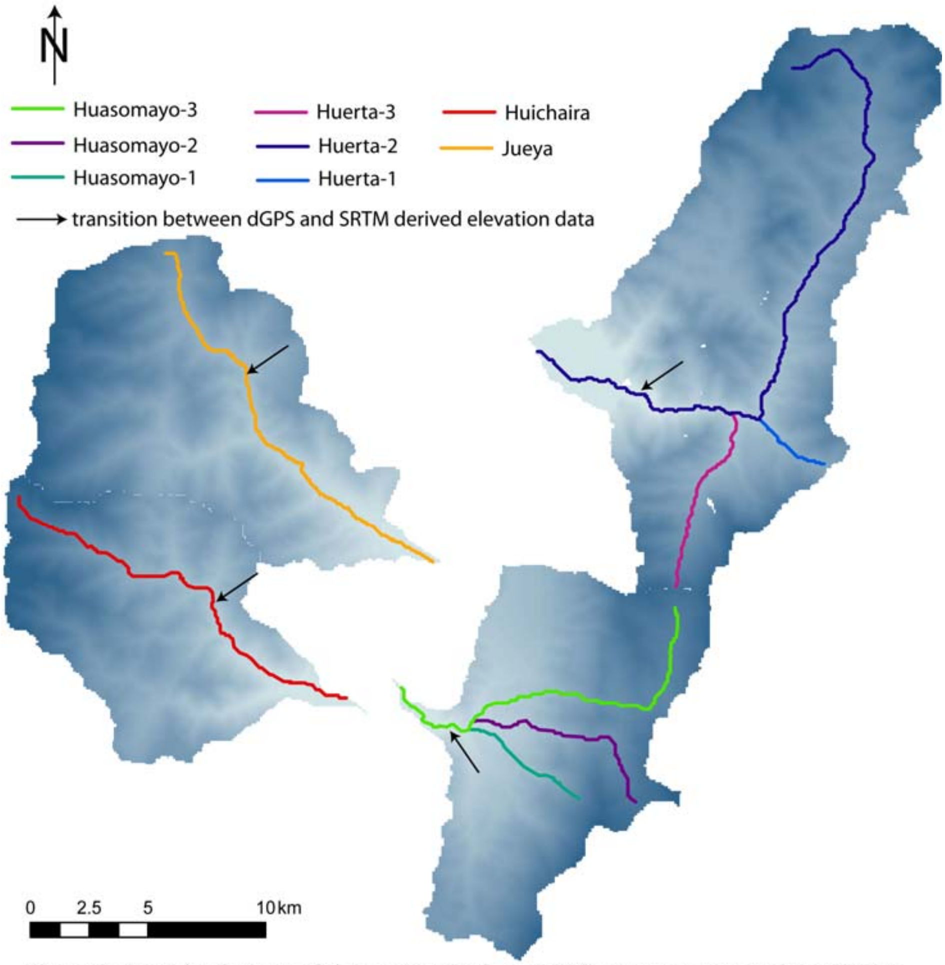

Figure 3. Combined traces of river networks from dGPS measurements and the SRTM (NASA) 90 m DEM. Arrows delineate between upstream SRTM and downstream dGPS derived longitudinal profiles.

proportion of resistant bedrock (Cambrian quartzite), have less alluvial cover to remove before hitting bedrock, and are undergoing higher amounts of uplift (Robinson and Fulton, in prep.). Geological mapping demonstrates that knickpoints tend to be positioned over Cambrian quartzite bedrock with smoother river profiles overlying shales and sandstone and Quaternary gravel sections and that the time required to achieve fluvial equilibrium is partially affected by the substrate. We are currently investigating the control these conditions impart to landscape response time.

