



NEOTECTONIC ACTIVITY IN ECUADOR AND PERU, from GEOMORPHIC to GEODETIC data, FOCUS AROUND ANDEAN MEGACITIES

Audin, Laurence (1), Carlos Benavente (2,1), Alexandra Alvarado (3), Swann Zerathe (1), Yepes Hugo (3), Champenois Johann (4), Baize Stéphane (5), Delgado Fabrizio (2), Beauval Céline (1), Robert Xavier (1)

- (1) ISTerre, UGA, France. Email: laurence.audin@ird.fr, laurence.audin@univ-grenoble-alpes.fr
- (2) INGEMMET, Peru.
- (3) IG QUITO, Ecuador.
- (4) CEA DASE, France.
- (5) IRSN, France.

Abstract: *The Andean range stretches for thousands of kilometers from Patagonia to Venezuela and its recent tectonic evolution results from the ongoing subduction of the Nazca plate. Less studied than the subduction mega earthquakes, several $M > 7$ continental earthquakes did affect the Andean human settlements since the Pre Incaic period. Although neglected in terms of archaeoseismic or neotectonic studies, the impacted regions display exponentially growing megacities, highly exposed to seismic hazards. In this study, we focus on investigating crustal deformation along newly described fault systems, in a seismically active urban setting (in Peru and Ecuador). High resolution satellite images, geodetic data, georadar and field studies provide striking examples and evidences of the ongoing tectonic deformation that can be the longer-term Quaternary geomorphic record. We focus here on the Quito and Ibarra regions in northern Ecuador, and on Arequipa and Cuzco regions in southern Peru.*

Key words: *Active tectonics, Geomorphology, Andes, Seismic Hazards.*

NEOTECTONICS ALONG THE ANDEAN RANGE: STATE OF THE ART and OBJECTIVES

Along the Pacific flank of the high Andes, the recent geodetic measurements do not provide informations on the long term continental deformation rates, due to the strong coupling and the ongoing subduction (Nocquet et al., 2014). Therefore tectonic geomorphology provides a unique and necessary tool to address longer term deformation. Over the past decades the urban population has been increasing in the Andean region. And since the return period of continental earthquakes is much longer than the periods of recent urbanization, further tectonic geomorphology studies in and around megacities are needed. Moreover, the instrumental crustal seismicity is also rather sparse in comparison to megathrust seismicity, so little is known about the active tectonics and fault sources in the continental Andes.

Here, we propose to provide combined data sets to study the ongoing tectonic deformation around an urbanized area in order to constrain the seismic activity rates on prominent crustal faults that could impact the megacities in Peru and Ecuador.

ACTIVE FAULTING IN ECUADOR

The Quito megacity (in terms of Ecuador's total population) lies at 2800 m elevation within the Interandean Depression (ID), in an active seismic and volcanic province (*Figure 1*) in northern Ecuador. Quito basin and the city itself are located on a structural bench, along the western border of the ID (Soulas et al., 1991). Beneath Quito, the subduction interface is located at a depth of ~120 km, without known influence on superficial tectonics of the upper plate (Yepes et al., 2016).

IS QUITO BLIND THRUST CREEPING?

The Quito Fault System (QFS) extends over 60 km and appears to be segmented en echelon. Multidisciplinary studies support an interpretation in which two major contemporaneous fault systems affect Quaternary volcanoclastic deposits (*Figure 1*). Hanging paleovalleys and disruption of drainage networks attest to ongoing crustal deformation and uplift in this region, further indicated by 15 years of GPS measurements and seismicity. The resulting new map displays an eastward migrating Quito Fault



System. Northeast of this major tectonic feature, the strike-slip Guayllabamba Fault System (GFS) aids the eastward transfer of the regional strain northeastward to Colombia. A new GPS data set and INSAR studies indicates active shortening rates for Quito blind thrust of up to 4 mm/yr, which decreases northward along the fold system as it connects to the strike-slip Guayllabamba Fault System (*Figure 2*). These two tectonic fault systems are active today, and the local focal mechanisms are consistent with the direction of relative GPS velocities and the regional stress tensors (Alvarado et al., 2014). Moreover, a sharp velocity gradient is observed across the Quito fault system and only a fraction of the fault plane is presently accumulating elastic stress, available for future earthquakes (Champenois et al., 2013, *Figure 2*). Alvarado et al. (2014) proposed that the depth over which elastic stress is presently accumulated is in the range of 3–7 km. We estimated a maximum magnitude range of Mw 5.7 to 7.1 for the GFS and QFS. But the best constrained estimation derives from the geodetic data and corresponds to a maximum value of Mw = 6.6 (Alvarado et al., 2014).

