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Holocene Faulting of the Cerro Goden Fault, Western Puerto Rico

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Abstract

Six trenches excavated across surface projections of subsurface disruptions revealed in high-resolution seismic reflection data exposed no evidence of surface faulting along the projection of the Cerro Goden fault in western Puerto Rico. The Cerro Goden Fault runs along the base of the La Cadena de San Francisco range north of the seismically active Añasco Valley in western Puerto Rico and joins with the Great Southern Puerto Rico Fault zone. The fault zone disrupts Eocene and older rocks but its Quaternary history is unclear. Offshore investigations suggest the fault cuts the sea floor (Grindlay et al., 2005), and a reconnaissance study by Mann et al. (2005) found geomorphic evidence of Quaternary displacement in the Añasco Valley. Results of a U.S. Geological Survey

high-resolution seismic survey across the projection of the fault in the Añasco Valley in 2004 suggested the presence of several possible fault strands reaching the surface. In 2004 and 2005, we excavated six trenches where the seismic data indicated fault strands disrupting sediments within the upper few meters. The trenches ranged in depth from 2 - 5 meters, but in none of the trenches was there evidence of surface faulting. However, in all but one of the trenches, a stratigraphic discontinuity appeared at the location of a predicted fault. Several trenches exposed a mountain-front-facing subsurface scarp, which may have been produced by faulting that terminated below the trench floor. Late Holocene fluvial sediments have been deposited against this scarp and have buried it but are unfaulted.

Introduction

Puerto Rico lies within the complex plate boundary zone between the North American and Caribbean plates (Figure 1). The Caribbean plate, of which Puerto Rico is a part, is moving east-northeast at 19-20 mm/yr relative to the North American plate (Jansma et al., 2000; Calais et al., 2002). To the east, at the lesser Antilles, the plate boundary trends north-northwest and results in nearly orthogonal subduction, but at Puerto Rico and to the west, the plate boundary is subparallel to the plate motion direction, generating dominantly left-lateral strike-slip (Mann et al., 1998; DeMets et al., 2000; Bilich et al., 2001; McCann, 2002). This plate configuration creates a complex deformation zone within and around Puerto Rico, which includes elements of compression, strike-slip, and extension accommodated on numerous major structures including the Puerto Rico Trench Fault to the north and Muertos Trough to the south, the North and South Puerto Rico Slope Fault Zones and the Septentrional Fault Zone to the north and northwest, and extensional faults in the Mona and Anegada Passages to west and east respectively (Masson and Scanlon, 1991) (Figure 2).

Neotectonic models of the Puerto Rico region based on seismicity (Dolan and Wald, 1998), marine geophysics (Dillon *et al.*, 1996; Grindlay *et al.*, 1997; van Gestel *et al.*, 1998), and GPS (Jansma et al., 2000), suggest that Puerto is moving eastward about 5 mm/yr faster than Hispaniola, possibly because Hispaniola's motion has been slowed by its collision with the Bahama platform (Vogt et al., 1976; Mann et al., 1995; Dolan et al., 1998). This relative motion between Hispaniola and Puerto Rico is probably accommodated primarily on extensional Quaternary faults within the Mona Passage, especially the Mona Rift graben. GPS studies indicate that most of the relative plate motion is accommodated on offshore structures. However, up to 3 mm/yr is not accounted for offshore, and some of the left-lateral plate motion and relative extension between Hispaniola and Puerto Rico is probably accommodated onshore in western Puerto Rico. Substantial shallow seismicity in western Puerto Rico supports this hypothesis (Asencio, 1980).

Onshore faulting

Until recently, there have been few investigations of active faulting in Puerto Rico (McCann, 1985; Moya and McCann, 1991; Joyce et al., 1987). Numerous bedrock faults have been mapped in Puerto Rico, most notably the Great Southern Puerto Rico fault zone and the Great Northern Puerto Rico fault zone, which traverse the northeastern and southwestern reaches of the island respectively, as well as smaller faults such as the Cerro Goden, Punta Algarobbo/Mayaguez, and Punta Guanajibo/Punta Arenas faults (Figure 3). None of these faults, however, has been shown definitively to have Holocene activity. Most rocks exposed in the island are older than Quaternary, limiting easy assessment of recent movement on faults. Furthermore, because most of the relative plate motion can be accounted for on offshore structures, Jansma and others (2000) concluded there is little if any onshore Holocene faulting, and early seismic hazard models reflected that assessment. However, the onshore seismicity as well as Puerto Rico's location between numerous large active structures suggests that there may be active faults in the western part of the island.

Prentice and Mann (2005) studied air photos of western Puerto Rico and saw a fault scarp in the Lajas valley in southwest Puerto Rico. Trenching across the fault scarp showed that the South Lajas fault was an active Holocene structure, with movement within the past 5000 years. This was the first fault to be examined in detail, and it has been active in the Holocene. In addition, recent paleoliquefaction studies have revealed evidence of liquefaction-inducing ground shaking in the late Holocene in western Puerto Rico (Tuttle et al., 2005). Although determining the source fault of earthquakes from liquefaction features can be difficult, the distribution and magnitude of liquefaction deposits suggests nearby sources, possibly onshore faults. These studies indicate that earlier assumptions that Puerto Rico lacks onshore Holocene active faults are incorrect, and complete seismic hazard estimations require further study to determine the extent, timing, and size of Holocene faulting throughout the island.

Although there are large faults offshore surrounding Puerto Rico that are capable of generating earthquakes greater than M7, which can cause significant damage on the island, the greatest risk may come from onshore faults that are nearer to population centers. The South Lajas fault is in a relatively unpopulated rural area and so may not pose a large risk to life and property. However, other faults in more populated regions whose activity levels have not yet been determined may present a serious hazard. One such fault is the Cerro Goden fault located near Mayaguez, the third largest city in Puerto Rico (Figure 3).

Previous work on the Cerro Goden fault

The Cerro Goden fault has been mapped as a left-lateral transpressional bedrock fault displacing Eocene and older rocks (Glover 1971; Erikson et al., 1990). However, until recently, its Quaternary history was unknown. It is associated with a steep south-facing escarpment in the Cadena de San Francisco range north of Rio Añasco (Figure 4). The escarpment is about 500 m north of the trace of the Cerro Goden bedrock fault, which outcrops in bedrock hills at the eastern edge of the Añasco Valley. This suggests that the escarpment may be ultimately tectonically controlled but has retreated northward due to erosion (Mann et al., 2005). The youngest rocks known to be affected by the Cerro Goden fault are Eocene in age, but the absence of post-Eocene rocks in the vicinity of the fault leaves open the possibility that the fault may still be active. Offshore bathymetric and seismic reflection studies suggest that there is a fault offshore and on strike with the projected Cerro Goden fault that disrupts Holocene sediments and the sea floor from the coast into the Mona Passage to the west (Grindlay et al., 2000; Grindlay et al., 2005). Field and air photo investigations show evidence of Quaternary faulting in at least the western reaches of the Cerro Goden fault (Mann et al., 2005).

Seismic Reflection and Refraction Surveys

In April 2004, researchers from the U.S. Geological Survey conducted two high-resolution seismic surveys crossing the projection of the fault in the Añasco Valley to locate possible fault strands in the subsurface. The sites for the surveys, called the Heno and Escuela sites, were selected to cross the projection of the Cerro Goden fault into the Añasco Valley where geomorphic expression of possible faulting was identified in aerial photographs (Figure 4). The seismic data were gathered using a shoot-through acquisition method with a BETSY-Seisgun shooting source consisting of 8-gauge, 400 grain shotgun blanks set in holes drilled about 30 cm below the ground surface. Both lines had shot and geophone spacings of 5 m. Common Depth Point (CDP) spacings for both lines were 2.5 m in the shallow section of the profiles. Results from those surveys revealed numerous disruptions of sediment layers in the subsurface. These were interpreted as possible faults, some of which extended from depth (1000+ m) to the surface. (M. Rymer, pers. comm., 2004; Zachariasen et al., 2005; Rymer et al. 2005)

Results

This investigation was designed to examine the Cerro Goden fault for definitive evidence for or against Holocene activity by excavating paleoseismic fault trenches across the projection of the Cerro Goden fault into the Añasco Valley. We used the results from the seismic surveys to site six trenches where the seismic data indicated fault strands disrupted sediments within the upper 2-3 meters. We excavated two trenches in 2004 at the Escuela site as part of a previous project, and in 2005, reexcavated and deepened one of those trenches and excavated 4 more trenches at the Heno site as part of the current project. All trenches were gridded with a 1-meter-spacing string grid and logged on graph paper at a scale of 1:20. All the trench logs appear as figures in the report; unit descriptions are included in the figures or in the Appendix. The results from the trenches are discussed in the following sections.

Escuela Site

The Escuela site was located at the eastern end of the Añasco Valley, less the a kilometer from where the Cerro Goden fault cuts through some low hills before entering the relatively narrow gorge of the Rio Añasco as it traverses the mountains and ultimately joining the Great Southern Puerto Rico fault zone. The site was a vacant field that had probably once been used for growing sugar cane but was fallow during the investigations. We excavated two trenches at this site.

Escuela 1 [ES1] trench

Trench ES1 was sited to span the northernmost feature identified as a possible surface fault in the seismic data at the Escuela site (Figure 5). It was 25 m long and up to 4.5 m deep, and oriented, along the trend of the seismic line. The trench log appears in Figure 6. The trench exposed a sequence of Holocene debris flows (gravelly units with unit numbers less than 200), probably derived from hills to the north, interspersed with quiet water sediments (fine sediments with unit numbers less than 200) overlying probably Pleistocene weathered red clay and gravel (units 200 through 225).

