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Tectonic geomorphic and paleoseismic investigation of the Gatún fault in central Panamá

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Abstract *The Gatún fault, a primary east-west structural feature in central Panama, has a strong geomorphic signature that can be readily observed in aerial photographs and digital elevation models. The fault forms an abrupt southern margin to the Sierra Maestra Mountains, and all rivers and streams that cross the fault are affected at the fault crossing. Most large rivers are left-laterally deflected, and all streams that cross the fault have a 1- to 2-meter, and locally as high as 5-meter near-vertical nickpoint at or immediately upstream of the fault. Paleoseismic trenching of the Gatún fault east of Gatún Lake has shown that this fault has experienced at least two, and possibly three, surface-rupturing earthquakes since 1490 AD. Based on 3-D trenching of a 3 ka channel thalweg that is offset 19-20 m, the left-lateral slip rate on the Gatún fault is 6-9 mm/yr with a maximum of 20% north-side up normal slip, and the most recent earthquake (possibly in 1849 AD) generated at least 0.7±0.2 meters of left-lateral surface offset that apparently went unnoticed at the time. Our best estimate is that this 40 km segment of the Gatún fault has a recurrence interval of ~M6.8 earthquakes every 100-170 years based on the last three events, but if the fault is capable of multi-segment, less-frequent ruptures, the earthquakes could potentially be as large as M7.4 if the entire 120 km fault were to rupture. We suspect, but cannot prove, that triggered slip resulted in soil fracturing on the Gatún fault during the 1991 M7.6 earthquake on the North Panama Deformed Belt off of Bocas del Toro. These findings are important for the seismic stability analysis of the AD 1913 Gatún Dam across the Chagres River, one of the most critical structures in the Panamá Canal.*

Key words*: Paleoseismology, neotectonics, Panamá, seismic hazard*

INTRODUCTION

As part of studies for the seismic hazard assessment for the Panama Canal Expansion Project, extensive geological studies were completed for several prominent faults within the east-central part of the Canal watershed (ECI 2005, 2006, 2007, & 2008). These faults (Fig. 1), previously assumed to be inactive, were instead all confirmed to have experienced multiple, Holocene-age, surface-rupturing earthquakes.

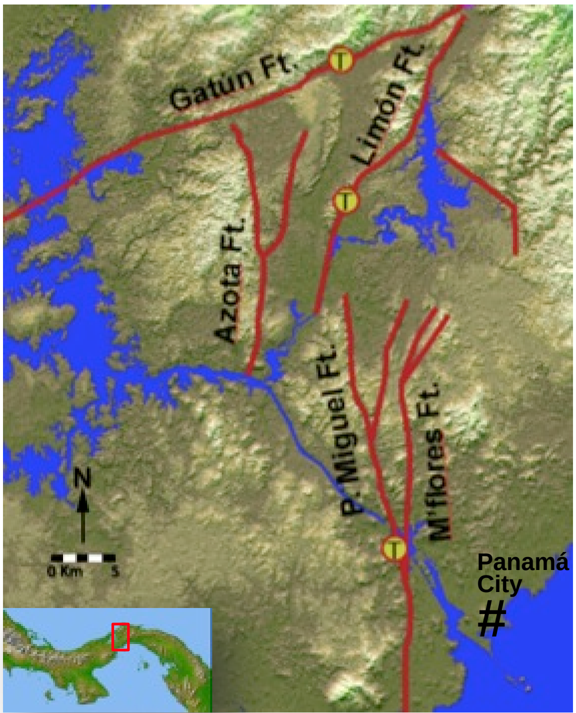

Fig. 1: Holocene fault map of Central Panamá and the Panamá Canal area, based on recent investigations (ECI 2005, 2006, 2007, & 2008). The circled T indicates sites where 3-D paleoseismic studies have been conducted.

The Limón and Pedro Miguel faults were both shown to have produced three large earthquakes in the last 1500 years, and ruptured together in a 3 m event as the 1621 AD Panamá Viejo earthquake (Rockwell et al., 2010b). The Azota and Miraflores faults were also both confirmed as Holocene structures (ECI, 2006). This paper summarizes the geomorphic mapping and paleoseismic trenching investigation for the Gatún fault at the location shown on Fig. 1.

