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Active tectonics around the Cusco city, Peru: Record of earthquakes in the last 14,000 years, from paleosismological data

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1. INTRODUCTION

The seismic activity of Peru has its origin in the convergent margin, where the Nazca plate subducts under the South American plate, a process that generates friction and accumulation of stress, reflected in deformation of the crust and superficial earthquakes (<30km of depth).

Cusco was affected by earthquakes in 1950, 1650 and recently in 1986, the first two, major earthquakes of magnitudes greater than 7 MM (Silgado,1978).

The Tambomachay active geological fault is located four kilometers to the north of the city of Cusco, and belongs to a large and wide deformation zone, where the structures have NW-SE and E-W trends, known as the Zurite-Cusco-Urcos-Sicuani Fault System (Benavente et al., 2013). Recent studies show clear morphological and structural evidence of Quaternary activity on these structures (Sébrier et al., 1985; Mercier et al., 1992; Cabrera, 1988; Benavente et al, 2013), so they should be classified as an important seismogenic source; however, there has not been complete characterization to assess the seismic hazard to the city of Cusco, which currently houses over ~500,000 inhabitants.

In this research investigation, we present a paleoseismological study of the western sector of the Tambomachay Fault. We present displacement rates, recurrence intervals and ages of recent seismic events.

2. GEOLOGICAL SETTING

The Tambomachay Fault is part of an extensive deformation zone ~200km long, located between the Eastern Cordillera and the Altiplano (Figure 1), in southern Peru. This zone is composed by Quaternary and active normal faults with E-W trending (Sébrier et al., 1985; Mercier et al., 1992; Cabrera, 1988; Benavente et al, 2013).

The Tambomachay Fault has a length of ~20km and a NW-SE trend. This fault puts in contact Cretaceous rocks in the hangingwall with Eocene-Oligocene rocks in the footwall (Carlotto et al., 2011). The deformation is the result of polyphasic tectonics with evidence of ancient inverse and strike slip movements, to which it owes its lineal trace (Gregory, 1916; Cabrera, 1988).

Recent activity on the Tambomachay Fault has formed an accumulated scarp of ~400m that exhibits triangular facets, offset streams, indicating its normal kinematics. The fault plane, generally covered by debris slope, dips at an angle ranging between 60º and 70ºS. The most recent activity has generated escarpments with average heights of ~2m, and a maximum vertical displacement above lateral moraines of ~4m exposed at its western end, at an altitude of ~4100m. Toward the East, these escarpments separate the basement (Eocene-Oligocene) from the Quaternary alluvial fans (Cabrera, 1988).

1. STUDY METHODS

Based on analysis of high-resolution satellite images (Pléiades), we identify the trace of the Tambomachay Fault, and locations where the fault cuts Quaternary deposits. The images show that the fault is well preserved in the western sector (Figure 2), unlike the central and eastern sector, where the escarpment has been erased by urban growth.

We excavated a trench and identified the stratigraphic sequence, and we defined the strata according to their composition, texture, color and lateral continuity. Likewise, structures and deformed horizons related to paleoearthquakes. To determine the ages of the events, samples of organic sediment were taken, which were dated by spectrometry with mass accelerator (AMS-C14) in the BETA Analysis Inc. (USA) laboratory.