No fault was exposed in the trench. However, the red clay was exposed only in the southern end of the trench where it formed a north-facing scarp buried by the overlying sedimentary package. There was no scarp evident at the surface above the buried scarp. The clay was largely massive with lenses of coarse, highly weathered gravel. The lateral extent of the gravel lenses was limited, making it difficult to assess if these sediments were folded, although gentle warping evident in some gravelly lenses nearest the scarp face (units 210 and 215) suggests they may be. The trench site is relatively far north of the current Añasco River, the debris flow units exposed in the trench appear to have come from the north, streams that drain the mountain are generally only a few meters wide, and we found no evidence to suggest any flow that would support that the east-west-trending scarp is a channel edge. It may be that the mountain-front-facing hill, which occurs at the disruption site identified in the seismic study, could have been upthrown by faulting, creating an uphill-facing scarp which has subsequently been buried by Holocene sediments.

We acquired a number of samples of charcoal and organic rich sediment for radiocarbon dating from trench ES1. Given the absence of faulting or evidence of folding within the sediments stratigraphically above the red clay, we were interested primarily in obtaining the age of the oldest deposits. We submitted charcoal samples from deep in the section but none had sufficient carbon to provide an age. Consequently, we submitted two samples, PR04ES1-26 and PR04ES1-27, of organic-rich silt from units 190 and 100, respectively. These had conventional radiocarbon ages of 3890 ± 40 BP and 2330 ± 40 BP, respectively (Table 1). We were unable to obtain an absolute age for the red clay and gravel unit, but the degree of weathering suggests it is Pleistocene. If the hill formed in this material is in fact a scarp or fold formed by faulting that is deeper than the exposure of the trench, the deformation has occurred since the Pleistocene, but not within the last 4000 years at this trench site.

Escuela 2 [ES2] trench

Trench ES2 was initially excavated in 2004; in 2005, we reexcavated and deepened the trench. It had a trend of N20E and spanned the projection of the southernmost feature identified as a possible surface fault in the seismic data at the Escuela site (Figure 5). The initial excavation was 18 m long and about 3 m deep; the reexcavation extended the depth to about 4.5 m in the central part of the trench. We logged the entire western wall and the central section of the eastern wall. The trench log appears in Figure 7.

The initial excavation exposed a sequence of fine Holocene sediments that are largely fluvial channel and overbank deposits (unit numbers less than 200) juxtaposed across a sub-vertical boundary against weathered red clay with gravel lenses similar to that exposed in the southern part of trench ES1 (units 210 through 240). The red clay and gravel units were truncated at the subvertical contact with the fluvial sequence. They fluvial deposits were generally flat-lying through most of the trench but commonly ramped upwards and thinned or pinched out within the last meter from the contact with the red clay. Along the contact and within the deposits on both sides of the contact were a series of subvertical seams of grey clay and occasional pebbles or pods of gravel. The contact was less simple on the east wall of the trench. Exposed in that wall were the same basic types of deposit, red clay and gravel against brown-grey Holocene deposits, but a large, irregularly shaped block of poorly sorted gravelly clay and gravel with a clay matrix was present within the brown-grey fluvial deposits near the base of the trench. The main subvertical contact had a strike of N15W across the trench.

Our initial interpretation of the exposure in trench ES2 was that the red clay and overbank deposits were probably in fault contact, although we could not identify specific fault planes with clear evidence of shearing and there were no units present on both sides of the contact that were unequivocally offset. Nevertheless, truncation of beds, bending of Holocene beds as they approached the contact, vertically rotated pebbles, and clay seams that could be developed along shear planes suggested that the vertical contact was likely a fault that had displaced Holocene sediments, although we could not rule out the possibility that the stratigraphic relations were fluvial. Furthermore, the contact was located at the surface projection of the discontinuity identified in the seismic data. The block of gravel exposed in the east wall, we speculated could have been a block of material disrupted within the fault zone. We concluded that Holocene activity of the Cerro Goden fault at this site was likely but not certain.

The uncertainties in this interpretation and the fact that a fluvial origin had not been ruled out led us to reexcavate and deepen the trench in 2005 to further expose the subvertical contact and the stratigraphy on either side (unit numbers greater than 300). The extended exposure revealed in the bottom few centimeters of the trench wall that the vertical contact shallowed to subhorizontal within about 30 cm. Based on the new exposure, we concluded that the contact was probably a buttress unconformity along a channel edge and that there was no evidence of faulting along the contact. The gravel block exposed on the east wall is most likely a chunk of the channel wall that fell into the channel and was buried by later deposition.

We submitted two charcoal samples (PR05ES2-1 and PR05ES2-2) to obtain radiocarbon ages for the oldest sediments exposed in the trench. We obtained no samples from the red clay, so these samples were from the fluvial deposits in the bottom meter of the trench. The conventional radiocarbon ages of the two samples, 920±40 BP and 660±40 BP (calibrated ages of AD 1020-1210 and AD 1280-1400, respectively; Table 1) were stratigraphically inverted for reasons that are unclear. However, both samples yielded ages less than 1000 years, indicating that there has been no faulting at this site in the last 1000 years and that sedimentation rates at this site are on the order of 5 mm/yr.

Heno Site

The Heno site was located in the north-central part of the Añasco Valley, just east of Highway 2 and south of the mountain front (Figures 4 and 8). Located on a large hay farm, this site was flat and primarily grass covered. The water table in this area was fairly shallow (2-2.5 m), which limited the depth of several of the trenches.

We excavated the following trenches in 2005:

<u>Heno 0 [H0]</u>

This north-south-trending trench was 10 m long and about 2 m deep. It was located along the trace of the seismic line and over the southernmost feature identified from the seismic data. During excavation a large fraction of the sediments exposed in the trench were clearly anthropogenic fill consisting of mud, silt, and straw, probably spoil associated with excavation of a nearby irrigation ditch. The trench collapsed over the projected feature during excavation, largely because the unconsolidated and water-saturated fill was too weak to stand even long enough to place shores. We abandoned this trench and excavated parallel trenches about 40 m west (H4) and 100 m east (H1). We did, however, observe weathered red clay exposed in the southern end of the trench juxtaposed against grey-tan and dark grey silts and clays in the northern part of the trench.

<u>Heno 1 [H1]</u>

Because of the presence of artificial fill in trench H0, which we determined was dredged from the irrigation ditch about 20 m east of the trench, we decided to excavate a parallel trench well away from the area that might be covered with deep fill. We excavated this trench about 100 m away from H0, on the other side of the ditch, centered on the projection of the feature on the seismic line along our best estimate of the fault strike. Given our uncertainty about the strike, we extended the trench on either side to encompass a wide range of strike projections. The resulting trench had a north-south trend and was 52 m long and about 2 m deep. The depth was limited by the relatively shallow water table. We logged the entire west wall and a 4 m long section of the east wall where a deep fissure was exposed. The trench log appears in Figure 9.

Trench H1 exposed a series of unfaulted, horizontally-bedded fluvial deposits. The basal unit, exposed only in the southern 30 m of the trench, comprised orange highly weathered clayey silt to silty clay. This unit appeared similar to the red Pleistocene clay exposed in the Escuela trenches although the color was less deep, more orange than red, and the silt:clay ratio was higher in H1. In the southern 15 m of the trench, the upper surface of this unit was overlain by a 15-30-cm thick, dark brown silty clay unit that we interpreted as a probable paleosol developed into the top of the orange clay. The uppermost unit overlay the paleosol in the southern end of the trench, directly overlay the orange clay in the middle of the trench, and was the only unit exposed in the northern 20 m of the trench. This unit was a very dry, tan, sandy silty clay with numerous sand lenses that became increasingly silty toward the surface.

The orange clay unit dipped slightly south in the southern end of the trench, was subhorizontal in the middle and pinched out abruptly to the north along a steep north-dipping contact with the overlying tan unit. The orange clay thus formed a north-facing subsurface scarp overlain by younger fluvial deposits and with backtilt to the south. This buried scarp is similar to that present in the red clay in trench ES1. Similarly too, if this contact represents a channel edge, it is a channel that trends highly obliquely to active channels in the area, which drain the mountains to the north and run approximately north-south, and there is no evidence of the opposite channel edge in the northern 20 meters of trench exposure. Thus, there is a possibility that this subsurface scarp in orange, possibly Pleistocene clay is also a tectonic feature overlying a buried fault.

The paleosol developed in the highly weathered orange clay also suggests possible deformation of the orange clay. The paleosol paralleled the surface of the underlying clay as expected and dipped south, along with the surface of the clay, in the southern end of the trench, However, the paleosol was present only on the southern, back edge of the scarp, and was missing from the northern, relatively horizontal section of orange clay. Since it is likely that the soil developed over the entire surface of the orange clay when it was at the surface, the fact that it is not preserved as a paleosol along the entire buried orange clay surface suggests erosion could have stripped the soil off the scarp after it was uplifted.

