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RESEARCH ARTICLE

10.1029/2026TC009634

Key Points:

- New mapping extends the active Cordillera Blanca Fault Zone ~90 km northward to Huamachuco, defining a ~300-km continuous trace
- Slip rates vary over an order of magnitude among segments, suggesting inherited structural control
- The fault can sustain Mw 6.5–7.0 ruptures and Mw 7.1–7.2 multi-segment cascades

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Benavente, C., Rosell, L., Palomino, A., Wimpenny, S., Rosell, J., & García, B. (2026). Active extension above the Peruvian flat slab: Segmentation, slip-rate variability, and paleoseismicity of the ~300-km-long Cordillera Blanca fault zone. *Tectonics*, 45, e2026TC009634. <https://doi.org/10.1029/2026TC009634>

Received 1 JUL 2026

Accepted 27 SEP 2026

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Active Extension Above the Peruvian Flat Slab: Segmentation, Slip-Rate Variability, and Paleoseismicity of the ~300-km-Long Cordillera Blanca Fault Zone

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Abstract The ~300-km-long Cordillera Blanca Fault Zone (CBFZ) is the longest and fastest-slipping active normal fault system in the central Andes, yet its paleoseismic record has remained constrained to a few sites since Schwartz (1988, <https://doi.org/10.1029/jb093ib05p04712>). We combine geomorphic mapping, 101 fault-scarp profiles, and six paleoseismic trenches spanning ~230 km across four structural segments. Our mapping extends the active fault trace ~90 km northward to Huamachuco, expanding the documented domain of upper-plate extension within the Peruvian flat-slab region. The 17 surface-rupturing earthquakes identified since ~12.6 ka produced per-event vertical displacements of 0.5–2.3 m, consistent with Mw 6.5–7.0 events. Bayesian modeling reveals tentative evidence for a temporal cluster at ~3.5–3.1 ka across sites spanning ~220 km, although adjacent trenches indicate the paleoseismic record is incomplete. Throw rates vary by more than an order of magnitude among segments—from 0.1–0.3 mm/yr at the northern tip to 1.9–3.7 mm/yr in the center—and co-vary with footwall relief and the geometry and thickness of the inherited mylonitic shear zone of the Cordillera Blanca Batholith, suggesting that inherited crustal structure may modulate fault kinematics. Low slip rates and immature scarp morphology in the northernmost ~90 km may reflect northward propagation of the fault tip into the flat-slab domain. The CBFZ can sustain single-segment ruptures of Mw 6.5–7.0 and multi-segment cascades of Mw 7.1–7.2 based on our preferred scaling relation (up to ~Mw 7.9 across alternative scaling relations), providing critical source parameters for seismic hazard assessment of ~500,000 people living within 20 km of the fault.

Plain Language Summary The Cordillera Blanca Fault Zone is a major active fault along the western side of the Cordillera Blanca in northern Peru. Movement on this fault can drop one side of the ground relative to the other and generate earthquakes that rupture the surface. About 500,000 people live within 20 km of the fault, but its earthquake history has remained poorly understood for nearly four decades. We mapped the fault using satellite images, drone-based topography, and field observations, and found that the active trace extends 90 km farther north than previously recognized, reaching a total length of ~300 km. We also excavated six trenches across the fault and identified 17 prehistoric surface-rupturing earthquakes during the past ~12,000 years. Individual events produced vertical ground offsets of 0.5–2.3 m, consistent with earthquakes of about Mw 6.5–7.0. Several events may have occurred within the same few-hundred-year interval across ~220 km of the fault, suggesting that larger cascading ruptures are possible. Slip rates vary strongly along the fault, apparently controlled by ancient rock structures formed millions of years ago during the construction of the Andes. These results provide new information for assessing earthquake hazard in northern Peru.

1. Introduction

The Cordillera Blanca Fault Zone (CBFZ) in the central Peruvian Andes is one of the longest continental and most prominent normal faults on Earth (Dalmayrac & Molnar, 1981). The CBFZ sits at the northernmost edge of a 1,500-km-long domain of Andean extensional deformation that extends into southern Peru, Bolivia and northern Argentina (Figure 1a). The distribution and rates of extension in the Andes are spatially heterogeneous and correlate broadly with along-strike variations in elevation, supporting the view that they are influenced by gravitational potential energy contrasts between the mountain belt and the forelands (Dalmayrac & Molnar, 1981; Lamb, 2000; Wimpenny et al., 2018).

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Despite having similar dynamical origins, the CBFZ is in many ways different to the normal faulting seen elsewhere in the Andes. Its first unique feature is its length. Schwartz (1988) conducted a pioneering, and until this study the only, systematic paleoseismic investigation of the CBFZ, documenting ~210 km of continuous fault trace between Chiquián and Corongo defined by late Quaternary scarps and triangular facets. Normal faults elsewhere within the Andes rarely exceed ~15 km in length (e.g., Benavente et al., 2013; Wimpenny et al., 2020).

Second, the CBFZ bounds the western flank of the Cordillera Blanca in north-central Peru (~7.5–10.5°S; Figure 1b), separating crystalline footwall rocks of the Cordillera Blanca batholith from Mesozoic sedimentary sequences and the Callejón de Huaylas intermontane basin in the hanging wall that require kilometers of accumulated fault throw. Normal faults in the south Peruvian Andes and northern Argentina are typically associated with small (<200 m) footwall relief, suggesting they have accumulated far less throw than the CBFZ since extension began ~5 Ma (Giovanni et al., 2010).

The CBFZ's unique length and throw both indicate that it poses a different seismic hazard to the other style of normal faulting within the central Andes and should be considered as a distinct source of earthquakes in fault-based probabilistic seismic hazard analyses. The only previous systematic paleoseismic investigation of the CBFZ was conducted by Schwartz (1988), who trenched two sites and established late Quaternary throw rates of 0.9–1.3 mm/yr and displacement-per-event values of 2–3 m. At Quebrada Querococha, stratigraphic and geochronologic evidence indicated 5–7 surface-faulting earthquakes during the past 11–14 ka. At Pachma Bajo, similar displacement-per-event values and a Most Recent Event (MRE) at ~1.5–2 ka were inferred. Schwartz (1988) also proposed a segmentation model for the CBFZ comprising four to five structural segments, each 35–70 km long, based primarily on range-front geometry and along-strike variations in fault scarp morphology. The displacement-per-event and segment lengths indicate capacity for Mw 7.0–7.5 earthquakes assuming they nucleate at 10–15 km depth. However, some key uncertainties remain about the fault's slip behavior needed to calibrate seismic hazard analyses, including whether the slip rate is spatially variable, the CBFZ's total length, and whether the fault ruptures in smaller but more frequent segmented earthquakes or larger but more infrequent multi-segment earthquakes (e.g., Valentini et al., 2019).

In this study, we re-evaluate the late Quaternary slip rate, total active fault length, late Quaternary to Holocene surface-rupture history, and rupture segmentation of the CBFZ using new paleoseismic trenches, accelerator mass spectrometry (AMS) radiocarbon dating, high-resolution satellite imagery, and UAV-derived digital elevation models (DEMs). In Section 2, we describe the methods used to map fault scarps, measure vertical throw and equivalent net dip-slip displacement, and reconstruct paleoseismic event histories from trench exposures. In Section 3, we present the results of our geomorphic and paleoseismic analyses, including the 90 km northward extension of the active fault trace and six new paleoseismic trenches containing 17 inferred surface-rupturing earthquakes. In Section 4, we discuss the implications of these results for earthquake clustering, rupture segmentation, and seismic hazard in the high Andes of central Peru.

2. Methods

2.1. Geomorphic Mapping, Fault Scarp Throw, and Age Constraints

We mapped the fault trace and measured cumulative throw using WorldView-2 panchromatic imagery (0.46 m/pixel), SPOT-5 imagery (5 m/pixel; used for throw quantification at Quebrada Cojup where sub-metric coverage was unavailable), and UAV-based structure-from-motion (SfM) photogrammetry (0.03–0.12 m/pixel) processed in Agisoft Metashape. All data sets were co-registered using GPS-surveyed ground control points. Fault traces were mapped at 1:5,000–1:10,000 scale based on rectilinear breaks in slope, deflected drainage networks, sag ponds, and linear range-front geometry, and were validated through field reconnaissance.

The Cordillera Blanca has undergone repeated Quaternary glaciations that has produced well-preserved geomorphic markers used here as displacement datums. Three moraine generations have previously been distinguished: Last Glacial Maximum (LGM; ~20–25 ka; Farber et al., 2005; Shakun et al., 2015), late-glacial (~12–15 ka; Clapperton, 1983; Wright, 1984), and Little Ice Age (LIA; ~1350–1850 CE; Solomina et al., 2007). The semiarid climate of the western Cordillera Blanca favors exceptional preservation of both fault scarps and these glacial landforms.

To determine the amplitude of surface offset and estimate equivalent net dip-slip displacement, we measured cumulative throw from 101 topographic profiles extracted perpendicular to local fault strike at 0.2–1 km spacing.

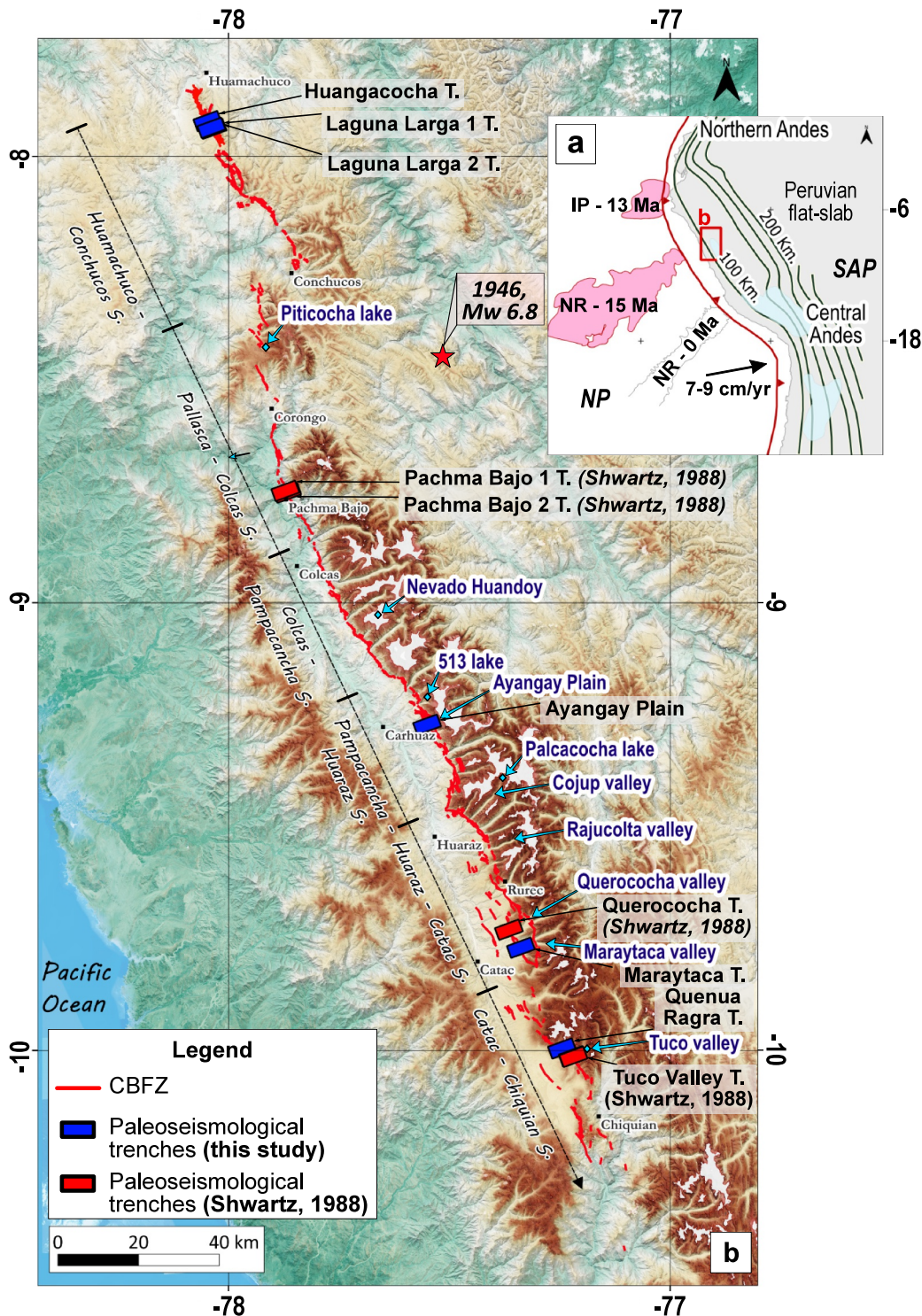


Figure 1. Regional tectonic setting and map of the Cordillera Blanca Fault Zone (CBFZ). (a) Location of the study area within the Pacific margin of South America and the Peruvian flat-slab subduction segment, modified from Ramos and Folguera (2009). Reconstructed positions of the Nazca Ridge at ca. 15 Ma and 0 Ma, and the Inca Plateau at ca. 13 Ma, are shown following Rosenbaum et al. (2005). Light blue polygons denote the Andean extensional deformation domain extending into southern Peru, Bolivia, and northern Argentina (Wimpenny et al., 2018). Plate convergence velocities are shown relative to stable South America, after DeMets et al. (2010). (b) Map of the active CBFZ trace between Huamachuco and Chiquián, with a total documented length of ~300 km. Schwartz (1988) originally mapped the active fault from Corongo to Chiquián (~210 km); our mapping extends the trace ~90 km northward to Huamachuco. The fault is subdivided into six structural segments: Huamachuco–Conchucos, Pallasca–Colcas, Colcas–Pampacancha, Pampacancha–Huaraz, Huaraz–Catac, and Catac–Chiquián. Blue rectangles indicate paleoseismic trench sites from this study; red rectangles indicate sites from Schwartz (1988). The red star marks the location of the 1946 crustal earthquake associated with surface rupture, reported by Doser (1987).

