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Earthquake Fault Segmentation In The Central Andes, Ecuador

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Abstract: *Field investigations have been carried out along the fault system that accommodates the relative motion between the North Andean Sliver and the South American Plate in Ecuador. The project aims at mapping the segmentation of this major active fault system. A series of fault strands newly mapped in direct continuation to the Pallatanga Fault (PF) to the north allow the definition of a large structure capable of triggering large events. This is confirmed by the presence of historical well-preserved scarps and decametric offsets (probably due to the 1797 M7.5 Riobamba event) disrupting the Igualata volcano. We could not find evidence for any structural continuity between the PF and the fault mapped in the Huisla volcano to the NE. We suggest that a 5-10 km wide step over separates the two segments and probably blocked the 1797 rupture. A recent surface rupture has also been recently discovered during the M5 Pisayambo quake along the Cosanga Fault (CF) system with uncommon surface rupture length and displacement. From the few unearthed evidences we estimate at a first glance that the mean slip rate along the PF and CF is similar (≈1 mm/yr).*

Key words: *Earthquake Geology Historical Surface ruptures Segmentation Ecuador.*

GEOLOGICAL FRAMEWORK

Relative motion between the North Andean Sliver (NAS) and the South American Plate (SAP) is accommodated along a large continental fault zone at 8 mm/yr rate, including the Pallatanga Fault (PF). The PF crosses the entire Western Cordillera and localizes the deformation between the SAP and NAS (Alvarado et al., 2016), and is suspected to have hosted large historical earthquakes (1698?, 1797, 1911, 1949) reported by Beauval et al. (2010). Its 65+ km surface trace is quite well known from Juan de Velasco (SW) to the Cajabamba area (NE) where three trenches were excavated, evidencing the occurrence of large prehistorical earthquakes, and among them the 1797 event (Baize et al., 2015). North of this, towards the Cosanga Fault (CF) in the Cordillera Real, the fault mapping is much less constrained and was the target of a 4m-high-resolved DEM analysis and field investigations.

NEW INVESTIGATIONS

Our recent efforts focused on mapping and documenting the fault in this transition area between PF and CF. We aim both at mapping the active fault traces, characterizing their long-term activity and evidencing recent or historical surface ruptures. These topics are relevant steps to infer the rupture segmentation during large past events and to contribute to a better assessment of seismic hazard. During these last campaigns, we could characterize several fault strands that continue the PF to the north, defining a large fault capable to trigger large events. Three sectors were investigated: San Andres, Igualata volcano, Huisla volcano (Figure 1).

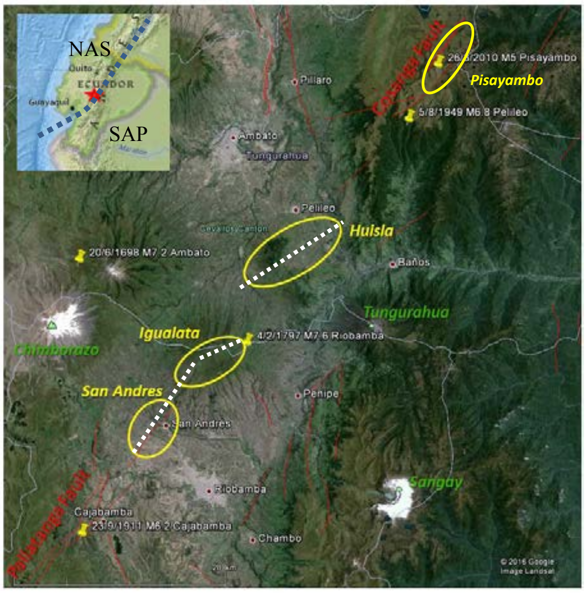

Fig. 1: Location of the study areas, between the known and mapped segments (Pallatanga Fault and Cosanga Fault) in red (fault traces from Alvarado, 2012). White dashed lines are fault traces investigated. Yellow pins locate the main historical earthquakes. In green, the major active or dormant volcanoes in the area. Insert: the blue dashed line depicts the shear zone that separates the North Andean Sliver (NAS) from the South-America Plate (SAP). Red star: study area.

