Landscape deformation in the Cordillera Blanca, Peru: Erosion rates within a glaciated orogen

By Keith Hodson

Introduction

The Cordillera Blanca, Peru lies within the active contractile Andean orogen, directly above a region of shallow, flat-slab subduction (Gutscher, 2002). Despite its position within a thickening mountain range, the Cordillera Blanca region is experiencing pronounced extension accommodated by a ~200 km long detachment fault (McNulty, 1998). The root cause of the observed extension in this region is an area of active research, and many questions remain regarding system’s behavior, as well as the tectonic and isostatic forces it is enduring (McNulty, 1998; Farber and Hancock, in prep; Giovanni, 2010). A handful of studies have produced thermochronologic exhumation rates (uplift relative to the surface) for the region, which apply to timeframes on the order of 1-10 Ma (Montario, 2001; Giovanni, 2007). There is a clear need for data representing more recent time intervals, especially considering that the earliest record of glaciation in the region is dated at <250 ka and represents a period of higher erosive activity (Farber et al., 2005)

Cosmogenically derived radionuclide (CRN) exposure age and erosion rate measurements can provide insight into how landforms deform over periods of ~10^3-10^6 years (Bierman and Nichols, 2004). Morphologic, tectonic, and climatic influences can all produce measurable effects on this time scale, and have been shown to correlate with, and potentially regulate, rates of denudation in a variety of environments (e.g. Cyr, 2010; Delunel, 2010; Jungers, 2009; Stock, 2009; Montgomery and Brandon, 2002). Conclusions regarding these controls vary between studies and study areas, and the complex nature of how landscapes form and evolve is still being determined.

Implications of Erosion and Incision Rates

Erosion rates can correlate with a variety of active and passive factors. Attributes of a basin or river channel such as area, slope, glacial history, relief, and lithology will often follow trends in measured erosion rates (von Blanckenburg, 2005; Bierman and Nichols, 2004, Stock et al., 2009). Other studies have correlated erosion rates to tectonic pressures and glacial activity (Cyr, 2010; Burbank et al., 1996). In the model described by England and Molnar (1990) rock uplift and erosion are intimately connected, with rock uplift responding to erosion through isostatic rebound. Tectonic response to erosion has also been the subject of recent studies, which suggest that erosion can greatly influence the way tectonic deformation is expressed in orogenic environments (Willett, 1999; Whipple, 2009).

While erosion may be a driving force for isostacy and thereby influence tectonic uplift, the controlling factors for erosion and incision rates are difficult to pin down. The interplay between climate and tectonics is intricate, and predictions about the first order control for denudation in the Cordillera Blanca are tentative. The region is situated in a highly active tectonic environment, but has a rich glacial history as well. Rapid base level changes along the CBDF and glacially modified valleys both hold potential for strong controls on erosion rate, making this site particularly interesting as a natural laboratory for studying their connections.
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Testable Hypotheses
This study will attempt to prove or explore the following claims regarding the Cordillera Blanca:
• Changes in relative base level have been shown to drive increases in rates of erosion (Bierman and Nichols, 2004). Along-strike variability of relief production along a major detachment fault in the Cordillera Blanca should produce a trend in erosion rate that scales proportionately.
• Current and prior glaciation will strongly affect erosion. Basin averaged erosion rates should be higher in catchments with greater degrees of modern glaciation, and valleys displaying prominent glacial morphology should be undergoing higher rates of erosion as well, regardless of current glaciation.
• Calculated incision rates from the northern Rio Santa Valley will provide insight into relative base level changes along the Rio Santa.

Geologic Setting
Western South America
The western margin of South America is commonly cited as the model for subduction zone scenarios. The active oceanic-continental collision zone between the Nazca Plate and the South American Plate extends from Northern Columbia to Southern Chile, driving associated crustal shortening and uplift (Gregory-Wodzicki, 2000). Relative motion of the Nazca Plate to South America, as determined by Norabuena et al (1998), trends N76°E at a rate of 68 mm yr⁻¹ (Fig. 1). Arc volcanism and granitoid batholith intrusions characterize the Andes Orogen as it stretches along the western coast, reaching some of the highest elevations on the planet. Continuous subduction has been ongoing since the Mesozoic although along-strike variations in style and angle of subduction exist, most notably the flat-slab segments in northern Peru (2-15°S) and central Chile (28-33.5°S; Gregory-Wodzicki, 2000).
Several aseismic ridges are currently being subducted along the western South American margin. Two of these, the Nazca and Juan Fernandez Ridges, closely correlate with the northern and southern flat slab segments, respectively (Fig. 1; Isacks, 1988). The added buoyancy of the ridges has been suggested as the cause of the shallow, 5-10° subduction angle, although it should be noted that ridges are subducting at “normal” (25-30°) angles in other parts of the world (Gutscher, 2002).