Surface correlatability across the fault was verified prior to displacement measurement using three criteria applied to every profile: (a) morphological continuity, where hanging-wall and footwall remnants share comparable down-slope gradients and surface textures in hillshade and slope-angle maps derived from UAV DEMs; (b) consistent glacial or fluvio-glacial depositional facies on both sides of the fault, identified from field mapping and orthophoto interpretation; and (c) where available, agreement between cosmogenic or radiocarbon ages from both sides within analytical uncertainty. Profiles where one or more criteria were not met were excluded from the displacement data set (17 of 118 initial profiles rejected).

We measured the vertical separation between correlated hangingwall and footwall surfaces by projecting regressed linear trends fitted to the preserved surfaces onto the fault zone, or by direct measurement of offset geomorphic markers, including moraine crests, fluvio-glacial terrace risers, and alluvial fan surfaces. Throw was converted to equivalent net dip-slip displacement following the kinematic decomposition approach of Mackenzie and Elliott (2017), accounting for fault strike, dip, rake where available, and reference-surface geometry. Fault dip was constrained from trench measurements and field observations, yielding a representative mean of $62^{\circ} \pm 8^{\circ}$ for the main normal-fault strands. This value was used as the reference dip for throw-to-net-slip conversions, and the uncertainty range was propagated through Monte Carlo simulations. Measurement uncertainties were propagated using 10,000 Monte Carlo realizations, sampling from Gaussian distributions in throw uncertainty ($\pm 5\%$ – 20%), dip ($\pm 8^{\circ}$), and surface-slope geometry ($\pm 2^{\circ}$). Where age control on offset markers was available, geomorphic slip rates were calculated as net dip-slip displacement divided by surface age.

Age control was drawn from: (a) in situ cosmogenic ^{10}Be exposure ages on moraine boulders; (b) regional correlation with independently dated glacial sequences (Farber et al., 2005; Hall et al., 2009); and (c) radiocarbon-dated overlying deposits, used only as minimum-age constraints on the displaced geomorphic marker. Our approach to estimating fault slip rate is methodologically comparable to that of Schwartz (1988) but improves on the original analysis through sub-metric UAV-derived DEMs, broader availability of moraine age constraints, and explicit Monte Carlo uncertainty propagation.

2.2. Paleoseismic Trenching and Stratigraphic Logging

Trench sites were selected based on three criteria: (a) the presence of well-preserved late Quaternary fault scarps with minimal anthropogenic or natural erosional modification; (b) stratigraphic settings conducive to preservation of diagnostic paleoseismic features, including colluvial wedges, fissure fills, and faulted deposits, with availability of datable organic material for radiocarbon dating; and (c) sufficient along-strike distribution to assess potential temporal correlations among rupture histories on different structural segments. Application of these criteria yielded six sites spanning ~ 230 km, from Huangacocha ($7^{\circ}56'S$) to Quenua Ragra ($10^{\circ}00'S$; Figure 2).

Excavation methods varied by site. Huangacocha, Laguna Larga 1, and Laguna Larga 2 were excavated using a tracked mechanical backhoe to depths of 2.5–3.5 m, approximately perpendicular to fault strike. Maraytaca and Quenua Ragra were accessed through existing road cuts with manual cleaning, and Ayangay was a natural exposure enhanced by hand excavation. All trench walls were cleaned manually and documented through georeferenced photomosaics assembled at ~ 1 – 3 mm/pixel ground resolution. Stratigraphic logging followed the protocol of McCalpin (2009): units were described by color (Munsell), texture, structure, and organic content; all contacts, fault traces, and sample locations were digitized at 1:20 scale on the photomosaic base.

2.3. Radiocarbon Dating, Event Characterization, and Magnitude Estimation

AMS ^{14}C samples were collected preferentially from in situ charcoal, plant macrofossils, and peat. Bulk organic sediment was used only where preferred material was absent and was assigned lower chronological quality because it may incorporate reworked older carbon and younger humic contamination. Such ages were retained only where stratigraphically consistent and were incorporated into the OxCal models with inflated uncertainty. All samples were analyzed at Beta Analytic (Miami) and calibrated using OxCal v4.4.4 (Bronk Ramsey, 2009) with SHCal20 (Hogg et al., 2020); calibrated ages are reported at 2σ , or 95.4% confidence.

To propagate uncertainties in stratigraphic unit ages into event-time estimates, we used Bayesian modeling implemented in OxCal with Sequence–Boundary–Phase model structures. Inter-segment event correlation followed the multi-site approach of Benavente et al. (2022, 2025). For bulk-sediment samples retained in the OxCal models, we adopted a minimum 1σ uncertainty of ± 500 years, or the laboratory analytical uncertainty where this

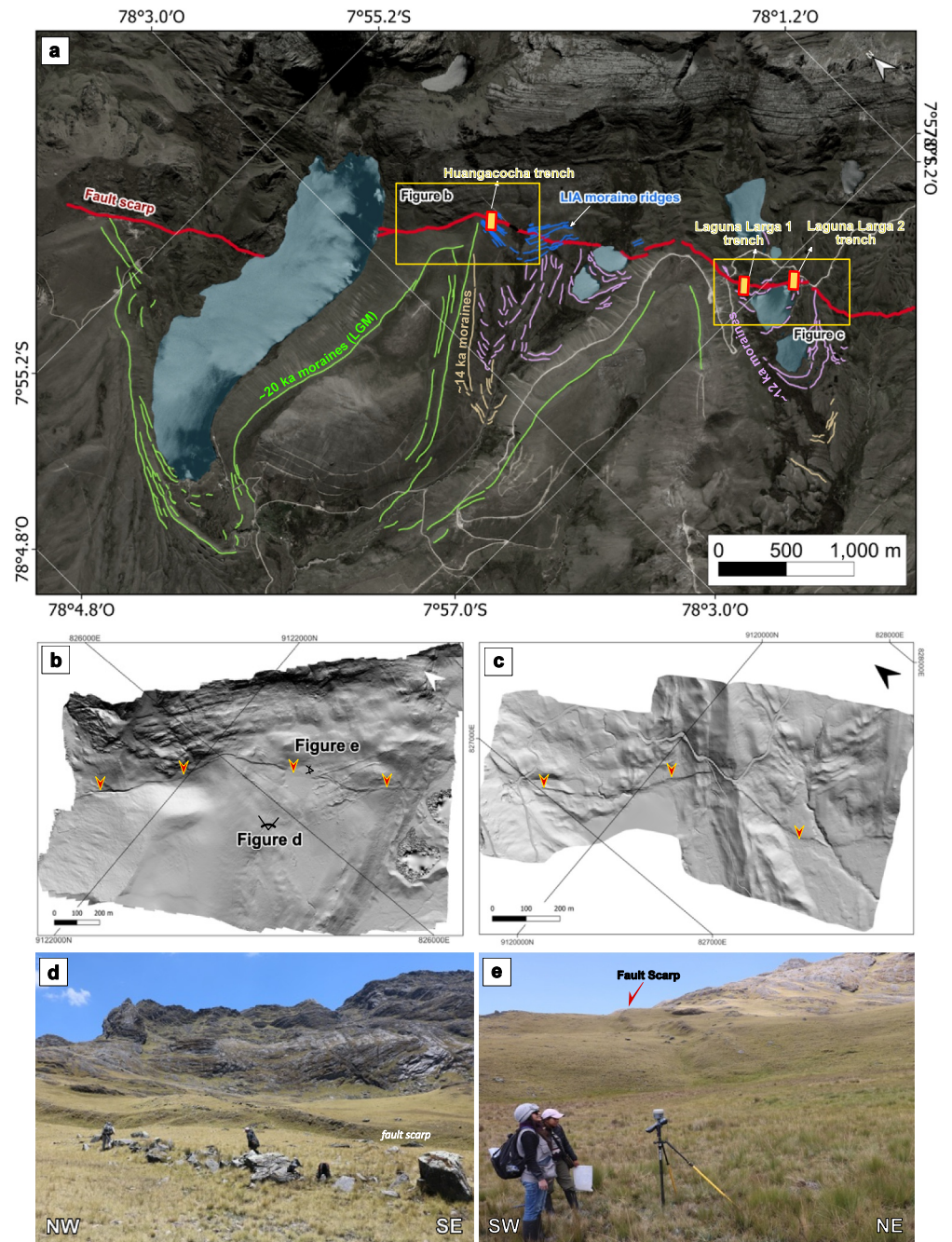


Figure 2. Geomorphic setting and paleoseismic trench locations in the Huamachuco–Conchucos segment, the northernmost segment of the Cordillera Blanca Fault Zone. (a) High-resolution satellite image of the Huangacocha–Laguna Larga area showing the active fault trace (red line) cutting glacial moraine complexes of different relative ages. Moraines assigned to ~20 ka and associated with the Last Glacial Maximum are shown in green; ~14 ka moraines in beige; ~12 ka moraines in purple; and Little Ice Age moraine ridges in light blue. These ages are interpreted by geomorphic correlation with previously established glacial chronologies for the Cordillera Blanca and central Andes (e.g., Farber et al., 2005). Red rectangles indicate the locations of the three paleoseismic trenches: Huangacocha, Laguna Larga 1, and Laguna Larga 2, distributed along ~4 km of the fault trace. Yellow boxes indicate the extents of panels (b) and (c). (b) UAV-derived hillshade digital elevation model (DEM) generated from structure-from-motion photogrammetry for the Huangacocha trench area. Yellow arrows indicate fault-scarp measurement points; locations of the field photographs in panels (d) and (e) are also shown. (c) UAV-derived hillshade DEM of the Laguna Larga 1 and Laguna Larga 2 trench area, where the fault scarp displaces late Pleistocene lateral moraines. (d) Field photograph looking NW–SE of the fault scarp at Huangacocha. (e) Field photograph looking SW–NE of the fault scarp near the Huangacocha trench; people and survey equipment provide scale.

was larger. Our lower bound captures systematic age dispersion not reflected in analytical precision, arising from the integration of organic matter of mixed ages within a single sediment horizon, including reworked older carbon and post-depositional infiltration of younger humic acids (Pessenda et al., 2001; Wang et al., 1996). In practice, this rule leaves AMS dates on macrofossils with their original analytical uncertainties and inflates only bulk-sediment dates whose reported precision is narrower than ± 500 years. The adjustment broadens the posterior distributions for events constrained by bulk dates at Huangacocha and Maraytaca but does not significantly change event-time medians.

Paleoseismic events were identified using diagnostic criteria from McCalpin (2009), including faulted stratigraphic units, upward fault terminations, colluvial wedges, fissure fills, growth strata, and event horizons. Where direct offset measurements were unavailable, displacement per event was estimated from colluvial-wedge thickness using the empirical assumption that wedge thickness represents $\sim 30\%$ – 70% of coseismic scarp height, with 50% used as the preferred value. Estimated vertical displacement was converted to net dip-slip displacement using $D = T/\sin(\theta)$, with $\theta = 62^\circ \pm 8^\circ$. Moment magnitudes were estimated from net displacement per event using the empirical displacement–magnitude relations of Wells and Coppersmith (1994). These estimates should be regarded as approximate because trench exposures sample local displacement, which may differ from mean or maximum displacement along the full rupture. A unified Quality Rank A–D scheme characterizes confidence in event identification and temporal constraint. Full methodological details, including radiocarbon procedures, OxCal model code, displacement and magnitude calculations, uncertainty propagation, and Quality Rank criteria, are provided in Methods S1–S3 in Supporting Information S1.

3. Results

In this section, we first describe the distribution of fault scarps along the CBFZ and break the fault up into segments based on changes in its geometry along-strike. We then consider variations in the time-average slip rate determined from offset landforms between each segment. Finally, we infer the history of surface-rupturing earthquakes on each segment based on reconstructions and dating of stratigraphy in paleoseismic trenches.

3.1. Distribution of Fault Scarps and Along-Strike Segmentation

Our morphostructural mapping reveals a ~ 300 -km-long active fault system extending from Huamachuco in the north to Chiquián in the south ($\sim 10^\circ$ S; Figure 1b). The new mapping adds a further ~ 90 km to the fault extent documented by Schwartz (1988), whose original fault map established a 210 km-long continuous trace between Corongo and Chiquián.

The newly documented fault scarps north of Corongo comprise two structurally-defined segments (Figure 1). The first extends ~ 40 km northward from Corongo to Conchucos, has a consistent strike of $N150$ – 160° and dips of 48 – 65° SW; scarps are morphologically continuous and offset late Quaternary moraines and fluvio-glacial deposits. A second segment begins ~ 3 km northeast of Conchucos and extends a further ~ 50 km to Huamachuco (Figure 1); here scarps reach up to ~ 5 m in height offsetting moraines and locally exhibit antithetic structures subparallel to the principal fault trace and field kinematic indicators compatible with a minor dextral component.

As previously identified by Schwartz (1988), the CBFZ south of Corongo also displays along-strike variation in the trend and distribution of fault scarps that can be split into structurally-defined fault segments (see, e.g., DuRoss et al., 2016). We define segments using three criteria: (a) no en-echelon step-over or along-strike gap exceeds ~ 3 km within a segment; (b) mapped scarps within a sector show consistent geomorphic expression and offset comparable late Quaternary marker classes where age control is available; and (c) cumulative throw varies continuously along strike, without abrupt drops to zero that would indicate structural independence. Segment boundaries were assigned where at least two independent criteria coincide within ~ 5 km along strike, including a change in fault strike of $\geq 15^\circ$, a structural complexity zone wider than ~ 2 km perpendicular to the fault, or a discontinuity in cumulative throw of > 30 m.

Applying these geometric and kinematic criteria, the fault trace is subdivided into six segments with lengths of 45–70 km: Huamachuco–Conchucos, Pallasca–Colcas, Colcas–Pampacancha, Pampacancha–Huaraz, Huaraz–Catac, and Catac–Chiquián (Figure 1). Segment boundaries broadly correspond to those proposed originally by Schwartz (1988) in the southern sector but we extend and refine them using quantitative criteria

applied to the full fault length. Mean strike, dip, and number of mapped scarp profiles per segment are summarized in Table S9 in Supporting Information S1.

