16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 4905
Registration Code: S-299167926

COSEISMIC FAULT DISPLACEMENTS ON THE PEDRO MIGUEL FAULT FOR DESIGN OF BORINQUÉN DAM, PANAMÁ CANAL EXPANSION

E. Gath[1] and T. González[2]

[1] *President, Earth Consultants International, gath@earthconsultants.com*
[2] *Vice President, Earth Consultants International, tgonzalez@earthconsultants.com*

Abstract

As part of the seismic hazard assessment for the Panamá Canal Expansion Project's design studies, we completed detailed paleoseismic investigations of the Pedro Miguel fault. Using tectonic geomorphic mapping, the previously assumed inactive fault was shown to right-laterally deform all fault-crossing streams. Paleoseismic trenching then demonstrated that the fault has experienced recurrent Holocene displacements. As such, the fault not only poses a shaking hazard to the Panamá Canal structures, it also crosses the proposed footprint of Borinquén Dam, a critical part of the Canal's expansion program. Borinquén Dam is composed of four discrete segments, is nearly 5 km in length and 10-12 meters high, and forms the approach channel from Gatún Lake to the new Pacific locks. Our studies of the fault are based in great part on the excavation and logging of about 90 trenches, including at four locations where we excavated the fault in 3-D to determine earthquake recurrence, displacement magnitudes and fault slip kinematics. At multiple sites we were able to determine and measure the displacement of three surface-rupturing earthquakes in the past 1600 years. The minimum displacement from all three events was 8.1 m, with the last event a 2.8 to 3.0-m rupture across the ca. AD 1533 Camino de Cruces occurring on May 2, 1621, indicating that all three earthquakes were of similar rupture magnitude. This paper reports on the last 3-D paleoseismic investigation conducted directly within the Borinquén Dam footprint that measured a 3.1 +0.3/-0.1 m right-lateral offset of a gravel-filled channel thalweg during the most recent earthquake, the AD 1621 Panamá Viejo event. At the surface, the fault exploits weak, low-angle, west-dipping bedding planes of the La Boca Formation to rupture as a series of north-stepping, en-echelon, west-dipping fault petals that roll over near the surface to near horizontal. The challenge for the dam's design was to correctly understand the location and geology of the fault crossing at the base of the dam's foundation, and to model the fault rupture kinematics through the foundation's geology and the dam's embankments.

Keywords: Fault Rupture; Dam Design; Paleoseismology; Panamá Canal

1. Introduction

Central Panamá had long been considered as having a low seismic hazard; however, in the past decade[1, 2, 3, 4, 5, 6] we have shown that not only is the area riddled with faults, but that many of these faults have experienced recurrent Holocene surface rupturing earthquakes[7]. Of these, the most important for the Panamá Canal's Expansion Project is the Pedro Miguel fault[8] because it extends across the Pacific Ocean portion of the project (Fig. 1). Our studies show that this 30- to 50-km-long fault, capable of a M7+ earthquake, has had multiple late Holocene surface rupturing earthquakes[7]. As such, the Pedro Miguel fault poses both a seismic shaking hazard to the overall project, and a surface rupture hazard to the new approach channel embankment dams that together are referred to as Borinquén Dam.

Between 2005 and 2007, based on the results of about 75 geologically logged trenches, numerous borings, and thousands of meters of geophysical transects, we mapped the Pedro Miguel fault through the expansion project's entire construction area, across the Canal between the Miraflores and Pedro Miguel Locks, and north almost to Lake Madden (Fig. 1)[4]. We also documented that the fault is almost a pure right-lateral strike-slip structure, has a late Pleistocene-Holocene slip rate of about 5 mm/yr (4.1 - 6.7 mm/yr), has ruptured at least three times in the past 1600 years (Fig. 2), and last ruptured about 2.8-3.0 meters right-laterally on May 2, 1621[7, 9].

