COSEISMIC OFFSET OF THE CAMINO DE CRUCES CONFIRMS THE PEDRO MIGUEL FAULT AS THE CAUSE OF THE AD 1621 PANAMÁ VIEJO EARTHQUAKE

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ABSTRACT (Coseismic offset of the Camino de Cruces confirms the Pedro Miguel fault as the cause of the AD 1621 Panamá Viejo earthquake): *We completed a study of the Pedro Miguel fault where it crosses the ca 1520 Camino de Cruces in Central Panama. Using tectonic geomorphic mapping, stream bank exposures, and hand-excavated trenches, we have demonstrated that the fault has generated a 2.8-3.0 meter displacement of the Trail, as well as of all fault-crossing geomorphic features in the local area. A unique cobblestone pavement used for the Trail, combined with the geomorphology, makes pre- and post-event reconstruction of fault slip highly accurate. Fault exposures demonstrate that the youngest alluvial deposits are offset, and the fault projects into the surface topsoil. We conclude that the Pedro Miguel fault last ruptured May 2, 1621 and caused the devastating Panamá Viejo earthquake.*

Key words: Panamá, paleoseismic, archeoseismic, Cruces

As part of the seismic hazard investigation for the Panamá Canal Expansion Project's design studies, we completed detailed paleoseismic investigations of the Pedro Miguel, and several other faults (Fig. 1). Our studies of the presumed inactive, but unexplored, Pedro Miguel fault involved logging of over 55 trenches, including three locations where we excavated the fault in 3-D to determine slip and timing in past earthquakes, and fault slip kinematics. These studies revealed the fault as having experienced at least three, 2-3 meter displacement events within the last 1500 years. As such, the fault not only poses a shaking hazard to the Panamá Canal structures, but it also crosses through the proposed footprint of Borinquen Dam. This new earthen embankment dam is 7 km long and 10.6 meters high, is segmented into four parts, and will contain the new approach channel from Gatún Lake to the new Pacific set of locks.

One key piece of data needed for the seismic hazard model was the age of the last displacement event. Based on the apparent youthfulness of offset soils and surface features, we proposed that the latest rupture of the Pedro Miguel fault might have been the earthquake that severely damaged many of the stone and adobe buildings in Panamá Viejo on May 2, 1621. The Panamá region has had other earthquakes between 1535 and 1850 (including in 1541, 1750, 1799 or 1800, 1849? and 1855), but only the historically recorded earthquake in 1621 seems strong enough to correlate with the measured surface fault displacement. However, extensive reworking of charcoal in the fluvial sediments prevented us from definitively proving a historical rupture within the principal trenching area.

Fortunately, the Camino de Cruces, a 1.5 meter wide, cobblestone paved trail (Fig. 2), was built from Panamá Viejo to the town of Cruces on the Chagres River, near the present town of Gamboa, in the early 1500s to transport goods via mule pack trains. From Cruces, the goods and passengers would be loaded onto boats that navigated the Chagres River to its mouth by Fort San