The structural continuity between the PF on top of the Pliocene Igualata Volcano (IV) and the CF in the Pleistocene Huisla volcano (HV) is unknown but, at the end of our field investigation, we defined a 5-10 km step-over which seems to have blocked the most recent surface rupture to the south. Finally, Holocene activity has been unearthed along the CF system, close to the

Pisayambo Lake, and we were able to document a new and clear surface rupture associated with a M5 earthquake in 2010 as described below. We hereafter describe the geological evidences and their analysis from south to north.

SURFACE RUPTURE EVIDENCES BETWEEN SAN ANDRES AND THE IGUALATA VOLCANO

The San Andres Village and the IV slopes

The 4m-resolution DEM reveals several lineaments aligned with the known trend of the Pallatanga Fault segments. These are developed within volcanic avalanche deposits (hereafter called "VAD") that filled the Riobamba basin 50 to 60 ka ago after the partial collapse of the Chimborazo edifice (Bernard et al., 2008). Along the lineament, we document evidences of folding and faulting of the volcanic and sedimentary deposits. Interestingly, the general course of a fault-perpendicular incised creek is deflected about 60 meters in the right-lateral sense, including a localized 10 meters nearby an abandoned water-mill. This latter smaller-scale offset could be due to the last large earthquake of the area, i.e. the M7.5 1797 Riobamba event. Considering the age of the VAD and assuming that this creek initially incised in a linear course across the fault, we can preliminary estimate the slip rate at ≈1 mm/yr.

Along the IV slopes north of San Andres, we could trace a series of compelling evidences of surface faulting affecting the thick Holocene organic soil, as well as large (5-10 m) cumulative NE-SW scarps, individual scarplets (1 m) and right-lateral displacements of creeks (several tens of meters).

The Igualata Volcano

The best evidence of recent surface faulting crops out nearby the IV summit, with cumulative displacements of morphologic features and coseismic signs of a major historical event (scarp with free-face, en echelon fractures). The 1797 quake seems to be the best candidate, because of the vicinity of the epicenter. However, we cannot completely rule out the M~7.2 1698 event (Beauval et al., 2010).

The general geomorphic expression is of a right-lateral fault zone generating a counter-slope scarp and related sag ponds (Figure 2). The right-lateral kinematics are attested by left-stepping en-echelon fractures during the last quake, and by successive displacements of morphological features, especially an erosional "channel" (CH) for which we could identify at least 5 remnants in the downthrown block (Figure 2). Successive dextral displacements of this "CH" are between 8 (last event) and 18 m. The cumulative vertical component is about 4 meters. These displacement values are really high, even for M≈7.5 events like the 1797 Riobamba quake, and we suggest that they could correspond to multi-event offsets. The fault trace can be mapped up to the northern IV slope, displacing moraine, terrace risers, Holocene marsh deposits.

Fig. 2: Cumulative fault trace across the Igualata volcano (IV) summit. En echelon left-stepping fractures and recent free face scarps represent the most recent surface rupturing event, probably the 1797 Riobamba earthquake (northern end of the same rupturing event observed in Baize et al., 2014). They reveal a prevailing right-lateral mechanism, consistent with current regional kinematics.

DISLOCATION OF THE HUISLA VOLCANO CLOSE TO PELILEO

In this area, we report evidences of cumulative fault displacement, but no clear proof of historical surface rupture. Five kilometers north of the trace in the IV, the dislocation of the inactive Huisla volcano is the closest recent geomorphic sign of coseismic deformation. The morphology of the edifice is symptomatic of a large sudden collapse of the cone, which beheaded the edifice and formed the large and hollowed valleys on top. The related slide and accumulation of avalanche debris reached the Patate River valley. According to P. Mothes (personal communication), the Huisla avalanche could have occurred 30 ka. Therefore, all the tectonic features