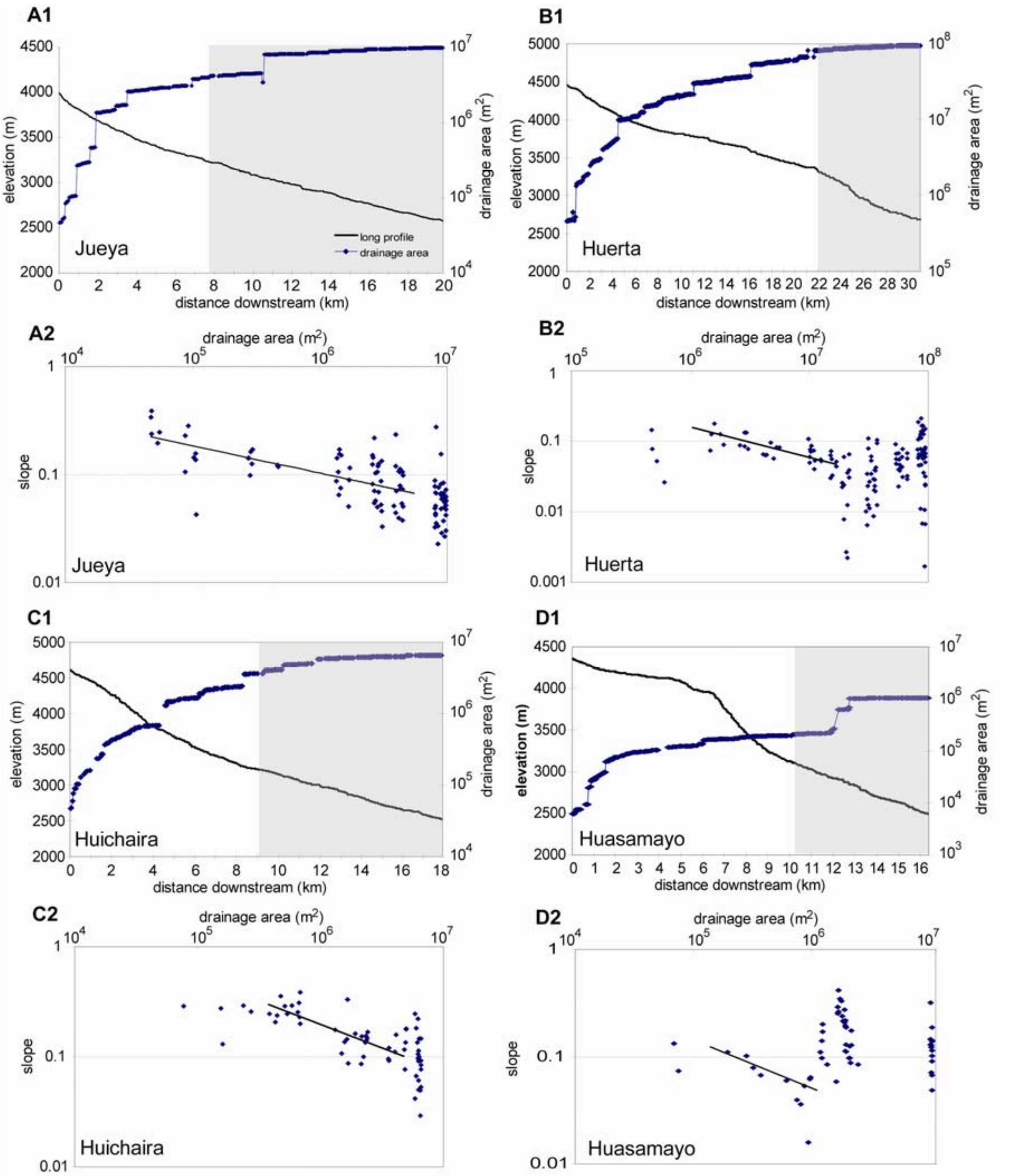

Figure 4. Longitudinal profiles, drainage area and slope-area plots of eastern and western tributaries to the Que. de Humahuaca. A1-A2. Jueya - western. B1-B2. Huerta - eastern. C1-C2. Huichaira - western. D1-D2. Huasamayo - eastern. Grey regions in longitudinal profile-area plots are based on dGPS measurements. Linear relationships between slope and area (A2,B2,C2,D2) are illustrated as straight lines and reflect equilibrated fluvial profiles. Transient fluvial behaviour is evident in the slope-area plots of the eastern catchments (B2, D2), but also in the confluence region of the Huichiara drainage with the mainstem river (C2).

The dGPS measurements of Quaternary terrace profiles adjacent to the active tributary river beds were used to investigate incision rates and these are compared to erosion rates and inferred uplift rates from the thrust fault offset in Huasamayo. In the Huasamayo catchment, incision is ~1.4mm/yr (over 70ka) and vertical uplift rate is not well constrained but is estimated from a local thrust offset as 0.3mm/yr (which is almost certainly an underestimate). In the Huerta catchment, incision from the last phase of terrace development to the active channel is ~0.2mm/yr (over ~35ka), while the catchment erosion rate based on the 35ka surface is ~0.15mm/yr (from cosmogenic-ray nuclide dating; Robinson et al. submitted). The Huichaira and Jueya river profiles measured by dGPS have incised over 70m through Quaternary alluvial cover and poorly consolidated Miocene-Pliocene sandstones since ~40ka, an incision rate of ~18mm/yr and an order of magnitude greater than the eastern tributaries. The concavity and steepness indices, and the incision data, support the interpretation that the Huasamayo catchment is more recently perturbed than the Huerta catchment, but that the Huichaira and Jueya catchments have equilibrated far more quickly (in ~40ka). Finally, knickpoints analysed for Huerta and Huasamayo sit at similar elevations in the catchments (for example, knickpoints cluster at ~3100m in Huerta and around ~4000m in the upstream reaches of Huasamayo). Further investigation of the response times and knickpoint retreat rate in these catchments is ongoing by analysing the steepness indices upstream and downstream of knickpoints.

