

## Análisis paleosismológico y neotectónico de la Falla Porotoyacu, Zona Subandina del Ecuador

*Paleoseismological and neotectonic analysis of the Porotoyacu Fault, Sub-Andean Zone of Ecuador*

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### Resumen

El conocimiento de la actividad neotectónica es esencial para evaluar el riesgo sísmico, salvaguardar la infraestructura y garantizar un uso sostenible del suelo. Sin embargo, la Zona Subandina del Ecuador sigue siendo insuficientemente estudiada, en particular la Falla Porotoyacu, que se extiende 19 km a lo largo de Tena y Archidona, en la provincia de Napo. Con una orientación SSO-NE, su actividad sísmica solo ha sido parcialmente estimada a partir del análisis de una sola trinchera, por lo que su comportamiento tectónico aún se comprende de manera limitada. Este estudio tiene como objetivo determinar la paleosismicidad y la actividad tectónica reciente mediante métodos morfotectónicos, morfológicos y paleosismológicos, combinando imágenes satelitales con observaciones de campo en un afloramiento de origen antrópico. La evidencia incluye rupturas, desplazamientos verticales y seismitas, como diques que interrumpen los horizontes del suelo, confirmando actividad cuaternaria. Se identificaron tres eventos sísmicos con magnitudes superiores a Mw 6.1. La deformación superficial y la presencia de seismitas en las unidades superiores del afloramiento indican que la Falla Porotoyacu ha experimentado una reactivación tectónica reciente, lo que resalta su potencial peligro sísmico.

Palabras clave: Diques; Afloramiento; Falla Porotoyacu; Paleosismología; Deformación superficial.

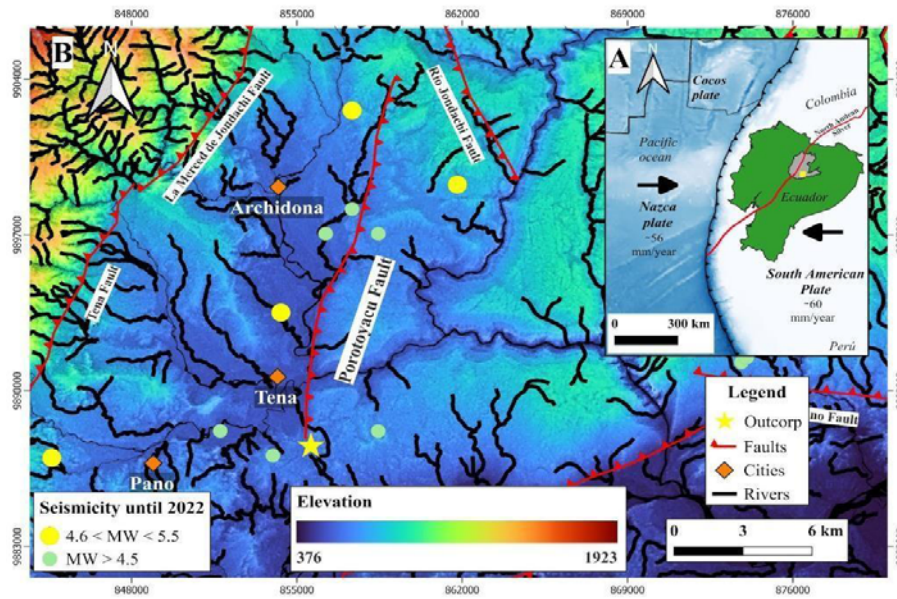
## Abstract

Knowledge of neo-tectonic activity is essential for assessing seismic risk, safeguarding infrastructure, and ensuring sustainable land use. However, the Sub-Andean Zone of Ecuador remains insufficiently studied, particularly the Porotoyacu Fault, which extends 19 km across Tena and Archidona in Napo Province. With a SSW-NE orientation, its seismic activity has only been partially estimated from a single trench analysis, leaving its tectonic behavior poorly understood. This study aims to determine paleo-seismicity and recent tectonic activity using morphotectonic, morphological, and paleoseismological methods, combining satellite imagery with field observations from an anthropogenic outcrop. Evidence includes ruptures, vertical displacements, and seismites such as dykes that disrupt soil layers, confirming Quaternary activity. Three seismic events with magnitudes above Mw 6.1 were identified. Surface deformation and seismites in the upper outcrop units indicate that the Porotoyacu Fault has experienced recent tectonic reactivation, highlighting its potential seismic hazard.