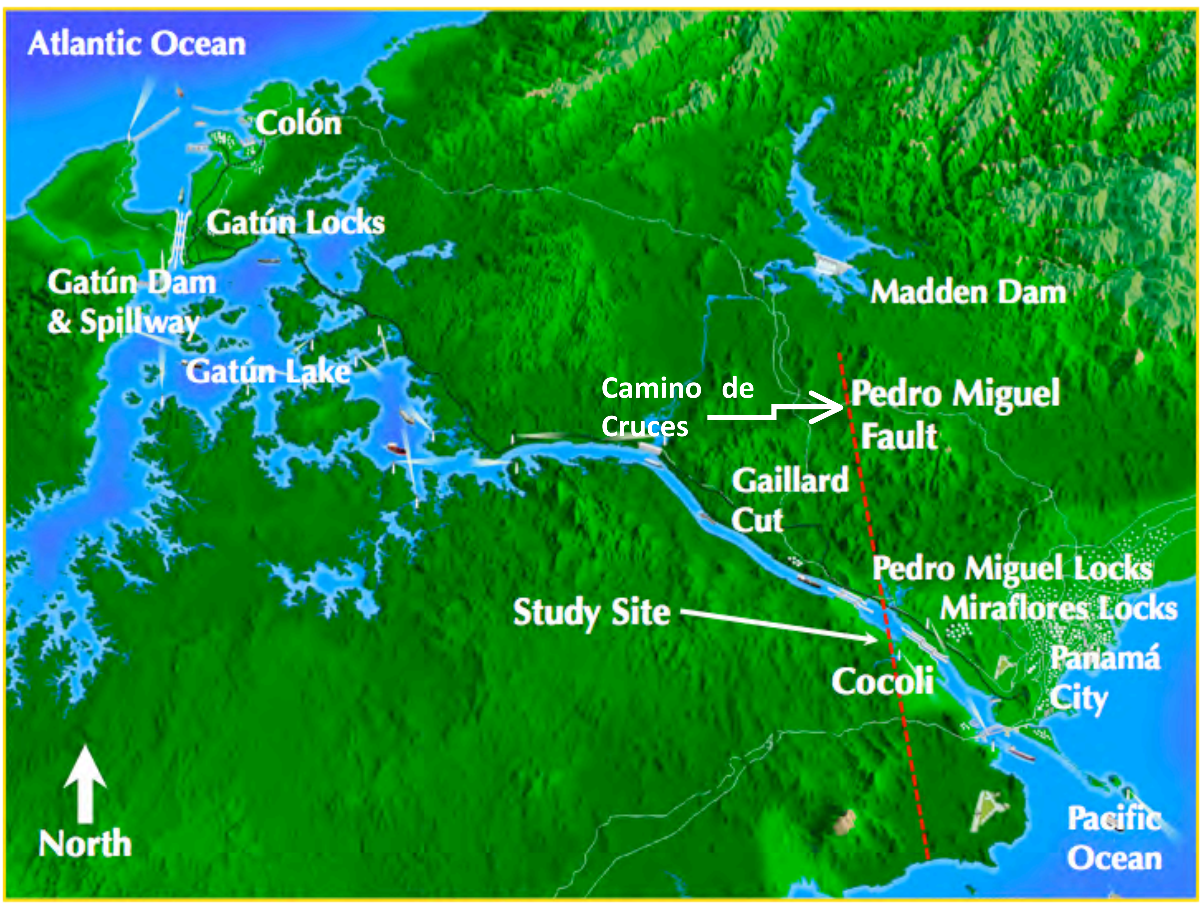


Fig. 1: Index map of central Panamá showing the principal features of the Panamá Canal, the trace of the Pedro Miguel fault (red dashed line), and the location of the Cocolí trenching site. The new Pacific approach channel lies to the southwest of both the Miraflores and Pedro Miguel Locks, bypassing them, with new locks in Cocolí, and elevating the channel with four dam segments to connect directly to the Gaillard Cut.

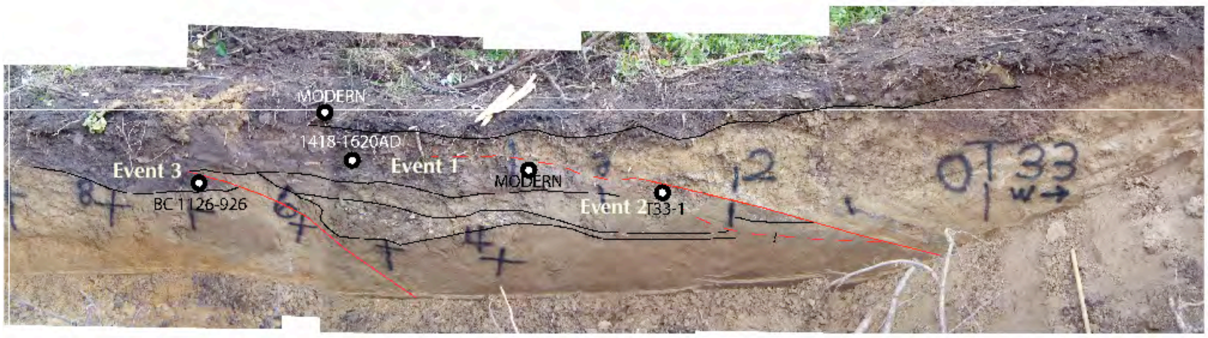


Fig. 2: Photo-mosaic of the south wall of Trench T-33[4] showing evidence for the last three events on the Pedro Miguel fault. The most recent event thrusts La Boca Formation (tan tuffaceous siltstone) over an A soil horizon that becomes the current modern soil horizon farther to the east (left in the photo). The surficial soil is significantly more fractured at the tip of the fault and the ground surface is deformed; both are indicators of a historical surface rupture. The low-angle nature of the fault at the surface is also well illustrated in this exposure.

The purpose of the study reported in this paper was to better quantify the slip kinematics from the AD 1621 earthquake directly within the Borinquén Dam's construction area. Considering the almost 400 years since the AD 1621 rupture, and at an ~5 mm/yr slip rate, approximately 2 m of strain have accumulated on the fault, providing a minimum displacement value for design. Prior studies within the expansion area were only able to generate minimum displacement values per event of about 2.1 meters due to site and geological constraints[7]. A 2.8- to 3.0-meter displacement measurement was tightly constrained (from the fault's offset of the Camino de Cruces (Fig. 1) and surrounding geomorphic features[7 & 9], but this location is more than 15 km north of the project. This paper summarizes a study we conducted directly within the Borinquén Dam's footprint, in an area where geomorphic evidence of the last earthquake appeared to be well preserved. The site is immediately south of and across the old Borinquén Road from our 2007 trenches PMS-45 and PMS-46[4], so the location of the Pedro Miguel fault in the near vicinity was already fairly well known (Fig. 3). Our objective was to investigate a small gully that appeared to be right-laterally deflected by about 3-4 meters (Fig. 4, left). If this could be confirmed as a single event, it would most likely be the AD 1621 event, providing a site-specific, and thus defensible value for use in the design of the dam. That the dam lies almost along the strike of the fault, and the fault's low dip angle, are significant additional complicating factors to the design (Fig. 3).