Finally, as for the urban setting, the capital is lying over the hanging wall of the reverse fault system. In case of a large earthquake, ground motions are expected to be much higher in Quito than in the suburbs (Beauval et al., 2015; Yepes et al., 2016). The 1797 Riobamba earthquake (MI 7.6) occurred 160 km south of Quito, but produced an intensity VII in the city. Years later, Quito experienced a similar shaking level during another large earthquake, the 1868 Ibarra event 80km north of Quito (MI 7.2, in Beauval et al., 2010).

1868 IBARRA LOST SCARP?

The 4m-resolution DEM of Ecuador reveals a sharp geomorphic lineament cutting through the western shoulder of the ID near Ibarra city. This scarp is developed within the volcanic formation of Chachimbiro edifice (Andrade et al., 2009). Along the lineament, we document evidences of captures, sag ponds and normal faulting of the volcanic and sedimentary deposits (*Figure 3*). This systematic offset could be due to previous large earthquakes in the area, possibly the M7.2 1868 Ibarra event (Beauval et al., 2010).

ACTIVE FAULT SCARPS in PERU

FIRST DIRECT DATING OF A FAULT SCARP by ¹⁰Be

Commonly in southern Peru, most of the previous studies have argued that low tectonic activity is recorded along the Andean forearc, and despite recent updating of the active fault map (INGEMMET, Neotec, Benavente and Audin, 2009), no direct quantification of the deformation rates have been proposed. To bring new constrains, we focus on the transpressive Purgatorio fault (*Figure 4*), located between the cities of Moquega and Mirave. The fault is 45 kilometers long and connects to the major and active Incapuquio fault system (Hall et al., 2008). It trends along the Western Cordillera piedmont where it disrupts the rocky and smooth landscape of the Atacama Desert (*Figure 4*). It forms a fresh vertical scarp ~4 m in height coseismic displacements and offers the opportunity to constrain the age of the last events and fault slip rates (Benavente et al., in prep). We performed direct ¹⁰Be surface exposure dating of the fault scarp along a vertical profile. Five samples were collected along a 4 m high profile (*Figure 4*). We systematically selected pebbles cut by the fault movement and marked by tectonic slickensides (Benavente et al., in prep, *Figure 4*). The obtained exposure ages suggest that 4 m of coseismic uplift happened during the last 2 thousands years (*Figure 4*). Based on the assumption that the scarp is coseismic, we can derived a new minimum vertical tectonic motion rate (~2 mm/yr) that is one order of magnitude higher than the previously obtained one from terraces river offsets (0.2 mm/yr, Hall et al., 2012). Our results challenge the accuracy of the recurrent vision defining the Peruvian Andean forearc as a non-deforming block, and raise up the question of the seismic hazard in the nearby cities, potentially exposed to strong shallow earthquakes of depth <10 km and Mw > 7 (Benavente et al., in prep).

ARE CUZCO FAULT SEGMENTS ACTIVE?

Unlike the Andean forearc, the tectonic regime in the High Peruvian Andes is mainly extensional and result from the competing convergence and gravity forces (Sébrier et al., 1988; Mercier et al., 1992; Benavente et al., 2013). The Cuzco normal fault system (Cabrera & Sébrier, 1998) limits the Altiplano basin from the Eastern Cordillera. The Cuzco fault and the associated fault system in southern Peru cross Cuzco city and is chosen here as an example to illustrate the needs of multidisciplinary approach for neotectonic studies in this touristic region.

Normal faulting during the historical times (back to 1650) indicate that N-S oriented extension is characteristic of the present-day tectonic regime. Prior to 1986, several Mw 6 shallow earthquakes



affected the Cuzco region (Silgado, 1978) in 1650, 1950 and 1986. In 1650, a massive earthquake hit Cuzco, the Inca capital at the time. For the 1986 event, Cabrera et al., 1998 consider that the rupture at depth is rather shallow (<10 km) after the coseismic scarps and the instrumental low magnitude (Mw 5.3). It is consistent with the longitudinal extension of well-preserved Holocene scarps along other regional active faults, that extend all the way from Cuzco to Puno region along the Altiplano basin.

CONCLUSIONS

Even if strong seismic events are not unfamiliar to Peru and Ecuador, appropriate earthquake engineering highly depends on the mapping, knowledge and detailed studies of the active fault systems and the related seismic hazard.

The proximity of previously unrecognized active structures to the densely populated Andean cities highlights the need for additional archaeoseismic, palaeoseismic, geomorphic and tectonic studies to characterize seismic sources and develop parameters for input to hazard assessments. Interdisciplinary studies must be pursued to better understand the recurrence and magnitude of crustal earthquakes that may affect the capital cities and megacities in South America.