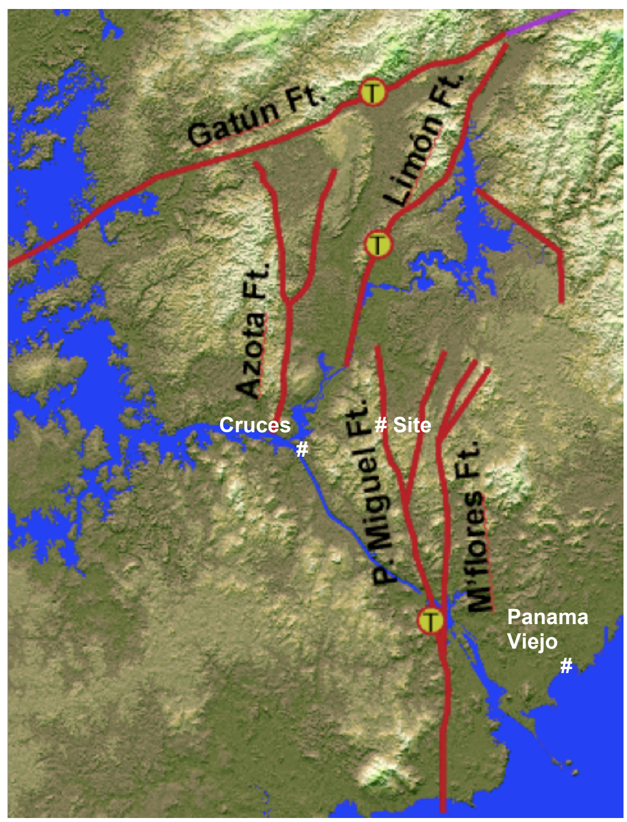

Fig. 1: Active fault map of Central Panamá showing the study site. Modified from ECI, 2009.

Lorenzo. These pack trains consisted of hundreds and even thousands of mules. During the California Gold Rush, thousands of "49'ers" used the Trail to traverse the Isthmus. It was in nearly continuous use until the mid-1800s when the Panamá Railroad was completed. The Trail crosses the northern extent of the Pedro Miguel fault and provides an excellent archeoseismic piercing line to determine whether the Pedro Miguel fault ruptured in

1621. We conducted a detailed geologic and geomorphic field study of this area to prove whether or not the Trail is offset at the fault, which would be a key factor in general acceptance of the Pedro Miguel fault as active, and its role in generating the 1621 earthquake.

Fig. 2: A photograph of the Las Cruces Trail as it appears today. Although erosion has removed some portions of the trail the cobblestone pavement and larger trail-margin cobbles are still visible in many locations. The rounded, basaltic cobbles that form the trail pavement are typically exotic to the trail location where they were placed.

The site reconnaissance successfully located the Pedro Miguel fault where it crosses the Trail (Fig. 3). At this location, the Trail is abruptly terminated into a projecting sidewall of the stream terrace riser along the toe of which the Trail had been constructed. During the site investigation, we made several other observations that support the theory of a youthful fault offset of the Trail. These observations are listed below from south to north, and illustrated on Figure 4:

- The rebuilt Trail immediately adjacent to the offset had been relocated to the east and north to smooth out the abrupt 3-meter, 90-degree jog in the Trail.
- The Trail followed along on the first elevated terrace of the stream, and the terrace tread/canyon wall riser is offset 3-4 meters.
- Detailed surveying of the Trail cobbles reveals a segment of the old Trail abruptly severed at the fault, with remnant Trail cobbles preserved under fault-scarp-derived colluvium.
- Right at the fault, the stream is diverted right-laterally over 30 m, forming an incised horseshoe meander.
- The south-facing stream cut exposes several soil-filled fault fissures that flare to the surface.
- The terrace formed between the river meanders has a low (<0.5-m high) scarp across its surface that is on trend with the fault trace.
- Trenches across this scarp reveal upwardly expanded, fissured, and fractured rock, several faults and fault-fissures filled with soil, all at the location of the low scarp.
- The southern wall of the northern river meander is offset at least 2.5 m right-laterally, exposing a fault contact between agglomerate and basalt.
- The north-facing stream cut exposure shows the fault cutting the terrace alluvium, juxtaposing a terrace strath cobble line against fine-grained alluvial deposits.
- The northern wall of the northern river meander is abruptly offset ~3 m right-laterally.
- Two small gullies north of the main river are abruptly offset ~3+ m right-laterally, directly on trend with the fault.
- The gullies expose faulted alluvium and surface soils.

Fig. 3: Photograph of the straight reach of the cobblestone trail as it approaches the fault. The trail is abruptly severed where the left ridgeline has been moved right-laterally in front of the trail, resulting in a 90-degree bend on the trail that would be difficult and inefficient to negotiate with the mule train convoys used on the trail. Photo by P. Williams.