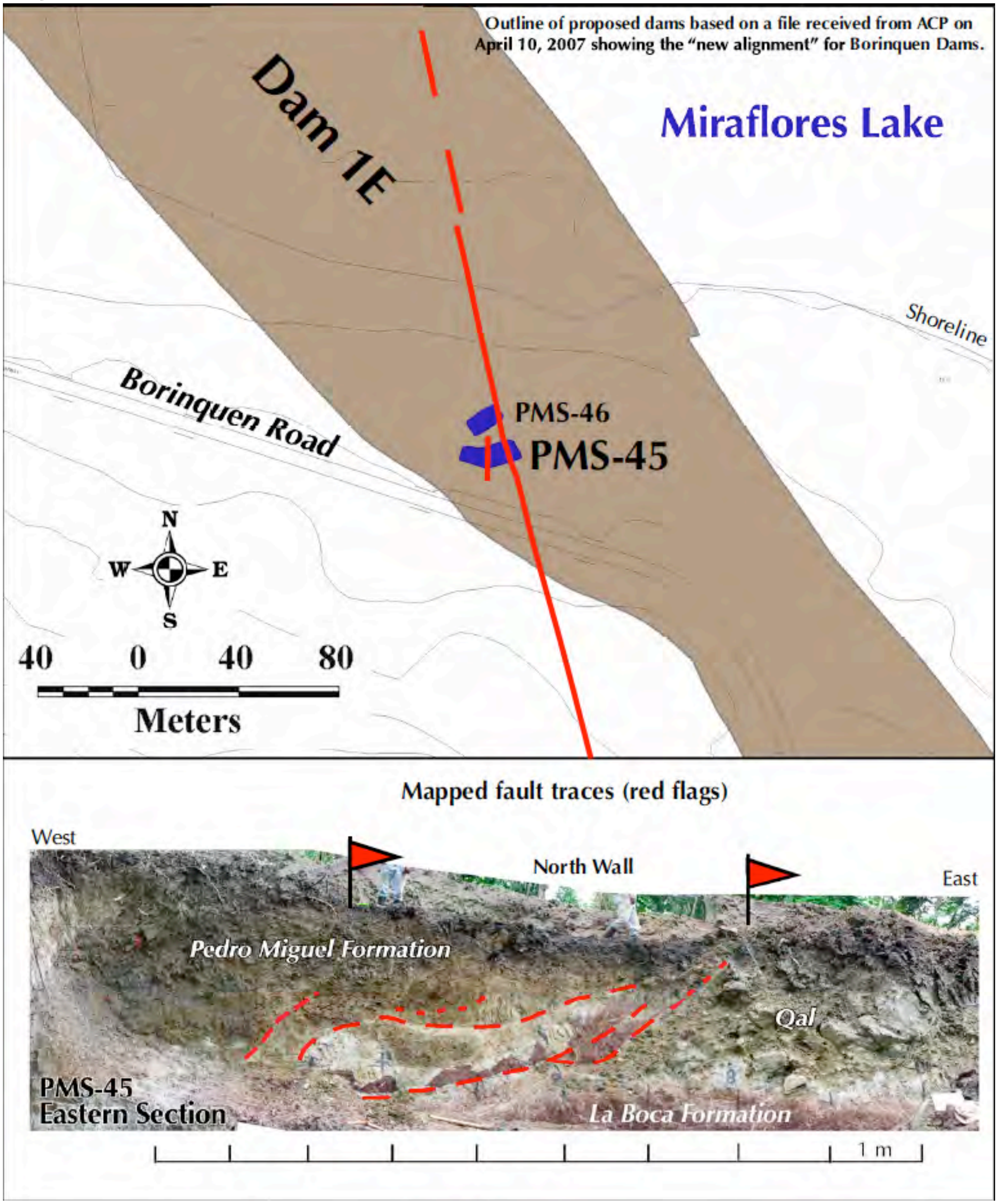


Fig. 3: Map and trench log from the ECI 2007 investigations of the location and activity of the Pedro Miguel fault through the proposed Borinquén Dam location[4]. Photo mosaic of the south wall of Trench PMS-45, excavated in 2007[4]. The exposure shows intercalated slivers of Pedro Miguel Formation (red volcaniclastics) and La Boca Formation (tan tuffaceous siltstones) thrust over latest Holocene alluvium composed of subrounded gravels and cobbles. The fault zone is composed of multiple, low-angle petals, the youngest of which appears to deform the modern A soil horizon and ground surface similar to T-33 (Fig. 2), strongly implying a historical age for the most recent event. Flags indicate the surface projection of the fault traces, but the shallow dip of the faults will affect their location at dam foundation depths.

2. Methodology

The intent of the investigation was to confirm the fault's location and identify piercing points that we could use to measure fault displacements across the site. This was done by excavating trenches on both sides of the offset channel (Fig. 5, left), and extending them perpendicularly across the fault (Fig. 5, right). The first trenches were to be located adjacent to, but outside the channel margins so as to locate the fault while preserving the channel form and the channel deposits for detailed reconstruction and measurements in subsequent trenches. Once the fault location was confirmed, fault-parallel trenches would be excavated across the channels on opposite sides of the fault, initially keeping them several meters from the fault (Fig. 4, right). These excavations would define the 3-D channel geometry away from the fault. After logging and surveying the channel margins and thalweg, both fault-parallel trenches would be progressively widened towards the fault by removing thin slices, with new logging and surveying of the channel forms after each slice. Eventually, the result would be a 3-D surveyed map of both sides of the channel as it interacts with the fault, and an accurate measurement of the channel's offset across the fault.

Fig. 4: (Left) Photo, looking south of the proposed trenching site before the vegetation was cleared. The Pedro Miguel fault was interpreted to trend sub-horizontally across the photo, between the two ACP geologists who are standing in the upper and lower channel courses, respectively, which appear to be displaced ~3 to 4 meters across the fault. On the left is the beheaded downstream segment of the channel, and on the right is the truncated upstream equivalent flowing into the fault. (Right) The same location with the vegetation removed, showing the planned trench locations perpendicular to, and parallel to, the Pedro Miguel fault, designed to reveal and accurately measure the offset of the small channel across the fault.

However, the complexity of the fault as expressed along multiple, low-angle, en-echelon, bedding-plane shears forced an equally complex investigation effort. In total, 15 trenches were excavated, geologically logged, and sequentially photographed for preparation of photo-mosaics. Key stratigraphic contacts and structural features were marked using various colored flagging tape, charcoal samples were collected, and each marked feature was GPS-surveyed. All survey data, including trench locations and surface topography (Fig. 5), were imported into a GIS environment for 3-D analysis.