The Gatún fault trends generally east-west across the southern margin of the Sierra Maestra mountain range separating the dominantly Mesozoic igneous rocks to the north from Cenozoic sedimentary strata to the south (Fig. 2). The fault extends east as far as the San Blas Islands for a total length of 100-120 km, and may extend another 100 km west of Gatún Lake along a prominent lineament. No historical earthquakes are associated with the Gatún fault, but its westward extension places it less than 10 km from Gatún Dam and Locks, the major structure across the Chagres River that allows the Canal to function. As such, understanding and mitigating its seismic hazard is critical to the Canal's future operations.

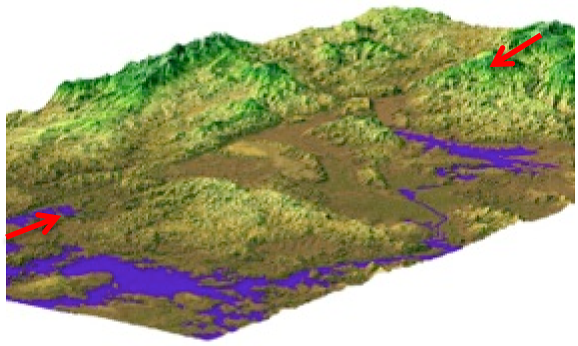

Fig. 2: DEM terrain model showing the spectacular geomorphic expression of the ~E-W trending Gatún fault

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(red arrows) across the southern front of the Sierra Maestra range.

A tectonic geomorphic strip map was prepared of the 40 km segment of the fault between Gatun Lake, east to the Chagres River (Fig. 1) (ECI, 2005). On the ground, the surficial geomorphology is equally spectacular with all drainages across the fault left-laterally deflected, stream knickpoints, and small scarps across fan surfaces. The smallest left-lateral deflection observed was ~2 m, with a 0.5 m vertical scarp, while the largest was ~150 m with a scarp over 10 m high (Figs 3, 4, & 5).

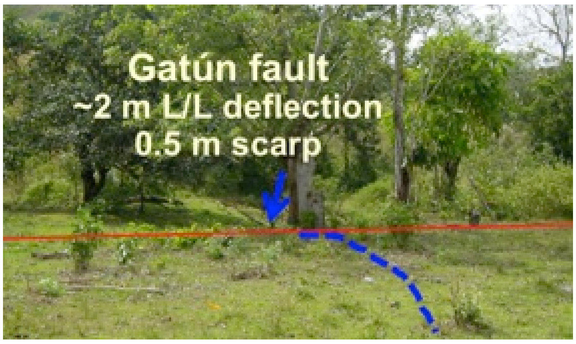

Fig. 3: Stream deflection of ~2 m left-lateral across the Gatún fault. This deflection is uphill to the regional drainage (to the left in the photo).

Fig. 4: Left-lateral stream deflection of ~150 m (well outside the photo view) across the Gatún fault east of Gatún Lake. An increased deflection of larger rivers is an indicator of progressive tectonic offsets.

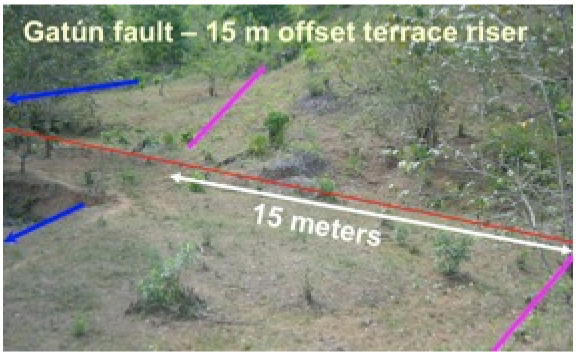

Fig. 5: Sharp stream deflection (blue lines) of ~10 m left-lateral across the Gatún fault east of Gatún Lake. Terrace risers (purple lines) are offset 15 m. Exposed in the terrace deposits is a piece of pottery (Fig. 6).