Unfortunately, no charcoal samples or other datable materials were recovered from the offset alluvial deposits. However, based on the relative lack of soil development on the meander terrace surface and their comparison to dated Holocene deposits in Panama, the sediments and subsequent fault rupture are interpreted to be late Holocene in age. Individually, none of these observations is conclusive evidence for a recent fault rupture. But, collectively they make a persuasive case for a 2.8-3.0 meter surface rupture on this fault some time after the Trail was completed around AD 1535 and before it was abandoned in the mid 1800s.

Figure 5 shows the site currently and as we envision it before the earthquake by back-slipping 2.8 meters along the fault. All of the principal geomorphic features reconstruct across the fault, and the repair of the Trail to eliminate the 90° jog becomes clear, strongly indicating that the displacement occurred post-Trail. The Trail follows the edge of the terrace riser on the east side of the fault, but deviates from a lower riser on the west side of the fault. It is likely that the trail was constructed around a prior displacement of the terrace riser. Particularly compelling is that some of the Trail cobbles are still preserved under the fault scarp-derived colluvium, even though most were recycled to repair the Trail. Because of the historical sensitivity of the site, we were not able to excavate into the scarp to better expose the fault directly offsetting the Trail. However, the presence of the Trail cobbles under the scarp colluvium is persuasive, especially with the consistency of the geomorphic offsets along the fault.