Keywords: Dykes; Outcrop; Porotoyacu Fault; Paleoseismology; Superficial deformation.

## Introduction

The Cutucú-Napo System is shaped by compressive-transgressive deformations and composed of high angle reverse faults with N-S and NNE-NNW orientations (Baby et al., 1999; Pratt et al., 2002; Baby et al., 2004). Although seismicity in the Sub-Andean Zone is generally of low magnitude, several atypical strong earthquakes have been reported. For instance, two significant events occurred on March 5, 1987, with magnitudes of 6.1 and 6.8 (Hall, 2011). Other major earthquakes, such as the 1995 Macas event (Mw 7.0) and the 1987 Baeza event (Mw 7.1), have also been linked to this fault system (Legrand et al., 2005; Font et al., 2013). Consequently, the region is characterized by slightly to moderate seismicity (Beauval et al., 2018; Tamay et al., 2021). Within this system lies the Porotoyacu Fault, near which 24 seismic events of Mw 2.5–6.3 have been recorded since 1927. At least eight events are associated with this fault, including a Mw 4.54 earthquake on December 28, 2021, near Archidona (IGEPN, 2024).



**Figure 1:** Ubication of the study area: A) Regional location of the study area: In the Ecuadorian territory base map from ESRI. The black line in the limit represents the contact and direction of movement of the Nazca and South American plates. The presence of the North-Andean Silver is a red line that divides the two blocks of Ecuador. The yellow square limits the study area. B) Ubication of the Porotoyacu Fault and study area in Napo (DEM-Geoportal): The numerous red lines represent geologic faults that cross the country. The yellow star represents the outcrop where the paleoseismological study is performed. The big red line in the center represents the Porotoyacu Fault with its kinematics of Project SARA (Costa et al., 2020), and the red rectangles represent the cities. The yellow and green circles are seismic events close to the Porotoyacu Fault. The map contains the topographic base, instrumental earthquakes as points until 2024, rivers, and the population centers of Tena and Archidona.

The Porotoyacu fault, with reverse transcurrent kinematics and an SSW-NE orientation, crosses Tena and Archidona in the province of Napo. Although classified as Quaternary and with an approximate length of 19 km (Conteron et al., 2024), its last activity, dated at 1.8 Ma, is based on satellite interpretation rather than field data, leaving its exact trace, recent seismicity, and the magnitudes of events (Costa et al., 2020). To clarify its recent tectonic behavior, morphotectonic, morphological, and paleoseismological analyses were carried out. This study focuses on the southern section, 0.43 km from the trace proposed by the SARA project, where a paleoseismological site was analyzed in an anthropogenic outcrop at coordinates  $1^{\circ}57.91''\text{S}$ ,  $77^{\circ}48'19.89''\text{W}$ . The outcrop, oriented SW-NE perpendicular to the fault, shows deformation characteristics suitable for paleoseismological analysis, providing information on recent seismic activity.

The research work aims to evaluate the Porotoyacu Fault as an active seismogenic source in a section located South of the fault's trace, applying morphotectonic, morphological, and paleoseismological analysis in an outcrop to contribute information about seismic hazard.

## **Methodology**

The methodology for this study was applied to an anthropogenic outcrop located in Tena, south of the Porotoyacu Fault trace. The study area was selected based on criteria such as the presence of morphotectonic indicators, outcrops exhibiting deformation structures caused by liquefaction/fluidization, and ruptures in strata. Additionally, its proximity to the fault trace was a determining factor. The regional characteristics as indicators were identified from the analysis of satellite images and subsequent field verification.