Cordillera Blanca Region, Peru
The Cordillera Blanca region runs from 8-11° S, situated directly above the northern flat slab segment in Peru (Fig. 1). Two N-S trending mountain lineaments, the Cordillera Negra to the west and the Cordillera Blanca Batholith (CBB) to the east, bound the Rio Santa Valley, which serves as an intra-mountain drainage for the entire region (Figs. 2 and 3). The Cordillera Negra is comprised of 54-15 Ma extrusive volcanic rock overlying the primarily granitic Cretaceous/Tertiary Peruvian Coastal
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Batholith (Petford and Atherton, 1992). The CBB consists predominantly of granitoid rock, and contrasts sharply with the Cordillera Negra in its higher relief and peak elevations, which include several of the highest mountains in Peru (most notably the 6768 m a.s.l. Huscaran; Garver, 2005). The CBB intrudes the Jurassic Chicama Formation, and is bounded to the west by the ~200 km long Cordillera Blanca Detachment Fault (CBDF) with associated relief exceeding 2500 m in the north (Giovanni, 2007). Fault motion varies southward along strike by an order of magnitude from ~5-0.5 mm yr\(^{-1}\) (Farber and Hancock, in prep), with average basin elevation and relief decreasing in tandem (Giovanni, 2007).

Notable Rock Units

The plutonic complex making up the Cordillera Blanca Batholith consists of a sequence of granitoid intrusions forming a nested, younging upward series (Atherton, 1987). The pluton is exposed for ~200km, striking NNW – SSE, and has a width of ~20km. Lithologies are primarily granodiorite to tonalite, with small, localized occurrences of dioritic rock (Atherton, 1987). Crystallization ages for the batholith range from 8-5 Ma, and emplacement depth has been interpreted to be at ~9 km (McNulty and Farber, 2002).

The Jurassic Chicama Formation is comprised of ~1500m of shale, and can be subdivided into two major units. The lower Chicama is pyritiferous and marine in origin, while the upper unit is much darker in color and contains substantial quantities of plant debris (Atherton, 1987).

The Llocclla formation is an ~1300m thick sedimentary sequence reflecting a general pattern of upwards coarsening. The base of the formation contains a 7m thick laminated tuff containing quartz, biotite and sanidine. One \(^{40}\text{Ar}/^{39}\text{Ar} \) age measurement places the tuff’s deposition at 5.4±0.1 Ma (Giovanni et al., 2010). The overlying portion of the Llocclla Formation transitions from thin carbonate bedding to a coarsening-upwards sequence of fine-grained sandstones to cobble and boulder conglomerates.

Cordillera Blanca Detachment Fault

Serving as a sharp delineation of the western extent of the Cordillera Blanca Batholith, the ~200km-long Cordillera Blanca Detachment Fault manifests as a striking, albeit somewhat enigmatic, locus for relief production in the Cordillera Blanca region. Relief exceeds 2500m to the north near Huallanca (~8.8° S) and tapers out to the south near Conococha (~10° S). An offset basal tuff from the Llocclla Formation within the Rio Santa Valley places a maximum age of 5.4 Ma for the initiation of motion along the CBDF (Giovanni, 2007). Vertical slip rates have been quantified through interpretations of offset moraines and river terraces, demonstrating a southward decrease in vertical slip rate from ~5-0.5 mm yr\(^{-1}\) (Farber and Hancock, in prep). Giovanni et al. (2010) were able to infer the southward development of the fault through analysis of the propagation of fan deposits in the adjacent valley. No northward development has been inferred and a bounding structure for the northerly extent of the CBDF has yet to be identified.
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The presence of such a large-scale extensional feature within the predominantly compressional Andean regime is an open topic of scientific discussion. A small collection of mechanisms has been suggested to explain how this can be accommodated:
1. Gravitational collapse due to over-thickening of the crust (Suarez et al., 1983).
2. Thermal weakening associated with batholith emplacement triggering reactivation of old thrust fault-planes (Le Pourhiet et al, 2004).
3. Mechanical coupling between the overriding and flatly subducting plates (McNulty and Farber, 2002).
4. Disproportionate support from subducting aseismic ridges (Gutscher et al., 1999).

Rates of Exhumation Within the Cordillera Blanca
Long-term exhumation rates for the Cordillera Blanca show very little variation along strike (Fig. 4; Montario, 2001; Giovanni, 2007). A collection of methods have been implemented including: zircon (U-Th)/Fission track, apatite (U-Th)/He, and $^{40}$Ar/$^{39}$Ar ages from biotite, muscovite, and potassium feldspar. A difference between biotite and apatite exhumation rates supports a decrease in rock uplift rate between their respective 300° C and 70° C closure temperatures.