3.2. Along-Strike Cumulative Throw Distribution

To determine how the cumulative fault throw varies along the fault trace we measured throw from 101 topographic profiles across all six structural segments (Table S7 in Supporting Information S1). Representative examples of the topographic profiles and field relationships used to measure scarp throw are shown in Figure 3. The higher profile density in the Huamachuco–Conchucos segment (~46% of all profiles) reflects our focus on the previously unmapped northern extension of the fault zone (Figures 3a and 3b; Figure S2 in Supporting Information S1). Nevertheless, throw magnitudes vary substantially within segments and across geomorphic markers of different ages, ranging from sub-meter offsets on Holocene surfaces (Figures 3a and 3b) to >100 m on Late Pleistocene moraines (Figures 3c and 3d).

We find the smallest throw values near the fault's northern and southern edges and the largest roughly within the center, irrespective of scarp age (Table S7 in Supporting Information S1; Figure 4). The northern-most Huamachuco–Conchucos segment ($n = 46$) records the lowest throw values, ranging from 0.4 to 4.8 m near the northern structural terminus. Moving south along the fault, the Pallasca–Colcas segment ($n = 5$) yields intermediate values (3.8–14.6 m), the Colcas–Pampacancha segment ($n = 13$) records the highest cumulative throws up to 126 m at Huandoy and defines a pronounced maximum (Figure 3c). The Pampacancha–Huaraz segment ($n = 12$) records 1.9–42.9 m, the Huaraz–Catac segment ($n = 19$) shows the widest scatter (1.8–59.2 m; Figure 3d), possibly reflecting distributed deformation across a ~12 km-wide graben system (Schwartz, 1988). The Catac–Chiquián segment at the southern end of the fault ($n = 6$) records throw values 5.0–17.1 m, consistent with previous estimates (Schwartz, 1988). Within this segment, the Maraytaca trench area exposes representative fault scarps with throws of 1.8–6.6 m on LGM and Holocene surfaces (Figures 3e and 3f), whereas the Quenua Ragra trench area to the south records the highest cumulative throws (12.7–17.1 m), where the fault offsets a sequence of LGM moraines and fluvio-glacial deposits (Figures 3g and 3h).

3.3. Slip Rate Measurements

We estimated net dip-slip rates by combining the net dip-slip displacements reported in Table S7 in Supporting Information S1 with surface-marker ages, using segment-specific glacial chronologies. For profiles with directly assigned cosmogenic ages ($n = 56$), we used published ^{10}Be exposure ages from Farber et al. (2005) for late-Pleistocene LGM moraines in the central Cordillera Blanca, and Glasser et al. (2009) for Younger Dryas (~12.4 ka) outer moraines and post-Younger Dryas (~10.7 ka) outwash terraces in the Tuco and Jeullesh valleys of the Catac–Chiquián segment. For 12 additional profiles in the Colcas–Pampacancha segment lacking direct cosmogenic ages, marker ages were assigned by geomorphic correlation with directly dated equivalents in adjacent valleys.

Slip-rate uncertainties combine measurement uncertainty in net dip-slip displacement (typically $\pm 5\%$ – 15% , propagated from throw and dip uncertainties as described in Methods S3 in Supporting Information S1) with surface-marker age uncertainty. Age uncertainties of ± 1.5 kyr for LGM moraines, ± 0.7 kyr for Younger Dryas moraines, and ± 0.5 kyr for post-Younger Dryas outwash terraces are taken from the published 1σ ranges of the ^{10}Be exposure ages of Farber et al. (2005) and Glasser et al. (2009) in the central Cordillera Blanca and Tuco–Jeullesh valleys, respectively. Both displacement and age uncertainties are propagated as independent 1σ Gaussian terms assuming uncorrelated sources, an approximation appropriate given that the dominant analytical and production-rate components of ^{10}Be ages, and the throw and dip measurement components of displacement, are themselves treated as Gaussian in the original sources.

The calculated net dip-slip rates across all 56 directly-dated profiles range from 0.05 ± 0.02 mm/yr to 6.3 ± 0.7 mm/yr, with substantial along-strike variation. Here we summarize the slip-rate measurements in Table 1, organized by structurally-defined segment and surface-marker age.

The maximum rate of 6.3 ± 0.7 mm/yr at Quebrada Huandoy (Colcas–Pampacancha segment) comes from a single LGM-age profile and is treated as a local maximum. Segment medians range from 0.05–0.07 mm/yr in the northernmost Huamachuco–Conchucos segment to ~2.0 mm/yr in the Pampacancha–Huaraz segment, with the largest values concentrated in the central part of the fault system. The Huaraz–Catac LGM range (0.41–3.0 mm/yr)

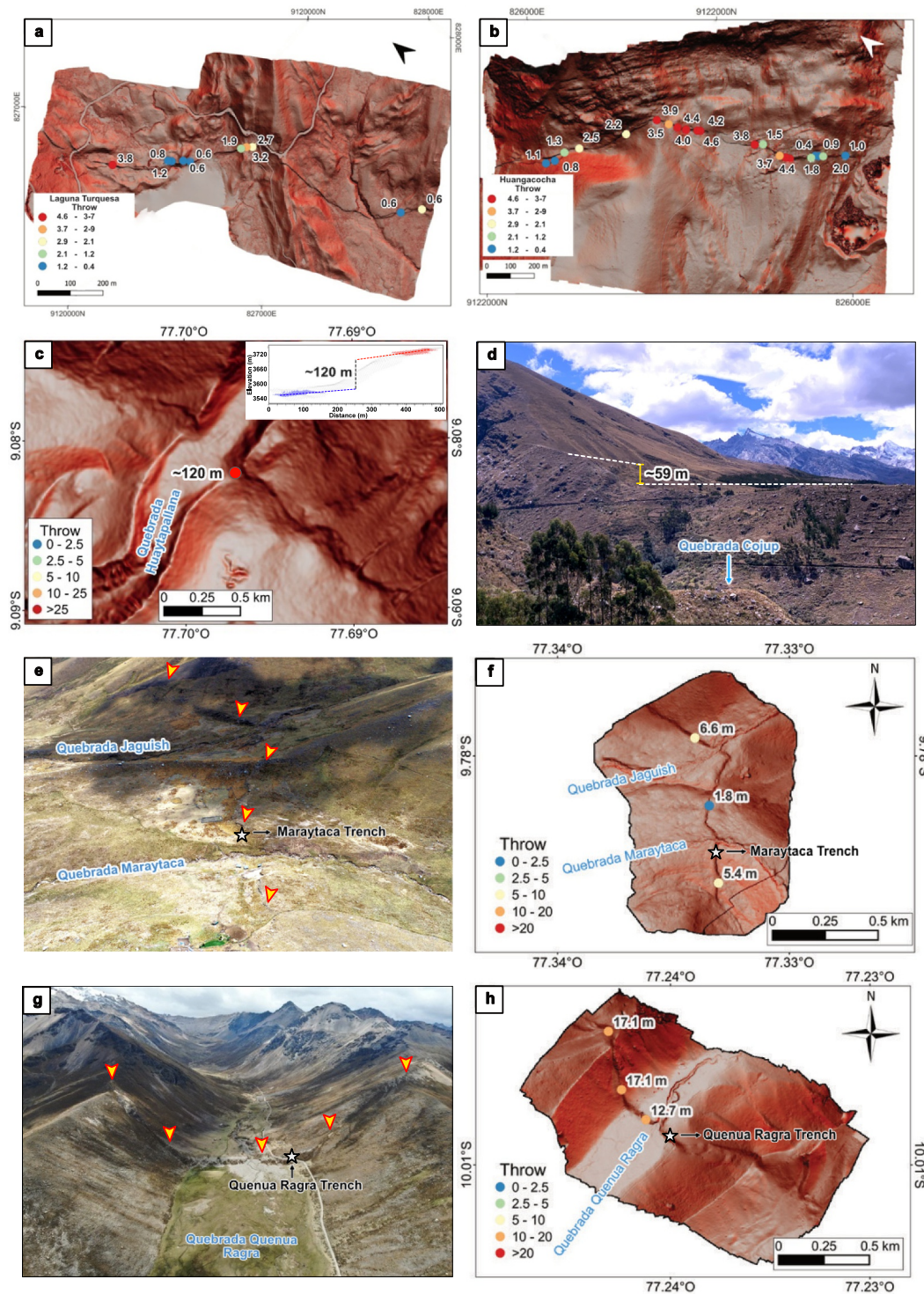


Figure 3.

yr) shows high within-segment variability that may reflect distributed deformation across the ~12-km-wide graben system reported by Schwartz (1988). Our YD and post-YD medians for the Catac–Chiquián segment (1.38 and 1.19 mm/yr respectively) are consistent with the 0.7–1.3 mm/yr reported by Schwartz (1988) for Quebrada Tuco within the same segment.

3.4. Paleoseismic Investigations

In this section, we present the interpretation of the paleoseismic trench exposures at six new sites along the CBFZ. Detailed trench logs are shown in Figures 5–10, whereas the corresponding high-resolution trench photomosaics are provided in Figure S1 in Supporting Information S1; complete stratigraphic descriptions are provided in Tables S1–S6 in Supporting Information S1. Table 2 summarizes site locations, structural settings, number of identified events, and temporal coverage.

All trenches expose Late Pleistocene to Holocene sequences overlying Jurassic basement or basal glacial diamict. The general stratigraphic framework in all trenches comprises: (a) basal units of glacial till or bedrock (unit U1 at most sites), representing the pre-faulting surface; (b) colluvial wedges derived from coseismic scarp collapse (units C1, C2, etc.); (c) fluvial, lacustrine, and paludal deposits accumulated during inter-seismic intervals; and (d) modern soil horizons capping the sequence. Colluvial wedges are distinguished by wedge-shaped geometry with maximum thickness adjacent to fault planes, chaotic internal fabric, clast imbrication parallel to fault dip, and abrupt contacts with underlying units. Lacustrine and paludal deposits are characterized by fine-grained matrix (silt to clay), elevated organic content, and evidence of low-energy aquatic deposition (lamination, gastropod shells, rooted horizons).

Radiocarbon ages within the trench sediments span 12.6 to 0.65 ka, with concentrations during early Holocene (12.6–10.0 ka), middle Holocene (6.0–4.0 ka), and late Holocene (3.7–0.6 ka) intervals. Material type exerts strong control on age reliability: charcoal and in situ peat yield the most robust constraints (Quality Rank A), whereas bulk sediment samples commonly yield ages older than depositional age (see Section 2.3), assigned Quality Ranks B–C.

We identified 8 instances of age inversions, all attributable to detrital carbon in bulk sediment samples; in these cases event sequence was established by stratigraphic superposition. Of the 17 documented surface-rupturing events within the trenches, two are Rank A (in situ peat), five Rank B (multiple coherent bulk-sediment ages or well-constrained stratigraphic bracketing), eight Rank C (single bulk-sediment age or broad constraints), and two Rank D (ambiguous relationships or unresolvable inversions). Complete 14C data (44 AMS dates) are provided in Table S8 in Supporting Information S1.

3.4.1. Huamachuco–Conchucos Segment

We opened three trenches along the Huamachuco–Conchucos segment (~50 km length) at Huangacocha (7°56′04″S, 78°02′34″W), Laguna Larga 1, and Laguna Larga 2 (both near 7°58′S, 78°01′W) distributed across ~15 km along strike (Figure 1b). These trenches contain evidence for seven surface-rupturing events spanning ~12.6 ka to ~1.4 ka.

Figure 3. Representative examples of cumulative fault-throw measurements along the Cordillera Blanca Fault Zone. UAV-derived digital elevation models (DEMs), oblique aerial photographs, and field photographs from six representative sites illustrate the range of throw values used to build the 101-profile data set summarized in Table S7 in Supporting Information S1 and Figure 4c. (a) UAV-derived DEM of the Laguna Turquesa area, Huamachuco–Conchucos segment, showing throw measurements on late Pleistocene moraines. (b) UAV-derived DEM of the Huangacocha area, Huamachuco–Conchucos segment, showing dense profile coverage across the northern extension of the fault. (c) Quebrada Huaytapallana, Colcas–Pampacancha segment, showing ~120 m of cumulative throw on an Last Glacial Maximum (LGM) moraine sequence; inset shows the corresponding topographic profile across the scarp. (d) Field photograph of Quebrada Cojup, Pampacancha–Huaraz segment, showing ~59 m of offset on an LGM-age moraine, with the Cordillera Blanca range front in the background. (e) Oblique aerial photograph of the Maraytaca trench area, Huaraz–Catac segment, along Quebrada Jaguash and Quebrada Maraytaca; arrows indicate the fault scarp, and the star marks the trench location. (f) UAV-derived DEM of the Maraytaca area showing throw measurements of 1.8–6.6 m on LGM and Holocene surfaces. (g) Oblique aerial photograph of the Quenua Ragra trench area, Catac–Chiquián segment, along Quebrada Quenua Ragra; arrows indicate the fault scarp, and the star marks the trench location. (h) UAV-derived DEM of the Quenua Ragra area showing cumulative throws of 12.7–17.8 m on LGM moraines. Throw values on all DEMs are color-coded by magnitude: blue = 0–2.5 m, green = 2.5–5 m, yellow = 5–10 m, orange = 10–20 m, and red = >20 m.