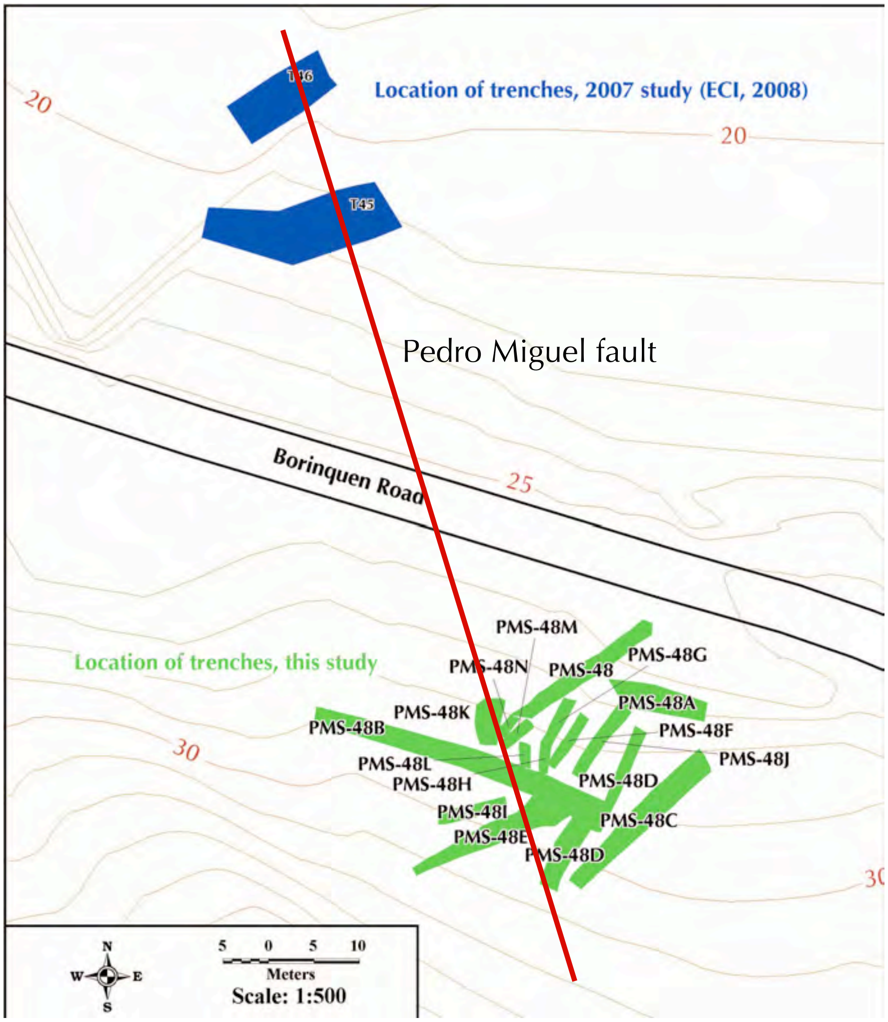


Fig. 5: Map of the trenching site (new trenches in green) relative to the 2007 trenches (in blue), the old Borinquén Road, and the simplified surface trace of the Pedro Miguel fault (red line) as mapped through the trenches. Miraflores Lake is just off the top of the map. In total 15 trenches were excavated to find the fault and to map an offset channel into, and across, the fault.

3. Results

We successfully located the Pedro Miguel fault trace and a channel that was truncated by, and was right-laterally offset across, the fault (Fig. 6). Trench PMS-48B (Figs. 7 & 8) exposed both the fault zone and a topographically subdued channel with a cobble-filled thalweg with well-defined margins. This deposit was overlain by less well-bounded sandy alluvium that was nevertheless discernible from the overlying colluvium. The basal cobbles were commonly encased in a distinctive light gray clay derived from weathered La Boca Formation. The channel itself was incised into weathered bedrock of the Pedro Miguel Formation which had been thrust atop the La Boca siltstone during previous earthquakes (Figs. 7 & 8).

We mapped the channel through the site using a series of closely spaced, 0.5- to 2-m wide trenches, with the channel margins flagged and then surveyed (Figs. 5 - 9). The survey data were plotted and the channel margins were projected into the fault (Fig. 10). The southern (right) margin of the upper channel deposits was better defined than the northern (left) margin, which tended to merge into slope-mantling colluvium. Using the survey data plots, both channel margins and both thalweg-filling cobble margins were projected into the fault from both sides. The projection of the cobbles is complicated by a 0.5-meter vertical (transpressional) component of slip at the tip of the most recently developed fault petal that elevated and exposed the cobbles at the surface, where they were removed by erosion in the area between the two walls of trench PMS-48H (Fig. 9). The sandy alluvial deposits were not affected by this uplift, implying that, following the most recent earthquake, the channel continued in its disrupted course, but transported only sand-sized sediments. The vertical component was localized to the fault tip where it ruptured through to the surface, as a long-channel gradient plot away from the fault does not show this uplift.

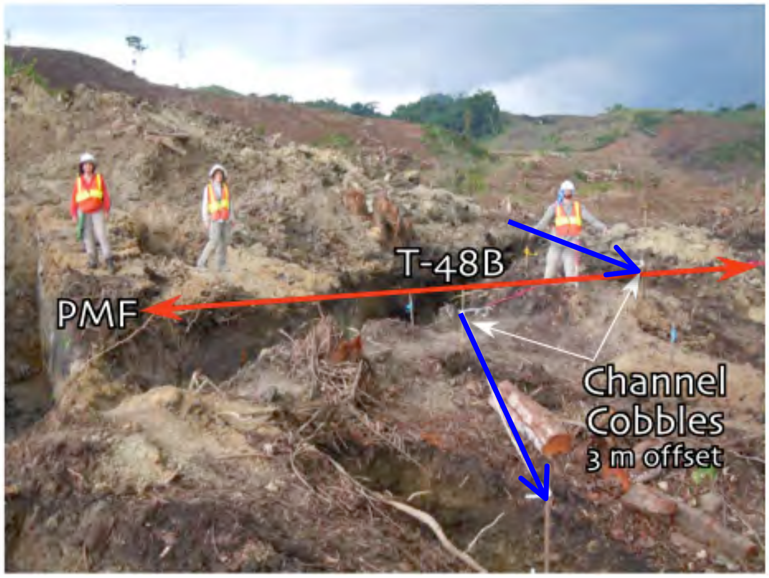


Fig. 6: Overview of the trenching site, showing the Pedro Miguel fault (PMF, red line), and the channel (cobbles) thalweg trend (blue lines) that is offset ~3.0 meters right-laterally across the fault. View to the southwest.

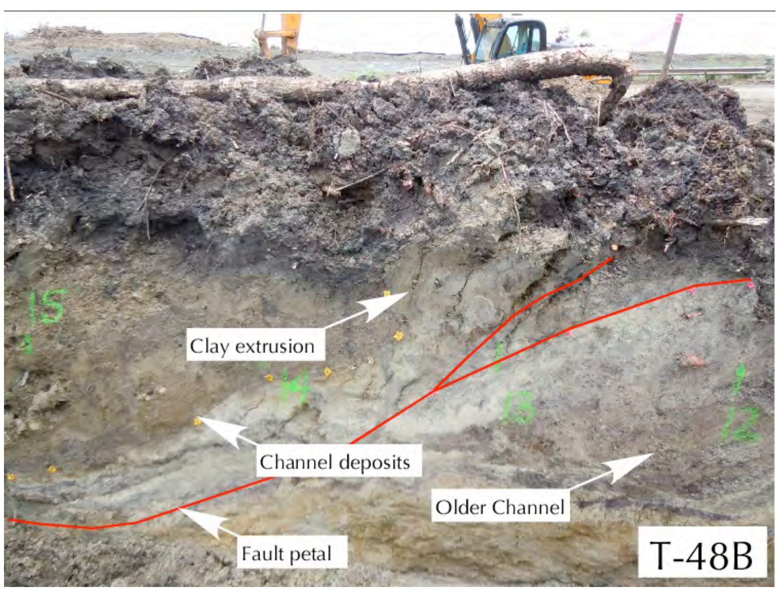


Fig. 7: Exposure of the Pedro Miguel fault on the northern wall of trench PSM-48B showing the near-surface low-angle petal structure of the fault as it extruded a grey clay plug into the modern A soil horizon and formed a surficial mole track during the last earthquake. The channel deposits in this exposure are not yet in fault contact, but were in contact at about the location of the backhoe at the top of the photo. The unit centered on Sta. 15, far right, is an older alluvial channel deposit thrust over by the most recent event fault petal, marked by the red lines.