that are described hereafter are younger (Upper Pleistocene to Holocene).
An overview of the edifice from the south enables roughly locating the fault zone (Figure 3) and, at closer distance, a series of benches which disrupt the major slope could indicate the fault trace. On its eastern flank, the HV also is cut by the fault which displaces an incised valley with a significant (≈60 m) right-lateral component. Down to the Rio Patate valley, the road-cuts of the new Pelileo - Riobamba highway offers massive outcrops. In one of these, we could document a Quaternary NE-SW fault between the Huisla VAD and a series of stratified deposits mixing colluvial layers and volcanic falls. The strike-slip fault kinematics of the shear zone there attests to a tectonic origin, despite the very steep slope which is affected by numerous mass movements. The northernmost fault segment investigated during our November 2015 field session was inferred from morphological analysis: a pressure ridge dams a paleo-valley on the right side of the Patate valley, in the exact continuation of the NE-SW shear zone described before. The area did not reveal any evidence of historical surface rupture and, to date; it seems that both the 1797 and 1949 earthquake faults did not reach the surface there. The road cut outcrop suggests that the most recent colluvial deposits are not deformed.

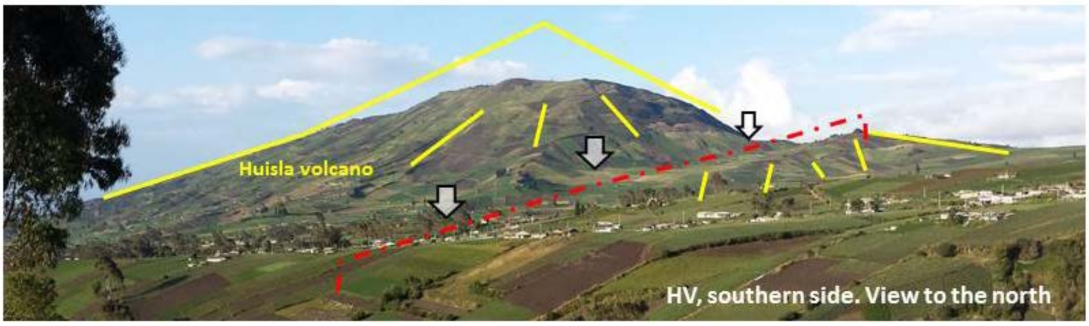

Fig. 3: View from south of the Huisla volcano (HV) disrupted by a dextral fault (red dashed line). Yellow lines represent the hypothetical flanks and slopes of the former edifice.

The epicentral area of the 1949 Pelileo earthquake suffered many landslides and other secondary effects during shaking. The former Pelileo city (nowadays re-built; La Moya) was destroyed by superficial movements during the 1949 quake. Archives also report that most of the Patate River valley slopes were affected by heavy and deep-seated movements mobilizing several millions of cubic meters.

THE PISAYAMBO EARTHQUAKE ON THE COSANGA FAULT ZONE

In 2010, a magnitude 5 earthquake occurred in the Pisayambo Lake region, 25 km north-east of Pelileo city. Surprisingly, this quake produced significant surface faulting that could still be discovered four years after from InSAR analysis. This study (Champenois et al., in prep.) has shown the occurrence of a 9 km long linear anomaly in interferograms, with relative displacements in the Line-of-Sight of about 50-60 cm, which we interpret as the evidence of a surface faulting event.
During a field reconnaissance in 2014, we could check the "InSAR" surface rupture trace and geologically map the field clues that have been preserved. The "coseismic" evidences are located along a cumulative fault which displaces the Pleistocene moraines and the Holocene soils. All along the investigated fault, we could document right-lateral offsets of 10 to 20 meters versus 1 to 2 meters of vertical throw. At some places, these offsets are distributed over several parallel segments. A stratigraphic section in a hand-made trench allowed the verification of the coseismic activity of the fault during the Holocene, with two major morphogenic quakes that produced a moraine free-face scarp between 2500-1000 years BC and between 800-400 years BC. The fault segment here described is assigned to the Cosanga Fault zone (Alvarado, 2012).
Four years after the quake, we could unearth the traces of surface faulting, which were conspicuously preserved: open cracks, ENE-WSW left stepping en-échelon fissures, NE-SW fractures with relative displacement and pop-up features. Fault strike is generally around N30°-N50°E consistent with the InSAR results (Alvarado, 2012). The overall deformation pattern is consistent with right-lateral kinematics. Average (AD) and maximum (MD) values of displacement are really high for such a moderate earthquake, respectively of 22 to 26 cm and 37 to 61 cm (according to field and InSAR measurements, respectively). Applying the classical empirical relationships (Wells and Coppersmith, 1994), these fault parameters should be associated with a M6.2-6.5 earthquake.
According to the InSAR data and their inversion, we can summarize the fault parameters as follows: surface rupture length is 9 km, fault width 2 km, fault dip 60° to the east (Champenois et al., in prep.). When converting the average slip (about 25 cm) over the fault surface area (18 km^2), the equivalent moment magnitude of such an event is Mw=5, assuming realistic shallow conditions for the local crust (i.e. Vs=2000 m/s, density 2.5 and therefore a shear modulus of 10 GPa). This is completely consistent with the seismological data (Figure 4) and we here emphasized that the Wells and Coppersmith (1994)