We submitted two samples of charcoal from trench H1 for radiocarbon dating. A sample (PR05H1-20) from the tan silty clay had a conventional age of 240±40 BP and calibrated age between AD 1530 and 1950 (Table 1). A sample (PR05H1-2) from the paleosol yielded a conventional age of 130±40 BP and calibrated age between AD 1660 and 1950 (Table 1). The radiocarbon age from the paleosol, then, would suggest that if tectonic uplift had created the scarp and caused stripping of the soil from the surface, that deformation occurred after 1660. This timing is not supported by the (limited) data from other trenches. The dates here, although poorly constrained, also suggest high latest Holocene sediment accumulation rates on the order of 5 mm/yr at this site too.

<u>Heno 2 [H2]</u>

We excavated this trench about 500 m north of trench H1, on the trace of the seismic line, and over a feature identified as a discontinuity in the seismic data. The trench was 14 m long and about 2.5 m deep. We logged the west wall of the trench at 1:20 scale. The trench log appears in Figure 10.

Trench H2 also exposed a series of largely flat-lying fluvial deposits comprising primarily clay with some silt, sand and sparse gravel. The sediments have undergone soft-sediment deformation, but there was no indication of faulting in the trench.

We submitted one sample (PR05H2-1) of organic-rich sediment from a dark-grey to black silty clay layer about one meter below the surface for radiocarbon dating. It had a conventional radiocarbon age of 600±60 BP and calibrated age of AD 1280-1430 (Table 1). This indicates that at this site, there has been no surface faulting or measurable folding in the last 600 years and probably the last ca 1500 years, if sedimentation rates have been constant at about 1.5 mm/yr.

Heno 3 [H3]

We excavated this trench about 20 m north of H2, across another feature identified as a possible fault in the seismic data. The trench was about 20 m long and 2.5 m deep. Stratigraphy in H3 was similar to that in H2 and also showed no evidence of faulting. We did not log this trench, but photographed the west wall. A photomosaic showing the undeformed sediments appears in Figure 11.

Heno 4 [H4]

We excavated this trench parallel to and about 40 m west of H0. The rationale for excavating this trench was that a trench closer to the seismic line than H1 might expose the features revealed in the seismic data. This trench was 30 m long and 2.5 m deep. A shallow water table limited the depth of the trench. The trench log appears in Figure 12.

This trench exposed similar deposits to those in trench H1. The bulk of the exposure was the uppermost unit, a thick layer of tan-grey massive silty clay with orange mottling and containing manganese nodules in varying concentrations. In the northern two-thirds of the trench, this unit overlay dark-grey to black organic-rich clay and clayey silt with layers of peat and clay containing abundant woody material. In the southern third of the trench, the grey to tan clay underlying the uppermost silty clay was less dark and organic-rich and itself overlay a weathered orange clay similar to that exposed in the southern part of trench H1 and also to the red, probably Pleistocene, clays exposed in the trenches at the Escuela site (Figure 13). The orange clay here also formed a north-facing scarp in the subsurface, although in this trench the contact with the overlying units was highly irregular, with a nearly vertical step at about station 27.5 before sloping off more gently north of station 24.

We submitted three samples for radiocarbon dating from this trench, all of which were very young (Table 1). A peat sample (PR05H4-3) from unit 100 in the northern end of the trench (Stn. 3) had a conventional radiocarbon age of 320 ± 50 BP and a calibrated age of AD 1450-1660. A wood sample (PR05H4-6) from the same unit just south of the cave-in (Stn. 9) had a nearly identical age, with a conventional age of 340 ± 40 BP and a calibrated age of AD 1450-1650. A wood sample (PR05H4-16) from a sandy lens in unit 85, which overlies unit 100, had a slightly older, out-of-sequence, conventional age of 610 ± 40 BP, calibrated to AD 1290-1420. The inverted ages could be due to PR05H4-16 not being buried and incorporated into the sediment as rapidly as PR05H4-6. In spite of the inversion, all three ages suggest that the deposits in this trench are young, less than 700 years old, and have not experienced a surface rupturing faulting event in that time. The depth and age of these samples suggests sediment accumulation rates on the order of 4.5 ± 2 mm/yr.

Discussion

Trenches

We found no faults exposed in any of the trenches we excavated at either the Escuela or Heno sites. All trenches at the Heno site revealed a suite of unfaulted, horizontally-bedded fluvial deposits. The deposits were primarily fine-grained, silt and silty clay, with sparse sand and gravel lenses. Most of the sediment was grey and brown, often with orange mottling, and several of the trenches also contained dark grey to black organic-rich horizons that suggest the now-arid area may have contained ponds or swamps at various times in the past. In addition, the three southernmost trenches (H0, H1, H4) contained a basal unit of red-orange weathered clay to clayey silt. The northern Escuela trench (ES1) exposed a series of debris flow and quiet water sediments overlying highly weathered deep red Pleistocene(?) clay. The younger sediments included debris flow units probably derived from the mountains to the north as well as quiet-water sediments that probably accumulated in a pond or swamp. The southern Escuela trench (ES2) included fluvial channel and overbank deposits juxtaposed across a buttress unconformity against the weathered red clay.

In both trench ES1 and the trenches located at the southern end of the Heno seismic line (H0, H1, and H4), the uppermost fluvial and quiet-water sediments overlie and bury a subsurface mountain-front-facing scarp formed in the highly weathered red-orange clay. If the scarps in the three Heno trenches are the same scarp, they form a linear, approximately east-west-trending scarp subparallel to the mountain front. It is possible that a fault (or faults) that has not cut through to the surface exists below the floor of trenches and has had a component of south-side-up displacement that has created the scarps at both Escuela and Heno. An alternative explanation for the scarps is that they represent one edge of channels incised into the clay and subsequently filled in with fluvial and pond deposits. If that is case, there should be another channel edge north of the one(s) exposed in our trenches. No such edge appeared in any trench. Furthermore, if the scarps are the edges of channels, the channels are very broad; flat-lying sediments were exposed for at least 20 m north of the scarp in trench H1with no sign of another channel edge, nor indication that the sediments were approaching a channel edge to the north (pinching out, rising up, etc.) Finally, the exposed scarps all occurred approximately above the projection of a disruption identified in seismic data. Thus, whereas we cannot rule out a fluvial origin for the mountain-facing scarps, there is some indication that they could be tectonic features, created by a buried fault.

<u>Radiocarbon</u>

The radiocarbon dates are all late Holocene (Table 1). The samples with the oldest ages (PR04ES1-26 and PR04ES1-27) come from trench ES1; they have conventional radiocarbon ages of 3890 ± 40 BP and 2330 ± 40 BP, respectively, which yield calibrated age ranges of 2470-2200 BC and 420-370 BC, respectively. The oldest dated samples in trench ES2 have calibrated ages of AD 1020-1210 and AD 1280-1400. The two ages from this trench are stratigraphically inverted, so clearly there are some complications with the dating. At the Heno site, some samples are also out of order, but they are also very young, all less than about 700 years. Obviously, sedimentation rates are high here, on the order of 5 mm/yr at most sites. Consequently, the absence of faulting exposed in the trenches, which are mostly 2-3 m deep, does not preclude that the Cerro Goden fault has been active even in the late Holocene. However, it does indicate that, if the trenches are in fact located over traces of the fault, it has not ruptured to the surface in the past ca. 600 years.

<u>Seismic data</u>

Because the geomorphic signature of the Cerro Goden fault is indistinct, we had used the results of the two USGS seismic reflection surveys to site our trenches. According to the interpretation of the data we obtained, there were disruptions of the sediment at several locations that extended from depth (ca 1000 m) all the way to the surface. We chose those locations to excavate our trenches. We found no fault in any trench. This brings into question the applicability of high-resolution seismic reflection and refraction for locating faults at the trench scale, since trench depths are at the limit of the precision of the seismic data. There were irregularities in the trenches at approximately the location of the disruptions in the interpreted seismic data. The coincidence of a disruption with the channel edge in trench ES2 is fortuitous; a channel edge does not continue to several hundred meters depth. The scarps in weathered clay, however, may not be channel edges but rather scarps over buried faults, which in turn could be the features identified at depth in the seismic data. In that case, the seismic data have allowed accurate location of faults in space, with just the vertical extent in question. Conversely, there could be problems with the seismic data and/or interpretation that led to our not excavating the trenches over the faults at all. In that case, we found no fault not because our trenches were too shallow to expose it, but because the trenches were mislocated relative to it.

Non-technical summary

We excavated several trenches across possible traces of the Cerro Goden fault in the Añasco valley of western Puerto Rico to investigate the Holocene earthquake history of the fault. We found no fault in any of the trenches, although a subsurface scarp in several trenches may have been caused by displacement on a buried fault. The sediments in the trenches are young, in all but one trench less than 1000 years old; the oldest sediments in the last trench were as old as 4500 years. If the trenches were accurately located over fault traces, this indicates that those traces have not experienced surface faulting in at least the past few hundred years, and in one trench within the past several thousand years.