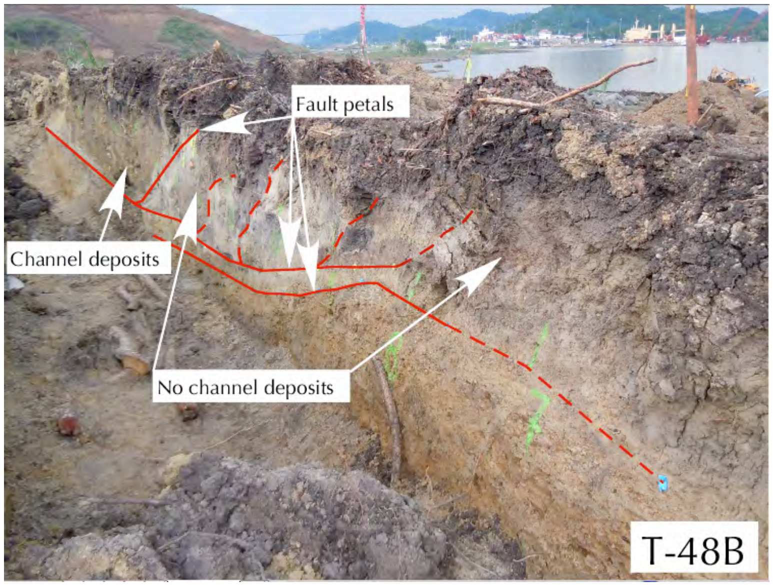


Fig. 8: Larger length exposure of the northern wall of trench PMS-48B looking to the north-northwest. The photo shows the low-angle nature of the fault and the multiple surfacing petals. The targeted channel deposits (Fig. 7) are in the distance (top left), flowing towards the location of Miraflores Lake to the right. The channel deposits were truncated by the fault at a location beyond this trench wall, to the right. The absence of equivalent channel deposits exposed on the southern wall of PMS-48B means that their displacement was less than the distance back to the trench wall. Therefore, the total offset of the channel lies within the area to the right of trench PMS-48B, and was not removed by the excavation of PMS-48B. (See Fig. 6 for an illustration.)

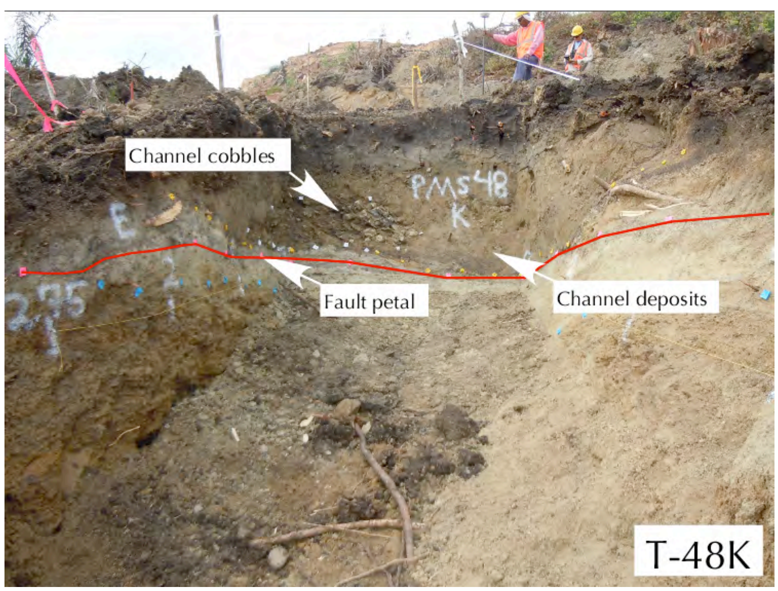


Fig. 9: Exposure of trench PMS-48K, looking south towards trench PMS-48B (Fig. 7), showing the full cross-section of the channel, still fully in the hanging wall, but nearly in fault contact.

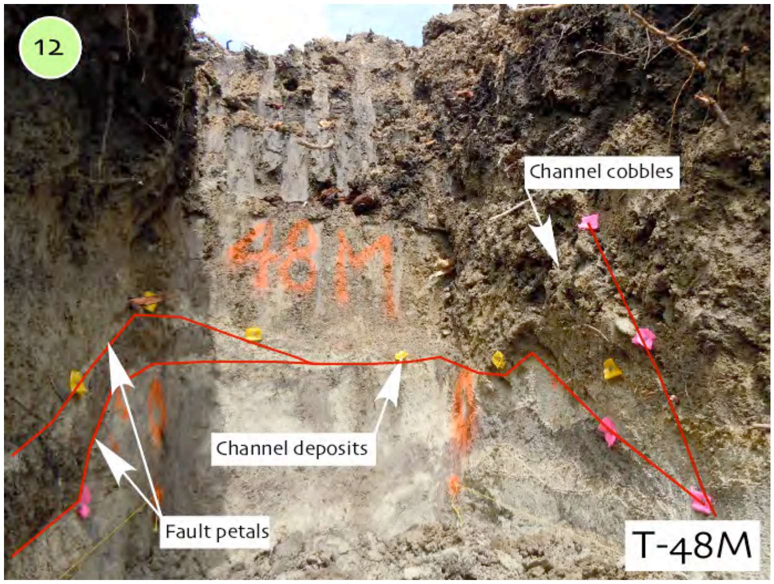


Fig. 9: Exposure of trench PMS-48M, immediately to the east of trench PMS-48K (Fig. 8) and looking south towards trench PMS-48B (Fig. 7). The photo shows the base of the channel deposits now partially in fault contact. Trench PMS-48N was subsequently excavated between K and M to provide increased accuracy to the fault/channel contact, and trenches PMS-48H and 48L were excavated to the east to provide similar control on the channel exiting the fault.