The morphological analysis of the study area followed the methodology of Baize et al. (2015), Jomard et al. (2021). A Digital Elevation Model (DEM) from the Alaska Satellite Facility (<https://search.asf.alaska.edu/>) was used to extract relief information, and QGIS tools helped identify subtle topographic features, allowing the discrimination of morphotectonic structures. This analysis aims to understand the relationship between landscape evolution and tectonic processes. Detailed topographic profiles were generated to quantify tectonic uplift and locate geological faults. Field verification was conducted to validate morphotectonic indicators, recording the location of each zone along with measurements of height, length, and distance, and documenting observations with photographs. Finally, all morphometric information was mapped using the processed DEM in a Geographic Information System (GIS), providing a comprehensive representation of the area's tectonic and morphological features.

The paleoseismological analysis was conducted on a 20 m long and 6.5 m high rocky outcrop that displayed clear deformation features, including stratigraphic displacement and seismites within an anthropogenic section. A 1m×1m grid was applied across the outcrop to document each stratigraphic unit, which was described according to textural and colorimetric characteristics (using the Munsell Rock Color Chart) as well as geometric properties such as inclination, height, and thickness. These observations were digitally represented, enabling the identification of major ruptures used to estimate the number and magnitude of seismic events. Furthermore, deformation structures were documented and classified following Rodríguez-Pascua et al. (2000) and Montenat et al. (2007).

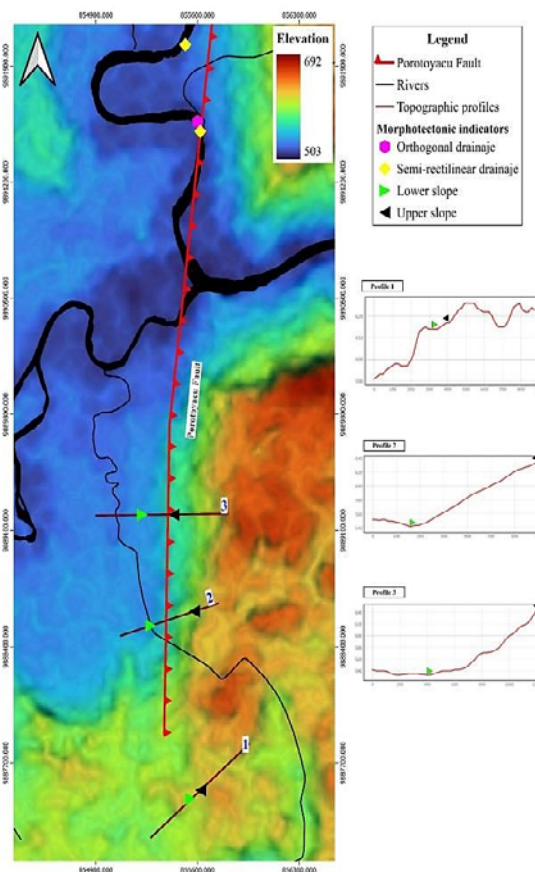
## **Results and Discussion**

In the southern sector of the Porotoyacu Fault, morphotectonic and paleoseismological

analyses were conducted. The results are summarized below:

### Morphotectonic in the south of the Porotoyacu Fault

By observing satellite images, we identified 3 main morphotectonic indicators. The first indicator is the relief difference; the other indicators are orthogonal and semi-rectilinear drainages. The morphotectonic analysis of the southern Porotoyacu Fault identified relief forms and indicators such as scarps, abrupt slope changes, and drainage anomalies.



**Figure 2.** Morphotectonic Indicators: The map base was obtained from Alaska Satellite Facility. The trace of the Porotoyacu fault proposed by Costa et al., (2020) is shown. In red color through the Tena and Archidona cities. Also, along with three types of morphotectonic indicators: orthogonal drainage (pink square), semi-rectilinear drainage (yellow diamond), and scarps (green and black triangles) to identify the slope and base used to detail the course of the Porotoyacu Fault. The profiles of scarps are indicated by green and red triangles, indicating the superior and inferior parts of the scarps. Close to the green square at the South indicates the outcrop

Topographic profiles (1, 2, 3) reveal scarps with a SW-NE orientation between 540 and 640 m in elevation, with slopes of  $3^{\circ}$ – $9.42^{\circ}$  and irregular to uniform morphologies reflecting local