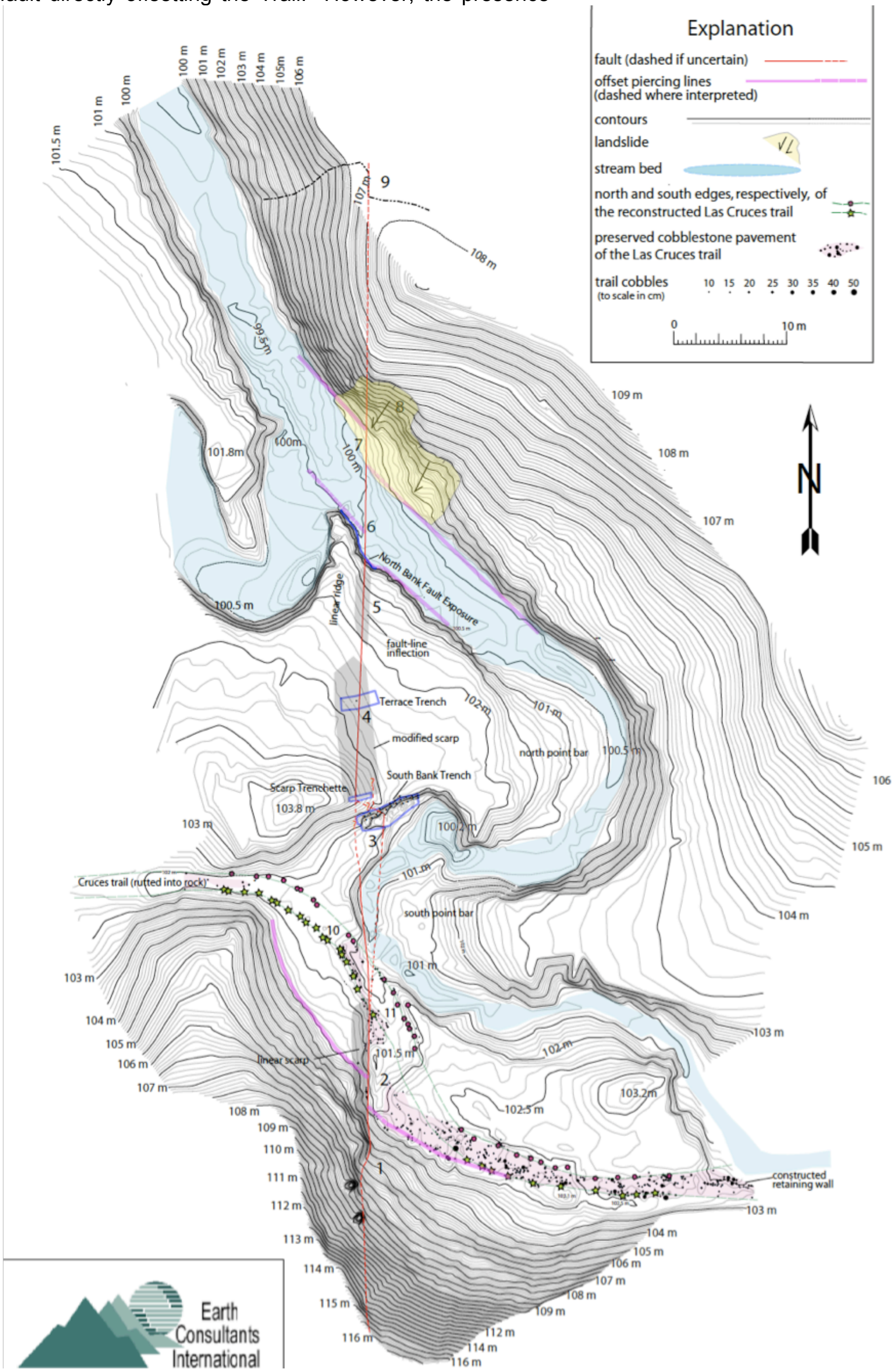

Fig. 4: Detailed map of the study location at the intersection of the Pedro Miguel fault with the Camino de Cruces showing the locations and relationships described in the text. 1: Sidehill scarp; 2: Offset terrace riser and Trail; 3: Fault exposure in stream bank; 4: Linear 0.5 m scarp; 5: Scarp; 6: Offset channel wall and fault exposure in bank; 7: Offset stream bank; 8: Landslide; 9: 3 m offset of gulley and fault exposure.