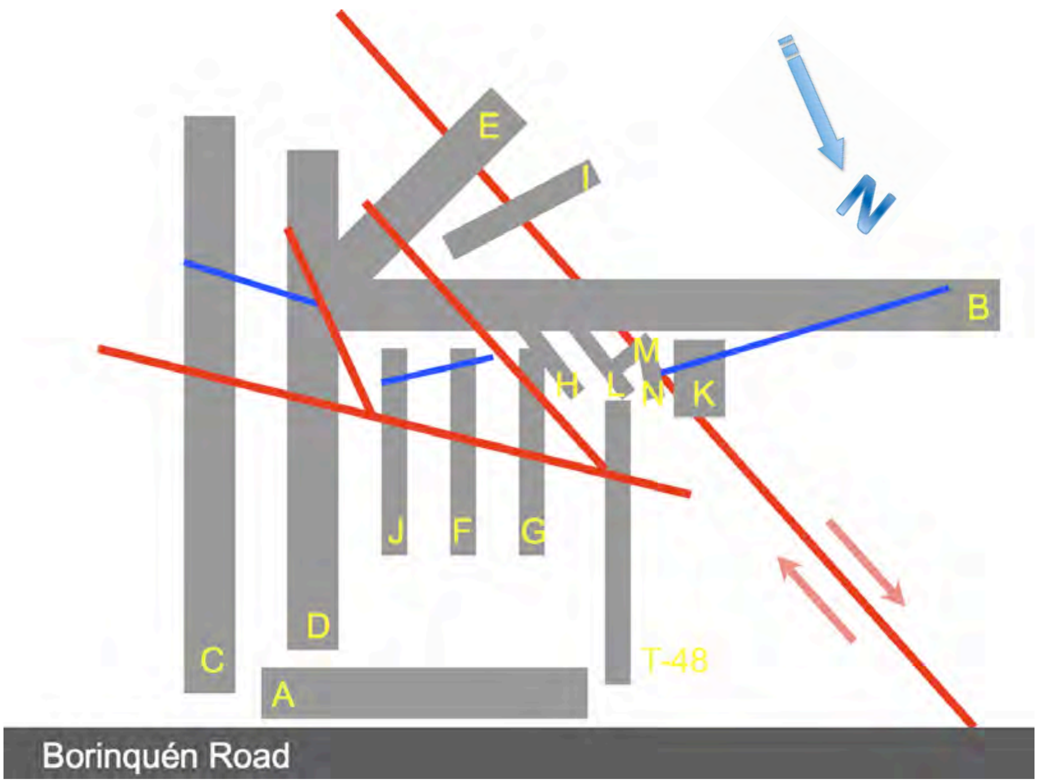


Fig. 10: Diagrammatic representation of the final Borinquén trenching site. Compare this figure with the surveyed map of the trenches in Figures 5 and 11. The en-echelon pattern of faulting, exploiting the low-dip bedding planes of the La Boca Formation (Fig. 8), acts as a conveyor belt, with each petal of the Pedro Miguel fault transferring strain from one to the next. As determined from the surveying of the trench data, the channel is sequentially displaced ~3 m across each fault petal.

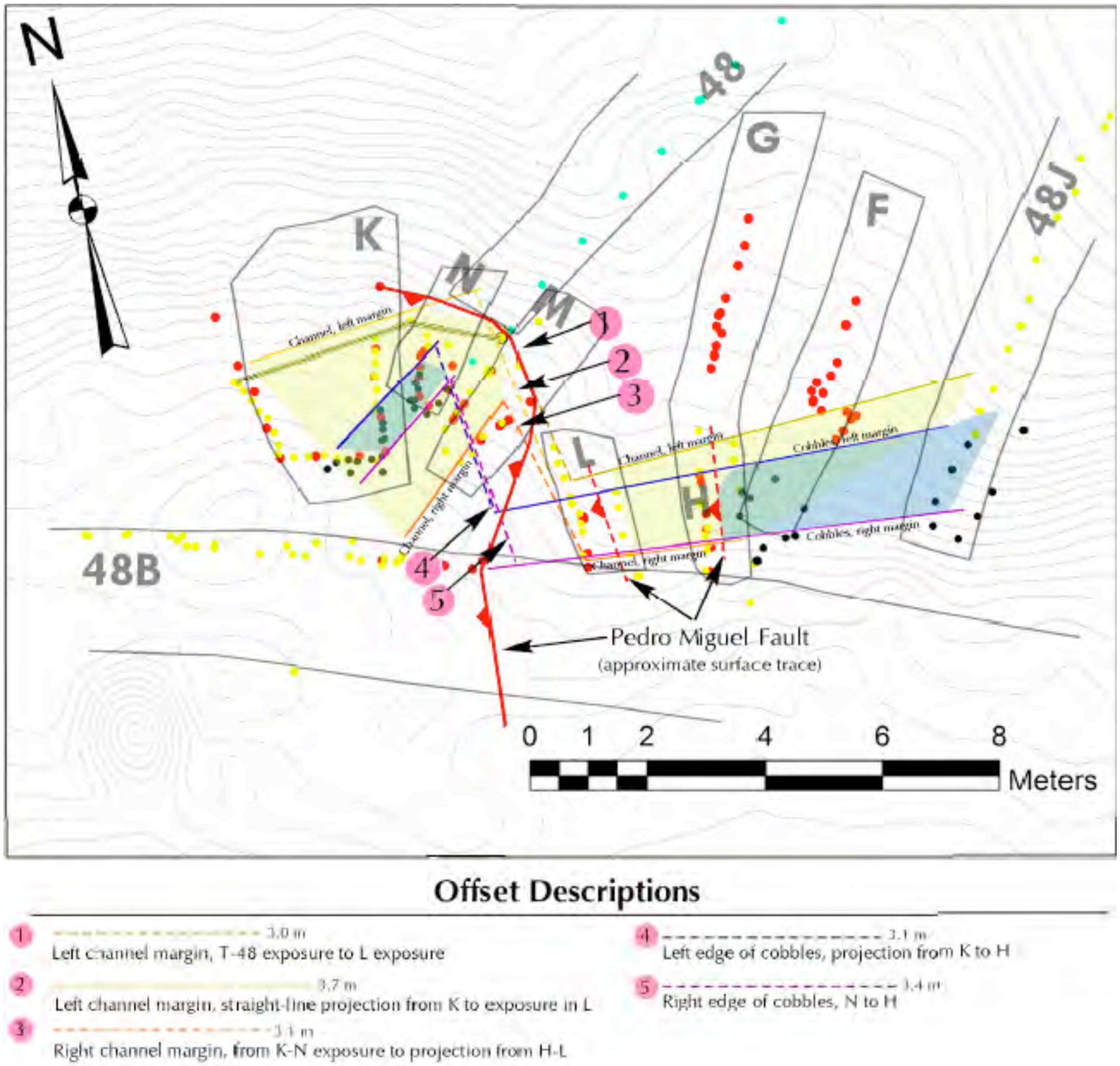
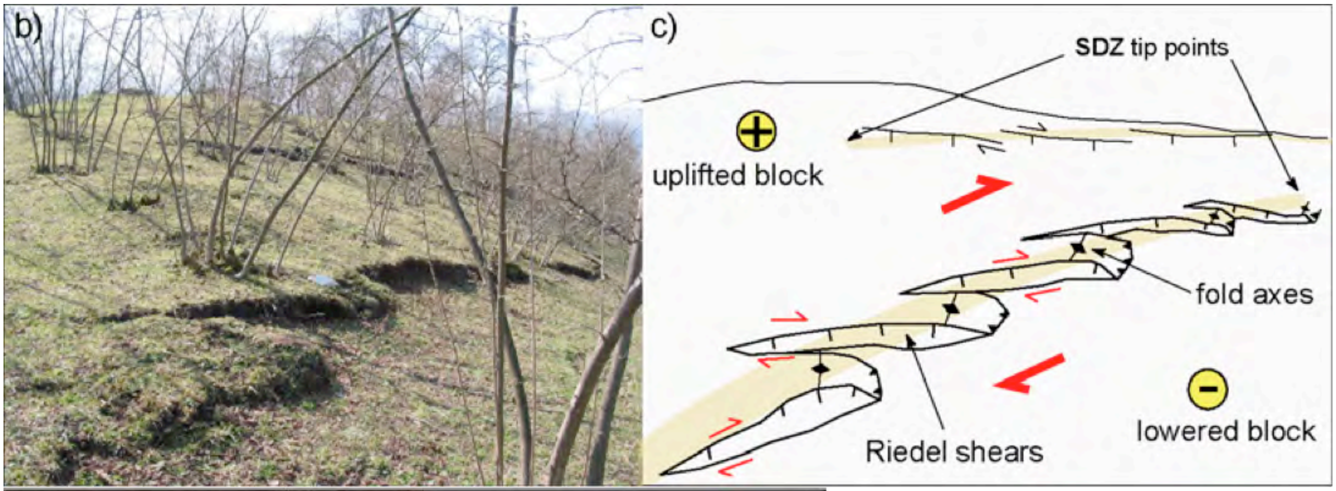