Biotite $^{40}$Ar/$^{39}$Ar ages increase with distance from the fault producing an east-west trend (Giovanni, 2007). Since elevation also increases with distance from the fault, the age gradient is interpreted to reflect the ongoing exhumation and uplift of the batholith (Fig. 5). The linear relationship between cooling age and elevation supports a consistent rate of cooling past biotite’s 300° C closing temperature, although differences in slope of regression for different basins suggests that cooling rate varied along the batholith. The steepest regression is observed in Llanganuco valley near the center of the range, which corresponds with the region of highest elevation (Figs. 4 and 5).

Climatic and Glacial Overview
Precipitation
The orographic divide manifested in the Cordillera Blanca Batholith largely governs local precipitation patterns for the Rio Santa Valley. A strong disparity exists between the rainforests of the Amazon Basin and the high desert environment west of the Andes. This effect is produced through adiabatic cooling of moisture-laden air originating from the tropical region of the South Atlantic as it is forced up and over the Sub-Andes and Cordillera Blanca. Precipitation across the Cordillera Blanca itself shows little E-W variation (Bookhagen and Strecker, 2008), and extensive evidence of prior glaciations is present on both flanks of the batholith. This “glacial symmetry” supports equal to sub-equal precipitation partitioning across the Cordillera Blanca Batholith, although it should be noted that the glacial features to the east are poorly characterized.

Glaciation
Modern alpine glaciers are limited to elevations over 4800 m a.s.l., representing cirque style glaciation and occupying high cliff faces (Mark and Seltzer, 2005). While large valley glaciers are not currently present, multiple sets of moraine material occupy the larger valleys, which exhibit clear “U-shape” glacial valley morphology. Multiple sets of moraines have been dated and used to develop a glacial history for the region,
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which records the Last Local Glacial Maximum (LLGM), Younger Dryas, and Late Glacial advances (e.g., Smith et al., 2005; Glasser et al., 2009). Evidence for more extensive glaciation predating the LLGM is prevalent in the Rio Santa Valley, with ages ranging from 120–440 ka (Farber et al., 2005).

Sampling Strategy
Basin averaged erosion samples were taken from two collections of westerly draining valleys located in the northern and central regions of the Cordillera Blanca. The site of sample collection was always just up valley from the detachment fault, and each grouping of valleys contains a range of areas and glacial cover. These samples, combined with a grouping from the south which will be collected this coming July, will allow an analysis of broad scale trends in erosion along the strike of the range. Similarly, the range of catchment areas, glaciation, and elevations will allow for detection of erosional controls that do not vary systematically along strike.

Incision rate samples collected from the northern stretch of the Rio Santa, downvalley from the erosion rate samples, will give insight into the dynamics of the Rio Santa Valley in relation to downstream base level. Four samples were taken along the wall of a fluvially carved valley, allowing determination of incision rate, which we will interpret as a background surface uplift rate in that locality.

Background Theory: Cosmogenic Radionuclides
The utilization of cosmogenic radionuclides (CRN) has allowed for huge advances in our understanding of how landscapes and landforms change over time. In situ and atmospherically produced CRNs, such as $^{10}$Be and $^{26}$Al, are powerful isotopes, which have provided a much needed method for determining absolute surface exposure ages. In addition to surface exposure dating, this method has been successfully applied to quantify erosion rate estimates on varying spatial scales (e.g. Dortz, 2009; Delunel, 2010; Farber, 2005).

Exposure Dating
Quantifying the CRN concentration in a sample retrieved from the earth’s surface can provide a direct means of estimating that surface’s duration of exposure as well as its rate of denudation (Lal, 1991; Gosse, 2001). As described by Lal (1991), the exposure time for a given sample can be calculated using the equation:

$$N = \frac{P}{(\mu\varepsilon + \lambda)} \exp(-\mu x) [1 - \exp(-t(\mu\varepsilon + \lambda))]$$

(1)

Where $N$ is the concentration (atoms g$^{-1}$) of the CRN in the sample, $P$ is the production rate (atoms g$^{-1}$ yr$^{-1}$), $\mu$ is the attenuation path length for the rock type (cm$^{-1}$), $\varepsilon$ is the erosion rate (cm yr$^{-1}$), $\lambda$ is the disintegration constant (yr$^{-1}$), $t$ is time (in years), and $x$ is the sample’s depth below the surface (cm).
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P is dependent on a variety of factors, and must be calculated individually for each sample location. Deviation from the standard production rate, taken at sea level and high latitude, is dependent on the latitude, altitude (or more accurately, the air pressure), and shielding effects from overburden and surrounding topography (Stone, 2010). Assumptions regarding the consistency of the production and erosion rates over time are necessary, and must be addressed when analyzing any result (Gosse, 2001). All CRNs subject to radioactive decay possess an upper age limit, known as the point of saturation, where the CRN concentration becomes large enough that the rate of decay matches the rate of production and the concentration is unable to increase further.