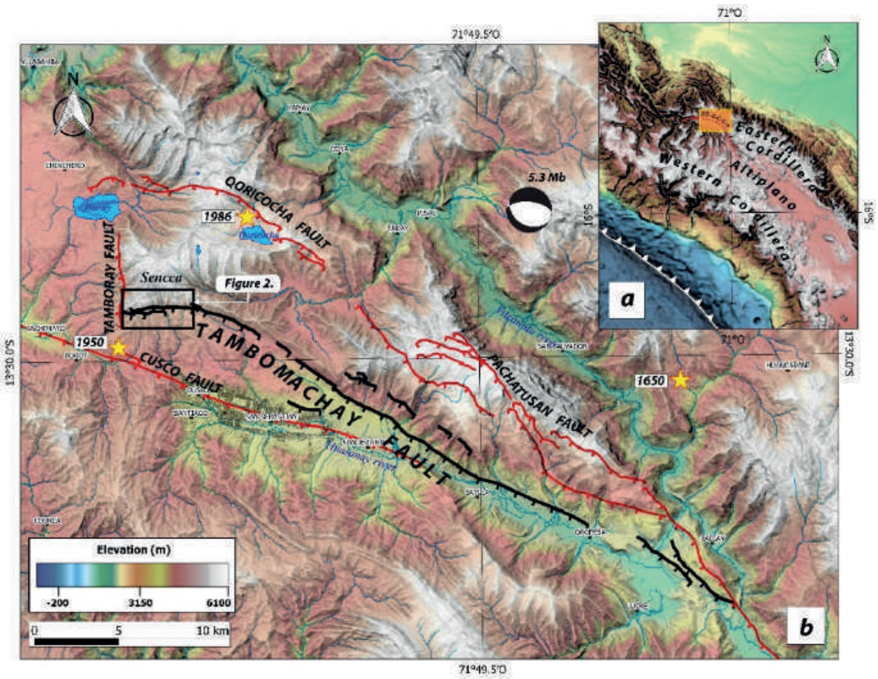

Figure 1. Topographic map, showing: (a) the location of the Zurite-Cusco-Urcos-Sicuani fault system (S.F. ZCUS, in red line) located between the Eastern Cordillera and the Altiplano, (b) Tambomachay Fault (black line) within the ZCUS fault system (red lines). Yellow stars indicate epicenters of the most important recent seismic events (1650,1950 and 1986) that occurred in Cusco (Silgado, 1978). Focal mechanism of shallow earthquake (<40km) of April 5, 1986 with moment magnitude > 5.0 is also shown (International Seismological Centre, 2015).

We interpret the number of seismic events based on the identification of dated stratigraphic horizons, identification and dating of colluvial wedges, and deformation structures; the results of C14 dating, and reconstruction of the trench.Then we elaborated a schematic model, which shows the chronological evolution of the sedimentary processes, and seismic events with their respective displacements or offset.

Finally, we have calculated the moment magnitude corresponding to each seismic event, using the empirical formula described by Wells and Coppersmith (1994), recurrence interval and the slip rate.

2. RESULTS

Tambomachay trench

It is located at the western end of the Tambomachay Fault on the southern slope of Sencca Hill, transverse to a preserved fault escarpment that displaces lateral moraines of Holocene age (Figure 2), dated by cosmogenic nuclides Be^{10}.

In the trench we identified displaced moraine deposits and a fault plane with some normal-slip striations, and with a strike of N90º and a dip of 72ºS.

Stratigraphic units exposed on the west wall of the trench are composed of displaced moraine deposits, sandy reddish silt deposit, sandy reddish silt bends with sub-angular sandstones clasts, fine sandy silt bends, sandy dark brown silt deposit with sub-angular to sub-rounded sandstones clasts bends.

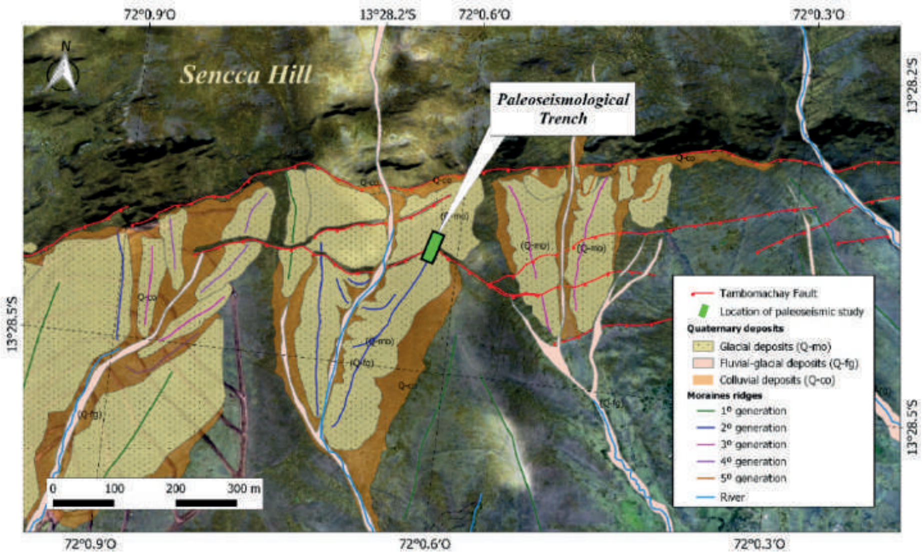

Figure 2. Map of Quaternary deposits affected by the recent activity of the Tambomachay Fault (west end), the green rectangle shows the location of the trench.