Fig.11: Composite plot of surveyed data showing trench locations, fault locations, channel margins, and channel margin projections into the fault. The yellow shading defines the channel margins, the blue shading defines the cobble-filled thalweg. The least-constrained channel margin is the northern margin of the sandy alluvial deposits. The southern margin of the channel was nearly vertical, cut into older fault petals and bedrock deposits. The best fit for the most recent offset of the channel is 3.0 to 3.4 meters, with 3.0 to 3.1 meters preferred because of the higher resolution of the offset thalweg margins.

The pattern of rupture for the Pedro Miguel fault is highly complex (Figs. 8, 10, & 11). In rupturing to the surface it exploits the shallow-dipping and low-strength bedding planes of the Pedro Miguel and La Boca formations as a series of transpressional rupture petals, stepping from one to the other along a series of high-angle faults that transfer shear from one petal to the next. This pattern of rupture is clearly surficial, and is not anticipated to extend below the depth at which the compressive loads would exceed the shear strengths of the bedding planes. Nevertheless, it makes the mitigation of surface rupture through the dam a significantly complex problem.

As an analogy, the surface rupture pattern of the 1999 Düzce earthquake in Turkey is proposed (Fig. 12). This M7.1 earthquake generated an average offset of 3 meters right-laterally, expressed across the landscape as an en-echelon, left-stepping, transpressional rupture[10, 11]. Each of these surficial fault petals is oblique to the true trend of the fault rupture, whereas the high-angle transfer faults best represent the strike of the fault.



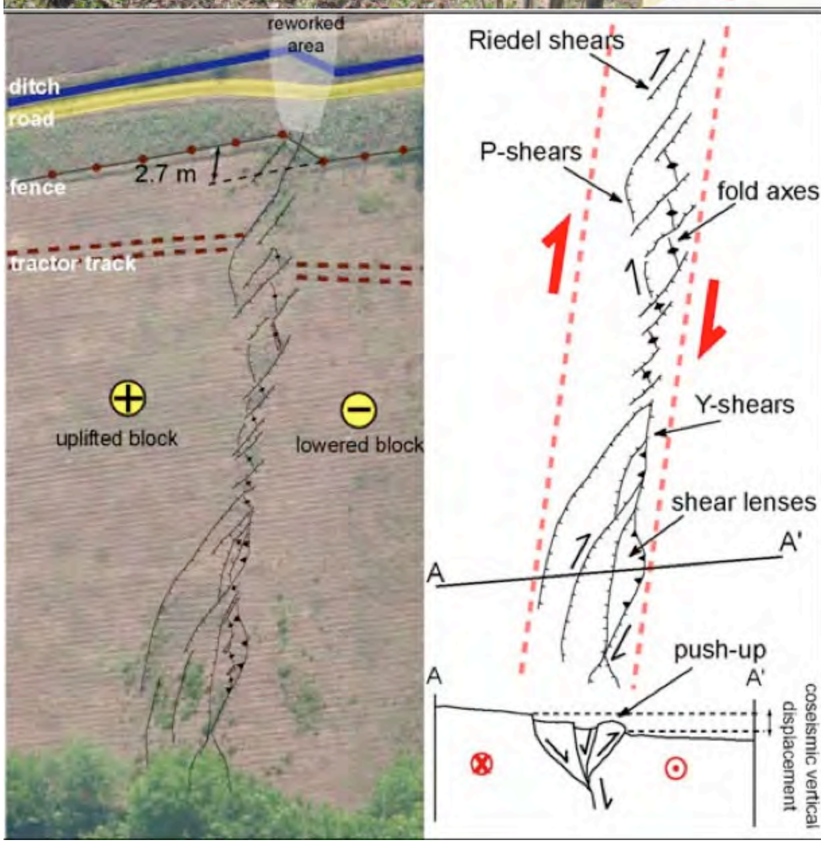


Fig. 12: The pattern of surface rupture from the 1999 Düzce earthquake (above) in Turkey is proposed as an analogy for the Pedro Miguel fault rupture. With a magnitude of M7.1, the Düzce fault ruptured with an average 3-meter offset, right-lateral, left-stepping, transpressional pattern (left) that is geologically similar to the Pedro Miguel fault through the Cocolí area. Figure modified from Pantosti et al. [10]