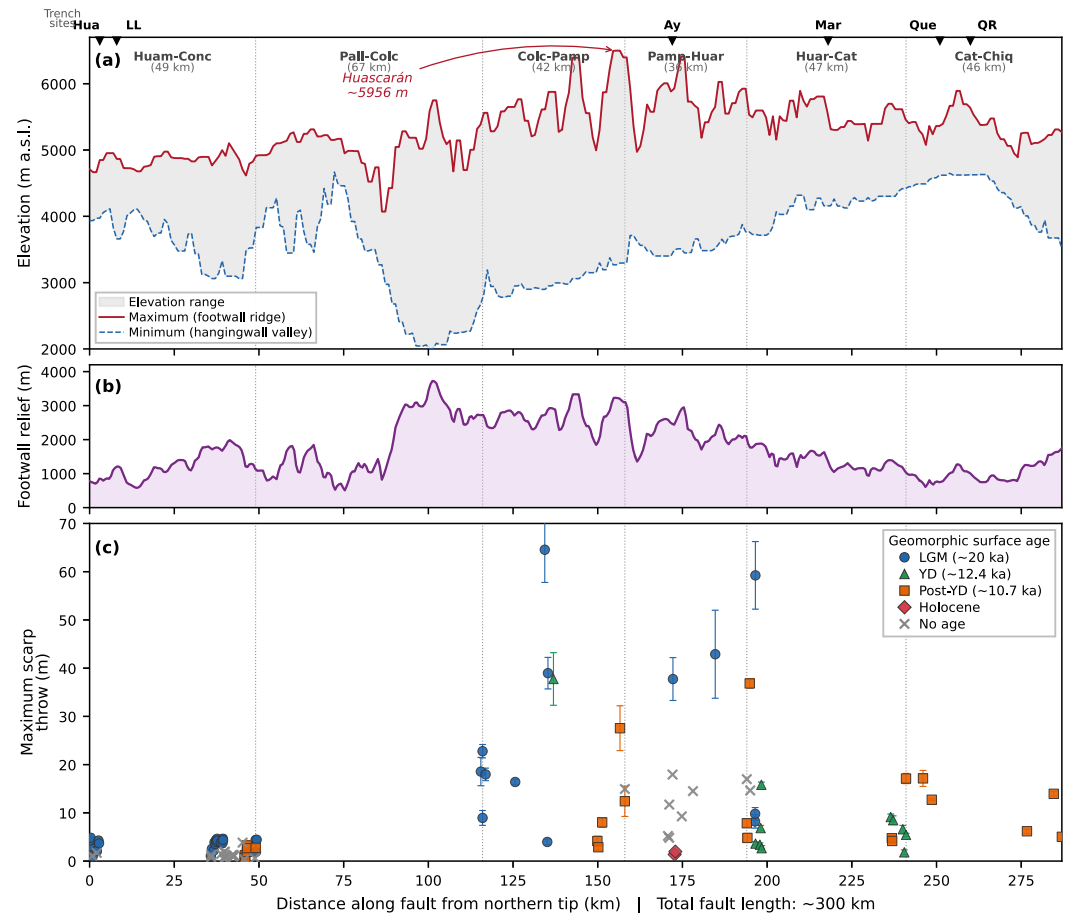


Figure 4. Along-strike variation in topographic relief and cumulative fault throw across the Cordillera Blanca Fault Zone. (a) Maximum footwall-ridge elevation (red) and minimum hanging-wall valley elevation (blue dashed) extracted from a 20-km-wide swath profile along the ~300-km-long fault trace using ETOPO1 topographic data (~1.85 km resolution). Grey shading indicates the elevation range between the two curves. Vertical dotted lines mark segment boundaries; segment names and lengths are shown at the top, and trench site locations are indicated above the panel. (b) Footwall relief, defined here as the difference between maximum and minimum swath elevations at each along-strike position. (c) Maximum scarp throw measured from 101 topographic profiles. Marker color and shape indicate the geomorphic surface age of the displaced marker: Last Glacial Maximum (~20 ka), Younger Dryas (~12.4 ka), post-Younger Dryas (~10.7 ka), Holocene, or undated. Error bars represent measurement uncertainty. One exceptionally large throw value (~126 m) in the Colcas–Pampacancha segment is excluded from panel (c) for visual clarity.

3.4.1.1. Huangacocha

The Huangacocha trench exposes a graben structure bounded by main fault F1 (N153°/52°SW) and three secondary faults (F2–F4), displacing glacial till and colluvial/lacustrine deposits (Figure 5). We identify three surface-rupturing events:

Event E1. The oldest event is inferred from presence of colluvial wedge C1 accumulated in the depression between F2 and F4. C1 exhibits wedge geometry with chaotic fabric and clast-long axes parallel to F1, diagnostic of coseismic collapse. Timing of C1 deposition is constrained by underlying till U2 (9.1–9.0 ka, TPQ) and overlying unit U3 (8.8–8.6 ka). A bulk sediment age from C1 itself (8.0–7.9 ka) is inverted relative to U3, likely reflecting reworked carbon. Event E1 occurred after ~9.1 ka, likely between ~9.0 and ~8.0 ka (Quality: Rank C). Displacement: 0.5 m vertical, 1.0 m net. Estimated magnitude: Mw 6.5.

Event E2. The second event is inferred by truncation and offset of C1, with activation of antithetic fault F3 and deepening of the graben structure. Units U3 and U4 filled the depression created by slip on F3. Timing is stratigraphically constrained to post-date C1 deposition (~8.0 ka) and pre-date unit U4 (6.3–6.2 ka), though U4

Table 1
Late-Quaternary Slip Rates by Segment and Age Class for the Cordillera Blanca Fault Zone

Segment	LGM (~20 ka) <i>n</i> /median (range) mm/yr	YD (~12.4 ka) <i>n</i> /median (range) mm/yr	Post-YD (~10.7 ka) <i>n</i> /median (range) mm/yr
Huamachuco–Conchucos	21/0.19 (0.05–0.24)	–	8/0.16 (0.06–0.32)
Pallasca–Colcas	5/0.22 (0.10–0.93)	–	–
Colcas–Pampacancha	1/6.34 (single profile)	–	–
Pampacancha–Huaraz	2/2.02 (1.89–2.14)	–	–
Huaraz–Catac	3/0.49 (0.41–2.96)	5/0.71 (0.45–1.22)	3/0.78 (0.48–3.68)
Catac–Chiquián	–	3/1.38 (0.41–1.38)	3/1.19 (0.58–1.30)

Note. The STRICT data set ($n = 56$ profiles) includes only profiles whose surface ages are directly assigned from cosmogenic exposure dating (Farber et al., 2005; Glasser et al., 2009). An EXTENDED data set ($n = 68$ profiles, reported in Table S7 in Supporting Information S1), which additionally includes 12 profiles in Colcas–Pampacancha with ages assigned by geomorphic correlation, yields qualitatively identical inter-segment statistics. Values shown are segment medians and full ranges (in parentheses) of slip rates computed from net dip-slip displacements (Table S7 in Supporting Information S1). n indicates the number of profiles. Hyphens indicate absence of profiles with that age class in that segment. Statistical tests for inter-segment differentiation are reported in Section 4.1.

was dated in its middle rather than base. Event E2 occurred between ~8.0 and >6.3 ka (Quality: Rank C). Displacement: 0.2 m vertical, 0.4 m net. Estimated magnitude: Mw 6.2.

Event E3. The most recent event is recorded by colluvial wedge C2, a two-facies deposit (basal clast-supported, proximal matrix-supported) adossed to F1. Three bulk sediment ages from C2 are internally consistent: 2.43–2.30, 2.27–2.15, and 2.02–1.98 ka. The coherence of these ages suggests relatively rapid wedge deposition characteristic of coseismic accumulation. Event E3 occurred at ~2.4–2.0 ka (Quality: Rank B), representing the

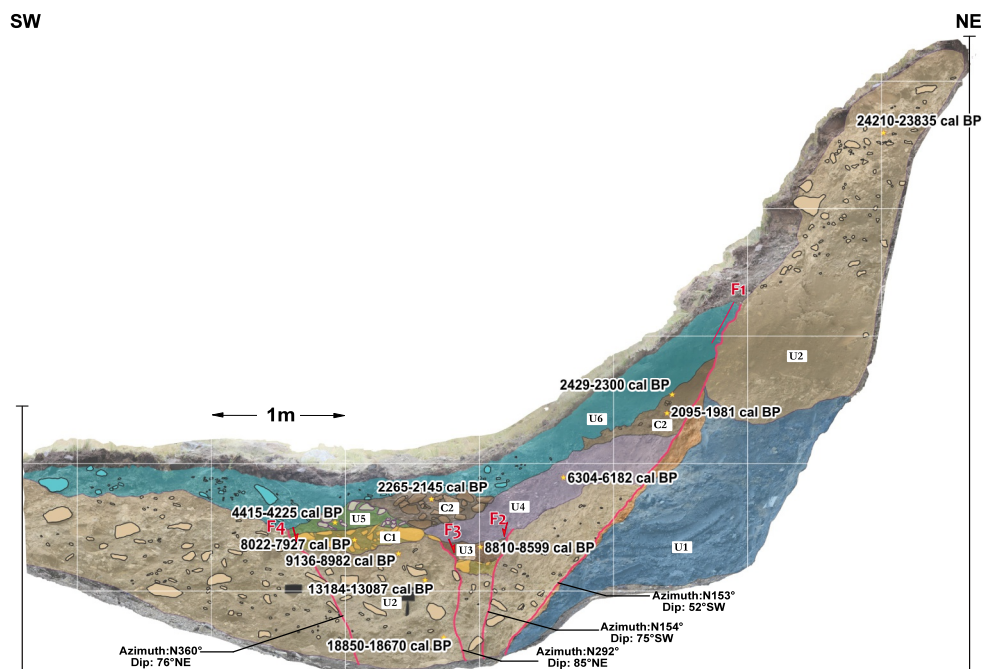


Figure 5. Interpreted trench log of the Huangacocha paleoseismic trench, Huamachuco–Conchucos segment. The trench wall is oriented SW–NE and exposes a small graben structure bounded by the main synthetic fault F1 (N153°/52°SW) and antithetic fault F4 (N360°/76°NE), with additional fault strands F2 (N154°/75°SW) and F3 (N292°/85°NE). Stratigraphic units U1–U6 and colluvial wedges C1–C2 are described in Table S1 in Supporting Information S1. Calibrated radiocarbon ages are shown as 2σ ranges in cal BP. The structural and stratigraphic relationships are interpreted to record three surface-rupturing events discussed in the text. Scale bar is 1 m.

Table 2
Summary of Paleoseismic Trench Sites

Site	Segment	Coordinates	Fault strike/dip	# Events	Age range (ka)	Mw range	Quality
Huangacocha	Huam–Conc	7°56′04″S, 78°02′34″W	N153°/52°SW	3	9.1–2.0	6.2–6.9	B–C
Laguna Larga 1	Huam–Conc	7°58′S, 78°01′W	N134°/65°SW	1	>2.8	6.8	A
Laguna Larga 2	Huam–Conc	7°58′S, 78°01′W	N120°/57°SW	3	12.6–1.4	6.7–6.9	B–C
Ayangay	Pamp–Huaraz	9°17′S, 77°38′W	N135°/–	1	>0.65	7.0	A
Maraytaca	Huaraz–Catac	9°47′03″S, 77°19′59″W	N–S/70°W	6	9.6–2.7	6.6–6.9	B–C
Quenua Ragra	Catac–Chiq	10°00′32″S, 77°14′24″W	N150°/84°SW	3	5.9–1.9	6.7–6.9	B–C
TOTAL	4 segments	–	–	17	12.6–0.65	6.2–7.0	A–D

Note. Fault strike/dip measured at or near trench site. Age ranges span oldest to youngest event at each site. Quality reflects the chronological and event-confidence ranking defined in Section 2.3 and Methods S1–S3 in Supporting Information S1. Huam–Conc = Huamachuco–Conchucos; Pamp–Huaraz = Pampacancha–Huaraz; Catac–Chiq = Catac–Chiquián.

best-constrained event at Huangacocha. Displacement: 1.8 m vertical, 2.1 m net, significantly larger than E1–E2. Estimated magnitude: Mw 6.9, the largest documented event in this segment.

3.4.1.2. Laguna Larga 1

Located ~4 km southeast of Huangacocha, Laguna Larga 1 exposes a simpler structural geometry with a single main fault (N134°/65°SW) displacing fluvioglacial deposits and overlying lacustrine fill. Bending of units U1–U2 toward the fault plane indicates syn-depositional deformation (Figure 6).

Event E1. Vertical separation of basal unit U1 between footwall and hanging wall, combined with flexure of overlying paleosol U2, documents a single surface-rupturing event. Timing is constrained by in situ peat from U2 dated to 2.78–2.70 ka, providing a robust TPQ given minimal susceptibility to old-carbon contamination. Overlying lacustrine unit U3 yielded an inverted age (3.36–3.15 ka), likely reflecting reworked carbon (see Section 3.5), and is not used for event timing. Event E1 occurred after ~2.8 ka (Quality: Rank A), with no

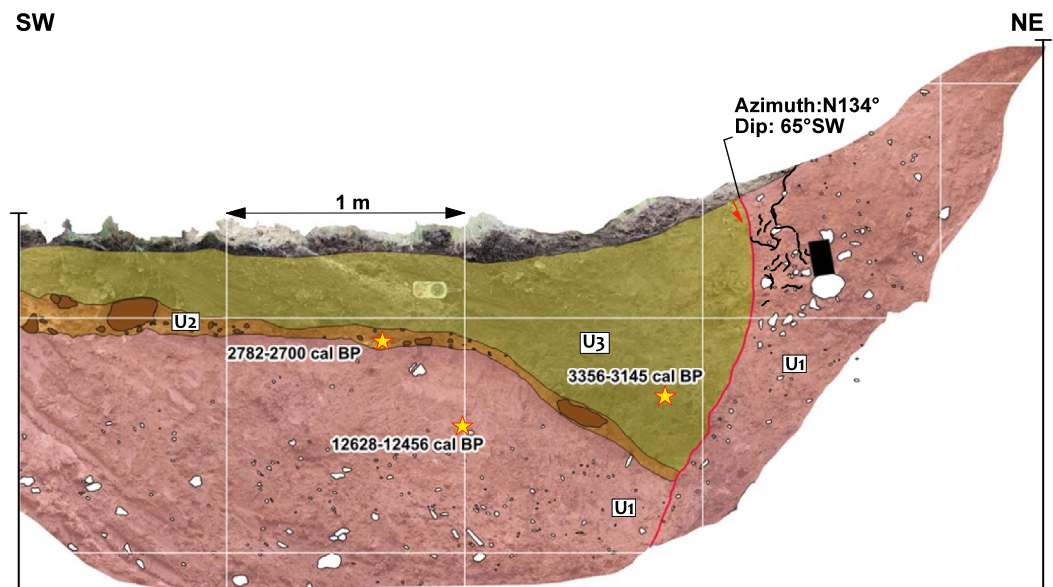


Figure 6. Interpreted trench log of the Laguna Larga 1 paleoseismic trench, Huamachuco–Conchucos segment. The trench wall is oriented SW–NE and exposes a single main normal fault striking N134° and dipping 65°SW. Stratigraphic units U1–U3 are described in Table S2 in Supporting Information S1. Calibrated radiocarbon ages are shown as 2σ ranges in cal BP. One surface-rupturing event is identified after ~2.8 ka. Scale bar is 1 m.