Paleoseismic interpretation

The radiocarbon ages of 11 samples and relationships between stratigraphic sequences and deformation structures, provide evidence of multiple seismic events that occurred during the Holocene.

The paleoseismic evidence is mainly characterized by layers of truncated sediments and colluvial wedges derived from the erosion of the fault escarpments (Figure 3).

According to the above, we identified four (04) seismic events (Figure 4).

The first event occurred on fault ***f1***, which displaces the moraine deposits (U-A); at the same time, colluvial wedge I (CI) formed. The age of the colluvial wedge I (CI) is ~8,400 Cal BP and represents the minimum chronological age of this event. The activity of this fault before 8,400 years is not visible in the trench, however at least one more event would have displaced the unit A (U-A). The colluvial wedge I (CI) is overlain by the deposit of unit B (U-B) with an age of ~7,000 Cal BP.

The second event is mainly characterized by the activity of fault ***f2***, generating displacement of moraine deposits and the colluvial wedge I (CI). The erosion of the escarpments generated the colluvial wedge III (CII) of age ~ 6,600 Cal BP. On top of this unit we find the deposit of unit C (U-C).

The third event happened after an erosion process and is characterized mainly by the activity of the faults ***f4***, ***f3*** and ***f2***, that together generate a negative flower structure. At the same time, the fault ***f1*** is reactivated; the erosion of the escarpments forms the colluvial wedge CIII (CIII). These units are overlain by units D and E.

The fourth event is characterized by the reactivation of the fault ***f1***, the erosion of the new scarp results in the colluvial wedge CIV (C-IV) with an age of ~ 1,000 Cal BP.

Finally, we observed the last layer of soil in the current configuration.

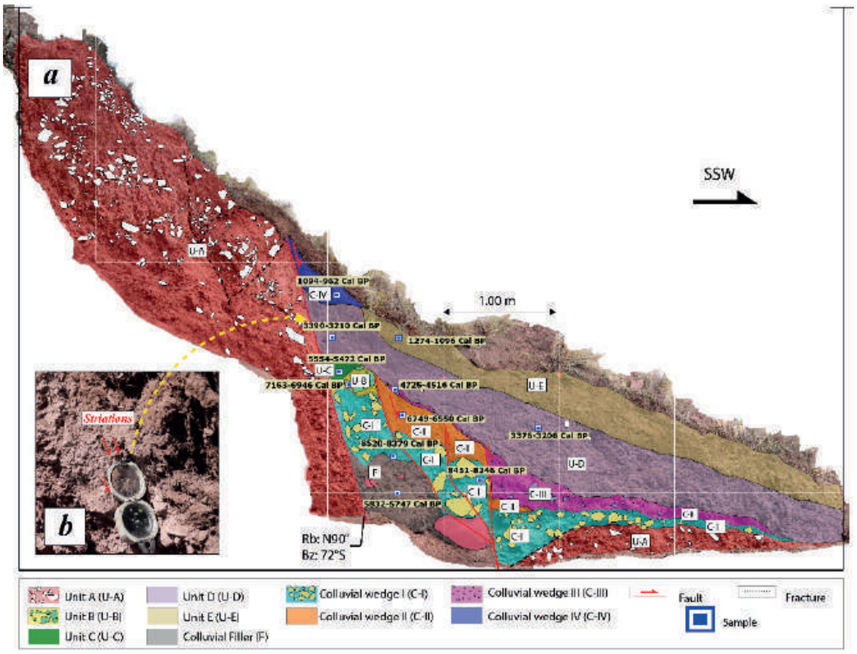

Figure 3. (a) Photointerpretation of the stratigraphic units, seismic evidence and deformation structures, (b) Photograph showing the slickenside kinematic indicator on the fault plane.