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Table 1: Radiocarbon Ages

Site/Trench	Sample Name	Material	Measured Radiocarbon Age	Conventional Radiocarbon Age	Calibrated Age (AD)	13C/12C ‰
Heno						
H1	PR05H1-2	charcoal	150 ± 40 BP	130 ± 40	1660-1950	-26.5
H1	PR05H1-20	charcoal	300 ± 40 BP	240 ± 40	1530-1560 1630-1680 1740-1800 1930-1950	-28.8
H2	PR05H2-1	organic silt	560 ± 60 BP	600 ± 60	1280-1430	-22.7
H4	PR05H4-16	wood	630 ± 40 BP	610 ± 40	1290-1420	-26.2
H4	PR05H4-6	wood	420 ± 40 BP	340 ± 40	1450-1650	-29.7
H4	PR05H4-3	peat	240 ± 50 BP	320 ± 50	1450-1660	-20.5
Escuela						
ES1	PR04ES1-15	charcoal		Not enough C		
ES1	PR04ES1-21	charcoal		Not enough C		
ES1	PR04ES1-29	charcoal		Not enough C		
ES1	PR04ES1-26	organic sediment	3760 ± 40 BP	3890 ± 40	2470-2270 BC 2260-2220 BC	-17.0
ES1	PR04ES1-27	organic sediment	2200 ± 40 BP	2330 ± 40	420-370 BC	-17.0
ES2	PR05ES2-1	charcoal	940 ± 40 BP	920 ± 40	1020-1210	-26.3
ES2	PR05ES2-2	charcoal	670 ± 40 BP	660 ± 40	1280-1400	-25.8

Appendix: Unit Descriptions

Trench ES1

10 brown clayey silt; sparse pebbles; brick?; tilled zone and A-horizon; loose, crumbly
20 sandy silty clay; orange-brown; B-horizon?; 10YR 4/6
30 silty dark brown-grey clay with Mn-staining; sparse very fine to coarse sand; 10YR 3/1
40 light grey with orange mottling; silty clay with sparse pebbles and gravel lenses (unit 45); Mn nodules; 10YR 5/8 mottled with 10YR 7/1
45 pebble gravel; occurs as pods and stringers in unit 40
50 light grey clay; some orange mottling; finer than unit 40; 10YR 7/1
60 gravel; angular small pebble in sandy clay matrix; poorly sorted; pebbles moderately weathered; orange weathered pebbles; orange brown matrix; clasts to 1 cm, occasional to 4 cm; 10YR 5/8 mottled with 10YR 7/1
70 silty very fine sand; slightly sandier in middle section than to north and south; grey with dense orange mottles; more orange where sandier
72 slightly sandy silt; grey with orange mottling; distinction from unit 70 clear at Stn. 4, becomes indistinct southward
75 grey silty clay with abundant Mn-staining
80 gravel; similar to unit 60; fines to south and pinches out
90 silty very fine sand at northern end; fines south to sandy silt and siklt; medium grey with moderate orange mottling; 10YR 5/8 mottled with 10YR 7/1
100 black clay; 7.5YR 2/0
110 grey clay with red mottles; occasional pebble
120 black clay; some root casts and dessication cracks infilled with lighter grey clay; 10 YR 3/1 at Stn. 3
130 grey clay with moderate orange mottling; merges with units 120 and 140 at Stn 8; combined unit is 10YR 5/1 at Stn 11
140 dark grey to dark brown to black clay with abundant grey and orange mottling
150 light grey slightly silty clay with abundant orange mottling; occasional siliter lenses; abundant subvertical gleyed zones; 10YR 5/8 mottled with 5Y 6/1
160 grey clay, similar to 150 but with less orange mottling; 5Y 6/1 mottled with 10YR 5/8 at Stn. 11; 10YR 6/1 mottled with 10YR 5/8 at Stn. 4
170 black clay; 10YR 2/1; merges with 190 at Stn. 12, where combined unit is 10YR 3/2
175 gravel in dark grey clay; mix of characteristics of 170 and 180
178 red and grey mottled sandy silty clay to silt with few pebbles; includes lenses of grit and coarse sand; fines upward to clay; to south, grit and pebbles decrease; 5Y 6/1 mottled with 10YR 5/8 at south end, Stn 12; at north end, Stn. 4, 10YR 5/8 mottled with 5Y 6/8
179 grey and red mottled slightly silty clay
180 very clayey sandy pebble gravel with some cobbles; angular clasts; poorly sorted; clasts often completely weathered; matrix-supported but rich in clasts; mottled red-grey; some green clasts
182 grey and red mottled clay with sparse pebbles
186 dark grey clay; merges with unit 193 into unit 190
188 light grey and red mottled slightly silty clay
189 pebbly gravel
190 dark grey clay; gradational contacts; more defined and darker to south; grey-black and red mottled; sparse small pebbles; merges with unit 170 at Stn. 12; 10.5YR 3/2
193 dark grey clay; merges with unit 186 into unit 190
200 red-grey-brown mottled clay; redder at south end and browner to north; also redder lower in section, browner in upper wall; massive; pebbles to 5 cm scattered throughout, more on northern end in upper 3m; contains lenses and pods of gravel (unit 205); pebbles completely weathered; abundant gleyed root lines and cracks; at south end, 5R 4/3 mottled with 5R 4/6 mottled with 5Y 7/3 mottled with 7.5YR 5/6; at north end, 7YR 3/6 mottled with 5GY 6/1 along subvertical zones
203 gravel; angular; matrix-supported; weathered clasts; matrix orange-brown sandy silty clay; clasts mostly 3-15 mm, occasional to 8 cm; poorly sorted; some clasts contain layered grey clay with small pebbles (rip-up clasts?)
205 gravel; clasts completely weathered; red; clasts subrounded; poorly sorted; clast-supported before weathering
210 small pebbly clay; moderate concentration of pebbles in clay matrix
215 matrix-supported gravel; clasts to 7 cm
217 red mottled clay; similar to 200
220 reddish clay with scattered pebbles
225 clayey gravel

Trench ES2 East Wall

west wall described on Figure 7 trench log

5 bottom of modern A-horizon on north end of trench; includes plow zone
10 brown slightly silty sand; modern A and B horizons; top is plowed
20 silt with sand and some clay; light grey with orange mottling; sandier to north; silty very fine sand at Stn. 11
22 grey sandy silt

25 grey sandy silt at south end; grades northward into silt then sand; indistinguishable from unit 40 and associated coarse sands north of Stn 13
30 very fine sandy silt; orange
40 slightly sandy silt; grey with mottling
45 fine-medium silty sand; fining south; grey
47 medium silty sand
50 slightly sandy silty clay to clayey silt; grey with organics; paleosol
52 grey clayey silt; sometimes indistinguishable from unit 50; coarsens northward
60 silty fine sand, fining up to very fine sandy silt; orange with grey mottles
70 orange silt with grey mottles
74 silty very fine to fine sand; orange with few grey mottles
75 grey silty clay with orange mottles
80 very fine sandy slightly clayey silt; orange with grey mottles; fines up into silty clay
90 clayey silt; orange with grey mottles; fines up to silty clay; from Stn 9.5 to Stn 7, top 10-15 cm is dark brown and organic rich and slopes upward at Stn 7
100 clayey silt fining up to silty clay; orange with grey mottles
101 dark grey clay with charcoal; upper contact well-defined, lower contact very gradational
102 grey silty clay with orange mottles
105 grey clay with orange mottling
110 grey clay
120 silty very fine sand; orange with grey mottles; fines north and merges with 110 at Stn 14
122 orange slightly sandy silt
130 slightly clayey silt; grey with orange mottles
140 medium-coarse sand fining up to fine sand; brown
150 clayey very fine sand; brown with some grey mottling; outlined above by orange-stained silt
160 grey-brown silt; similar to unit 110+130
200 dark brown clayey silt; A-horizon paleosol
210 light brown silty clay; B-horizon paleosol
220 red and grey mottled clay; contains pebble-rich pods
230 pebbly red and grey clay
240 red clayey gravel
300 brownish red clay; less dense than red clays to north
310 reddish clay with pebbles
320 pebbly clay to clay-rich gravel; occurs in pods; much red-brown-yellow clay matrix; weathered clasts
390 weathered yellow-red clayey gravel to pebbly clay
400 deep red mottling in creamy white clay
490 orange-grey mottled slightly silty clay
500 very fine sandy clay
510 grey clay
520 yellow clayey very fine sandy silt
530 yellow very fine sandy clayey silt with scattered pebbles from Pleistocene red clay unit
540 yellow-grey clayey silt, with scattered pebbles
550 grey clay
560 grey and orange mottled clay with slight sand and occasional pebbles; Mn nodules
570 clayey silty very fine sand, coarsens downward to coarse sand with small pebbles

Trench H4

50 tan silty clay at south end of trench grading to slightly silty clay at north end of trench, with medium sand component in middle of trench; color changes to grey downwards; silt decreases downwards; grades to grey clay with orange mottling and little silt at base of unit; Mn inclusions and staining common, decreasing northward; very dry
70 poorly sorted, subrounded clayey sandy gravel; clast supported; clasts to 3 cm, unweathered; strong iron oxidation
75 tan to brown clay with reddish-brown mottles; paleosol?
80 light-grey clay grading to grey clay to south; gradational contact with basal section of unit 50 to north; distinction between units 80 and 50 decreases to north; distinction between unit 80 and underlying unit 100 decreases to south
85 grey sandy clay
100 dark grey to brown to black organic-rich clay; increasingly organic-rich and containing peat at north end of trench; very wet with water streaming from unit at north end; contains horizons of reddish-brown fibrous organic (woody?) material; organic component decreases to south; south of cave-in clay is largely dark grey with few areas containing organics and woody fragments; contains pods of oxidized clayey sand with sparse pebbles (krotovina?) between Stns. 24 and 25;
105 lens of pebbly sand with wood fragments
110 light blue-grey and orange mottled clay
150 grey clay
160 black peat
170 grey clay
200 orange clay; grades into greenish-gray and then grey clay to north (Stn. 24); medium sandy to south, pebbly to north; sharp color change across vertical contact with dark grey unit 100 and very wet at Stn. 27.4; Pleistocene?