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References

Alvarado A., L. Audin, J. M. Nocquet, S. Lagreulet, M. Segovia, Y. Font, G. Lamarque H. Yepes, P. Mothes, F. Rolandone, P. Jarrín, X. Quidelleur (2014) Active tectonics in Quito, Ecuador, assessed by geomorphological studies, GPS data, and crustal seismicity. *Tectonics*. (2014) doi: 10.1002/2012TC003224.

Andrade, D., 2009. The influence of active tectonics on the structural development and flank collapse of Ecuadorian arc volcanoes. PhD Thesis, Université Blaise Pascal, France, p. 239.

Beauval C., H. Yepes, W. Bakun, J. Egred, A. Alvarado and J-C. Singaicho (2010). Locations and magnitudes of historical earthquakes in the Sierra of Ecuador (1587-1996), *Geophys. J. Int.*, DOI: 10.1111/j.1365-246X.2010.04569.x

Beauval C., H. Yepes, A. Alvarado, L. Audin, J.-M. Nocquet, D. Monelli, and L. Danciu. (2014) Probabilistic seismic hazard assessment in Quito, estimates and uncertainties *Seismological Research Letters*, 85:1316-1327.

Benavente, C., Zerathe, S., Audin, L., Robert, X., Delgado, F., Hall, S., Faber, D. ASTER TEAM (*In preparation*). Using 10Be cosmogenic surface exposure dating to determine the evolution of the Purgatorio active fault in the Andean forearc, southern Peru.

Benavente C. & Audin L. (2009) Geometry, Morphology And Seismic Hazard Of The Purgatorio Mirave Fault-Forearc Southern Peru, *Bol. Soc. geol. Perú*, 103: 15.

Benavente, C.; Delgado, F.; Taipe, E.; Audin, L & Pari, W. (2013) - Neotectónica y peligro sísmico en la región Cusco, INGEMMET. *Boletín, Serie C: Geología Ambiental y Riesgo Geológico*, 55, 245p.

Cabrera J. & Sébrier M. (1998) - Surface rupture associated with a 5.3 mb earthquake: the 5 April 1986 Cuzco earthquake and kinematics of the Chincheros-Qoricocha faults of the High Andes, Peru. *Bull. Seism. Soc. Am.*, 88, 242-255.

Champanois J., L. Audin, S. Baize, JM Nocquet, A. Alvarado (2013), Interseismic deformations along Ecuador active fault systems: Contribution of space-borne SAR Interferometry. AGU Cancun Meeting of the Americas T22A-01. 2013, Mexico.

2008 Hall S.R., Farber, D.L., **Audin L.**, Finkel, R.C., Mériaux, A.S.; Geochronology Of Pediment Surfaces In Southern Peru: Implications For Quaternary Deformation Of The Andean Forearc, *Tectonophysics*, doi: 10.1016/J.Tecto.2007.11.073; 459 (2008) 186-205.

Hall S., Farber, D.L., Audin L. and Finkel, R.C.; Recently active contractile deformation in the forearc of southern Peru *Earth and Planetary Science Letters* 337-338 (2012) 85-92.

Mercier, J.L.; Sébrier, M.; Lavenu, A.; Cabrera J.; Bellier, O.; Dumont, J.F. & Macharé, J. (1992) - Changes in the tectonic regime above a subduction zone of Andean type—The Andes of Peru and Bolivia during the Pliocene-Pleistocene: *Journal of Geophysical Research*, v. 97, no. B8, p. 11,945-11,982.

Sébrier, M.; Lavenu, A.; Fornari, M. & Soulas, J.P. (1988) - Tectonic and uplift in Central Andes (Perú, Bolivia and northern Chile) from Eocene to present. *Géodynamique*, 3(1-2): 85-106.

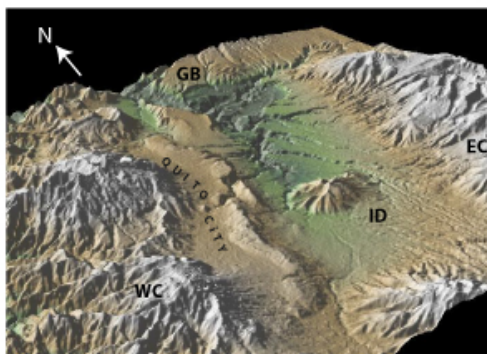
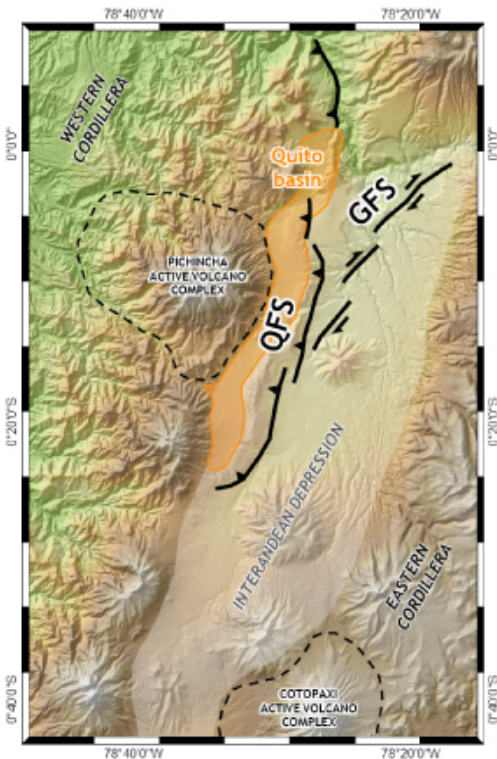