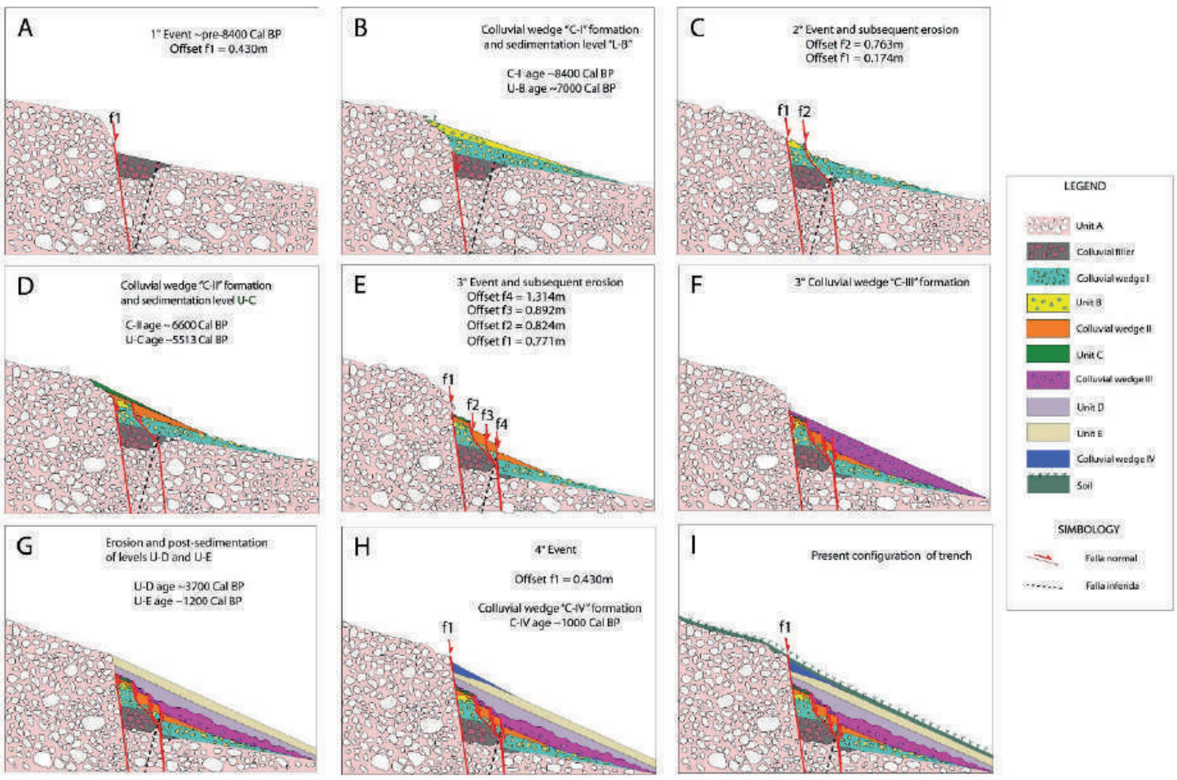

Figure 4. Simplified cross sections showing the inferred sequential development of the east wallof the trench, west sector, Tambomachay Fault.

3. DISCUSSIONS AND CONCLUSIONS

PALEOMAGNITUDES, RECURRENCE INTERVAL AND SLIP RATE CALCULATE

Based on published parameters of a large number of known earthquakes in the world, empirical equations between the maximum displacement, average displacement, and moment magnitude were established for normal faults by Wells & Coppersmith (1994), the data calculated in our study for the four events identified are shown in the table 1.

Event	*AD (m)*	*Mw*
1	0.430	6.542
2	0.763	6.704
3	1.314	6.857
4	0.430	6.542

Table 1. The first column shows the seismic events determined from the reconstruction and interpretation of the trench, the second column shows the displacement values (AD) corresponding to each event, here we emphasize that these displacements is considered as the average displacement to avoid underestimating the displacement rates, and the third column shows the calculation of the moment magnitude (Mw) for each event, based on the value of the displacements.

Cabrera et al. in 1988, estimated a recurrence interval of 5,000 years. We constrain refine the recurrence interval, estimating a minimum value of ~1,800 years and a maximum value of ~2,800 years.

For the first time, we have calculated slip rates for the Tambomachay Fault. These rates being a maximum of 0.35 mm/year and a minimum of 0.29 mm/year, this result allows us to classify the Tambomachay Fault as having slow fault with moderate activity (Slemmons, 1977).

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