Units in other trenches described on trench logs.

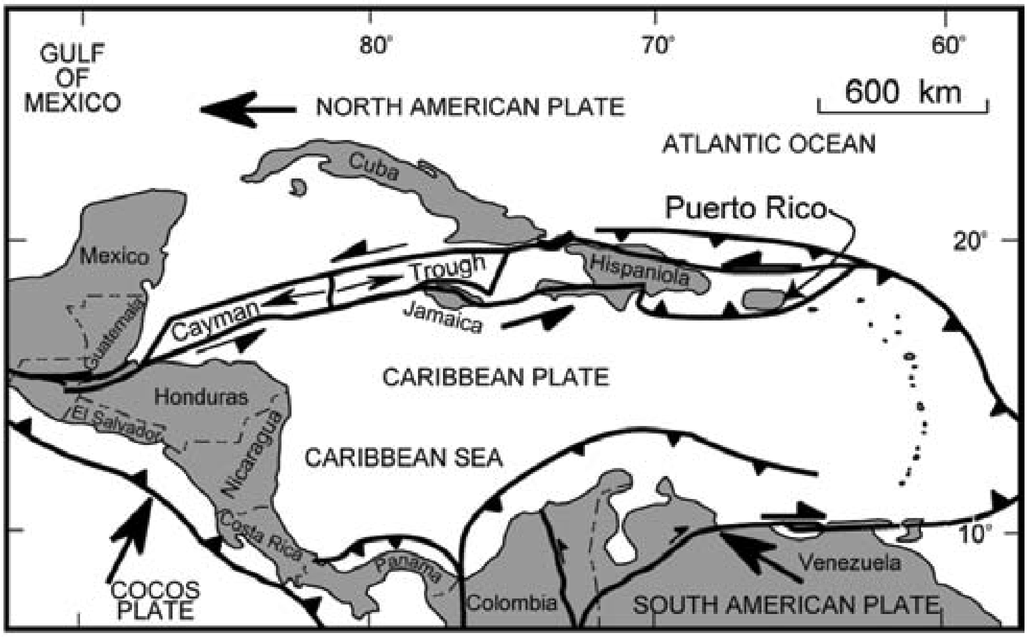


Figure 1. Plate tectonic map of the Caribbean (Prentice and Mann, 2005).

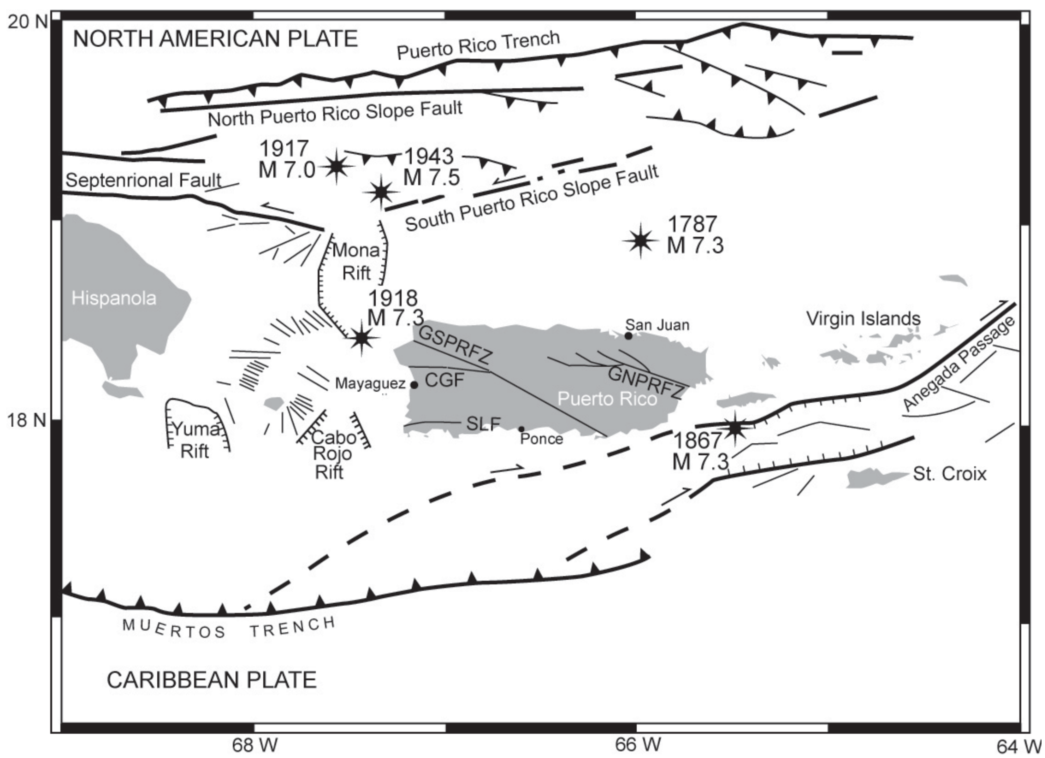


Figure 2. Tectonic setting of Puerto Rico showing major tectonic structures (modified from Jansma et al., 2000, Van Gestel et al., 1998, and Prentice and Mann, 2005). Stars represent approximate locations of epicenters of large-magnitude historical earthquakes. GNPRFZ, great northern Puerto Rico fault zone; GSPRFZ, great southern Puerto Rico fault zone; CGF, Cerro Goden Fault; SLF, South Lajas fault.

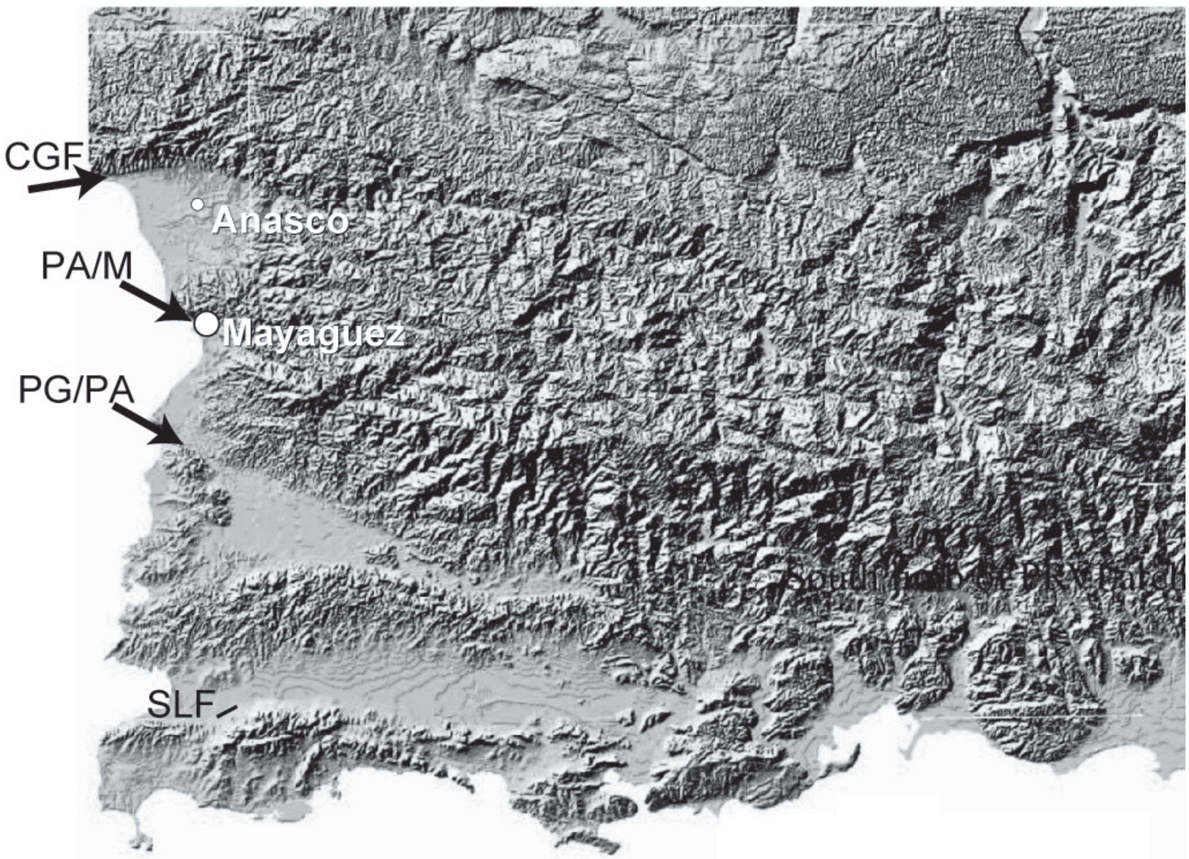


Figure 3. Digital elevation model of western Puerto Rico showing several major faults, including the Cerro Goden fault (CGF), Punta Algarrobo/Mayaguez fault (PA/M) Punta Guanajibo/Punta Arenas fault (PG/PA), and the South Lajas fault (SLF). Mayaguez is the largest city in western Puerto Rico. A detailed figure of the region around Añasco and the Cerro Goden fault appears in Figure 4. Modified from Mann et al. (2005).