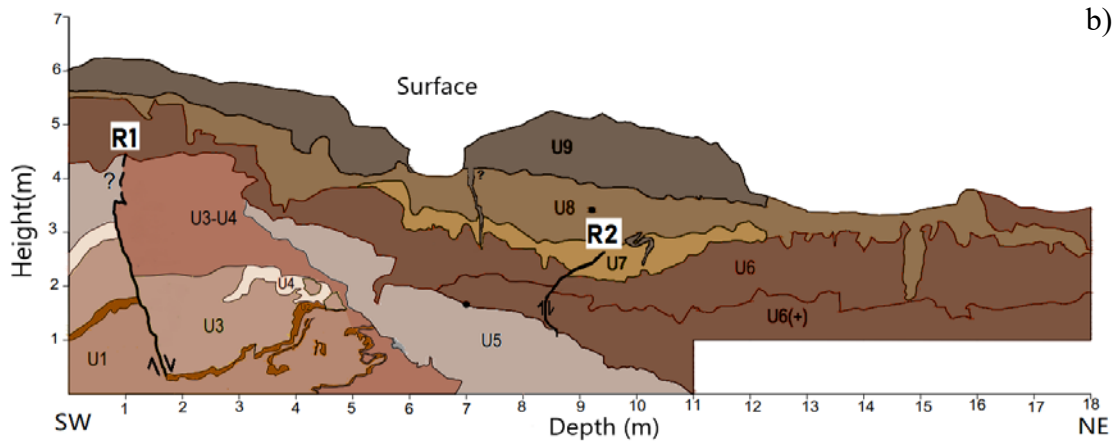
deformation. Orthogonal drainages, caused by abrupt river course changes due to tectonic activity, include a segment shifting from W-E to N-S, aligned with the relief. In the southern zone, semi-rectilinear drainages of 300 m and 330 m alternate between meandering and rectilinear patterns.

This work studied morphotectonic elements in the southern segment through photo interpretation and field verification to determine the extension of the fault. These analyses, based on geomorphic indicators, are classified into planar and linear features, including terraces, scarps, semi-rectilinear drainages, and orthogonal drainages (Audemard, 1999; Perucca et al., 2015; Onorato et al., 2020). In this research, we identified most indicators as scarps, orthogonal drainage, and semi-rectilinear drainage. These indicators provide preliminary evidence of the tectonic activity associated with the Porotoyacu Fault (Figure 2).

### **Stratigraphic and paleoseismic analysis**

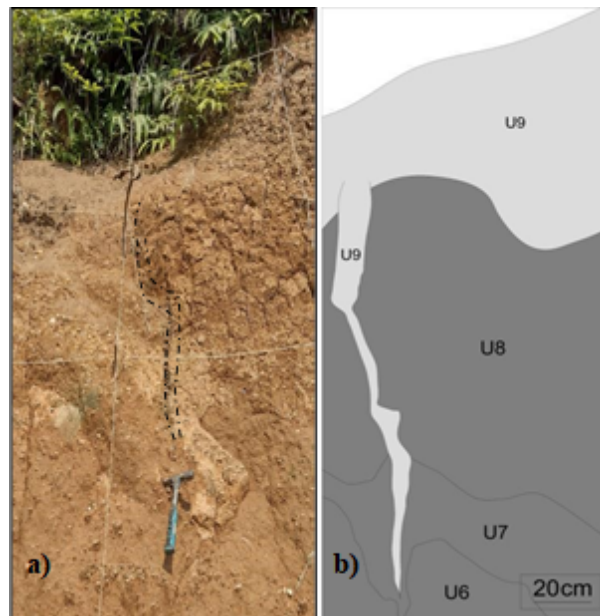
We constructed a stratigraphic profile of the outcrop, which is composed of siliciclastic Cretaceous rocks. This analysis revealed that the outcrop comprises nine units predominantly composed of claystone, siltstone, and Breccia. The basal units have been identified as Cretaceous and covered by Quaternary deposits that have undergone a pedogenesis process, which is deduced by their lithological properties and color.