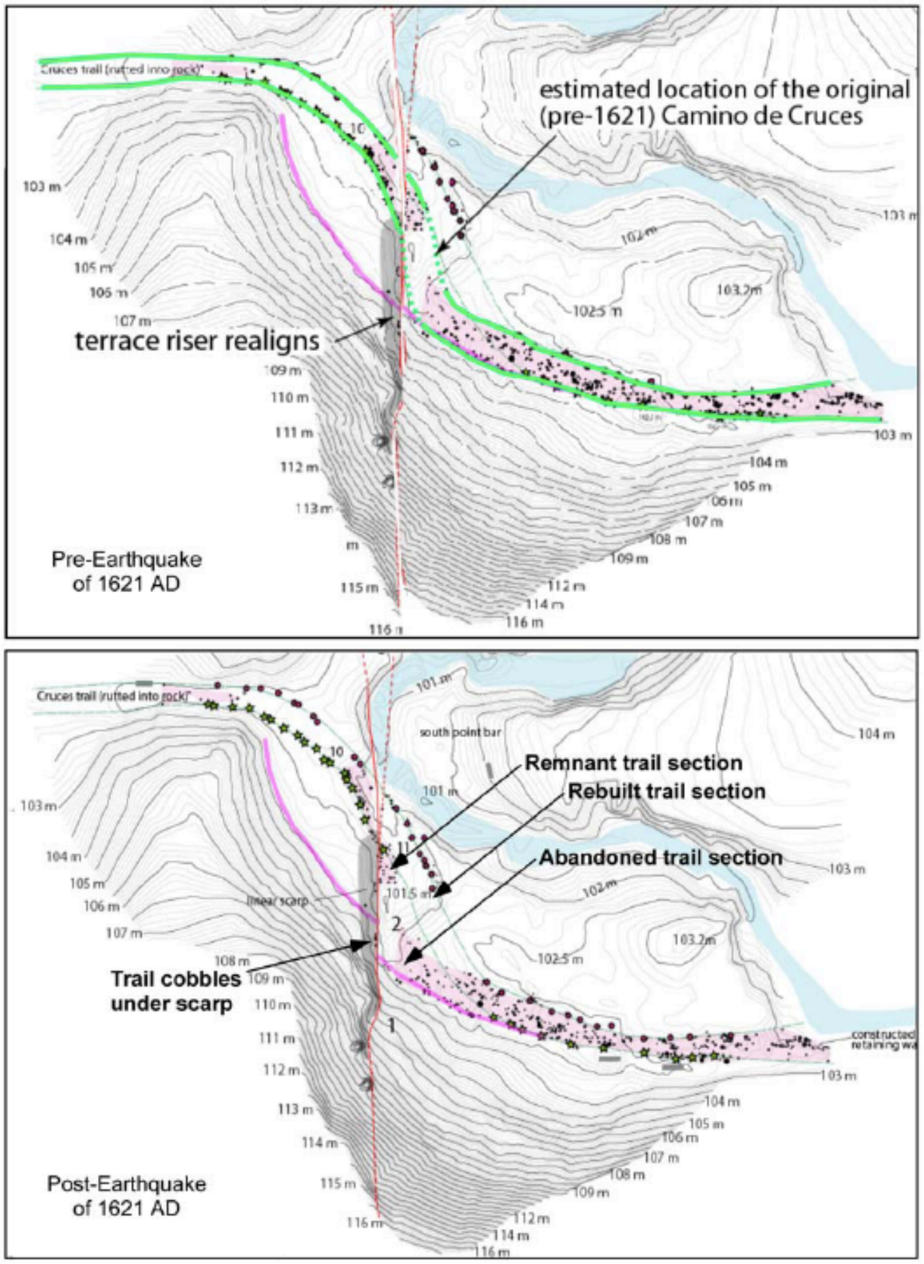

Fig. 5: Reconstruction of the Trail offset by back-slipping 2.8 meters along the fault results in a good fit for the pre-earthquake Trail location. The Trail cobbles and sizes are shown in their surveyed locations. The back-slipping results in a restoration of the terrace riser, and explains the pattern of pre- and post-displacement Trail cobbles adjacent to the fault.

Conclusions: Using numerous and independent lines of evidence, we conclude that the Pedro Miguel fault has historically ruptured through this area, producing a right-lateral surface offset of the Camino de Cruces of about 3 m, consistent with the findings from paleoseismic studies 20 km south. The displacements of all small-scale geomorphic features are consistent with the amount of displacement of the Camino de Cruces. The observation of Trail cobles under the fault scarp-derived colluvium strongly supports that the Trail had been completed before the offset.

The only reported earthquake, since the 1530s, large enough to generate a 3-meter displacement, is the May 2, 1621 Panamá Viejo earthquake. From this we conclude that the last rupture on the Pedro Miguel fault was the AD 1621 event, an earthquake that significantly damaged Panamá Viejo, and if repeated, would strongly shake the modern Panamá City and all of the Panamá Canal structures on the Pacific side. Because the Pedro Miguel fault has long been assumed to be inactive, these findings have been a surprise to the engineering community. Although the exposures of the fault offsetting late Holocene alluvium are geologically convincing, the archeoseismic evidence of the Camino de Cruces being offset by the fault has proven to be invaluable in gaining general acceptance of the seismic hazard posed by the Pedro Miguel fault.

Acknowledgments: We thank the Autoridad del Canal de Panamá for their support of this project, especially Luis Alfaro, Pastora Franceschi, Rodrigo Lam, and the Survey Division. We also thank all of the ECI staff that assisted, particularly Danielle Verdugo and Patrick Williams.

Reference: ECI, 2009, Appendix D: Documenting the Pedro Miguel Fault's AD 1621 Offset of the Camino de Cruces; *in* Quantitative Characterization of the Pedro Miguel and Miraflores Faults; unpublished Earth Consultants International consulting report prepared for the Autoridad del Canal de Panamá, February, 2009.

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