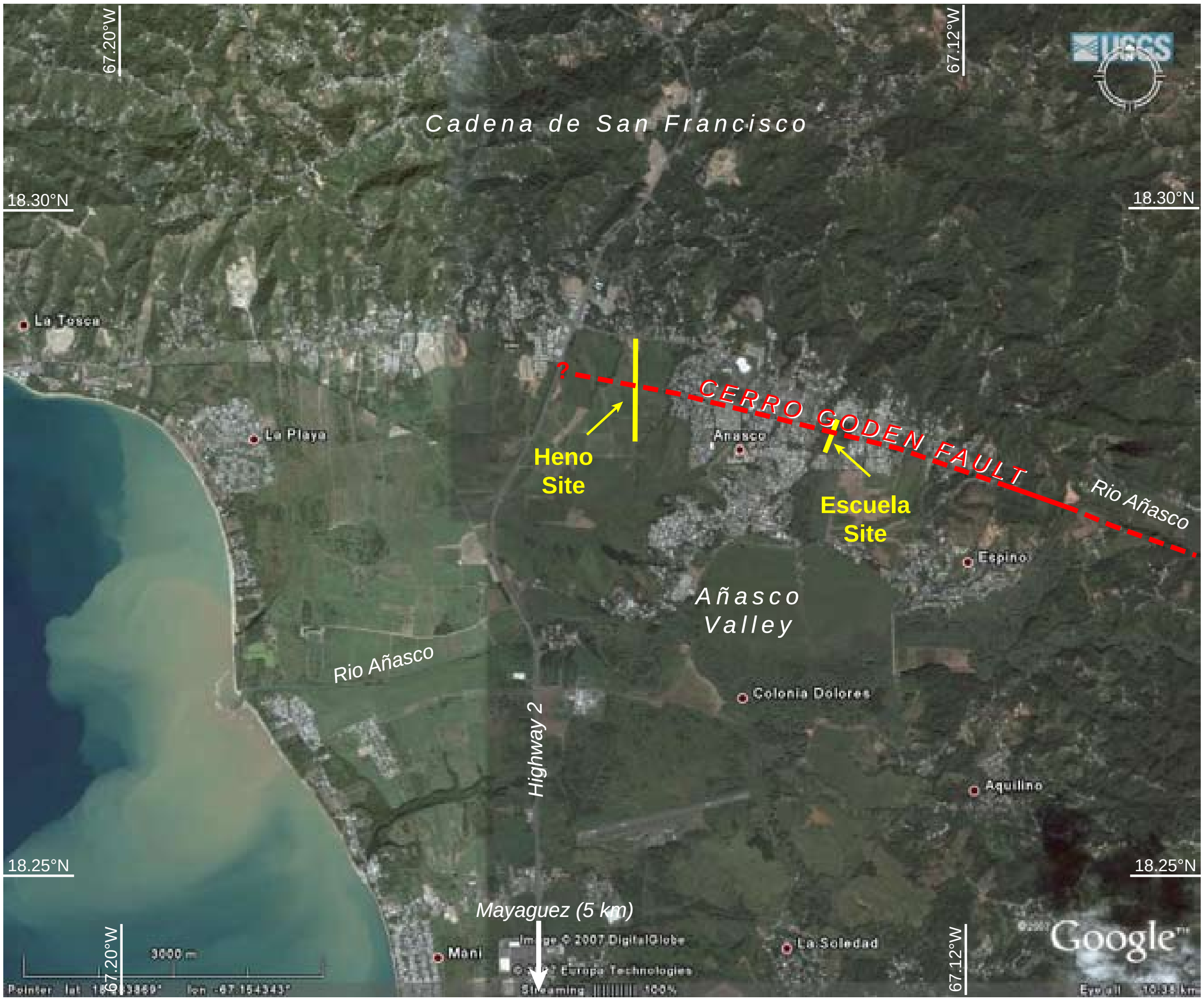


Figure 4. Añasco Valley. Red line depicts the Cerro Goden fault, solid where it occurs in bedrock exposures, and dashed where inferred in Quaternary alluvium. Note that the range front escarpment is several hundred meters north of the mapped fault, implying significant scarp erosion and retreat. Also shown are Heno and Escuela study sites. Image from Google Earth.

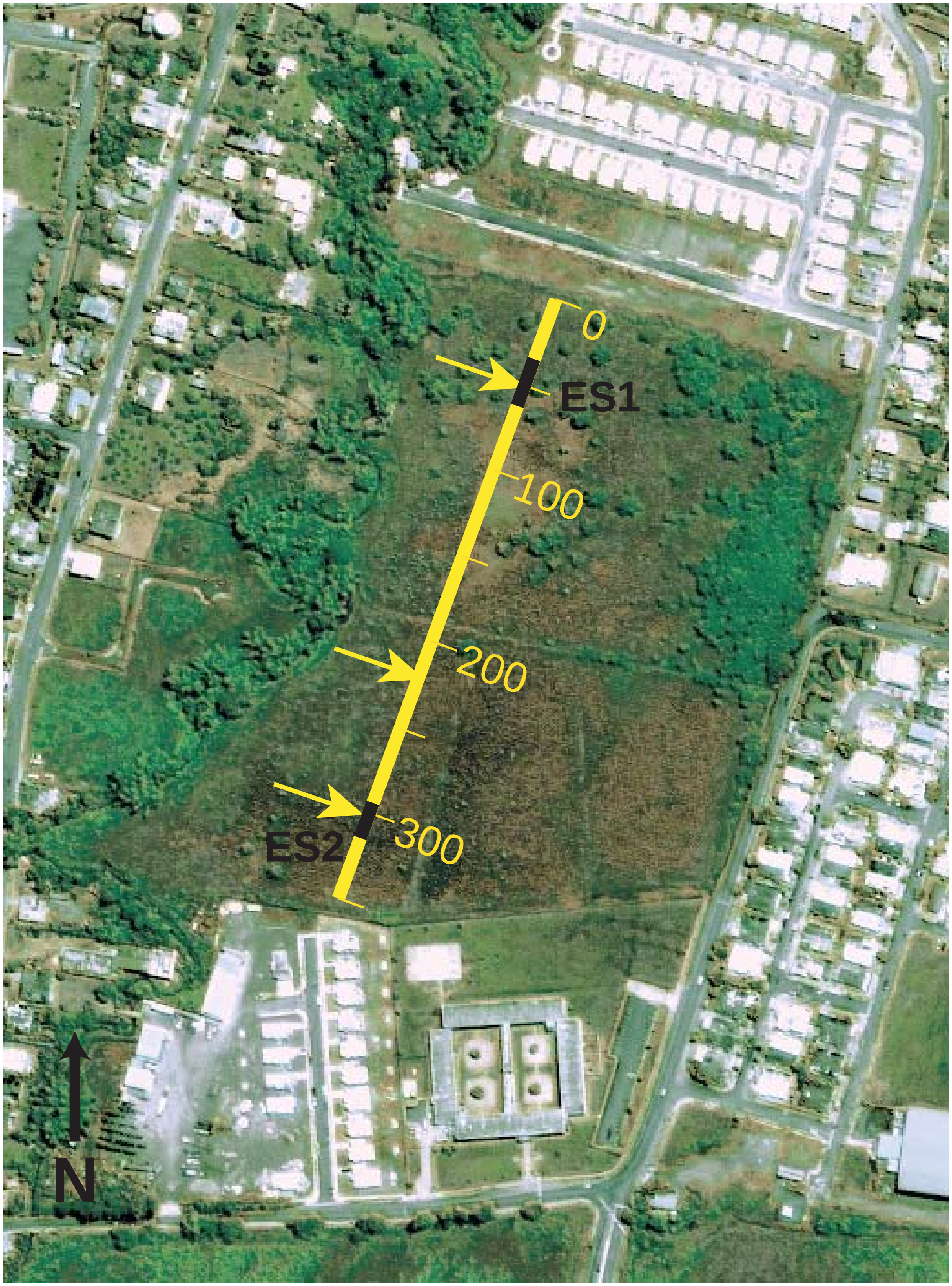


Figure 5. Satellite (IKONOS) image superimposed on 1936 air photo of the Escuela site, located northeast of Añasco. Scale marks seismic line. Trench locations indicated in black.

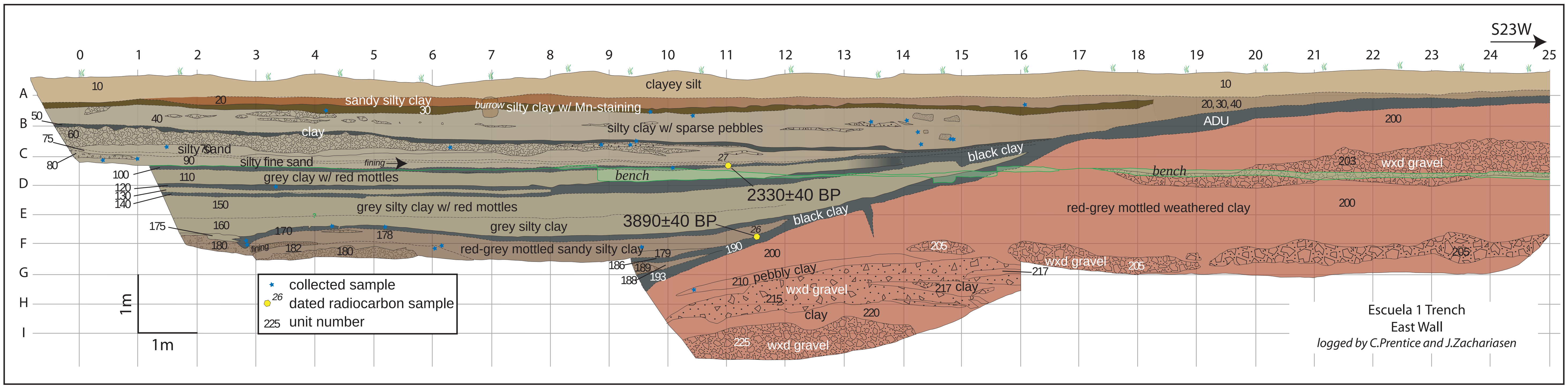


Figure 6. Log of east wall of ES1 trench. Fine-grained fluvial and pond deposits interspersed with debris flow deposits sourced from the north lap onto a scarp developed in weathered red clay. Possible folding of gravel lenses in the red clay remains uncertain; overlying sediments may merely lap onto the scarp rather than having been deformed. Dated samples show conventioanl radiocarbon ages.