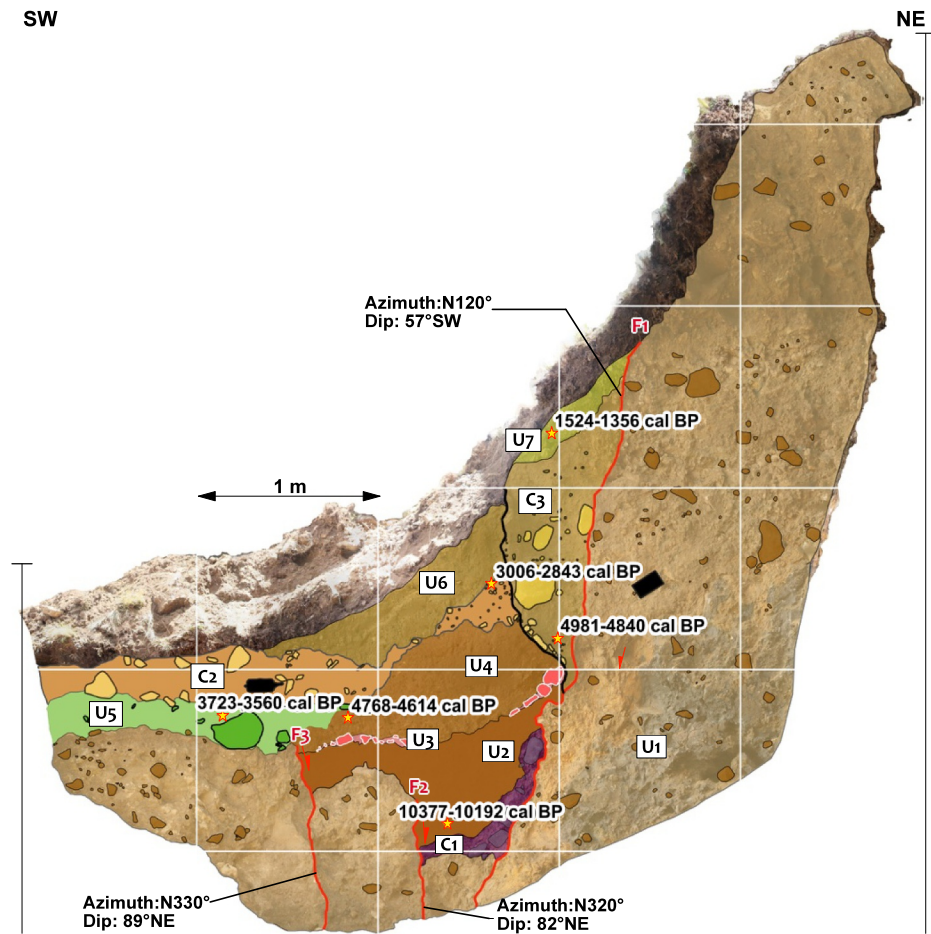


Figure 7. Interpreted trench log of the Laguna Larga 2 paleoseismic trench, Huamachuco–Conchucos segment. The trench wall is oriented SW–NE and exposes a graben structure bounded by the main normal fault F1 (N120°/57°SW) and antithetic faults F2 (N320°/82°NE) and F3 (N330°/89°NE). Stratigraphic units U1–U7 and colluvial or fissure-fill deposits C1–C3 are described in Table S3 in Supporting Information S1. Calibrated radiocarbon ages are shown as 2σ ranges in cal BP. Three surface-rupturing events are identified: E1 (~12.6–10.4 ka), E2 (~3.7–2.8 ka), and E3 (~1.5–1.4 ka). Scale bar is 1 m.

independent TAQ available from current data. Displacement: 1.1 m vertical, 1.3 m net. Estimated magnitude: Mw 6.8.

3.4.1.3. Laguna Larga 2

Laguna Larga 2 is located ~400 m southeast of Laguna Larga 1 and exposes a three-fault graben system (F1: N120°/57°SW; F2–F3 antithetic) displacing lateral moraine deposits correlated with the Late Pleistocene surface dated at Laguna Larga 1 (12.6–12.5 ka). We identified three events in this trench (Figure 7).

Event E1. Colluvial wedge C1, deposited in the graben between F1–F2–F3, records the oldest rupture. Wedge geometry, clast imbrication parallel to F1, and lack of internal stratification are consistent with coseismic origin. Overlying unit U2 (10.4–10.2 ka) provides TAQ. Combined with moraine age (12.6–12.5 ka, TPQ), E1 occurred between ~12.6 and ~10.2 ka (Quality: Rank B). Displacement: 1.4 m vertical, 1.6 m net. Estimated magnitude: Mw 6.9.

Event E2. Colluvial wedge C2 abutting to F1 records reactivation following deposition of units U2–U5. Underlying unit U5 (3.72–3.56 ka) establishes TPQ; C2 itself yielded 3.01–2.84 ka, providing TAQ. Event E2 is constrained to ~3.7–2.8 ka (Quality: Rank B). Displacement: 0.7 m vertical, 0.8 m net. Estimated magnitude: Mw 6.7.

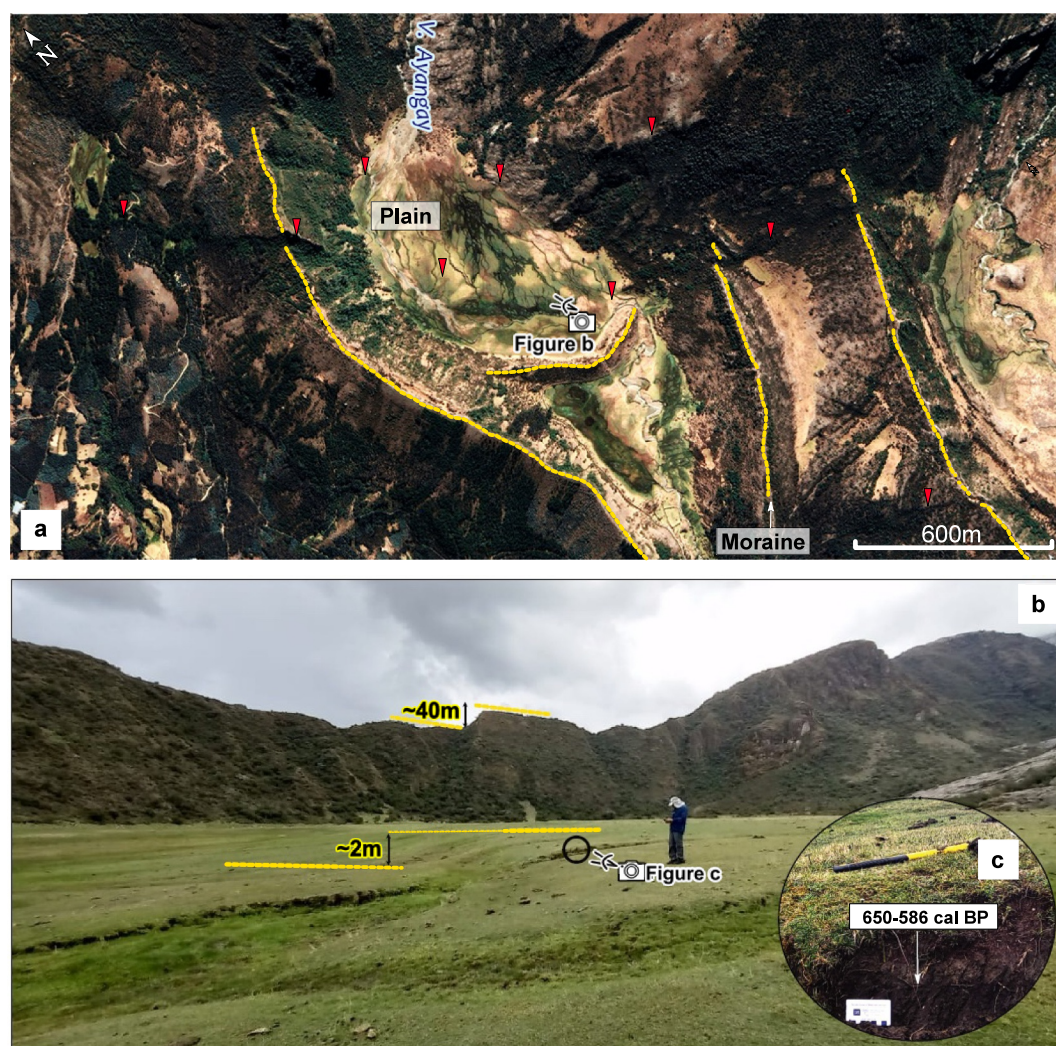


Figure 8. Ayangay paleoseismic site, Pampacancha–Huaraz segment. (a) Satellite image of Quebrada Ayangay near Carhuaz ($9^{\circ}17'S$, $77^{\circ}38'W$). Yellow dashed lines delimit glacial moraine ridges; red arrows indicate the active fault scarp. The fault displaces both the moraine deposits (~ 40 m cumulative throw) and a younger alluvial plain (~ 2 m throw). The camera symbol marks the location and viewing direction of panel (b). (b) Field photograph looking south across the alluvial plain, showing the contrast between the large cumulative scarp on the moraine (~ 40 m, background) and the small scarp on the Holocene plain (~ 2 m, foreground); person for scale. The circle marks the location of the exposure in panel (c). (c) Close-up of the fault-zone exposure enhanced by hand excavation, from which a bulk sediment sample yielded a calibrated radiocarbon age of 650–586 cal BP (2σ), providing a terminus post quem for the most recent surface-rupturing event at this site.

Event E3. The most recent event is recorded by tensional fissure fill C3, exhibiting V-shaped geometry with clast-long axes subvertical at the base transitioning to less inclined toward top, characteristic of incremental filling during and after opening. A bulk sediment age from C3 (4.98–4.84 ka) is inverted relative to host units U4–U5 (bulk sediment, TAQ; see Section 2.3). The overlying unit U7 (1.52–1.36 ka) seals deformation, providing TAQ. Event E3 occurred between ~ 2.8 and ~ 1.4 ka (Quality: Rank C). Displacement could not be quantified from fissure geometry so no magnitude estimate is provided.

3.4.2. Pampacancha–Huaraz Segment

We opened a single trench along the Pampacancha–Huaraz segment (~ 45 km length) near the village of Carhuaz in Quebrada Ayangay ($9^{\circ}17'S$, $77^{\circ}38'W$), where late Quaternary fault scarps displace both glacial moraines and younger fluvioglacial surfaces (Figure 8). Road construction exposed a natural cross-section of the fault zone, and this was enhanced by hand excavation to expose the stratigraphic relationships.

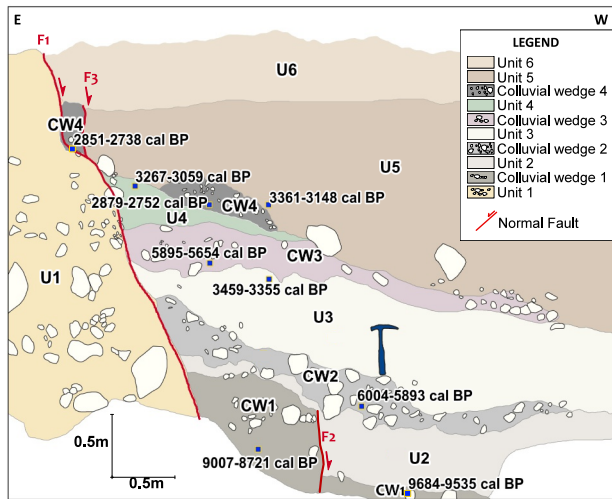


Figure 9. Interpreted log of the Maraytaca paleoseismic exposure, Huaraz–Catac segment ($9^{\circ}47'S$, $77^{\circ}20'W$). The E–W-oriented road-cut exposure shows faults F1, F2, and F3 displacing fluvioglacial and colluvial deposits. Stratigraphic units U1–U6 and four colluvial wedges (CW1–CW4) are described in Table S5 in Supporting Information S1. Calibrated radiocarbon ages are shown as 2σ ranges in cal BP. Six surface-rupturing events are identified, spanning ~ 9.5 to ~ 2.7 ka. Scale bars are 0.5 m.

3.4.2.1. Ayangay

The Ayangay exposure reveals a main west-southwest-dipping normal fault (strike approximately $N135^{\circ}$) displacing two principal stratigraphic units: (a) basal brown silts (unit U1) interpreted as fluvioglacial outwash or reworked till; and (b) overlying organic-rich horizon (unit U2) approximately 10 cm thick, interpreted as peat accumulated in a low-gradient valley bottom. The peat horizon exhibits visible vertical offset across the fault plane, with progressive deformation toward the fault indicative of syn-depositional or post-depositional rupture. The youngest faulted deposit is overlain by modern colluvium showing no evidence of deformation (Figure 8).

Event E1. Surface rupture is inferred by vertical displacement of the peat horizon (U2), with approximately 2.0 m throw measured between footwall and hanging wall. The peat itself yielded an in situ radiocarbon age of 0.65–0.59 ka, providing a robust TPQ given minimal susceptibility to old-carbon contamination. The overlying modern colluvium seals the deformation but lacks independent age control. Event E1 occurred after ~ 0.65 ka (Quality: Rank A), representing the youngest well-constrained minimum age for surface rupture documented in this study. Historical earthquake catalogs for Peru extend to approximately 1500 CE (~ 0.45 ka) but are incomplete for moderate-magnitude normal-faulting events in sparsely populated high-elevation sectors, therefore no definitive correlation with historical events is possible. Displacement: 2.0 m vertical, 2.3 m net. Estimated magnitude: Mw 7.0 and the largest single-event displacement documented in this study.

3.4.3. Huaraz–Catac Segment

We excavated one trench along the Huaraz–Catac segment (~ 50 km length) at Maraytaca ($9^{\circ}47'03''S$, $77^{\circ}19'59''W$) located 11 km east of Catac where a road cut provided access to faulted deposits (Figure 9). This site documents the highest density of paleoseismic events per trench in our study, with six surface ruptures spanning early to late Holocene. The structural setting comprises a main N–S-striking fault (F1: dip $70^{\circ}W$) with two secondary faults (F2: $N170^{\circ}/87^{\circ}W$ synthetic; F3: $N178^{\circ}/89^{\circ}W$ forming Y-junction with F1). Detailed stratigraphy is provided in Table S5 in Supporting Information S1.