**Figure 3.** The outcrop profile a) Photomosaic of outcrop with nine stratigraphic units identified, rupture planes, and deformation structures. The broken white line superficially defines the deformation of the outcrop. b) Digitating the outcrop with the nine stratigraphic units, paleo-ruptures denominated R1 and R2 with cinematics and seismites.

The overall structure of the outcrop was documented using detailed millimetric-scale drawings (Figure 3a), which illustrate deformation and displacement among the stratigraphic units caused by seismic activity. The units, numbered U1 to U9, are offset by two principal rupture planes (R1 and R2), associated with three seismic events. Magnitude estimates indicate values of  $M_w > 6.1$  (Figure 3b)



**Figure 4.** Dykes observed at the top of the outcrop: a) The dyke is in the central part of the outcrop, originating from U9 and extending to U6.

## Superficial deformation of the outcrop-Pedogenesis process

Pedogenesis is the process by which soils form and evolve from parent material under climatic and vegetative influences (Duchaufour, 1982). It begins with a thin surface layer that thickens over time, while horizons differentiate in texture, structure, and color. Soil color is a key indicator of pedogenesis, particularly in subtropical and tropical regions such as the Ecuadorian Amazon, where yellowish-brown and dark-brown tones result from iron oxide deposition (Torrent et al., 1983; Schwertmann & Taylor, 1989). These colorimetric properties indicate the degree of weathering and pedogenic development (González et al., 2008). In the 13 de Abril outcrop, superficial deformation reflects tectonic activity linked to the Porotoyacu Fault. Two main flexures were documented: the first, in the central sector at 11–12 m, measures 4–5 m in height with a 1 m slope; the second, at 16 m to the northeast, is 3.5 m high with a 0.5 m slope. Similar flexures in unconsolidated sediments (Sagripanti & Villalba, 2009; Tejada et al., 2021) indicate recent tectonic activity. Soft sediment deformation (SSDS) in the outcrop

The outcrop presents several types of seismites; however, this study focused on characterizing the current activity of the Porotoyacu Fault. We will only discuss the description of the dyke identified on the Quaternary deposits of the outcrop. Most of the seismites observed are appropriately described in Lluno et al., (2024).

The first dyke is situated in the southwest and central part, 7 m long and 3-4 in high of the outcrop, this deformation structure exhibits a morphology of columns measuring a 1m in length and 6 cm in diameter. This dyke is composed of material from U9, which is liquefied breccia that intruded the U8, U7, and U6 (Figure 4a, 4b).

Now, it is crucial to highlight the process involved in the formation of dykes. Usually, the size of dykes varies from 30 cm to 1 m (Topal & Özkul, 2014). The formation mechanism is related to the process of gravitational collapse (Lowe.,1975; Rodríguez-Pascua, 2005; Moretti & Sabato, 2007), which follows liquefaction fluidization processes induced by seismic shocks.

## Conclusions

The analysis of morphotectonics, morphological, and paleo- paleoseismological of 13 de Abril demonstrated a quaternary activity of the Porotoyacu Fault. It is supported by 1-The morphotectonic indicators that served as evidence of recent tectonics and indicated an extension to the Fault of 1.67 km (Figure 1). 2- The superficial morphology of the study area with abrupt changes of slope is considered a scarp (Figure 2). The outcrop analyzed content 3 three paleo seismic events in their stratigraphy, whose magnitude  $M_w > 6.1$ . 3-The

pedogenesis process in superficial units such as U9 is based on colorimetric and thickness characteristics. 4-The surface, instead of being lateral continuous, is deformed with soft flexures (Figure 3a, 3b). 5-The presence of Dykes in the superficial units close to deformation zones in the outcrop (Figure 4a, 4b). All the evidence mentioned is more concrete than active tectonics in this section of the Porotoyacu Fault.

These findings confirm the Porotoyacu Fault as a potential seismogenic source, emphasizing a key recommendation: the need for further paleoseismological studies along other sections, particularly northwards, to better assess its seismic hazard.

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