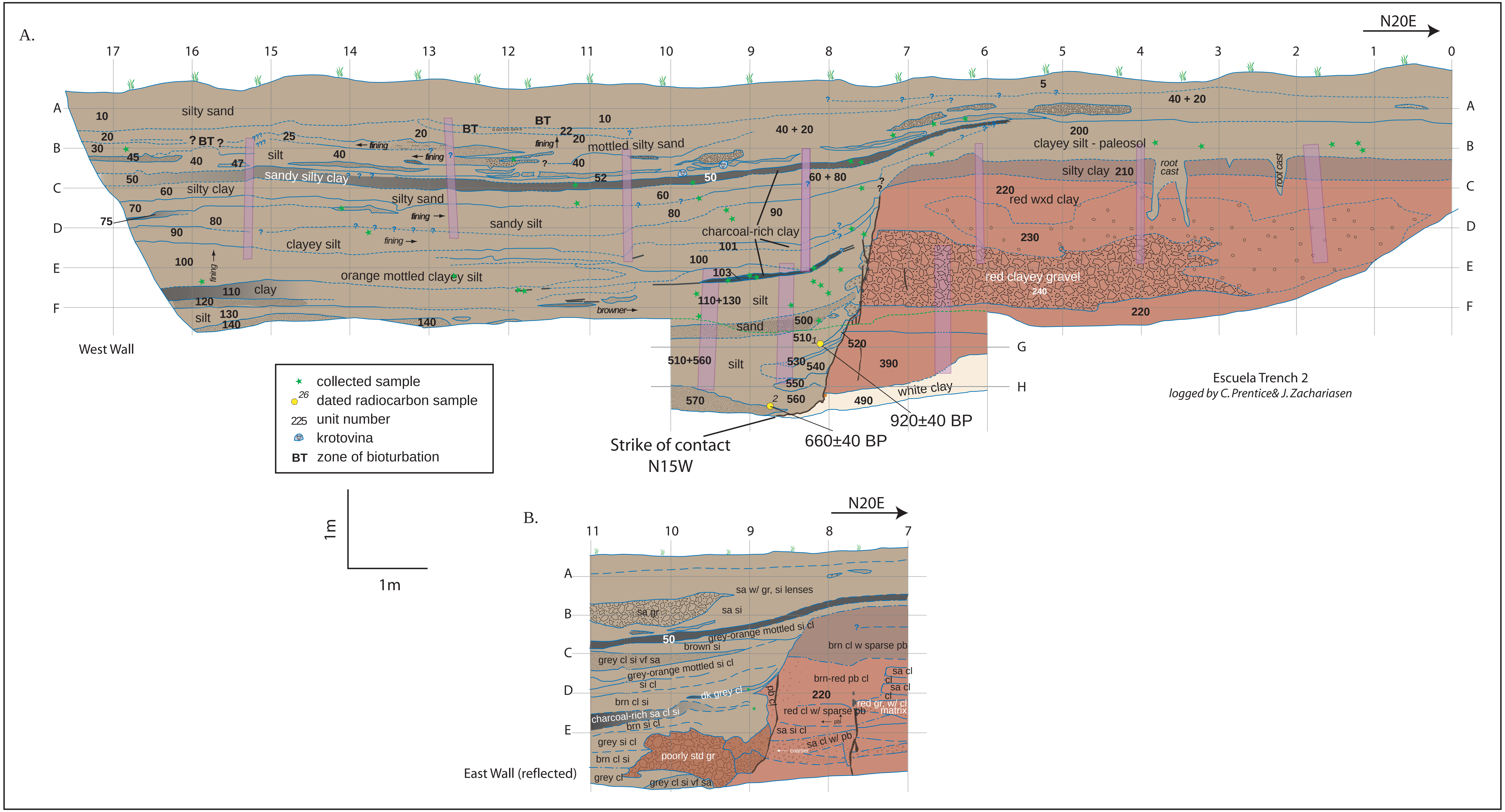
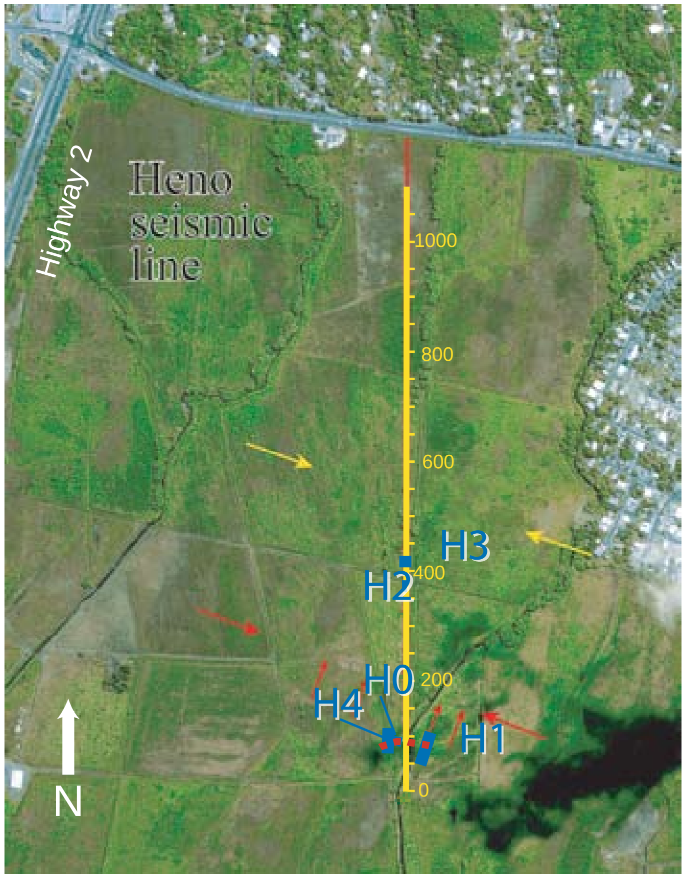


Figure 7. Log of trench ES2. a) West wall of trench. b) Central portion of east wall of trench, exposing subvertical contact between Holocene fluvial deposits and Pleistocene clay and weathered gravel. Dated samples show conventioanl radiocarbon ages.

A.



B.

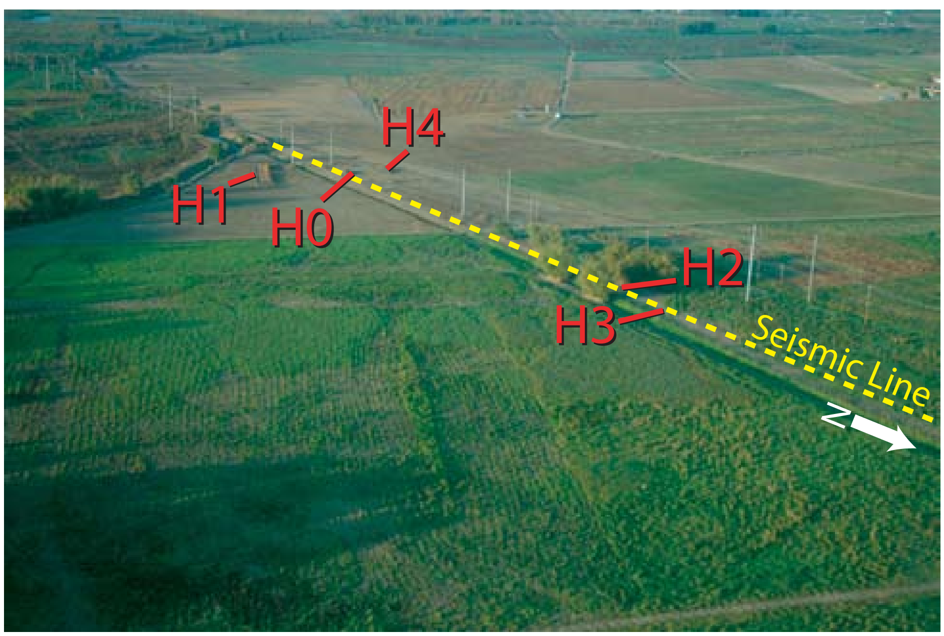


Figure 8. a) Satellite (IKONOS) image superimposed on 1836 air photo of Heno site, northwest of Añasco. Yellow and red arrows mark faint image lineaments. Scale shows seismic line. Dashed red line marks location of subsurface scarp(s). b) Oblique aerial view of the Heno site with trench locations. View is to the southeast