Fig. 6: Large pottery fragment exposed ~1 m below the surface, lying on top of a buried paleosol within the offset terrace deposits. Assuming that such pottery was first found in Panamá <2500 years ago, its presence incorporated into the abandoned terrace surface indicates that it has been offset equivalently to the terrace riser, yielding a 6-9 mm/yr slip rate.

The clear presence of youthful tectonic geomorphic features, the increased deflections of larger rivers over smaller streams indicating a temporal progression of offsets, and the potential for a 6-9 m/yr slip rate were dramatic findings for an assumed inactive fault. A paleoseismic trenching study was authorized to confirm the geomorphic observations and collect data on slip rate, event recurrence, displacement magnitudes, and slip kinematics.

INVESTIGATION

Based on the strip map and field reconnaissance, several locations were considered for the trenching study. Shallow groundwater was a constraint at the site in Fig. 3, while site access was a constraint at the pottery site (Figs. 5 & 6). A site about 300m east of Fig. 4, and geomorphically similar to the Fig. 5 site, was chosen for the trenching study (Figs. 7 & 8). At this site, the primary objective was to determine a Holocene slip rate by accurately measuring the offset and determining the age of a channel that had been left-deflected ~20 m across the fault.

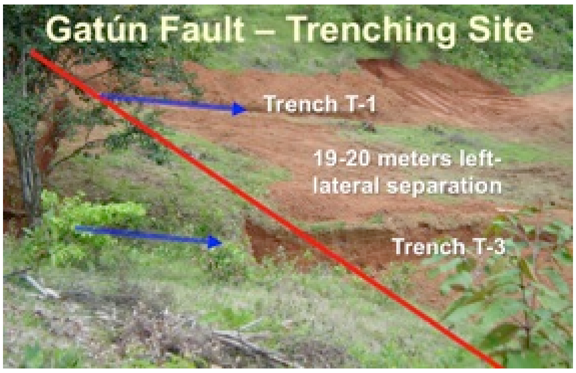

Fig. 7: Site of the 3-D trenching study of the Gatún fault. A stream enters the fault from the left of the image, and its former channel margin (rising from the T-1 location) has been translated 19-20 m leftward across the fault. The modern channel exposed in T-3 has recently been captured to the right, into the large river system shown in Fig. 4.

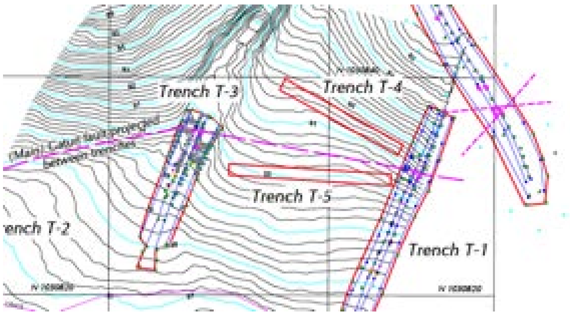

Fig. 8: Map of the principal trenches. T-1 was emplaced to constrain the long-term slip rate, T- 4 & 5 were dug to look for secondary entry and exit channels, and T-3 focused on the youngest event chronology and kinematics. Primary (blue) contours are meters.

Fig. 9: Trenching parallel to the fault (red line) to look for younger channels that would indicate smaller offsets to help confirm the long-term slip rate calculated from the Trench T-1 offset of the ~3 ka basal sediments (Fig. 10). No additional channels were found.

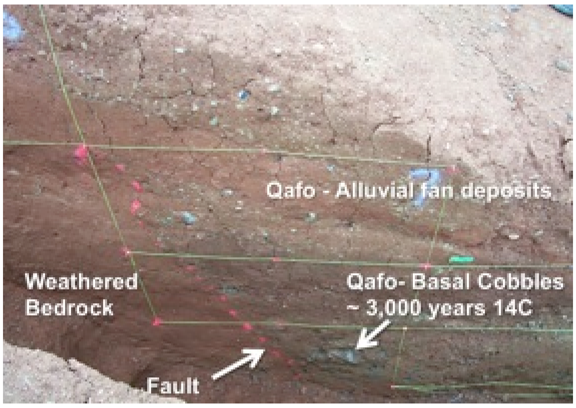

Fig. 10: Offset alluvial deposits against the weathered bedrock as exposed in Trench T-1. Undated colluvial and alluvial units cap the fault within the uppermost 75 cm of the trench exposure, but upslope fractures (not shown) penetrate to the original ground surface. Grids are 1.0 m horizontal and vertical.