3.4.3.1. Maraytaca

Stratigraphic exposures reveal basal glacial till (U1) overlain by alternating colluvial wedges (CW1–CW4) and paludal/alluvial deposits (U2–U6). Four colluvial wedges exhibit diagnostic coseismic geometries (wedge-shaped, chaotic fabric, maximum thickness adjacent to F1), representing four distinct surface-rupturing events. Two additional events are inferred from truncation relationships and secondary fault activation.

Event E1. Colluvial wedge CW1 records the oldest rupture, dated to 9.68–9.54 and 9.01–8.72 ka (two samples from different levels). The younger age likely reflects deposition timing, establishing TPQ at ~ 9.0 ka. No TAQ available. Event occurred before ~ 9.0 ka (Quality: Rank C). Displacement: 1.6 m vertical, 1.9 m net. Estimated magnitude: Mw 6.9.

Event E2. Displacement of CW1 and activation of secondary fault F2 indicate a second rupture. Constrained by youngest age from CW1 (TPQ: ~ 8.7 ka) and overlying CW2 dated to 6.00–5.89 ka (TAQ). Event occurred between ~ 8.7 and ~ 6.0 ka (Quality: Rank C). Displacement: 0.7 m vertical, 0.8 m net. Estimated magnitude: Mw 6.7.

Event E3. Colluvial wedge CW2 formed immediately following rupture, dated directly to 6.00–5.89 ka. Event occurred immediately before ~ 6.0 ka (Quality: Rank B). Displacement: 0.8 m vertical, 0.9 m net. Estimated magnitude: Mw 6.7.

Event E4. Colluvial wedge CW3 formed after deposition of unit U3 (3.46–3.36 ka, TPQ) and before U4 (3.27–3.06 ka, TAQ). Event constrained to a narrow window of ~ 3.36 – 3.27 ka (Quality: Rank B), the best-

constrained event at Maraytaca. Displacement: 0.8 m vertical, 0.9 m net. Estimated magnitude: Mw 6.7. A radiocarbon sample from within CW3 yielded an inverted age of 5.89–5.65 ka, which is older than the bracketing ages of U3 and U4. This out-of-stratigraphic-order date is a recognized characteristic of colluvial wedges, which incorporate older material exhumed from the scarp face during coseismic collapse following surface rupture (McCalpin, 2009). The inverted age within CW3 is therefore consistent with expected wedge accumulation processes and is excluded from the Bayesian event-time model. The event remains tightly constrained to the ~3.36–3.27 ka window by the stratigraphically-ordered TPQ from U3 (3.46–3.36 ka) and TAQ from U4 (3.27–3.06 ka).

Event E5. Colluvial wedge CW4 formed immediately following rupture. Two ages from CW4 (2.88–2.75 and 2.85–2.74 ka) are statistically consistent, suggesting rapid deposition. Event occurred immediately before ~2.85 ka (Quality: Rank B). Displacement: 0.8 m vertical, 0.9 m net. Magnitude: Mw 6.7. The colluvial wedge interpretation for CW4 is supported by: (a) its position directly adjacent to F1, with no equivalent unit observed elsewhere in the trench; (b) its matrix-supported texture distinct from the underlying fluvial unit U4; (c) the temporal consistency of two AMS dates (2.88–2.75 and 2.85–2.74 ka), suggesting rapid post-event deposition typical of coseismic scarp collapse; and (d) the documented offset of CW4 by F3 in the Y-junction geometry, indicating the wedge predates subsequent fault movement. Although the wedge geometry is more subtle than for CW1–CW3 due to the lower-energy conditions of the late Holocene scarp environment, the combined stratigraphic, lithological, and chronological evidence supports the colluvial wedge interpretation (Rank B).

Event E6. The most recent event is evidenced by displacement of CW4 and formation of Y-junction fault F3, with deformation of modern soil (U6). Constrained only by post-dating CW4 (~2.74 ka); no independent TAQ available. Event occurred after ~2.74 ka (Quality: Rank D). Displacement: 0.6 m vertical, 0.7 m net. Magnitude: Mw 6.6. The reality of E6 as a discrete surface-rupturing event is supported by three independent lines of evidence: (a) the measurable vertical displacement of the previously-deposited CW4 unit (offset of 0.6 m), which requires a post-CW4 slip event; (b) the geometric activation of the secondary fault F3 forming the Y-junction, indicating new rupture propagation along a kinematically distinct fault strand; and (c) the warping of the modern soil U6 across both F1 and F3, consistent with surface rupture postdating soil development. While shear of U5 across F4 is not visible in the trench exposure, this likely reflects the limited displacement (<1 m) of the most recent event combined with the unconsolidated, easily-bioturbated character of the modern soil horizon, which can obscure discrete shear surfaces. The post-2.74 ka timing is conservative; the absence of historical surface-rupture records in the Spanish colonial archive (since ~1530 CE) suggests E6 likely occurred between ~2.74 and ~0.5 ka. We retain E6 in the event catalog as a low-confidence candidate event (Rank D), reflecting the lack of an independent TAQ and the ambiguity of the youngest stratigraphic relationships.

3.4.4. Catac–Chiquián Segment

We documented three cleaned exposures along the Catac–Chiquián segment (~45 km length) at Quenua Ragra (10°00'32"S, 77°14'24"W), located ~18 km northwest of Chiquián where road construction exposed a multi-fault system (Figure 10). The exposure comprises four fault strands with variable kinematics: main fault F1 (N150°/84°SW), two synthetic faults F2–F3 (N158°/79°SW and N157°/80°SW), and one antithetic fault F4 (N158°/60–17°NE with variable dip). These faults form graben structures that acted as sediment traps, preserving a detailed stratigraphic record. We identified three exposures along the road cut revealing different portions of the fault system. Detailed stratigraphy is provided in Table S6 in Supporting Information S1.

3.4.4.1. Quenua Ragra—Section 1 (Main Fault F1)

Section 1 exposes main fault F1 displacing fluvioglacial deposits (U1) and overlying organic-rich units. Two colluvial wedges (C1, C2) document surface ruptures, with inter-seismic lacustrine/paludal deposits (U2–U5) recording quiescent intervals (Figures 10a–10f).

Event E1. Colluvial wedge C1 formed immediately following rupture, dated at base to 5.92–5.73 ka. The top of C1 was dated to 4.16–3.97 ka, indicating prolonged exposure or incremental filling. Overlying lacustrine unit U2 (3.69–3.49 ka) confirms post-event deposition. Event occurred before ~5.73 ka (Quality: Rank B). Displacement: 1.7 m vertical, 2.0 m net. Estimated magnitude: Mw 6.9.

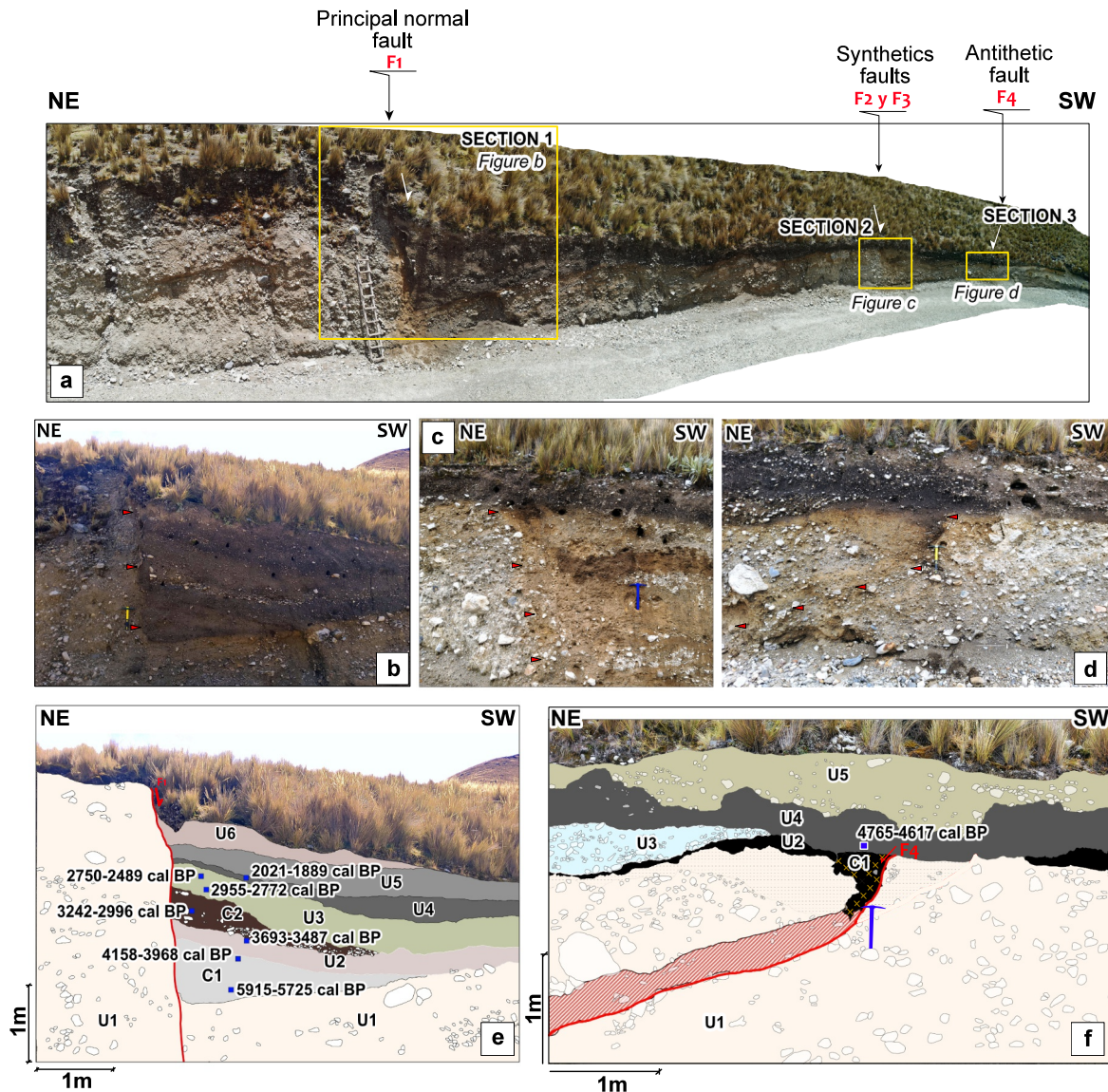


Figure 10. Quenua Ragra paleoseismic exposure, Catac-Chiquián segment ($10^{\circ}00'S$, $77^{\circ}14'W$). (a) Panoramic photograph of the NE-SW-oriented road-cut exposure, showing the principal normal fault F1, synthetic faults F2-F3, and antithetic fault F4. Yellow boxes indicate the three logged sections, whose close-up photographs are shown in panels (b-d). (b) Close-up of Section 1 at fault F1. (c) Close-up of Section 2 at synthetic faults F2-F3. (d) Close-up of Section 3 at antithetic fault F4. Red arrows indicate fault strands in all photographs. (e) Interpreted log of Section 1, showing principal fault F1, stratigraphic units U1-U6, and colluvial wedges C1-C2. (f) Interpreted log of Section 3, showing antithetic fault F4, units U1-U5, and colluvial wedge C1. Stratigraphic descriptions are provided in Table S6 in Supporting Information S1. Calibrated radiocarbon ages are shown as 2σ ranges in cal BP. Three surface-rupturing events are identified, spanning ~ 5.9 to ~ 2.0 ka. Scale bars are 1 m.

Event E2. Colluvial wedge C2 formed following rupture of F1. Underlying unit U2 (3.69–3.49 ka) provides TPQ; C2 itself dated to 3.24–2.99 ka, establishing TAQ. Event constrained to ~ 3.49 –3.24 ka (Quality: Rank B). Displacement: 0.8 m vertical, 0.9 m net. Estimated magnitude: Mw 6.7.

Event E3. Inferred from angular discordance in units U3–U4 and deformation of uppermost colluvium U6. Unit U4 (2.01–1.89 ka) provides TPQ; no TAQ available. Event occurred after ~ 1.89 ka (Quality: Rank C), representing the most recent documented rupture in this segment. Displacement not quantifiable from preserved stratigraphy, therefore no magnitude estimate provided.

3.4.4.2. Quenua Ragra—Sections 2 and 3 (Synthetic and Antithetic Faults)

Sections 2 (faults F2–F3) and 3 (fault F4) expose secondary faults within the broader deformation zone. Stratigraphic relationships suggest these faults may have activated during the same events as F1, though current chronological data are insufficient for definitive correlation. An organic-rich unit (U8) sealing deformation in Section 2 yielded 4.77–4.62 ka, consistent with post-Event 1 quiescence documented along F1. Detailed event correlation between sections will need further radiocarbon dating.

3.5. Paleoseismic Event Timing and Along-Strike Correlation

To test for whether there is any correlation in the timing of surface-rupturing on faults across the trench records we calculated probabilistic constraints on the timing of the 17 surface-rupturing earthquakes documented in the trench sections, together with two external constraints from Schwartz (1988), using Bayesian event-time modeling implemented in OxCal. For trenches with multiple sub-exposures and fault strands of ambiguous kinematic correlation—specifically Maraytaca (six events expressed across the main fault and two secondary faults) and Quenua Ragra (three events expressed across F1 with tentative correlation to F2–F4 in adjacent sections of the road cut)—each sub-exposure was modeled as a separate OxCal site to avoid imposing false simultaneity constraints, yielding 22 individual event-time priors in the Bayesian model. The 17-event count in the main text refers to the aggregated—that is, counting a rupture expressed across multiple sub-exposures or fault strands as a single event—surface-rupturing events; the 22 priors represent the same events viewed through the lens of unaggregated stratigraphic constraints (Methods S2 in Supporting Information S1 details the Bayesian model architecture).

Our multi-site model integrates 44 AMS ^{14}C dates and the historical and stratigraphic constraints across four of the six structural segments. The two constraints from Schwartz (1988) at Querococha and Pachma Bajo lack calibrated radiocarbon data and are retained as external chronological references rather than modeled inputs. The posterior probability distributions for all 17 surface-rupturing earthquakes are shown in Figure 11; complete radiocarbon data are provided in Table S8 in Supporting Information S1. Below we provide a description of the key results.