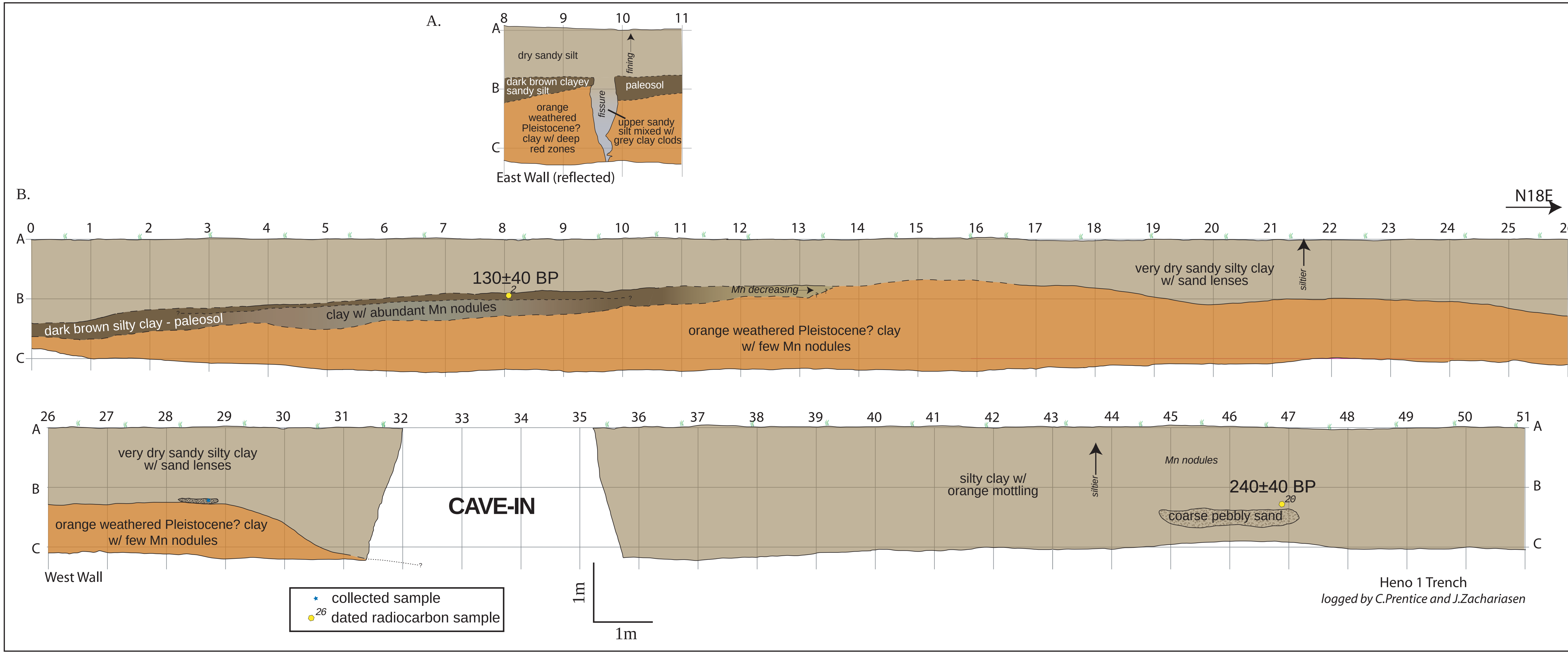


Figure 9. Log of west wall (B) and portion of east wall (A) of trench H1. Radiocarbon ages shown are conventional ages.

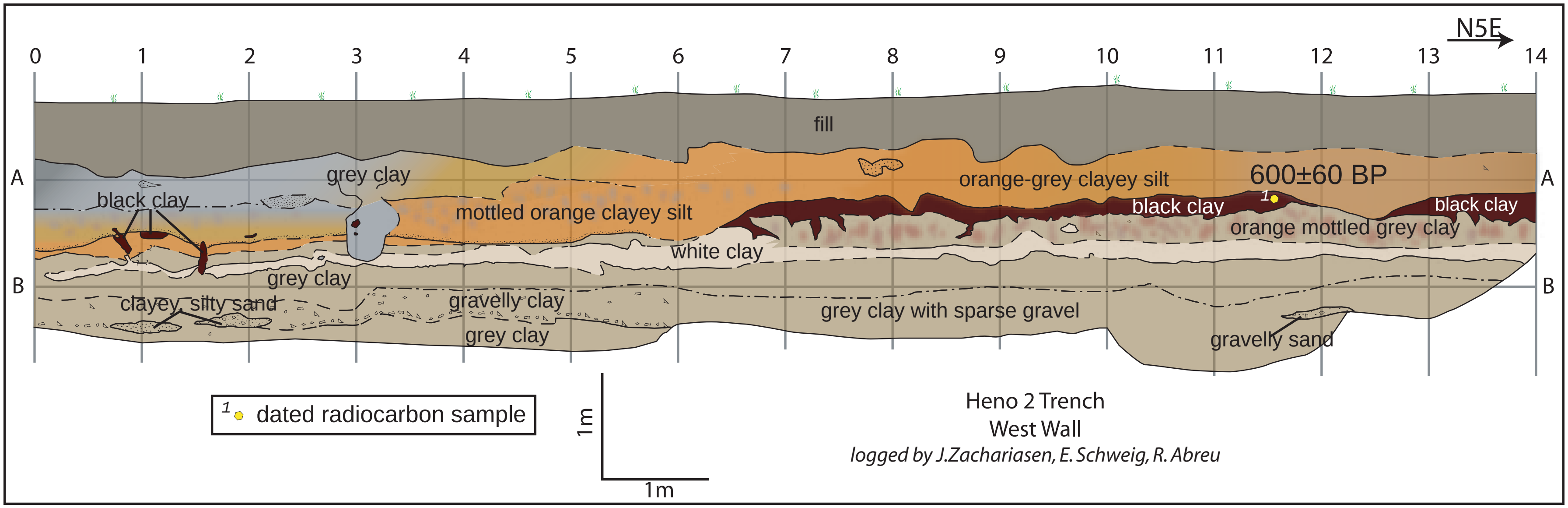


Figure 10. Log of west wall of trench H2. Fluvial sediments have undergone soft-sediment deformation, but there is no indication of faulting in the trench. Radiocarbon age is conventional age.

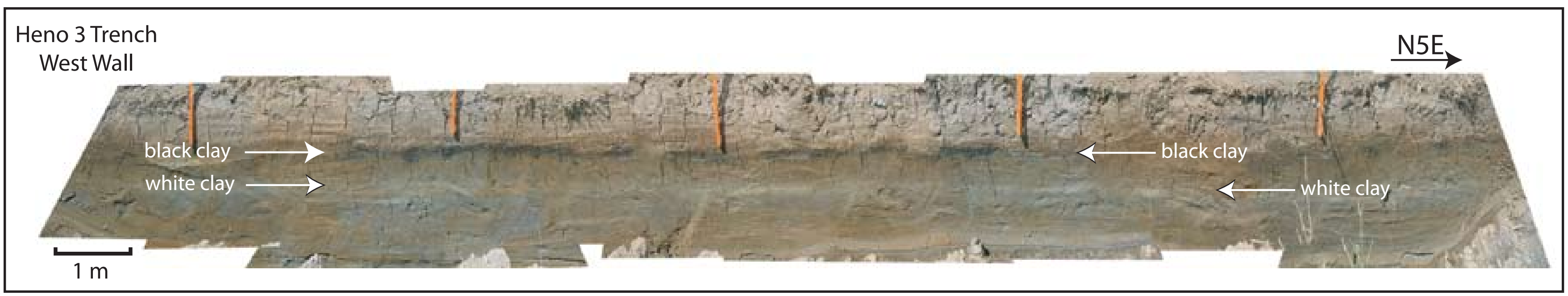


Figure 11. Photomosaic of west wall of trench H3. Deposits in H3 were similar to those in H2 and also showed no sign of faulting.

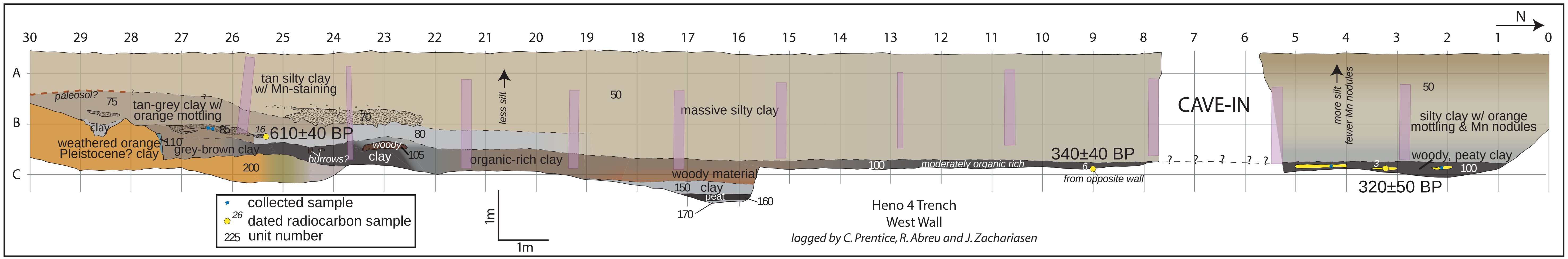


Figure 12. Log of west wall of trench H4. A subsurface scarp developed in highly weathered red clay appears in this trench. It is overlain by fluvial silt, sand and clay, as well as numerous lenses of black organic-rich, woody clay and peat. Radiocarbon ages shown are conventional ages.

Figure 13. West wall of trench H4. View to northwest shows scarp in orange clay and dark grey to black organic-rich clay layers.