A charcoal sample collected from within the basal cobbles of T-1 (Fig. 10) yielded an age of 3155±35 ybp and a second sample 2730±35 ybp was obtained 1.5 m higher. We interpret these cobbles to represent when the stream first penetrated across the fault, and thus this represents the total fault offset since that time. Based on the 19-20 m left-lateral offset of the channel margin from its piercing point entry across the fault, and the absence of any other entry or exit channels, we conclude that the entire separation is due to fault offset.

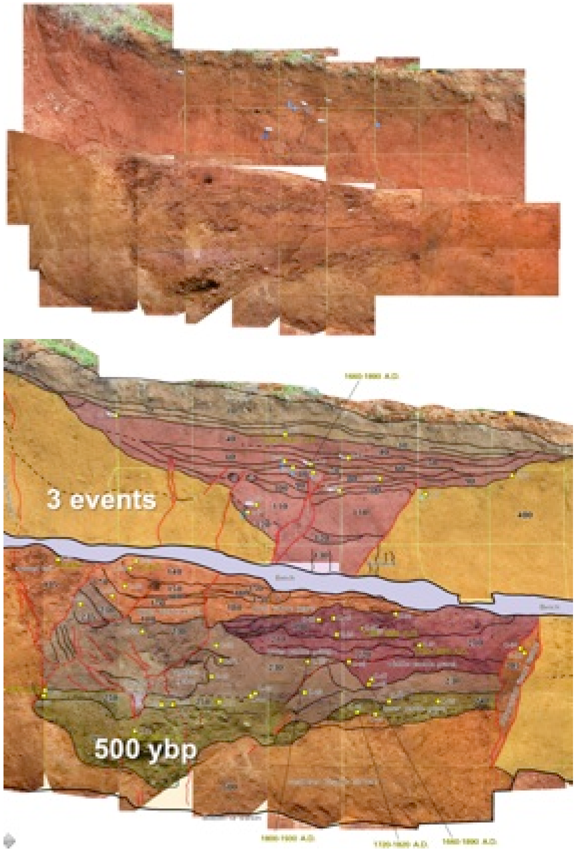

Fig. 11: Photo mosaic (upper) and graphic log (lower) of the eastern wall of Trench T-3 (see Fig. 11) showing the youngest alluvial deposits incised post-capture into the older (1-3 ka) deposits. Based on stratigraphic fault terminations, we interpreted 3 events within these 500-year deposits, with the last event potentially in 1849 AD. Charcoal within fractures that penetrate almost to the ground surface yielded post-1950 AD radiocarbon dates, from which we infer a potential (small) triggered slip event from the M7.6 1991 Limón (Costa Rica) earthquake on the North Panama Deformed Belt.

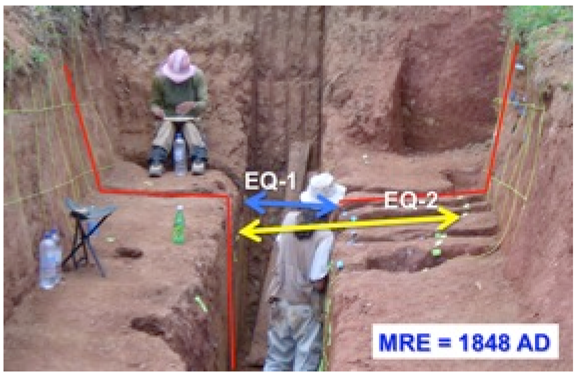

Fig. 12: Hand excavation of small trenches into the eastern bench of Trench T-3 allowed us to define and measure the fault displacement for the most recent (blue flags) and penultimate (yellow flags) events based on the offset of discrete channel margins. The MRE was measured at 0.7±0.2 m and the penultimate event a cumulative 1.4±0.3 m. The ~500 year third event was displaced beyond the 2 m exposure afforded by the bench.