Silgado, E. (1978). Historia de los sismos más notables ocurridos en Perú, 1513-1974. Inst. Geol. Minero de Perú, 131 pp.

Yepes H., L. Audin, A. Alvarado, C. Beauval, J. Aguilar, Y. Font, F. Cotton (2016), A new view for the geodynamics of Ecuador: implication in seismogenic sources definition and seismic hazard assessment. 35. Tectonics.

Figures

Figure 1: A/ Quito region, topography and fault systems, B/ 3D topography.



ID Interandean Depression WC Western Cordillera
 GB Guayllabamba Basin & EC Eastern Cordillera
 GFS Guayllabamba Fault System QFS Quito Fault System

Figure 2: Quito region, 1993-2000 PS InSAR versus GPS deformation across the Quito Fault System after Champenois et al., 2013.

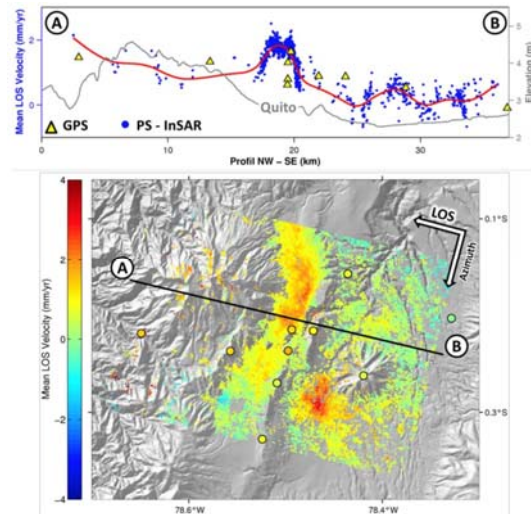


Figure 3: Ibarra region and a Google Earth photo of a potential scarp associated to the seismic source of historic 1868 Mw 7 earthquake.



Figure 4: Southern Peru region and the active fault systems (Benavente et al., in prep)

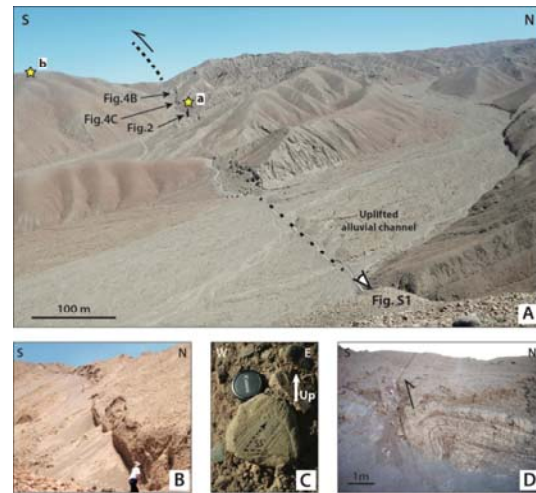
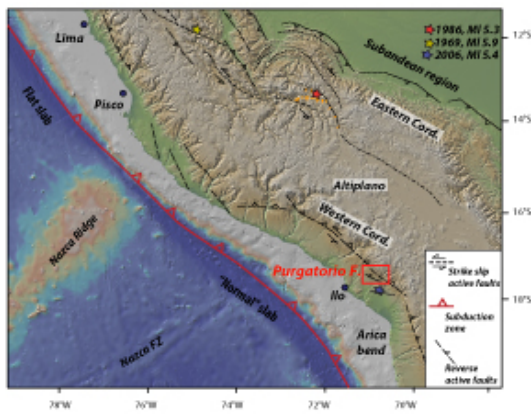


Figure 5: Field evidences of the recent co-seismic activity of the Purgatorio Fault in Southern Peru forearc region. B/ Sampled scarp along the thrust fault. C/ Broken pebbles along the fault plane, sampled for ¹⁰Be dating. D/ Folded recent ashes and sediments in the Purgatorio plain along the fault trace.