All proposed earthquakes post-date the deposition of the late Pleistocene to late-glacial geomorphic markers that bracket the trench records. However, there are significant differences in the age constraints for individual events—some have age uncertainties approaching several thousand years (e.g., SE1 at Quenua Ragra), while others have tighter age bounds of ~ 0.5 kyr (e.g., SE1 at Ayangay) due to favorable stratigraphy and smaller radiocarbon dating uncertainties. These age uncertainties preclude definitive event-by-event correlation between segments. However, they can be used to assess whether there is, broadly, any temporal clustering of events at ~ 2 kyr intervals along the fault's length. In addition, they demonstrate that all four sampled segments must be treated as seismogenically active in any future hazard models.

One critical limitation of using paleoseismic trenching to infer event clustering is the incompleteness of individual trench records, which is exemplified by comparing the inferred timing of surface-rupturing earthquakes between the Huangacocha, Laguna Larga 1 and Laguna Larga 2 trench sites. These sites are less than 2 km apart but on the same section of fault trace, so might be expected to capture a similar record of past surface-rupturing earthquakes. The MRE in all three trenches is consistent within uncertainty and is in the range 2–3 ka. However, Laguna Larga 1 does not contain any evidence for earlier surface-rupturing earthquakes between units dated at 12.5–2.5 ka, while Laguna Larga 2 and Huangacocha both contain evidence for two surface-rupturing earthquakes in the same time span. However, these two earlier events at Laguna Larga 2 and Huangacocha do not overlap within uncertainty on their date estimates. It is possible that surface ruptures terminated between these trenches, but the most likely interpretation is that surface rupture heights during earthquakes are heterogeneous even over distances of a few hundred meters, as is commonly observed in surveys of contemporary normal-faulting earthquake scarps (e.g., DuRoss et al., 2016). Therefore, any interpretation of the trench records must be predicated on them being an incomplete representation of past surface-rupturing earthquakes, with the absence of evidence for a surface rupture not necessarily reflecting the absence of an earthquake on that fault segment.

With this limitation in mind, we adopt the null hypothesis that earthquake timings are uncorrelated between adjacent fault segments and test this hypothesis against our event record. We find there is tentative evidence for temporal overlap in the timing of surface-rupturing earthquakes along the four fault segments at ~ 3.5 – 3.1 ka,

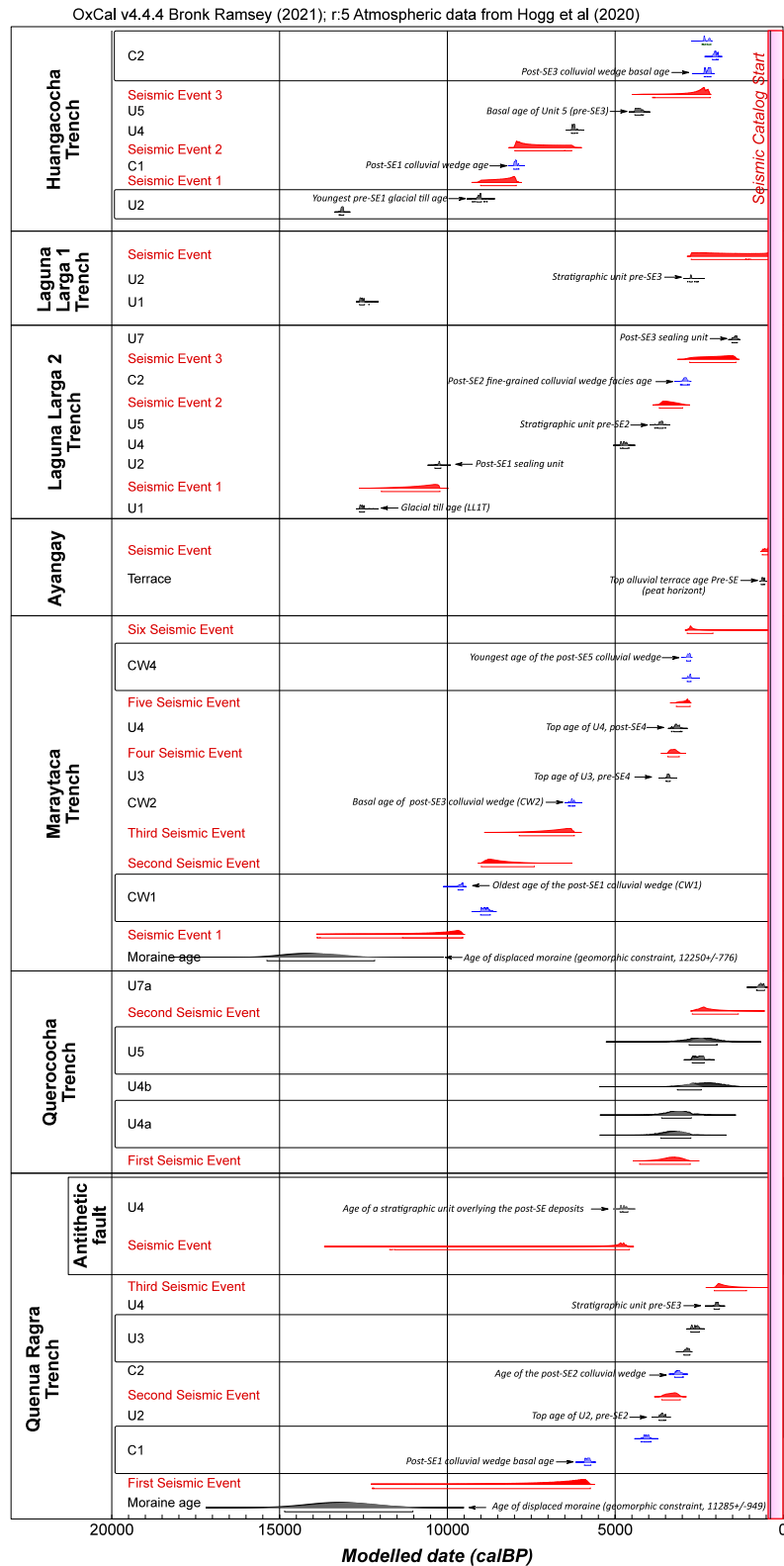


Figure 11.

where posterior probability distributions from Maraytaca SE4, Quenua Ragra SE2, Laguna Larga 2 SE2, and the penultimate Querococha event (Schwartz, 1988) are consistent at the 2σ level across four independent localities spanning ~ 220 km of fault length (Figure 11). Although radiocarbon dating resolution precludes confirmation that these surface-rupturing earthquakes occurred at the same time, the observed overlap is unlikely under a random temporal-coincidence model (Monte Carlo test, $p < 0.05$; Methods S4 in Supporting Information S1).

Two potential artifacts must be excluded before interpreting the cluster as a possible signal. First, the SHCal20 calibration curve between $\sim 3,800$ and $2,800$ cal BP contains no extended plateau capable of systematically collapsing independent probability distributions from different depositional contexts and laboratories toward a single narrow temporal window; the curve slope in this interval is moderate and uninterrupted. The posterior widths at Maraytaca (~ 90 years) and Quenua Ragra (~ 250 years) are substantially narrower than any calibration artifact produced from single bulk-sediment samples. Second, the four contributing localities represent independent trench investigations with different stratigraphic frameworks, datable materials, and event identification criteria; their temporal convergence does not reflect a shared methodological bias. If the 3.5–3.1 ka cluster represents near-synchronous rupture or cascading failure across multiple segments within a short (~ 400 years) time period, then it is perhaps surprising that the same event is not recorded in either trenches at Laguna Larga 1 or Huangacocha.

Prior to ~ 5 ka, correlating events across segments becomes more challenging as the event timing uncertainties are generally broader. There is weak temporal clustering around ~ 7 ka with events in the Huangacocha (SE1-2), Maraytaca (SE2-3) and Quenua Ragra (SE1) trenches, though further dating and trenching is needed to test this hypothesis.

4. Discussion

4.1. Fault Zone Segmentation and Slip-Rate Variability

The CBFZ is segmented at Earth's surface, with six structural segments defined by range-front geometry, fault-scarp continuity, and along-strike variations in cumulative throw. Segment lengths range from ~ 45 to 70 km, consistent with displacement–length scaling relationships for normal-fault segments capable of generating Mw 6.8–7.0 earthquakes for seismogenic thicknesses of the order of ~ 10 – 15 km (Wells & Coppersmith, 1994). Previous studies have shown that the present-day fault trace is closely associated with a pre-existing mylonitic shear zone that bounds the western margin of the Cordillera Blanca Batholith (Hughes et al., 2019, 2020). Hughes et al. (2020) showed that the fault surface is also sub-parallel to the mylonitic foliation, and that mylonitic stretching lineations are sub-parallel to fault slickenlines, suggesting that the active fault trace reactivates and follows this inherited fabric. A first-order question is therefore whether the structurally-defined segments of the CBFZ are also reflected in the distribution of late Quaternary slip rates.

To assess whether the inferred late Quaternary slip-rate variability between structurally-defined segments is significant we used a Kruskal–Wallis rank-based test (Kruskal & Wallis, 1952) applied to the slip rate measurements grouped by segment, which tests whether these groups of measurements come from different underlying distributions. The Kruskal–Wallis test does not require normally distributed data and is appropriate given the small per-segment sample sizes. Pairwise comparisons were carried out using Dunn's post-hoc test (Dunn, 1964) with Bonferroni correction (Dunn, 1961). As a sensitivity check, we also conducted one-way ANOVA with Tukey HSD (Honestly Significant Difference; (Tukey, 1949); these tests are reported in Methods S5 in Supporting Information S1 and yield qualitatively similar results, although they should be interpreted cautiously given the small sample sizes. To avoid conflating spatial variability in slip rate with differences in marker age, we stratified the analysis by age class: LGM (~ 20 ka), Younger Dryas (~ 12.4 ka), and

Figure 11. Bayesian age models for paleoseismic events along the Cordillera Blanca Fault Zone, showing the relationship between stratigraphy, radiocarbon ages, geomorphic constraints, and earthquake timing at each paleoseismic site. Modeled ages are shown as posterior probability density functions calculated using OxCal v4.4.4 (Bronk Ramsey, 2009) and the SHCal20 calibration curve (Hogg et al., 2020). For each site, samples and stratigraphic constraints are arranged in stratigraphic order within Sequence–Boundary–Phase model structures. Probability distributions for stratigraphic units, colluvial wedges, and geomorphic constraints provide pre- and post-event age limits, whereas red probability distributions represent model-constrained ages of surface-rupturing events. The figure includes the 17 surface-rupturing events identified in this study from Huangacocha, Laguna Larga 1, Laguna Larga 2, Ayangay, Maraytaca, and Quenua Ragra, together with external constraints from the Querococha trench of Schwartz (1988). The apparent temporal overlap of events at ~ 3.5 – 3.1 ka across four independent sites spanning ~ 220 km is discussed in the text. Full radiocarbon data are provided in Table S8 in Supporting Information S1; model input files are listed in Data and Resources.

post-Younger Dryas (~10.7 ka). We also conducted the statistical analyses two data sets: a STRICT data set of 56 profiles with directly assigned cosmogenic exposure ages, and an EXTENDED data set of 68 profiles that additionally includes 12 Colcas–Pampacancha profiles whose ages were assigned by geomorphic correlation.

We report the Kruskal–Wallis statistic H , its associated p -value, and η^2 as a non-parametric effect-size estimate. Here, H measures the degree of separation among ranked slip-rate distributions, p gives the probability of obtaining an equal or larger H under the null hypothesis of equal slip rate distributions on each segment, and η^2 expresses the proportion of rank-based variance associated with segment membership.

In our LGM-class STRICT data set, the global test has 32 observations distributed across four segments, yielding adequate power to detect the observed rank separation ($H = 13.83$, $p = 3.2 \times 10^{-3}$). The large effect size ($\eta^2 = 0.65$, well above the conventional “very large” threshold of 0.26; Tomczak & Tomczak, 2014) reflects inter-segment median differences of factor ~30X, which are well outside the range of sampling fluctuations expected at these sample sizes. Pairwise comparisons involving segments with $n < 5$ are far less robust, however, and we therefore emphasize the global Kruskal–Wallis result and effect size rather than relying on any single pairwise contrast.

To further demonstrate that the observed inter-segment differentiation may reflect genuine structural control rather than artifacts of the segment-grouping scheme, we conducted a non-parametric permutation test. The 31 LGM-class slip-rate measurements (STRICT data set, 4 segments) were pooled and randomly reassigned to segments while preserving the original per-segment sample sizes; the Kruskal–Wallis test was then re-applied. Repeating this procedure 10,000 times yielded a permutation null distribution with median $H = 2.56$, 95th percentile $H = 7.24$, and 99th percentile $H = 9.49$. Only 2 of 10,000 randomized assignments produced an H statistic equal to or larger than the observed value ($H = 13.62$), corresponding to an empirical permutation p -value of 2×10^{-4} . This confirms that the inter-segment slip-rate differentiation is highly unlikely to have arisen from random reassignment of measurements to segments under the null hypothesis of no real segment structure (Figure S3 in Supporting Information S1).

A potential concern is that inferred slip rates depend on the age of the displaced geomorphic marker, because rates calculated from older surfaces average deformation over longer time windows than rates calculated from younger surfaces. Segment-level differences could therefore arise if different segments are sampled by markers of different ages and might reflect temporal variability rather than from spatial variability in fault slip. We address this potential confounding effect in two ways. First, we evaluate whether slip rate correlates with marker age within individual segments where sufficient data are available. Second, we compare slip-rate distributions only within fixed marker-age classes, so that all profiles in a given statistical test share a comparable time-averaging window. This age-stratified approach reduces the likelihood that the observed inter-segment differences are simply an artifact of comparing markers of different ages.