## Acknowledgements

Acknowledgment is made to the NERC Geophysical Pool for loan of the dGPS and to the donors of The Petroleum Research Fund, administered by the American Chemical Society, for support of this research. The Carnegie Trust For the Universities of Scotland funded the cosmogenic $^{10}$Be analysis through an AMS Beamtime Award and contributed to the costs of one field season for Robinson and Spencer. The field work was carried out by Kirsty Fulton and the author. This report is a contribution from the Scottish Alliance for Geoscience, Environment and Society (SAGES).

## References

Allmendinger, R., T. Jordan, S. Kay, and B Isacks (1997), The evolution of the Altiplano-Puna Plateau of the Central Andes.

Echavarria, L., R. Hernandez, R. Allmendinger, R., and J. Reynolds (2003), Subandean thrust and fold belt of northwestem Argentina: Geometry and timing of the Andean evolution. *AAPG Bulletin 87*, 965-985.

Hermanns, R. and M.R. Strecker (1999), Structural and lithological controls on large Quaternary bedrock landslides in NW-Argentina, *Geological Society of America Bulletin*, 111, 934-948.

Hermanns, R.L., M.H. Trauth, S. Niedermann, M. McWilliams, and M.R. Strecker (2000), Tephrochronological constraints on temporal distribution of large landslide in Northwest Argentina, *Journal of Geology*, 108, 35-52.

Hilley, G. E., and M.R. Strecker (2005), Processes of oscillatory basin filling and excavation in a tectonically active orogen: Quebrada del Toro Basin, NW Argentina, *Geological Society of America Bulletin*, 117, 887-901.

Kirby, E and Whipple, K. (2001) Quantifying differential rock-uplift rates via stream profile analysis Geology, 29, 415-418**.**

Marrett, R., and M.R. Strecker (2000), Response of intracontinental deformation in the central Andes to late Cenozoic reorganization of South American Plate motions, *Tectonics*, 19, 452-467.

Pratt-Situala, B. and Burbank, D.W. (2004) Landscape disequilibrium on 1000-10,000 year scales, Marsiyanid River, Nepal, central Himalaya. Geomorphology, 58, 223-241.

Reynolds, J.H., C.I. Galli, R.M Hernandez, B.D. Idlemand, J.M. Kotila, R.V. Hilliard, and C.W. Naeser (2000), Middle Miocene tectonic development of the Transition Zone, Salta Province, northwest Argentina: Magnetic stratigraphy from the Metan Subgroup, Sierra de Gonzalez, *Geological Society of America Bulletin*, 112, 1736-1751.

Robinson, R.A.J., J.Q.G. Spencer, M.R. Strecker, A. Richter, and R.N. Alonso (2005) Luminescence dating of alluvial fans in intramontane basins of NW Argentina. In: Alluvial Fans: Geomorphology, Sedimentology, Dynamics. *Geological Society, London, Special Publications*, 251, 154-168.

Robinson, R.A.J., Phillips, W.M., Spencer, J.Q.G., Strecker M.R., Alonso, R.N., Kubik, P.W., Binnie, S., Freeman, S. (submitted) Late Quaternary erosion, sediment storage and landscape evolution in NW Argentina using terrestrial cosmogenic-ray nuclide and optically stimulated luminescence dating.

Sklar, L.S. and Dietrich, W.E. (2008). Implications of the saltation-abrasion bedrock incision model for steady-state river longitudinal profile relief and concavity. Earth Surface Processes and Landforms, 33, 1129-1151.

Snyder, N.P., Whipple, K.X., Tucker, G.E., and Merritts, D.J. (2000) Landscape response to tectonic forcing: digital elevation model analysis of 52 stream profiles in the Mendocino triple region, northern California. Geological Society of America Bulletin, 112, 1250-1263.

Strecker, M.R. and R. Marrett (1999), Kinematic evolution of fault ramps and its role in development of landslides and lakes in the NW Argentine Andes, *Geology*, 27, 307-310.

Whipple, K.X. (2001) Fluvial landscape response time: how plausible is steady state deundaiton? American Journal of Science, 301, 313-325.Willett, S.D. (2002) On steady states in mountain belts. Geological Society of America Bulletin, 30, 173-178.

Wobus, C.W., Whipple, K.X., Kirby, E., Snyder, N.P., Johnson, J., Spyropolou, K., Crosby, B., and Sheehan, D., 2006, Tectonics from topography: procedures, promise and pitfalls, in Willett, S., Hovius, N., Brandon, M., and Fisher, D., eds., GSA Special Penrose publication on Tectonics, Climate and Landscape Evolution, 55-74.