relationships are to be applied carefully, especially when trenching data like AD or MD are used.

One question still remains open: we cannot rule out that part of the measured surface slip has been released aseismically during the 16 days-time period covered by the successive radar data.

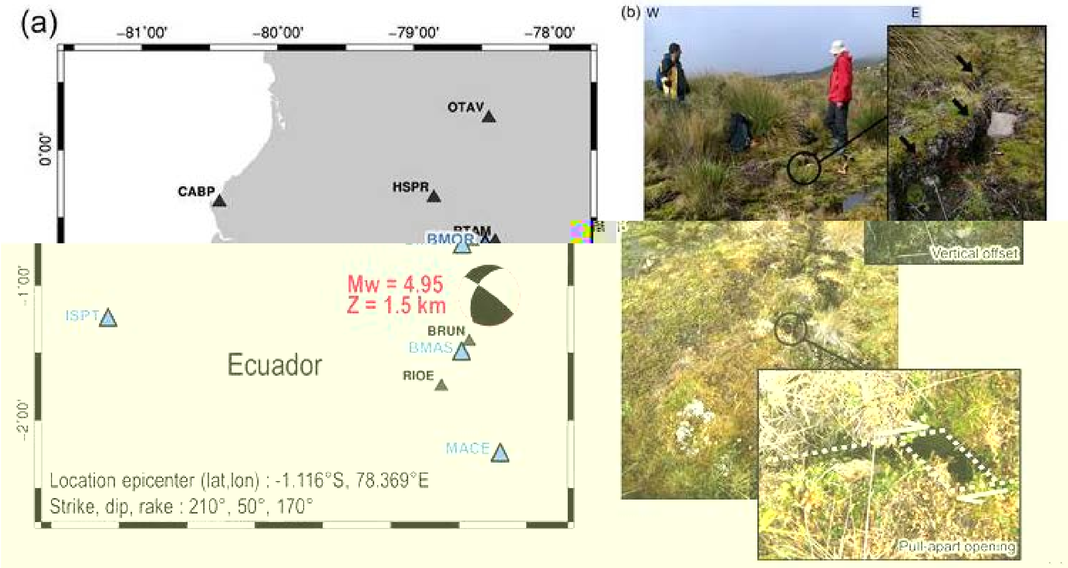

Fig. 4: Focal parameters of the 26/3/2010 M5 Pisayambo earthquake and associated surface rupture as observed in 2014 (from Champenois et al., in prep.). Surface right lateral and vertical offsets are around 25 cm and ~10 cm, respectively, coherent in scale from both the field observations and the INSAR imagery.

FUTURE WORKS

Future field surveys and optical imagery analyses will focus on completing the active fault and surface rupture mapping, in the framework of the newly re-funded “REMAKE” project. To date, we could drastically refine the fault segmentation of the PF and CF, but the final product is not achieved yet. The paleoearthquake history of the fault zone has not been continued since the successful trenches in Rumipamba (Baize et al., 2015). We emphasize that, with the future segmentation map of the fault system, we would be able to propose scenarios for the earthquake rupture propagation through the system which was able to cause magnitude 7.5 quakes in the past. Trenching in the Igualata summit area or in the Huisla zone could be relevant targets for achieving that project.

In addition, we emphasize that the CF and PF system only accommodates 1 mm/yr over the 8 mm/yr of dextral shearing between NAS and SAP: further works will also have to focus on figuring this deficit out: how this deformation is absorbed; or is this due to other unmapped active faults?

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