4. Conclusions

This study located the Pedro Miguel fault through the Borinquén Dam's footprint, and was able to resolve the near-surface fault-rupture kinematics and the May 2, 1621 coseismic displacement of a fault-crossing channel. The channel was displaced 3.0 to 3.4 meters (3.0 to 3.1 meters preferred) right-laterally (3.1 +0.3/-0.1 m), with approximately 0.5 meters of localized reverse uplift at the tip of the fault where it ruptured to the surface. These results are compatible with those of studies farther south that showed 8.1 meters of offset in the last three earthquakes, and the 2.8 to 3.0 meters of displacement measured at the Camino de Cruces offset farther north. The fault rupture is complicated by its en-echelon stepping, transpressional pattern which is due to the surface rupture exploiting the lower strength bedding planes of the La Boca and Pedro Miguel formations in the shallow subsurface. The fault rupture is probably simpler at depth, where the compressive loads exceed the bedding plane shear strengths. As such, the design of Borinquén Dam should have considered both the 3 meters of right lateral shear and the geology of the foundation upon which it is being constructed, and through which the fault will rupture.

5. Acknowledgements

Multiple people from the Autoridad del Canal de Panamá assisted in the logistics and field efforts for this study, especially Pastora Franceschi and Derek Irving from the geology staff. We also acknowledge Kay St. Peters and Barrett Salisbury of ECI for their valuable field assistance and Barrett's processing of the extensive survey data.

6. References

[1] Earth Consultants International, Inc. (ECI), 2005, Paleoseismic investigation of the Gatún and Limón faults in Central Panamá, ECI Project No. 2505; unpublished consulting report prepared for the Autoridad del Canal de Panamá, Project No. 2505, September 2005, 89p. + figures and appendices.

[2] Earth Consultants International (ECI), 2006, Geomorphic Evaluation of the Miraflores, Pedro Miguel, Azota, and Caballo Faults, Central Panamá; unpublished consulting report prepared for the Autoridad del Canal de Panamá, Project No. 2614.01, November 2006, 36p. + figures and appendices.

[3] Earth Consultants International (ECI), 2007, Paleoseismic Trenching of the Pedro Miguel Fault in Cocolí, Located Immediately Southwest of the Panamá Canal, Panamá; unpublished consulting report prepared for the Autoridad del Canal de Panamá, Project No. 2614.02, February 2007, 31p. + figures and appendices.

[4] Earth Consultants International (ECI), 2008, Quantitative Characterization of the Pedro Miguel Fault, Determination of Recency of Activity on the Miraflores Fault, and Detailed Mapping of the Active Faults Through the Proposed Borinquén Dam Location; unpublished consulting report prepared for the Autoridad del Canal de Panamá, Project No. 2708.05, January 2008.

[5] Earth Consultants International (ECI), 2009, Appendix D: Documenting the Pedro Miguel Fault's AD 1621 Offset of the Camino de Cruces; unpublished consulting report prepared for the Autoridad del Canal de Panamá, Project No. 2708.05, February 2009.

[6] Earth Consultants International (ECI), 2010, Additional Trenching of the Pedro Miguel and Miraflores faults in Cocoli, immediately southwest of the Panamá Canal; unpublished consulting report prepared for the Autoridad del Canal de Panamá, Project No. 3012, August 2010.

[7] Rockwell, T., Gath, E., Gonzalez, T., Madden, C., Verdugo, D., Lippincott, C., Dawson, T., Owen, L.A., Fuchs, M., Cadena, A., Williams, P., Weldon, E., and Franceschi, P., 2010, Neotectonics and paleoseismology of the Limón and Pedro Miguel faults in Panamá: Earthquake Hazard to the Panamá Canal; Bulletin of the Seismological Society of America, Vol. 100, No. 6, p. 3097-3129, doi: 10.1785/0120090342.

[8] Stewart, R.H., and Stewart, J.L., (compilers), in cooperation with Woodring, W.P., 1980, Geologic Map of the Panamá Canal and Vicinity, Republic of Panamá: U.S. Geological Survey Miscellaneous Investigations Series, Map I-1232, Scale: 1:100,000.

[9] Gath, E.M. and Rockwell, T.K., 2009, Coseismic offset of the Camino de Cruces confirms the Pedro Miguel fault as the cause of the AD 1621 Panamá Viejo earthquake: in Pérez-López, R., Grützner, C., Lario, J., Reicherter, K, and Silva, P.G. (eds), *Archeoseismology and Palaeoseismology in the Alpine-Himalayan Collisional Zone*: 1st INQUA-IGCP-567 International Workshop on Earthquake Archaeology and Palaeoseismology, Baelo Claudia (Cádiz), Spain, Abstracts Volume, p. 32-35.

[10] Pantosti, D., Pucci, S., Palyvos, N., De Martini, P.M., D'Addezio, G., Akinci, A., Zabci C., Collins, P., Storia Geofisica Ambiente, and Fantucci, R., 2006, Large Earthquake Faulting and Implications for the Seismic Hazard Assessment in Europe: The Izmit-Düzce earthquake sequence of August-November 1999 (Turkey, Mw 7.4, 7.1), Final Report: EC Project, EVG1-CT-2002-00069, 24p.
[Available: http://www.earth-prints.org/bitstream/2122/1046/1/RELIEF_INGV_final_report.pdf]

[11] Pucci, S., Palyvos, N., Zabci, C., Pantosti, D., and Barchi, M., 2006, Coseismic ruptures and tectonic landforms along the Düzce segment of the North Anatolian Fault Zone (Ms 7.1, November 1999): Journal of Geophysical Research, Vol. 111, B06312, doi:10.1029/2004JB003578.