**Basin Averaged Erosion Rates**

A sample of fine to medium grained sand taken from an active river channel can be used to calculate an average erosion rate for an entire drainage basin (Brown, 1995). If equation 1 is simplified by assuming sample material originated at the surface and that ε has been constant over a prolonged t, an erosion rate is readily calculated based on a measured CRN concentration:

\[ N = \frac{P}{(\mu \varepsilon + \lambda)} \]  

An erosion rate is readily calculated based on a measured CRN concentration:

Care must be taken in interpretation of calculated erosion rates due to effects of intra-basin dynamics. Drainage systems with complex sediment storage patterns and high degrees of mass wasting are subject to biases due to unequal representation of different sections of the basin. Samples should be taken from locations away from recent landslide activity, and valleys with excessive amounts of stored sediment are not favorable to CRN based erosion estimates (Bierman and Nichols, 2004; Niemi, 2005). These types of environments are not always avoidable in practice, and many locations sampled for this study could be subject to the influences of mass wasting and sediment storage. Modeled corrections can be made for basins not meeting the ideal criteria (e.g. Yanites, 2009).

**Conclusion**

CRN erosion measurements are a powerful tool for determining rates of landform change and, when combined with data gathered from DEMs and other methods, can help find the primary controls on denudation for a region. This study will utilize basin averaged erosion rates and bedrock incision rates to discern the speed and causes of denudation in the CB. Both climate and tectonics should produce signals within the batholith, and these new data will assist in characterizing the response of this dynamic geomorphic environment.
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Project Time Line

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<tr>
<th>Milestone</th>
<th>Description/Purpose</th>
<th>Date</th>
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<tbody>
<tr>
<td>Field Season 1</td>
<td>Trip to Cordillera Blanca for sample collection, mapping, introduction to field site.</td>
<td>July, 2010</td>
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<tr>
<td>Sample Cleaning and Preparation</td>
<td>Mineral separations and acid leaches.</td>
<td>Mid May, 2011</td>
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<tr>
<td>$^{10}$Be Extraction</td>
<td>Acid dissolution and precipitation of BeO. To be performed at UC Santa Cruz.</td>
<td>Late May to Mid June, 2011</td>
</tr>
<tr>
<td>Sample Analysis</td>
<td>AMS run at Lawrence Livermore National Labs, CA.</td>
<td>Mid June, 2011</td>
</tr>
<tr>
<td>Field Season 2</td>
<td>Trip to Cordillera Blanca for sample collection, mapping</td>
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<td>Mineral separations and acid leaches, batch 2.</td>
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<tr>
<td>$^{10}$Be Extraction</td>
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<td>Manuscript Submission</td>
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<td>February, 2012</td>
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<td>Final Thesis Submission</td>
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References


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Fig. 1. Regional map of northern South America displaying locations of the Nazca Ridge and northern flat-slab subduction zone. Yellow arrow indicates direction of motion with magnitude for the Nazca Plate from Norabuena et. al., 1998. Red box delineates Cordillera Blanca Region (figs 2 and 3).
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Fig. 2. Geologic map of the Cordillera Blanca region.
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Fig. 3. Shaded relief DEM of the Cordillera Blanca produced from 30 m ASTER imagery. Basin erosion samples were taken from locations immediately upstream from the active CBDF trace. Proposed locations are subject to modification upon arrival for collection. Glacial cover data taken from GLIMS. Watershed and catchment delineation were performed using ArcMAP GIS system.
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Fig. 4. (Previous Page) Swath profiles from the CBB with exhumation rate data correlated with distance along strike. Solid black lines represent maximum, mean, and minimum elevations calculated using 30 m E-W trending swaths stretching from the Rio Santa to the Rio Maranon to the east. Exhumation rate data are plotted as colored diamonds and CRN derived slip rates are plotted as red triangles. Error bars represent analytical uncertainty.
(a) Data taken from Giovanni, 2007.
(b) Data taken from Montario, 2001.
(c) Data taken from Farber and Hancock, in prep.

Fig. 5. Biotite $^{40}$Ar/$^{39}$Ar cooling ages from Giovanni, 2007. Catchment position from north to south is: Yanac, Pachma Alta, Llanganuco, and Honda. Best-fit line for Pachma Alta basin is purely speculative due to insufficient data points, and is represented by a dashed line. Regression slope represents possible cooling rate. Note that a higher possible rate is present just north of the center of the range in Llanganuco.
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Table 1. Characteristics of basins from this study. Basins ordered from northern most to southern most outlet. Area, elevation, and slope measurements performed using ArcMap GIS System and 90 m resolution SRTM DEMs. Glacial cover calculated using GLIMS data.

<table>
<thead>
<tr>
<th>Basin Name</th>
<th>Area (km²)</th>
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<th>Slope (degrees)</th>
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