Based on the geomorphic expression of the terrace riser, and the elevation of the base of the alluvial cobbles and the upstream channel thalweg, the vertical separation across the fault is about 3-4 m in 3 ka, or 15-20% of the ~20 m left-lateral horizontal displacement.

An event chronology was obtained from the youngest sediments exposed in T-3, incised into the 3 ka older alluvium. These deposits were radiocarbon dated at ~1460 AD at the base, up to about the mid-1800s. Three events were interpreted based on stratigraphic terminations of fault tips, with the last two events accurately measured at ~0.7 m left-lateral per event, and the most recent event possibly 1849 AD. Modern-dating charcoal was obtained from a fissure that cut across all other strata, from which we infer a more recent small surface cracking, potentially triggered slip from the 1991 Limón event on the North Panama Deformed Belt.

DISCUSSION

The Gatún fault has been shown to be a significant seismic hazard to central Panamá and the Panamá Canal. Based on detailed paleoseismic investigations, it has a late Holocene (3 ka) slip rate of 6-9 mm/yr, and has generated three surface-rupturing earthquakes of ~0.7 m left-lateral offset each in the past 500 years, Three events in 500 years averages 167 years. But, the most-recent event is clearly historic, possibly 1849 AD, or 166 years ago. Subtracting that time since the 1849 AD event from the ~500 year oldest determined event, leaves 334 years into which to squeeze three events. Assuming the oldest event occurred exactly 500 years ago leaves two additional events in 334 years, or 167 years between events.

But, for a 40 km fault, 0.7 m displacements (M6.8) seem small. It is possible that these last three events are the tip of a seismic cluster, and the 166-year recurrence interval is abnormally short. Using the 20-meter displacement of the 3 ka channel in T-1, and 0.7 m events, requires ~30 similar events with a recurrence of 100 years, or a few larger events. No matter how the numbers are examined, this is a fault that is near its seismic recurrence, based on the last three ruptures.

Lastly, it is not yet clear how significant a role the Gatún fault plays in the overall tectonic deformation of Panamá, but Fig. 13 shows a possible 20 km reconstruction of the principal mountain ranges of central Panamá along the Gatún fault and an additional 80+ km westerly extension. This model, incorporated by Rockwell et al., (2010a), restores the two mountain ranges, explains the lowlands now forming Gatún Lake, fills in the basin now bounded by the Limón fault, and extends the Gatún fault well to the west into the interior of Panamá. Obviously earthquake ruptures larger than a M6.8 are a possibility.

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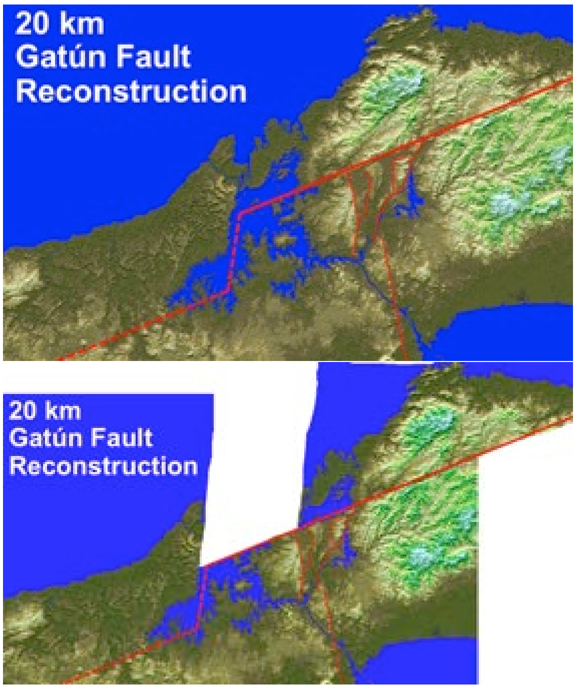

Fig. 13: 20 km displacement reconstruction of central Panamá by retro-deforming along the Gatún fault. At 6-9 mm/yr, this displacement would require 2-3 Ma, almost exactly when Panamá is thought to have sealed the gap between the Pacific and the Atlantic Oceans at the beginning of the Pleistocene.

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