Within individual segments where multi-age data are available, Spearman rank correlation between slip rate and marker age is statistically insignificant in all four testable cases (Huamachuco–Conchucos: $\rho = +0.01$, $p = 0.98$, $n = 29$; Colcas–Pampacancha: $\rho = +0.45$, $p = 0.12$, $n = 13$; Huaraz–Catac: $\rho = -0.19$, $p = 0.58$, $n = 11$; Catac–Chiquián: $\rho = +0.30$, $p = 0.57$, $n = 6$). The weak negative correlation observed in the pooled dataset ($\rho = -0.21$, $p = 0.08$, $n = 68$) likely reflects differential temporal sampling among segments—where high-slip-rate central segments are over-represented in older age classes—rather than a systematic within-segment temporal dependence (see Figure S2 in Supporting Information S1). When slip-rate distributions are compared within fixed age classes, inter-segment differences persist. LGM-age markers yield significant inter-segment differentiation in the STRICT dataset ($H = 13.83$, $p = 3.2 \times 10^{-3}$, $\eta^2 = 0.65$), and post-YD markers also differ significantly among the sampled segments ($H = 9.67$, $p = 0.008$, $\eta^2 = 0.44$). In contrast, Younger Dryas markers do not show significant differentiation, possibly because the YD dataset covers fewer contiguous segments and has lower statistical power.

The persistence of slip-rate contrasts between segments within fixed age windows supports the interpretation that inter-segment slip-rate variability is real, rather than only reflecting temporal sampling effects. However, the strength of this inference varies among segments because several segment–age bins contain small sample sizes. These tests should therefore not be interpreted as fully characterizing the underlying slip-rate distribution of each segment. Rather, they test whether the available measurements show first-order differences large enough to be detected despite low statistical power. We therefore emphasize effect size, consistency across age-stratified

comparisons, agreement between the STRICT and EXTENDED data sets, and comparison with independent estimates such as Schwartz (1988), rather than relying on individual pairwise p-values alone.

The highest LGM-age value in the data set, 6.3 mm/yr at Quebrada Huandoy, comes from a single profile. Excluding this single-profile, the contrast between the low slip rates in the northern Huamachuco–Conchucos segment and the higher rates in the central part of the fault system remains substantial. Similarly, the post-YD data set shows higher median rates in the southern and central sampled segments than in Huamachuco–Conchucos, although the small number of profiles in some segment–age bins limits the strength of individual pairwise interpretations.

The differentiation among segments at LGM and post-YD timescales, the consistency of segment-level patterns across the STRICT and EXTENDED data sets, and the agreement with the independent estimate of Schwartz (1988) at Quebrada Tuco together support the interpretation that the structural segmentation of the CBFZ is expressed in the distribution of late Quaternary slip rates, rather than representing only a geometric subdivision of the range front. However, this inference is strongest at the fault-system scale and less robust for individual pairwise comparisons.

4.2. Segmentation and Paleoseismic Record

The chronological resolution of the new paleoseismic record does not permit discrimination between two end-member rupture scenarios for the CBFZ: predominantly single-segment ruptures that may cluster through stress interaction, and less frequent multi-segment ruptures or near-synchronous rupture cascades. This uncertainty should be represented explicitly in future fault-based probabilistic seismic hazard models.

The paleoseismic record provides support for both end-member interpretations. Many of the 17 documented surface-rupturing events do not show resolvable temporal overlap with events in neighboring sampled segments at the 2σ level, which is compatible with predominantly single-segment ruptures. In contrast, the apparent ~ 3.5 – 3.1 ka cluster, involving Maraytaca SE4, Quenua Ragra SE2, Laguna Larga 2 SE2, and the penultimate Querococha event of Schwartz (1988), indicates that multi-segment rupture or near-synchronous cascading failure cannot be excluded. However, given the incompleteness of individual trench records, the limited number of sampled sites, and the broad age uncertainties on many events, the current data set is not sufficient to assign robust quantitative probabilities to these rupture scenarios.

For future PSHA applications, we therefore recommend treating rupture segmentation as an epistemic uncertainty rather than prescribing fixed rupture probabilities. Logic-tree implementations should retain at least three branches: single-segment ruptures, multi-segment or near-synchronous cascading ruptures, and floating ruptures with lengths sampled from empirical scaling distributions. The relative weights assigned to these branches should be explored through sensitivity analysis and updated as additional trenching, geochronology, and structural data become available.

Independent single-segment ruptures, potentially clustered through stress interaction, represent the more conservative interpretation on parsimony grounds. Per-event vertical displacements at sites involved in the ~ 3.5 – 3.1 ka cluster range from 0.5 to 2.3 m and are broadly consistent with single-segment ruptures of ~ 40 – 70 km length generating Mw 6.8–7.0 earthquakes. Geometric complexities at segment boundaries, including stepovers, gaps, and fault branching, may reduce the probability of along-strike rupture propagation, although their effectiveness as rupture barriers remains unresolved for the CBFZ. Stress transfer following Mw 6.8–7.0 events could plausibly promote temporal clustering on adjacent segments, but this mechanism remains untested without explicit stress modeling.

Multi-segment rupture or near-synchronous cascading failure also remains credible. If two to three central segments ruptured during the same earthquake or within a short cascade over $L = 140$ – 210 km, expected moment magnitudes are Mw 7.1 – 7.2 ± 0.27 (1σ) using our preferred scaling relation for slow normal faults (Wessnousky, 2008, normal-fault SRL relation), following the selection guidance of Stirling et al. (2013); when the full range of empirical magnitude–rupture relations applicable to normal faults is considered (Anderson et al., 1996; Leonard, 2010; Shaw, 2023; Wells & Coppersmith, 1994), the multi-segment Mw estimates span Mw 7.1–7.9, reflecting epistemic uncertainty in the choice of scaling relation. Common parameters in all calculations are: seismogenic thickness $H_s = 15$ km; fault dip $\delta = 62^\circ \pm 8^\circ$ (mean of $n = 6$ trench measurements); fault width $W = H_s/\sin \delta \approx 17$ km; rupture area $A = L \times W \approx 2400$ – $3,600$ km² for the cited length range (see Section 2.3 and

Methods S3 in Supporting Information S1 for the full magnitude estimation framework). The local displacements measured in trench exposures are lower than the mean displacements expected for such events, but this discrepancy is not diagnostic because trench sites sample local displacement, which may differ substantially from along-rupture mean or maximum displacement. Therefore, both single-segment and multi-segment scenarios should be retained as credible source-model branches until higher-resolution chronological and structural data resolve the ambiguity.

4.3. Earthquake Recurrence and Historical Seismicity

The six-event Maraytaca paleoseismic record, spanning ~ 9.5 – 2.74 ka, is the longest and most densely sampled single-site record in this study and provides the only site-specific basis for estimating recurrence on an individual CBFZ segment. The mean inter-event interval at this site is $\sim 1,600$ years, broadly consistent with the $2,440 \pm 1,060$ years estimated by Schwartz (1988) at Querococha. However, this mean conceals an apparently clustered pattern: short intra-cluster intervals within the late Holocene sequence contrast with longer inter-cluster gaps separating earlier rupture episodes.

This pattern is difficult to reconcile with a simple time-independent Poissonian recurrence model, although the short record and event uncertainties preclude formal rejection of such a model. A clustered or time-dependent recurrence model may better describe the Maraytaca record, but additional trenching and dating are required before this behavior can be generalized to the full CBFZ. The practical implication is that mean recurrence intervals should be used cautiously, because they may overestimate recurrence time during active cluster phases and underestimate it during longer inter-cluster periods.

First-order slip-deficit estimates provide an additional perspective on relative loading state among segments, but should be interpreted cautiously because they depend on whether the dated trench event represents the most recent segment-scale rupture. For the Pampacancha–Huaraz segment, the Ayangay event post-dates ~ 0.65 ka and the central slip rate is ~ 2.3 mm/yr, implying a possible accumulated deficit of ~ 1.5 m. This is of the same order as the local displacement documented at Ayangay, suggesting that this segment may be relatively more advanced in its interseismic loading cycle if the Ayangay event represents the most recent segment-scale rupture. For the Cat-ac–Chiquián segment, the last well-bracketed event at Quenua Ragra is E2 at ~ 3.49 – 3.24 ka, although a younger event post-dating ~ 1.89 ka is inferred with lower chronological precision. The resulting slip-deficit estimate is therefore highly sensitive to the event catalog used. For the Huamachuco–Conchucos segment, lower geomorphic slip rates imply a smaller accumulated deficit since the late Holocene events documented in the northern trenches.

The absence of an instrumentally recorded surface-rupturing earthquake on the CBFZ is not unexpected given the long recurrence intervals inferred from paleoseismology. Under a simple Poissonian approximation and recurrence intervals of $\sim 1,600$ – $2,400$ years, the probability of observing one surface-rupturing event during a 60–100-year instrumental window is only a few percent. Thus, the lack of instrumental surface rupture should not be interpreted as evidence for inactivity.

4.4. The CBFZ as a Probe of Upper-Plate Dynamics in Flat Slabs

Our new mapping documents 300 km of continuous active CBFZ trace, ~ 90 km longer than the ~ 210 km recognized by Schwartz (1988), extending the documented zone of active upper-plate extension in the central Andes by $\sim 30\%$ to the north. Combined with the segment-scale slip-rate heterogeneity documented in Sections 4.1 and 4.2, this supports three tectonic inferences.

First, our mapping extends active orogen-perpendicular deformation northward to $\sim 7.5^\circ\text{S}$, well within the Peruvian flat-slab domain and farther north than previously documented. Our results indicate that flat-slab subduction and active upper-plate extension coexist from $\sim 7.5^\circ\text{S}$ to $\sim 10.5^\circ\text{S}$ (a latitudinal range of $\sim 3^\circ$), consistent with reduced compressional coupling at the plate interface (Wimpenny et al., 2020) and gravitational-collapse-driven extension of overthickened crust (Wimpenny et al., 2018), but extending the spatial domain over which these mechanisms operate.

Second, the factor-of- ~ 30 variation in late-Quaternary slip rate among structurally-defined segments (Section 4.1) implies that the active CBFZ is mechanically heterogeneous along strike. Such pronounced variability is difficult to reconcile with a uniform driving stress field acting on a homogeneous fault and instead it is possible that slip is modulated locally by along-strike variations in the geometry, thickness or grain size of the underlying mylonitic

shear zone on the margins of the Cordillera Blanca Batholith (Hughes et al., 2019, 2020; Petford & Atherton, 1992). This rheological inheritance appears to control not only the exceptional continuity of the active fault system but also the segment-scale kinematic heterogeneity documented here. This along-strike pattern is broadly consistent with recent InSAR observations of present-day deformation along the CBFZ (Michel et al., 2026), which show the clearest geodetic signal along the well-resolved section between $\sim 8.5^{\circ}\text{S}$ and $\sim 9.5^{\circ}\text{S}$, spatially overlapping the central segments where we document the highest late-Quaternary slip rates, and more diffuse deformation farther south. However, the InSAR data do not robustly constrain the newly mapped northernmost segment, so we regard this correspondence as qualitative rather than a segment-by-segment comparison.

Third, the very low slip rates documented along the northernmost ~ 90 km of the fault (Huamachuco–Conchucos segment: 0.05–0.24 mm/yr)—an order of magnitude lower than in the central segments—together with the comparatively immature scarp morphology in that segment (Section 3.1), are consistent with the northern portion representing a propagating fault tip rather than a mature segment. If correct, this would imply that the CBFZ is currently growing northward in the flat-slab zone and that the pattern of active extension across the central Andes between $\sim 7.5^{\circ}$ and 10.5°S is still evolving. Alternatively, the low slip rates and immature scarp morphology may reflect distributed or off-fault deformation, lithological or rheological controls, or fluvial reworking of older scarps rather than active tip propagation, and the available data do not uniquely discriminate among these possibilities.

5. Conclusions

We show that late Quaternary fault scarps on the CBFZ extend 90 km further north than previously recognized, increasing the total length of the active fault to 300 km stretching from Huamachuco to Chiquián. We find no strong evidence that the structurally-defined fault segment boundaries that are most likely inherited from the underlying mylonitic shear zone act as barriers to earthquake rupture, but testing these hypotheses is limited by the incompleteness of the existing paleoseismic trench records. These uncertainties are important to translate into fault-based probabilistic seismic hazard analyses. We identify tentative evidence for a cluster of surface-rupturing earthquakes within a ~ 400 year period between 3.5 and 3.1 ka across trench sites 220 km apart with per-event displacements of 0.5–2.3 m, meaning multi-segment ruptures cannot be ruled out. When averaged over the Holocene, the fault slip rate varies between structurally-defined segments, from 0.1 to 0.6 mm/yr along the northern and southern segments, peaking at 1.9–3.7 mm/yr in the central segment. Slip rates broadly correlate with the thickness of the underlying mylonitic shear zone and the footwall relief.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

All data needed to understand, evaluate, and reproduce the analyses and conclusions of this study are available at the time of peer review and publication, with no restrictions. The complete cumulative fault-throw data set (Table S7 in Supporting Information S1), the complete radiocarbon data set and calibrated age ranges (Table S8 in Supporting Information S1), structural parameters and earthquake-magnitude calculations (Table S9 in Supporting Information S1), and the detailed trench stratigraphy (Tables S1–S6 in Supporting Information S1) are provided in Supporting Information S1 accompanying this manuscript. The OxCal Bayesian age model, posterior probability distributions, and associated geomorphic and trench data sets are openly archived in the Zenodo FAIR-compliant repository (Benavente Escóbar et al., 2026, <https://doi.org/10.5281/zenodo.21086514>). Radiocarbon ages were calibrated and Bayesian chronological models were developed using OxCal v4.4.4 (Bronk Ramsey, 2009) together with the SHCal20 Southern Hemisphere calibration curve (Hogg et al., 2020). Statistical analyses were performed using Python 3, including the NumPy, SciPy, and pandas libraries.

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Acknowledgments

This work was supported by the Instituto Geológico, Minero y Metalúrgico (INGEMMET), Peru, through the national Neotectonics Project. SW was supported by COMET the NERC Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics, a partnership between UK Universities and the British Geological Survey. We are grateful to Alan Hull and Carlos Costa for their constructive reviews, technical comments, and insightful discussions, which contributed to improving the quality and clarity of the manuscript. We also thank Associate Editor Judith Hubbard and an anonymous reviewer for their careful evaluation and constructive comments, which helped improve the final manuscript.

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